* Author presenting Paper

Session: U1-H

ABERRATION CORRECTION
Chair: G. Trahey
Duke University

U1-H-1 510AC 8:30 a.m.
(Invited)

TIME REVERSED ACOUSTICS

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In the field of acoustics, time-reversal experiments may be achieved simply with arrays of piezoelectric transducers, allowing an incident acoustic field to be sampled, recorded, time-reversed and re-emitted. Time reversal mirrors (TRMs) may be used to study random media and reverberating structures. Common to these complex media is a remarkable robustness exemplified by observations that the more complex the medium between the probe source and the TRM, the sharper the focus. TRMs open the way to new signal processings. Acoustic and ultrasonic time reversal mirrors have plenty of applications including ultrasonic therapy, medical imaging, non destructive testing, underwater acoustics, telecommunications and sound control. An overview of these fields will be presented.

U1-H-2 510AC 9:00 a.m.

A NOVEL PHASE ABERRATION MEASUREMENT TECHNIQUE DERIVED FROM THE DORT METHOD: COMPARISON WITH CORRELATION-BASED METHOD ON SIMULATED AND IN-VIVO DATA

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Clinical ultrasound image quality is degraded by tissue velocity inhomogeneities that distort the phase of the traveling wavefronts, degrading image resolution and contrast. Most phase aberration correction methods proposed in the literature use a thin-film phase screen model and follow a three step process: 1) measurement of arrival-time differences between elements; 2) estimation of a thin-film phase screen through an inversion algorithm; 3) correction of the beamforming delays in Receive or Transmit-and-Receive. This paper investigates an entirely new approach for aberration measurement that uses a modified DORT

(French acronym for decomposition of the time reversal operator) method to replace the first two steps of the process. The new approach could provide better aberration estimates where correlation-based methods are weak, such as in areas with multiple strong scatterers. In this novel scheme, the aberration profile is directly estimated from the unwrapped phase of the first DORT eigenvector. The time reversal operator is adapted to a region-of-interest (ROI) imaging mode and is constructed using the individual channel RF signals received from transmissions focused in a given ROI. We term this method Focused DORT (FDORT). We compare the FDORT method with a correlation-based, least-mean-squares (LMS) method using 1-D arrays on: simulated data; experimental phantom data with a thin-film rubber aberrator; and *in-vivo* breast data. Measurements were carried out in regions of speckle and point-like scatterers. Corrections were then performed using a near-field phase screen aberration model. In simulation, the residual rms error (between applied and estimated aberrator) was 12.8ns with FDORT and 8.3ns with LMS; the point target brightness improvement was 94% ($\pm$21%) for FDORT and 102% ($\pm$17%) for LMS. Speckle brightness showed improvements of 39% for FDORT and 42% for LMS correction. The phantom experiments showed 48% ($\pm$28%) and 48% ($\pm$22%) improvements in point target brightness for FDORT and LMS, respectively. In clinical data, microcalcifications were identified and used to estimate the aberrations. FDORT measured an average 153ns rms, 3.2mm FWHM aberrator with an average brightness improvement of 47% (n=3). LMS measured an average 50.2ns rms, 7.0mm FWHM aberrator with an average improvement of 61% (n=3). FDORT is observed to follow wavefront variations, even where LMS does not perform well due to low correlation values. This is particularly evident in the breast data where coherent wavefronts do not extend across the entire aperture. The initial results presented here indicate that FDORT is a useful method to estimate aberrators for adaptive imaging. Although the performance of the FDORT algorithm is not consistent in speckle regions, it works well near point-like scatterers. LMS breaks down in the presence of interfering wavefronts from off-axis and multiple strong scatterers. We see the potential for FDORT to cope with these conditions and thereby estimate aberrations with greater robustness.

U1-H-3 510AC 9:15 a.m.

ITERATION OF ULTRASOUND ABERRATION CORRECTION METHODS

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Aberration in ultrasound medical imaging is usually modeled by time delay and amplitude variations concentrated on the transmitting/receiving array. This filter process is here denoted a TDA-filter. The TDA-filter is an approximation to the physical aberration process, which occurs over an extended part of the human body wall. Estimation of the TDA-filter and performing correction on

transmit and receive, has proven difficult. It has yet to be shown that this method works adequately for severe aberration. Estimation of the TDA-filter can be iterated by re-transmitting a corrected signal and re-estimating until a convergence criterion is fulfilled (adaptive imaging). In the presented work, two aberration estimation methods are investigated in order to obtain qualitative data concerning their convergence in an iterative aberration correction process. Both methods estimate the arrival time and amplitude fluctuations using back-scattered signals from a region of incoherent random scatterers. The estimated arrival time and amplitude fluctuations are then used in a matched TDA aberration correction filter. The first estimation method correlates each element signal with a reference signal. The reference signal is a weighted and modified beam former output of the received signal. The second method use eigenvalue decomposition of the receive cross-spectrum matrix, based upon a receive energy maximization criterion. In order to evaluate the quality of an aberration correction method Mallart and Fink [1] developed a focusing criterion based on the van Cittert-Zernicke theorem. Lacefield and Waag [2] discuss the utility of this focusing criterion since the van Cittert-Zernicke theorem is only valid for distortionless propagation. They calculated the width of the averaged receive coherence function at different levels, as an evaluation of the aberration correction method. Both of these approaches are investigated in this work, in order to evaluate the convergence of the iteration process. Two dimensional simulations of iterating aberration correction with a TDA-filter have been performed to study iterative aberration correction. Aberration was introduced using a weak and strong aberrator, both created to emulate the human abdominal wall. Results show that both methods converge after 2-3 iterations. After convergence, the transmitted aberration corrected beam profiles in the focal plane of the array are very close to correction obtained using a TDA-filter estimated from a point source in the focal point of the array. The results also show that the focusing criterion developed by Mallart et. al. clearly indicates when convergence is reached, whereas the coherence widths are not precise enough. [1] R. Mallart and M. Fink, Adaptive focusing in scattering media through sound speed inhomogeneities: The van Cittert-Zernicke approach and focusing criterion, J. Acoust. Soc. Am., 96(6), pp. 3721-3732, December 1994. [2] J. C. Lacefield and R. C. Waag, Spatial coherence analysis applied to aberration correction using a two-dimensional array system, J. Acoust. Soc. Am., 112(6), pp. 2558-2566, December 2002.
The work presented in this article was supported by the Medicine and Health program of the Research Council of Norway.

U1-H-4 510AC 9:30 a.m.

EXPERIMENTAL COMPARISONS OF THE IMPACT OF ABDOMINAL WALL ABERRATORS ON LINEAR AND NONLINEAR BEAM PATTERNS

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Background: One hypothesis for improved image quality in harmonic imaging is the reduction of the impact of phase and amplitude aberration artifacts. Christopher [IEEE Trans-UFFC, 44, pp.125-139 (1997)] simulated the effects of tissue aberrations on the distributions of energy for the linear and nonlinear field components using a model consisting of dual offset phase screens. **Objective**:The goals of the present work were to quantify the relative impact of aberrations on the linearly propagated fundamental *(1f)* fields, the nonlinearly generated second harmonic *(2f)* fields, and the fields due to linear propagation at twice the fundamental using an effective apodization *(2f-EA)* for in-vitro, finite- thickness, porcine aberrators. **Methods**: Building upon our results presented at previous Ultrasonics Symposia, we used a modified imaging system (ATL HDI5000) to generate two distinct transmit beamforming configurations, a Riesz window apodization at 1.8 MHz [for the fundamental *(1f)* and second harmonic *(2f)*], and the corresponding effective apodization at 3.6 MHz [for the linear effective apodization *(2f-EA)*]. In both cases a 20 mm wide aperture was focused to a depth of 100 mm. Azimuthal field patterns were measured at the nominal focal distance, with and without the imposition of a salt-cured porcine abdominal aberrator. The 12 aberrators were each approximately 4 cm thick and included layers of skin, fat, and muscle. Azimuthal integrations of the average power of the unaberrated and aberrated fields were used to quantify the spread of energy. **Results:** For the unaberrated fields, the 90% levels of total integrated power for the nonlinear second harmonic *(2f)* and the linear effective apodization *(2f- EA)* cases were approximately two-thirds the width of that for the fundamental *(1f)* case. For the fundamental *(1f)*, nonlinear harmonic *(2f)* and the linear effective apodization *(2f-EA)* cases, respectively, the average effect of the abdominal aberrators was to broaden the widths of the 90% power levels to 3.0, 2.6, and 3.8 times the unaberrated-fundamental *(1f)* value. Relative to their unaberrated values the widths of the 90% power levels increased by factors of 3.0, 3.8, and 6.0, respectively. **Conclusions:** The aberrators studied exhibited a 3- fold degradation of the fundamental *(1f)* field. In the presence of these aberrators, the fields generated with the effective apodization *(2f-EA)* are not as good of an approximation to the nonlinearly generated second harmonic *(2f)* fields as they were with a homogeneous propagation path. Both the nonlinearly generated harmonic *(2f)* and the linearly propagated effective apodization *(2f-EA)* fields are more severely impacted by aberrating layers than the *1f* field. In spite of this, however, the nonlinearly generated second harmonic *(2f)* fields remain more compact than the corresponding fundamental *(1f)* fields in the presence of aberrators, consistent with improvements associated with harmonic imaging.
NIH R01 HL72761 & Philips Ultrasound

U1-H-5 510AC 9:45 a.m.

EFFICIENT AND ACCURATE SPLINE-BASED TIME DELAY ESTIMATION

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Time Delay Estimation (TDE) is the process of determining the relative time shift between a reference signal and delayed signal. TDE lies at the core of many modern signal-processing algorithms. In medical ultrasound, TDE is employed in blood flow estimation, phase aberration correction, motion compensation for synthetic receive aperture imaging, tissue elasticity estimation, radiation force imaging, and a number of other algorithms. Because of its central significance, TDE accuracy, precision, and computational cost are of critical importance to these and numerous other algorithms. We have previously presented a highly accurate, spline-based time delay estimator (TDE) that directly determines sub-sample time delay estimates from sampled data. The algorithm uses cubic splines to produce a continuous time representation of a reference signal, then computes an analytical matching function between this reference and a delayed signal. The location of the minima of this function yields estimates of the time delay. In this paper we present a more computationally efficient formulation of this algorithm, which is based on FIR filtering to determine the cubic spline coefficients, and polynomial approximation to determine the time delay estimates. We have performed a series of simulations using ultrasound data to test the performance of this algorithm and compare it to the original spline method. The results show that the bias of the proposed algorithm is about 7 times worse than the original spline-based TDE. However, if compared with the performance of other widely known algorithms, such as normalized correlation and Sum Squared Differences (SSD), the modified spline TDE clearly achieves higher performance. Comparison indicates that the bias of the modified spline TDE is about 2.5 orders of magnitude lower than that of the SSD and normalized correlation coupled with parabolic fitting, and 1.5 orders of magnitude lower than those algorithms coupled with Grid Slopes. Similarly, the standard deviation of the proposed algorithm is comparable with that of the original spline-based TDE across all sub-pixel shifts. Furthermore, at a sub-sample shift of 0.25, the standard deviation of our algorithm is about 10 times smaller than that of the SSD with Grid Slopes interpolation, about 50 times better than that of normalized correlation with spline interpolation, and about 100 times better than that of normalized correlation with either parabolic or cosine interpolation. Furthermore, the proposed algorithm can be particularly useful in applications such as blood flow estimation and tissue elasticity estimation since it can be easily modified to include companding.
We acknowledge the support from the Whitaker Foundation.

Session: U2-H

THERAPY: CAVITATION
Chair: K. Hynynen
Harvard

U2-H-1 510BD 8:30 a.m.

EFFECT OF PULSE PARAMETERS ON CAVITATION AND ACOUSTIC STREAMING IN ULTRASONIC SURGICAL DEVICES

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Over the last 15 years, ultrasonic surgical devices have become the preferred instruments for cataract surgery within the ophthalmologic community. This approach, called phacoemulsification, uses needle tips which vibrate longitudinally at frequencies between 28 and 50 kHz (depending upon the manufacturer). Mechanical impact and inertial cavitation at the tip both act to erode and liquefy the lens material, which is then aspirated out through the needle core. Surgeons have reported that despite the aspiration flow through the needle, which would tend to bring the lens material into contact with the needle tip, lens material seemed to be repulsed from the tip region. It was theorized that acoustic streaming caused by sound radiation from the tip was the reason for this effect. One recent advance in phaco technology was the introduction of microbursts, or very short (less than 5ms) pulse lengths. These short bursts appeared to reduce the repulsion effect, while at the same time retaining the cutting effectiveness of continuous wave (CW) excitation. The purpose of this study was to investigate both the potential acoustic streaming and cavitation effects as a function of burst length. Cavitation was detected using a PVDF bilaminar membrane hydrophone (Sonora Medical System) placed 1.0cm from the tip. By selecting the appropriate time sampling and integration periods, it is possible to derive a relative measure of cavitation energy (energy radiated by inertial bubble collapse). A commercial phacoemulsification system (Sovereign WhiteStar, Advanced Medical Optics) was measured over a series of excitation levels and burst lengths, including CW conditions. The acoustic streaming caused by the tip vibration was detected using an ATL HDI 3000, with L12-5 38mm linear array scanhead. The scanhead was immersed in a water tank and aimed upwards towards the water surface. The phaco tip was submerged to a depth of approximately 1.0cm. By setting the ATL system to Color Flow mode, and adjusting the Flow sensitivity, it was possible to image the flow patterns around the tip. The results of the cavitation study indicated that the short burst mode produced similar levels of cavitation energy as CW mode at the same excursion level, even though the duty cycle was as low as thirty-three percent. The flow imaging study indicated significantly reduced streaming effects in the region of the tip for the short burst mode. For CW, the flow effects completely overcame the aspiration flow into the needle tip, resulting in a net force pushing

the lens material away from the tip region. In summary, this study is the first to demonstrate the different flow patterns caused by acoustic streaming in the region around phacoemulsification tips, and correlate these to burst conditions. Further, the results show that cavitation levels from these short burst modes are similar to CW excitation at the same excursion levels. This matches with clinical results, which indicate superior cutting effectiveness when compared to CW operation.

The support and cooperation of Advanced Medical Optics and Sonora Medical Systems are acknowledged.

U2-H-2 510BD 8:45 a.m.

RELATIVE EFFECTS OF ACOUSTIC NONLINEARITY AND CAVITATION ON THE DYNAMICS OF HIFU LESION FORMATION IN A TISSUE PHANTOM

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Two nonlinear effects are known to significantly influence high intensity focused ultrasound therapy (HIFU): nonlinear acoustic wave propagation and ultrasound-induced cavitation. The respective roles of these two basic nonlinear phenomena in the dynamics of a HIFU induced lesion are not well understood. Both effects may act simultaneously at high acoustic pressure and both are responsible for distortion of the thermal lesion. The effect of acoustic nonlinearity results in formation of shocks and thus in more effective heating of the HIFU focal region. The presence of cavitation also leads to enhanced heating due to nonlinear scattering, thermal diffusion, and viscous damping of bubble oscillations. Effective heating of the focal zone may ultimately result in boiling. The relative importance of these two nonlinear heating mechanisms is studied in this work experimentally and theoretically using a polyacrylamide gel tissue mimicking phantom. A 2 MHz transducer of 40 mm diameter and 45 mm focal length was operated at different powers, and in CW or duty cycle regimes with equal mean intensity. Elevated static pressure of up to 10 MPa was applied to suppress bubbles, increase boiling temperature, and thus to isolate the effect of acoustic nonlinearity in the enhancement of lesion production. Lesion formation in a BSA (bovine serum albumin) loaded acrylamide gel was observed visually in a longitudinal section, and captured on video for later temporal and morphological analysis. These experimental data were compared with the results of simulations performed using a KZK acoustic model combined with the bioheat transfer equation and thermal dose formulation. Typical tadpole-shaped lesion growth back toward the transducer and boiling were observed under standard atmospheric pressure. With adequate overpressure, no boiling was detected and lesions formed symmetrically. Longer lesion inception times were consistently observed with overpressure. This effect was hypothesized to be due to suppressed

microbubble cavitation dynamics in the gel. The effect of acoustic nonlinearity was revealed as a substantial decrease in lesion inception time and an increase in lesion size for high-amplitude waves under both standard and overpressure conditions, in the latter case in the absence of cavitation.
Work was supported by ONRIFO, NASA/NSBRI, NIH Fogarty, and CRDF grants.

U2-H-3 510BD 9:00 a.m.

SPATIAL CONTROL OF CAVITATION: THEORETICAL AND EXPERIMENTAL VALIDATION OF A DUAL-FREQUENCY EXCITATION METHOD

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Cavitation has been implicated as the primary mechanism for a host of emerging applications. In all these applications, the main concern is to induce cavitation in controlled locations in the field; this means specifically to surpass the cavitation threshold at the focus of the transducer while being sub-threshold in the near field. Studies dealing with the excitation waveforms effects on cavitation at the focus have already been carried out. However, none of these works on waveform manipulation for cavitation control study the cavitation properties of the transducers acoustic field outside the focal point. Here we developed dual-frequency methods to preferentially lower the cavitation threshold at the focus relative to the rest of the field. Dual-frequency sinusoidal pressures combined with different phases were tested on a modified Rayleigh-Plesset non-linear bubble model to identify waveform shapes that have lower cavitation thresholds. A bubble model incorporating rectified diffusion was used to predict the cavitation threshold for a given waveform. Once an optimal waveform shape that would lower the cavitation threshold at the focus was determined, the acoustic pressure field generated by a spherically curved phased array transducer to yield that waveform at the focus was computed using the Rayleigh-Sommerfeld integral. In all cases, each frequency was generated by half of the elements. The transducers field was then inputted into the bubble model to determine the relative cavitation threshold (in terms of acoustic pressure and intensity) in the field which we call the cavitation field. A maximum cavitation threshold differential along the transducer axis was achieved by using the previously predicted optimal phase between the 1.2 and 2.4 MHz sine waves which were used as our dual-frequency excitations. These results were then verified by experiment. Our setup consisted of inducing cavitation with a spherically curved 8-sector transducer in a vial filled with mixed water and Optison bubbles. The position of the vial along the transducer axis was then varied to characterize the axial cavitation field. We successfully showed that with this simple phased array, dual-frequency excitations could be used to generate fields where the cavitation threshold intensity is 70 % higher in the near field than at the focus. This cavitation threshold difference supplements the focusing of the transducer which makes cavitation events in the near field even less likely to occur. The cavitation fields developed could be used to tightly

control the site of cavitation near tissue interfaces, blood vessels, or fat which might exhibit lower thresholds and induce unwanted cavitation in the near field of the transducer. This study shows that multi-frequency phased arrays could be used to spatially control cavitation.
This work was supported by grant CA76550 from the National Institute of Health

U2-H-4 510BD 9:15 a.m.

HEATING MECHANISM OF MICROBUBBLES AND BUBBLE PROPERTIES

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In recent years, High Intensity Focused Ultrasound (HIFU) is used in the treatment of cancer, and the medical applications with microbubbles such as ultrasound imaging, sonodynamic therapy have attracted much attention. In the field of the bubble dynamics, it is known that the bubbles can play a role in converting mechanical energy into heat when they are subjected to an acoustic field. If the heating effect of microbubbles is utilized in a well controlled manner, the HIFU treatment can be done more efficiently and less invasively. The heating mechanism of microbubbles in the ultrasound field is discussed and analyzed with both experiment and numerical simulation, extending previous work to include experiments with argon or various gases filled bubbles. It is noted that the dynamics of bubbles are strongly influenced by the internal phenomena such as thermal diffusion, mist formation, heat transfer through the bubble wall. We consider these phenomena and numerically simulate the energies that are radiated from a microbubble, such as thermal conduction and acoustic radiation. Comparing with the thermal energy which is absorbed around the focal region between the case with microbubbles and without them, the energy in the former case is much larger than in the latter case. Next, it is also indicated that the properties of a microbubble, such as the type of gas inside a bubble, bubble radius and the existence of the shell, have a strong effect on the energy emission from the bubbles. The heat depositions from the bubbles with different properties are calculated. As the gas property, the argon (Ar), air and sulfur hexafluoride (SF_6) bubbles are calculated. It is revealed that an Ar bubble deposits heat about 1.5 times more than a SF_6 bubble when the frequency is 1.0 MHz and the amplitude is 100 kPa, because of the difference of specific heat ratio and thermal conductivity. In the experiment, we construct various microbubbles with different gases inside bubbles; Ar, Xe, air, SF_6, C_3F_8 and so on, and analyze the difference of the heating effect of these bubbles. The polyacrylamide gel is placed in the ultrasound field and the gel forms the cylindrical space at the focal region. The liquid with the bubbles which have different gas cores are injected in the space, whose temperature is measured by the thermocouple. Comparing with the temperature rise at the ultrasound focus, the case of Ar bubbles is around 1.8 times larger than that of SF_6 bubbles when the frequency is 1.08 MHz and the output power from the amplifier is 30 W. The tendency is consistent with the results of numerical

simulation. Furthermore, the temperature distribution around the region where various microbubbles exist is measured by the thermal liquid crystal sheet, and the difference of the behavior of heat transfer is observed. From these results, it is determined that the heat energy from the microbubbles can be controlled by changing the kind of gas inside the bubbles. In particular, the Ar bubble deposits the thermal energy effectively, and a microbubble which includes the gas like Ar has a greater potential for therapeutic use.

U2-H-5 510BD 9:30 a.m.

NONLINEAR ULTRASOUND PROPAGATION IN A SPHERICAL BUBBLE CLOUD

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HIFU (High Intensity Focused Ultrasound) medical applications have attracted much attention recently because they are less invasive than the traditional treatments. However, the behavior of acoustic cavitation caused by high pressure amplitude at the focal region has not been clarified. In this study, it is assumed that the acoustic cavitation forms a spherical bubble cloud which consists of many micro bubbles. The nonlinear ultrasound propagation and the collapse of bubbles in the cloud are numerically simulated. In the bubble cloud model, the compressibility of liquid, the evaporation and condensation of liquid at the bubble wall, heat transfer through the bubble wall are taken into account. Initial cloud radius is equal to 0.5 mm, bubble radius is 1 μm, and void fraction is 0.1 %. The irradiated ultrasound wave is a sinusoidal pulse, and its frequency extends from 5 kHz to 10 MHz for amplitudes of 10 kPa, 25 kPa, 50 kPa, 75 kPa, 100 kPa or 125 kPa. The maximum pressures inside the bubbles are calculated under various conditions in the simulation. In case that the frequency is sufficiently low, around 10 kHz, the maximum pressure normalized by the pressure amplitude is nearly equal to 1. This means that the ultrasound doesn't focus in the cloud and the attenuation of the bubbly liquid is negligible due to the long wavelength of the ultrasound. On the other hand, the normalized pressure converges to 0 when the frequency is around or higher than the natural frequency of the single bubble, which is about 4 MHz. This is because the bubble oscillates in opposite phase of the ultrasound and the ultrasound can't propagate in the cloud. In case that the frequency is about 170 kHz $\sim$ 210 kHz, which is almost equal to the natural frequency of the cloud, 220 kHz, the bubble cloud resonates and the normalized maximum pressure becomes very high. The ultrasound propagation in the bubbly liquid shows strong nonlinearity and the shock wave is generated in the cloud when the ultrasound pressure is greater than 75 kPa in these cases. The shock wave in the cloud causes the collapse of the bubbles, so that the high energy is concentrated near the center of the cloud. As a result, the normalized pressure becomes much higher when the pressure amplitude becomes large enough to generate the shock wave. The maximum pressure reaches 400 MPa, in case of 125 kPa pressure amplitude at a frequency,

170 kHz. Additionally, in the case of 100 kPa and 125 kPa pressure amplitudes, even when the frequency is much lower frequency, the shock wave is generated and the high pressures appear. The results indicate that the bubbles inside a bubble cloud violently collapse when the frequency of the irradiated ultrasound is the same or lower than the natural frequency of the cloud at large pressure amplitude of the ultrasound. The effects of the bubble radii distribution and the ultrasound waveform are also discussed.

U2-H-6 510BD 9:45 a.m.

BUBBLE INTERACTIONS IN CLOUDS PRODUCED DURING SHOCK WAVE LITHOTRIPSY

E. A. ZABOLOTSKAYA*, Y. A. ILINSKII, G. DOUGLAS MEEGAN, and M. F. HAMILTON, Applied Research Laboratories The University of Texas at Austin. Corresponding e-mail: zhenia@arlut.utexas.edu

Objective: A new theoretical model, accounting for bubble-bubble interaction, is proposed for bubble clouds produced during kidney stone treatment with shock wave lithotripsy (SWL). The associated cavitation is a mechanism for stone comminution, but the cloud itself may reduce the effectiveness of subsequent shock wave pulses. Since the bubbles in the cloud are close to each other, their interactions can be important. The objective of the work reported here is to identify bubble cloud dynamics, especially bubble interaction in clouds, that inhibit stone comminution. **Methods**: Bubble motion observed in high-speed photographs near a stone (Pishchalnikov et al., J. Endourol. 17, 435, 2003) is studied with a model based on the equations derived by Zabolotskaya (Sov. Phys. Acoust. 30, 365, 1984). Her equations, derived originally for interaction of two bubbles, are generalized to N interacting bubbles. Each bubble thus interacts with all other bubbles. The bubble cloud is placed near a rigid boundary that represents the stone. The presence of the rigid wall is taken into account by introducing a mirror image of each bubble. The initial, three-dimensional spatial distribution of bubbles is determined by letting their coordinates be uniformly distributed random variables. The nonlinear dynamic equations for N=100 bubbles were solved numerically with a Runge-Kutta algorithm. A negative pressure corresponding to a typical SWL pulse is applied, and the bubbles start expanding. When two bubbles come in contact, they are merged into a single bubble that contains the same mass of gas. Calculation time is on the order of one minute on a personal computer. **Results**: Several significant effects are revealed by the model. Bubble interaction is found to reduce the maximum sizes to which the bubbles grow. The bubbles near the rigid kidney stone are constrained by neighboring bubbles and grow less rapidly, and to smaller sizes, than other bubbles. The extent of bubble interaction is affected by the waveform of the lithotripsy pulse. **Conclusions**: Bubble interactions within the cloud thus suppress bubble growth and cavitation and may act to shield the stone. Alternatives to typical lithotripsy pulses may provide a means of improving the effectiveness of kidney stone treatment with SWL.

The authors are supported by the Internal Research and Development program at Applied Research Laboratories of The University of Texas at Austin.

Session: U3-H
HIGH FREQUENCY TRANSDUCERS
Chair: G. Lockwood
Queens University

U3-H-1 511AB 8:30 a.m.

DEVELOPMENT OF A HIGH FREQUENCY (35 MHZ) LINEAR ULTRASONIC ARRAY USING 2-2 COMPOSITE ELEMENTS

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This study investigates the design tradeoffs involved in the development of a high frequency (35 MHz) 128-element linear ultrasonic array. This array was designed primarily for medical imaging applications, and features 2-2 composite elements mechanically diced out of a fine grain high density PZT-5H ceramic. Array elements were spaced with a 50 micron pitch, interconnected via a flexible circuit and matched to the 50 Ohm system electronics via a 75 Ohm transmission line coaxial cable. The time domain based finite element model (FEM), PZFlex (Wiedlinger Associates, Palo Alto, CA), proved to be a very useful tool for determining the optimum composite element geometry. The final array design was based upon tradeoffs between the ease of fabrication, level of array encapsulation, suppression acoustic crosstalk, as well as, the time domain response bandwidth and sensitivity. A prototype 128-element composite array was fabricated, yielding promising results. An average center frequency of 36 MHz was achieved with and average -6 dB bandwidth of 50% and 40 dB pulse length of 100 ns. A maximum combined electrical and acoustical crosstalk for adjacent and next adjacent elements was less than -33 dB, which is a significant improvement over our 35 MHz monolithic array developed in recent years.
The authors would like to thank the NIH for providing funding support through contract P41-EB2182-07.

U3-H-2 511AB 8:45 a.m.

PIEZOCOMPOSITE 30MHZ LINEAR ARRAY FOR MEDICAL IMAGING: DESIGN CHALLENGES AND PERFORMANCES EVALUATION OF A 128 ELEMENTS ARRAY

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The range of applications demanding the development of high frequency ultrasound imaging is very broad from dermatology and ophtalmology to intravascular and small animals imaging, to improve the resolution of the images on a small penetration depth. However the manufacture of such imaging systems remains very challenging from both transducer manufacture (small dimensions of the elements, difficult knowledge of the properties of the passive and active thin layers) and associated electronic system perspectives. This article extends the current state of the art limited at 20MHz for fully operational array devices and presents the acoustical design, manufacture and evaluation of a 128 elements 30MHz ultrasound array based on the 1-3 piezocomposite technology, with a 100μm pitch and a 2mm elevation aperture. Electroacoustical characterisation of the full array will be reported (in terms of bandwidth, pulse duration and homogeneity performances). The array is subsequently integrated into probe housing and interfaced to an ultrasound system to provide images that will be discussed from a clinical perspective.

U3-H-3 511AB 9:00 a.m.

WIDE FREQUENCY BAND AND HIGH INTENSITY THICKNESS VIBRATION OF HYDROTHERMAL LEAD ZIRCONATE TITANATE POLYCRYSTALLINE FILM

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The ultrasonic characteristics of the transmission sensitivity and high intensity vibration capability of hydrothermal lead zirconate titanate polycrystalline thick film was measured. A hydrothermal PZT was deposited on a titanium substrate by solution including Pb^{2+}, Zr^{4+} and Ti^{4+} in an autoclave at 180 degree Celsius. The deposition rate was about 4mm/6h. The deposit film had a polycrystalline structure. The atomic ratio of the film was Zr:Ti= 80:20. A PZT film about 60μm thick was deposited on a 50μm thick titanium substrate surfaces by the mentioned method. The electrode of Au was deposited on the PZT film surface by the vacuum evaporator on one side in 8$\times$8mm square area. Counter electrode was the titanium substrate. The hydrothermal PZT ultrasonic transducer was fixed in water by a clamp, and a calibrated hydrophone in frequency range between 1 MHz to 20 MHz was set the horizontal distance of 20mm from the hydrothermal PZT ultrasonic transducer. Driving signals of 250 V burst wave between 2 MHz to 20 MHz were applied to the PZT film. Then, after 14 μs from the arriving signal, the hydrophone signal was obtained in all frequency range. The transmission sensitivity in wide frequency range from 2 MHz to 20 MHz was in the deviation of $\pm$6dB. The peak transmission sensitivity was 80 kPa. The frequency response of the thickness mode vibrator was measured by the laser Doppler vibrometer in the bandwidth was 20 MHz. The measuring point was at center of the surface of the electrode at under the condition of a constant driving voltage. The result of measured vibration was the vibration displacement and the vibrator velocity were 13 nm and 2 m/s when the driving voltage was 150 Vo-p at the frequency of 20 MHz. Additionally, the powder density of the deposited PZT polycrystalline thick film was 4.310^3 kg/m^3 and we estimated the phase velocity of longitudinal wave was about 2000m/s, consequently the acoustic impedance was estimated to be about 8.610^6 kg/m^2 s. This amount is 0.3 less than the amount of the ceramics PZT. The experiment shown that this PZT film was broadband ultrasonic transducer that enables ultrasonic waves to transmit in water at 2 MHz to 20 MHz with the transmission sensitivity in the range of $\pm$6dB and high intensity operation as 2m/s in water at 20 MHz. And further the acoustic impedance was very low compared to ceramics PZT. In general, desirable attribute of medical ultrasonic assessment transducer is wide frequency band and low acoustic impedance. And high intensity ultrasonic transmission is imperative for ultrasonic therapy. We find out about hydrothermal PZT thick film was completely meet the various requests on medical ultrasonic transducer. It is expected that this hydrothermal PZT will be utilized for development of medical ultrasonic transducer that serve double duties as assessment and therapy

U3-H-4 511AB 9:15 a.m.

SHEAR WAVE TRANSDUCER USING (11-20) TEXTURED ZNO FILM

T. YANAGITANI*, T. NOHARA, M. MATSUKAWA, Y. WATANABE, and T. OTANI, Doshisha University.
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The ZnO film is highly expected as a shear wave transducer at high frequencies, because its c-axes can be aligned unidirectionally in the substrate plane. It is, however, difficult to fabricate such films on the various substrates without the technique of epitaxy. Owing to their crystallographic nature, the polycrystalline ZnO thin films tend to have c-axes which are perpendicular to the substrate surface. On the glass substrates, the appearance of the crystallites with c-axes parallel to the substrates plane has been reported by several researchers. It seems, however, difficult to realize the shear wave transducers which does not excite any longitudinal waves. In this study, using a RF magnetron sputtering system, we have successfully obtained the ZnO films in which c-axes of crystallites unidirectionally aligned in the plane without the technique of epitaxy. These obtained films have almost pure (11-20) textured films. The performance of the ZnO films as shear wave transducers, strongly depend on the crystallinity and the extent of c-axes alignment in substrate plane. The crystallinity of the obtained films was discussed by XRD. The alignment of c-axes in the plane was then carefully investigated by the X-ray pole figure analysis and AFM. The structure of the sample was the layers of (11-20) textured ZnO film / Al electrode film / Corning 7740 glass substrate. The sample was fabricated at the position across the anode center to the fringe in the sputtering apparatus. By the ω-2θ x-ray diffraction pattern of the sample which was fabricated at the opposite position of the erosion region of the target, we found high crystallinity of (11-20) texture. In the (11-22) pole figure of the sample fabricated at the anode center,

the poles were found concentrically around ψ=58° which is theoretically estimated angle of (11-22) poles of ZnO crystal. In the sample deposited at fringe of the anode, however, poles highly concentrated at ψ=32°, ϕ=0° and ψ=32°, ϕ=180°. These results show that, c-axes of crystallites orient randomly in the anode center, whereas they are unidirectionally aligned in the fringe. The c-axes of crystallites clearly aligned in the radial direction of the anode. The results of the pole figure analysis completely corresponded to the surface morphology obtained by AFM. The surface morphology clearly indicates that crystallites grains of the film oriented randomly at the anode center and unidirectionally aligned in the fringe of the anode. We have also confirmed the similar fabrication of (11-20) textured ZnO films on the glass, SUS-304, copper, aluminum and rough surface glass. Using the ZnO film, we have fabricated the ultrasonic transducer which consist of metal electrode /(11-20) textured ZnO film/Al electrode film structures. The ultrasonic waves generated by the transducer were observed using the pulse-echo method. The transducer clearly excited shear wave without any longitudinal waves. These results indicate the wide application of this film as shear wave transducers and SH-type acoustic wave devices on any substrates.

U3-H-5 511AB 9:30 a.m.

LEAD-FREE THICK PIEZOELECTRIC FILMS AS MINIATURE HIGH TEMPERATURE ULTRASONIC TRANSDUCERS

M. KOBAYASHI*[1], C.-K. JEN[2], and Y. ONO[2], [1]Dept. of ECE, McGill University, [2]IMI, National Research Council Canada.
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Real-time ultrasonic monitoring of polymer processing of medical or biomedical devices and of food processing is desired for the improvement of the production efficiency, yield and quality of the product. It is well known that lead-zirconate-titanate (PZT) ceramics are the most used piezoelectric materials for ultrasonic transducer (UT) application. Since the lead oxide present in the PZT composition is volatile and thus causes environmental pollution during processing. PZT may not be permissible for the above-mentioned applications. For this reason it is desirable that lead-free piezoelectric ceramics can be used to replace PZT. In addition, it is also of our interest to develop lead-free transducers to operate at temperatures higher than 250°C, which may be the highest operation temperature of PZT UT and required for certain polymer processes.

In this paper, thick film piezoelectric lead-free ceramic sensors have been successfully deposited on different metallic substrates with different shapes by a sol-gel spray technique. The ball-milled bismuth titanate (BIT) fine powders were dispersed into BIT solution to achieve the gel. The BIT sol gel solution was prepared as follows: (1) bismuth nitrate pentahydrate was dissolved in glacial acetic acid heated at a temperature of 40°C; (2) after cooling, it was mixed with titanium isopropoxide in a proper molar ratio; and (3) this solution was hydrolysed with water and the volume ratio of BIT solution to water was 2 to

1. An air gun was then used to spray the BIT/BIT sol gel composite directly onto the metallic substrates. After spray coating, thermal treatments such as drying, firing and annealing were carried out at temperature of 90, 430, and 700°C, respectively with the optimal time duration. The films with desired thickness up to 50 μm have been obtained through multilayer coating approach. Piezoelectricity was achieved using a corona discharge poling method. The area of top silver paste electrode was also optimized. The center frequencies of ultrasonic signals generated by these films on steel samples ranged from 5 to 30 MHz and their bandwidth was broad as well. The ultrasonic signals generated and received by these UTs operated in the pulse/echo mode had a signal to noise ratio more than 30 dB. The main advantages of such lead-free piezoelectric transducers are that they (1) do not need couplant, (2) can serve as piezoelectric sensor and UT, (3) can be coated onto curved surfaces and (4) can operate up to 500°C. The capability of this BIT/BIT thick composite film UTs for real-time ultrasonic monitoring will be demonstrated.

Session: U4-H

TRANSDUCERS I
Chair: Y. Yong
Rutgers University

U4-H-1 513AB 8:30 a.m.

DEVELOPMENT OF STRONG ELASTICOLUMINESCENCE FROM FERROELECTRIC PHASE

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Recently we have found a new phenomenon, named as elasticoluminescence, which can emit intensive visible light by the application of mechanical stress in elastic deformation region. This phenomenon, contrary to the piezoelectricity, it can sense the changes in mechanical stress without any electrical contacts and electrodes. [1-3] In principle, mechanoluminescence (ML), also called triboluminescence, can arise from elastic deformation and plastic deformation aside from fracture during application of mechanical stress on a solid; we refer to these phenomena as elastico-deformation luminescence (elasticoluminescence), Plastico-deformation luminescence (plasticoluminescence), and fractoluminescence, respectively. Elasticoluminescence and plasticoluminescence are deformation luminescences attributable to non-destructive ML, whereas fractoluminescence is destructive ML. Until now, destructive ML has been observed extensively in various inorganic and organic materials, but non-destructive ML has been found only in a few limited cases. So far, no practical application of deformation luminescence has been realized because intensity is too low. Recently, we carried out a systematic research to explore high performance non-destructive ML materials and search for new applications as a smart material for various mechano-optical devices. Consequently, we found several materials showing strong deformation luminescence allowing visualization of stress distribution in a solid. In particular, composition near (Sr, Ba, Ca, Mg)Al2O4, shows strong deformation luminescence and fractoluminescence. The ML intensity can be improved greatly by controlling lattice defects. However, the mechanism of the deformation luminescence remains unclear. In this paper, elastico-deformation luminescence has been investigated systematically using precisely controlled pure-phase of various oxides and their mixed phases. This study revealed that only certain ferroelectric phases produce strong elastico-deformation luminescence; other pure-phases of non-piezoelectricity, show no deformation luminescence. Correlation of deformation luminescence and crystal structure has been found. This finding can be applied in designing strong elastico-deformation-luminescent materials. Strong elasticoluminescence materials and/or coatings can give real-time stress images, so that it is a prospective candidate for developing a new non-destructive evaluation technology. 1. C.N. Xu, in Encyclopedia of Smart Materials, Vol.1, 190 2002. 2. C. N. Xu, T. Watanabe, M. Akiyama, X.G. Zheng, Appl. Phys. Lett., 74, 2414 (1999). 3. C.N. Xu, H. Yamada, X. Wang and X.G. Zheng, Appl. Phys. Lett. in press (2004).

U4-H-2 513AB 8:45 a.m.

SPHERICAL Φ1MM SAW DEVICE BASED ON BALL SEMICONDUCTOR/MEMS TECHNOLOGY

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This paper introduces Φ1mm ball SAW(surface acoustic wave) device using 3-dimensional Ball Semiconductor/MEMS technology. The key technology has 3D design tool, spherical lithography and clustering package with bump process. SAW on the sphere is excited by an interdigital transducer (IDT) fabricated on an equator of the sphere, propagated along the equator and detected by the identical IDT. This ball SAW device detects SAW signal according to surface status variation on the sphere, by measuring a delay time and an amplitude change. The former is caused by the SAW velocity change and the latter is caused by the attenuation change. These variations are enhanced by the multiple roundtrips of the SAW with repeated interaction. Substrate material of the device utilized single crystal quartz ball of 1mm diameter and the ball was prepared by mechanical polishing of Z-axis cut crystal wafer. The devices structure is designed by

the 3D design tool. The IDT electrode of five finger pairs at center frequency of 150 MHz is designed to realize the multiple roundtrip using collimate coherent wave mode on the Z-axis cylinder. A micro-resistor is also integrated on the ball in order to measure the temperature by itself, so as to precisely compensate the temperature effect on SAW velocity. The IDT electrode and electrical connection pads for bumping on the glass substrate are fabricated by general metal lift-off process in the semiconductor and MEMS technology. After the metalization, the device is bumped with micro-gold balls on the glass substrate, and then it is fixed on the ceramic package and wire bonding is done for connecting electrically to the glass substrate. The multiple roundtrips were verified by using a tone burst heterodyne detection circuit with frequency bandwidth of 50 to 400 MHz of which it was originally developed for acoustic microscopy. At the center frequency of 156 MHz, we observed an envelop-detected video signal after as many as 160 turns with a signal to noise (S/N) ratio higher than 20 dB. In order to easily test any gas or bio-sensing capability after packaging, sensing film is deposited by using a developed stencil mask with a pinhole or a slit. In the ball SAW sensor using palladium sensing film, the amplitude signal is particularly sensitive to presence of hydrogen (H2) gas. Since we can detect 0.1 vol. % H2 by the amplitude change of SAW RF signal after 70 turns, we could enhance the sensitivity down to 0.01 % by using the video signal after 160 turns. In conclusion, we illustrate fabrication technology and present possibility as gas sensor so as to show the operation characteristics of ball SAW . This device will find a wide range of applications such as in gas sensors, bio-sensors and gyro sensors, as well as ball acoustooptic devices for manipulating light beam.

U4-H-3 513AB 9:00 a.m.

SINGLE CRYSTAL PIEZOMOTOR FOR LARGE STROKE, HIGH PRECISION AND CRYOGENIC ACTUATIONS

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Cryogenic actuators with large stroke, high precision, and position set-hold at power-off characteristics are desired for NASA adaptive optics, deployable truss structures, active vibration control, structure morphing, and RF communication tuning. TRS Technologies has developed a novel single crystal piezomotor for large stroke, high precision, and cryogenic actuations with capability of position set-hold with power-off. The device has the potential to advance the state-of-art cryogenic actuations considering the excellent cryogenic properties (with d_{33} and d_{31} at 30K similar or higher than that of PZT at room temperature) and the great electromechanical coupling of single crystal piezoelectrics, and the novel design of the wobbling mode piezomotor with 33 mode single ring stacks instead of the conventional 31 mode plates for excitation. The cryogenic properties of single crystal piezoelectrics with various crystal cut were investigated.

FEA modeling that takes into consideration the special properties of single crystals and a cryogenic environment were conducted and a novel piezomotor with 33 mode single crystal ring stacks and screw driven structures was built and characterized at temperatures from 300 to 20K. The performance and the feasibility of wobbling mode piezomotor for large stroke cryogenic actuation will be discussed.
We would like to thank NASA for funding this research under contract #NNC04CA87C.

U4-H-4 513AB 9:15 a.m.

NEW TECHNOLOGY FOR CONTROL OF LIGHT INTENSITY USING ACOUSTICAL ACTIVITY IN FERROELECTRICS

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The proposed new technology is differed from all the existing technologies for measuring and control of light intensity. In the proposed method is used the Bragg light diffraction on the hypersonic wave in gyrotropic crystal. In this case the intensity of diffracted light is dependent on the sound frequency by square law. We can change the light intensity by modification of generator frequency by which the acoustic wave is excited. So the increasing or decreasing of light intensity is provided electronically, fluently and with high accuracy because the frequency of electromagnetic vibrations can be determined very precisely. Using previously the standard calibration, it is possible to measure and to change the light intensity to the necessary value. In present work acoustical activity and Bragg light scattering on hypersonic waves in ferroelectric crystal LiNbO3 have been used for control and measuring of the light intensity. The applied sample of LiNbO3 was cut from optically clear single crystal and oriented along the crystallographic axis of the third order with the accuracy of 10. Piezoelectric transducers of Lithium Niobate of appropriate cuts are used to excite the plane-polarized transverse acoustic waves in the frequency range from 900 MHz to 1.1 GHz. Measurements of the dependence of the scattered light intensity from the distance to the piezoelectric transducer along the direction of the acoustic wave propagation have been carried out in automatic regime by using the computer, which worked under the control of the program adapted specially for solving this problem. In the experiment we have been obtained different values of the scattered light intensity in the range from 0 to the maximum intensity of the scattered light. These intensities can be used for determination of the specific rotation of polarization vector in given acoustic wave by modeling simultaneously. All necessary calculations have been made for speculation of experimental curves by varying factors, which can be changed in a real experiment. As a whole this method is interesting new way that will allow to control and to measure the intensity of a laser light beam electronically, fluently and with high accuracy.

U4-H-5 513AB 9:30 a.m.

HIGH FREQUENCY FILTERS BASED ON PIEZOELECTRICALLY TRANSDUCED MICROMECHANICAL RESONATORS

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This paper presents the design, simulation, fabrication and test of a novel piezoelectrically transduced micromechanical filter. The filter is composed of two identical free-free beam resonators coupled with two torsional beams. The resonators are designed to work in the free-free mode, in contrast to the clamp-clamp mode. The free-free mode provides at least two advantages over other beam designs. First, the resonant frequency is higher with the same general dimensions compared to fixed-fixed beams. Second, there are two nodes in the resonant mode, which can be the anchoring points that minimize energy dissipation into the substrate and thereby improving the device quality factors. Anchor beams are designed to be quarter wave length to further reduce energy loss. The center frequency of the filter is determined by the resonant frequency of the free-free-beam resonators, while the bandwidth is determined by the stiffness ratio of the torsional coupling beams and effective stiffness of the resonator at the coupling location. This fact can be used to design the pass band of the filter, with a soft coupling spring to achieve a narrow bandwidth, for example. Since the resonator has higher effective stiffness at the location with lower modal displacement, the coupling beams are designed to be located at the node position to maximize the stiffness ratio. The FEA simulated percentage bandwidth of the resonator versus different torsional beam dimension using ANSYS will be presented in a figure. Piezoelectric transduction is employed for the filter for better power handling capability than capacitive transduction. Sputtered ZnO is used as the piezoelectric material due to its high piezoelectric coefficient and mature deposition process. In addition to power handling capability, piezoelectric transduction does not require sub-micron fabrication to create the small gap required by capacitive designs. A series of mechanical filters of different sizes are fabricated from silicon-on-insulator (SOI) wafers with a simple 4-mask process. The highest processing temperature is kept below 250C, (ZnO sputtering temperature). This low processing temperature is attractive because it offers the opportunity for integration of the mechanical filters with CMOS circuits in a two-step fabrication, in which the delicate CMOS fabrication is done first, followed by fabrication of the filter (post-CMOS integration). SEM pictures of two fabricated devices with different dimensions will be presented. The prototype with 160x40x20 μm3 resonators and two 20 μm-long coupling beams has been tested under atmospheric pressure with a spectrum analyzer. Measured data and ANSYS simulated result will be presented. The measured data differs by 1 MHz from the simulated result, which is well within the expected fabrication

variations and the initial non-optimized measurement setup. Frequency tuning is also possible in future designs by incorporating electrostatic pulling on the beams.

The authors would thank Wei Pang and Prof. E.S.Kim in MEMS group of University of Southern California for partially providing the fabrication facilities.

U4-H-6 513AB 9:45 a.m.

PIEZOELECTRIC MICROMECHANICAL DISK RESONATORS TOWARDS UHF BAND

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This paper presents the design, fabrication, and test results of a new type of piezoelectrically transduced disk-type resonator. The disk geometry offers the potential of reaching UHF band without resorting to sub-micron fabrication for ultra-miniaturization that is otherwise required for beam-type resonators. The current disk resonator is designed to resonate in wineglass mode with four quasi-nodes on the perimeter of the disk, which offer convenient anchor points that minimize mechanical coupling (and thus mechanical energy loss) to the substrate. Four self-aligned anchor beams supporting the resonator at these nodes are designed with length equal to a quarter wavelength of acoustic wave, which further inhibit energy loss through anchor to the substrate [1]. The device is fabricated from silicon-on-insulator (SOI) wafers, with the structural silicon layer at 20 μm thickness to suppress the out-of-plain spurious modes. Sputtered thin-film ZnO is used as the piezoelectric transducer for its high piezoelectric coupling coefficient and mature deposition process [2]. 500 evaporated gold is used as the top electrodes and the heavily doped structural silicon serves as the bottom electrodes.

A series of disk resonators is fabricated with a simple 4-mask, low-temperature process on SOI wafers. The process flow will be described with step-by-step cross-sectional illustrations. The highest process temperature is during the ZnO sputtering step at 250°C, which offers the opportunity to integrate the resonator with CMOS circuits on the same chip by fabricating the mechanical device after the delicate CMOS fabrication is completed (post-CMOS integration). Fabricated devices with 60 μm measured diameter, both in one port and two ports configurations, will be shown on SEMs. This resonator is tested under atmospheric pressure with a network analyzer, and resonant peaks of 56 MHz and 211 MHz are obtained. These resonant peaks are derived from the measured microwave reflection coefficient (S11) and microwave transmission coefficient (S21), which will be presented in this paper. These results match well with the simulation results from finite element analysis using Ansys. The preliminary quality factors derived from the test results are 14 and 18 for the first and second peaks, respectively. A substantially higher quality factor is expected

using optimized measurement setups in vacuum and with calibrated cables. By moderately reducing the diameter of the resonators, resonance at UHF band is expected without resorting to nanofabrication.

[1] Kim Wang et.al VHF Free Free Beam High Q Micromechanical Resonators 12th IEEE Micro Electro Mechanical Systems Conference. Orlando, Florida, Jan 1721, 1999, pp 453458 [2] Tao Xu, et.al The compatibility of ZnO Piezoelectric material with microfabrication process Sensor and Actuator V. A104, pp 6167. [3] Le Yan, et al, "High Frequency Micromechanical Piezo Actuated Disk Resonator," to appear in Hilton Head 2004: Solid State Sensor, Actuator, and Microsystems Workshop, June 6 - 10, 2004.

The authors thank Wei Pang and Prof. E. S. Kim in MEMS group of University of Southern California for providing partial fabrication facilities.

Session: U5-H

WAVE PROPAGATION
Chair: W. Arnold
Fraunhofer Institute

U5-H-1 512C-H 8:30 a.m.

OPTIMIZED EXCITATION SOURCES AND VELOCITY EXACT SOLUTIONS FOR ULTRASONIC FIELD PROPAGATION IN A NONLINEAR MEDIUM WITH HYSTERETIC BEHAVIOR

S. DOS SANTOS*[1], V. GUSEV[2], L. HAUMESSER[1], F. VANDER MEULEN[1], and O. BOU MATAR[1], [1]LUSSI FRE 2448 CNRS -GIP Ultrasons, [2]LPEC UPRESA-CNRS 6087.
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Ultrasonic wave propagation in an micro-homogeneous material with hysteretic strain-stress behavior has been studied by application of an algebraic method [1] (recently used in bubble dynamics by Maximov [2]) in order to find optimized excitation sources. Starting from previous published work (Gusev [3]), the particle velocity of the ultrasonic wave propagating in the nonlinear medium is described avoiding the term with modulus (the latter commonly coming from the hysteretic behavior). The proposed higher order nonlinear differential equation is then studied, and simplified using algebraic group reduction methods (leading to simplifications of the mathematical description). This powerful algebraic method provides exact solutions for the particle velocity describing propagation of pulse sources in the nonlinear medium. Velocity behavior is compatible with previously published work and experimental results showing the broadening in time of pulse width during the propagation in the nonlinear medium, due to the hysteretic nonlinearity.

The algebraic reduction method and numerical simulations will be presented showing the broadening of the initial excitation acoustic pulse; caused by the dependence of the local velocity of sound propagation and the global amplitude of the acoustic excitation. The advantages of this method will be emphasized and linked to the problematic of finding optimized excitation sources for any ultrasonic beam propagating in damaged samples analyzed in nondestructive testing.

[1] Dos Santos, S and Bou Matar O., Symmetry of KZ (Khokhlov-Zabolotskaya) equation, Submitted to JASA [2] Maksimov A. O. , Symmetry in bubble dynamics, Communications in Nonlinear Science and Numerical Simulation, 9, (2004) [3] Gusev, V., Propagation of acoustic pulses in material with hysteretic nonlinearity, JASA, 107, (2000)

U5-H-2 512C-H 8:45 a.m.

A NOVEL NUMERICAL METHOD FOR SIMULATING WAVE PROPAGATION IN MOVING MEDIA

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In this paper, simulation of acoustic wave propagation in moving media is considered. Various acoustic systems (such as sound protection shields in a windy atmosphere, ultrasonic flowmeters etc.) represent large simulation problems which require solution of acoustic fields in moving media. The existing tools based on the finite element method (FEM) often do not allow to perform a full 3D analysis due to the extensive size of the solution domain with respect to the characteristic acoustic wavelength. Furthermore, usage of the boundary element method (BEM) is limited by unavailability of the appropriate Green's functions.

An alternative numerical method is introduced in this work. It enables 3D simulation of acoustic wave propagation in moving media and reduces the memory demands significantly in comparison with the FEM. The method is generally applicable for predicting open-domain acoustic fields in an arbitrary flow field at low Mach numbers. It is designed to interact with another method (such as FEM) which provides the necessary input data along the boundary of the solution domain typically representing a fluid-structure interface. By means of a hybrid simulation scheme [1], it can be used for computing wave propagation between a transmitter and a receiver (scatterer) in pulse-echo acoustic systems.

The novel method is based on combination of the ray-tracing technique and the Helmholtz radiation integral. The Helmholtz integral can be regarded as the mathematical formulation of the Huygens' principle. This interpretation leads to the constitutive idea of the proposed alternative method. The propagation of the elementary waves from every elementary source to the target point is modeled by means of ray tracing, while the structure of the Helmholtz integral stays unchanged. This way its applicability is extended to moving media.

In order to realize this idea, a generalized free-space Green's function for moving media is proposed. It is based on parameters obtained by solving the ray-tracing equations. In the special case of a uniform flow field at low Mach numbers, it can be shown that the generalized Green's function reduces to the analytical solution [2].

The extended Helmholtz integral is validated by means of two simulation setups. The obtained results are compared with the FEM results. The propagation of sound waves into shadow zones (regions without direct rays from the source due to the presence of flow velocity gradients) is demonstrated and a simple ray model of this diffraction phenomenon is introduced. Furthermore, application of the ray tube theory is considered in order to cover the focusing and defocusing phenomena. Finally, numerical implementation and efficiency of the novel method are discussed.

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[2] Wu, Lee: "A Direct Boundary Integral Formulation for Acoustic Radiation in a Subsonic Uniform Flow," J. Sound and Vibration, vol. 175, no. 1, pp. 51-63, 1994.

U5-H-3 512C-H 9:00 a.m.

ANALYSIS OF ULTRASONIC WAVE PROPAGATION IN METALLIC PIPE STRUCTURES USING FINITE ELEMENT MODELLING TECHNIQUES

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In non-destructive testing (NDT) the interaction between the propagating ultrasonic energy and the defect under inspection can produce complex temporal waveforms for analysis. In many NDT applications, a number of ultrasonic waves can co-exist within the material under test and importantly, additional wave modes can be generated through wave conversion at discontinuities, or boundaries, within the path of the propagating energy. Furthermore, large propagation distances can be associated with many NDT applications. Hence, it can be difficult to analyse such wave propagation and defect interaction especially where there are multiple reflections from the component surfaces. Techniques, such as ray tracing, are commonly used to predict the behaviour of these systems. Unfortunately, these techniques do not produce a full temporal analysis of the system, which can be critical for defect characterisation and discrimination.

This paper describes the development of a large finite element (FE) model representing ultrasonic inspection in a metallic pipe. The model was developed using PZFlex and comprises two wedge transducer components, water coupled onto the inner wall of a 36 inch diameter steel pipe. The 2MHz transducers are separated by 430mm and configured to generate/receive ultrasonic shear waves. One device is used in pulse-echo mode to analyse any reflected components within the system, with the second transducer operating in a passive mode. Importantly, to minimise the models computational requirements, an external pressure loading function was applied to the wedge component within the model to simulate the transducer excitation. A number of simple defect representations have been incorporated into the model and both the reflected and transmitted ultrasonic wave components acquired at each wedge. Both regular slot and lamination defects have been investigated, at three different locations to evaluate the relationship between propagation path length and defect response. These defect responses are analysed in both the time and frequency domains and good correlation with experimentally measured waveforms is demonstrated. Moreover, the FE modelling has produced visual interpretation, in the form of a movie simulation, of the interaction between the propagating pressure wave and the defect. A combination of these visual aids and the predicted temporal/spectral waveforms has clearly demonstrated the essential differences in the response from either a slot or lamination defect. It should be noted that these modelled representations correspond to a propagation path length in excess of 150 wavelengths. Consequently, it was necessary to incorporate denser meshing within the FE model and run the simulations on a multi-processor SGI computer facility to produce accurate results.

U5-H-4 512C-H 9:15 a.m.

WAVE PROPAGATION IN TRANSVERSELY ISOTROPIC CIRCULAR CYLINDERS

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A new mathematical model for the propagation of longitudinal and flexural guided waves in free transversely isotropic cylinders is developed in this paper. The model uses three scalar potential functions to represent the three wave modes which can propagate inside the cylinder, i.e. compression (P), vertically polarized shear (SV) and horizontally polarized shear (SH) waves. This results in the decoupling of the equations of motion such that SH wave is completely decoupled from P and SV waves. Unlike other models in which the displacement field is guessed a priori, in the new model the resulting partial differential equations are solved by the method of separations of variables and the frequency equation is derived in a systematic manner. The dispersion curves as well as displacement fields inside the cylinder at various frequencies are plotted for longitudinal waves propagating along a number of transversely isotropic cylinders. The results obtained from this mathematical model agree with those obtained from the previous model. The new model has several advantages in comparison with the pervious ones. In this approach the equations are solved systematically and unlike other models, there is no need to guess the form of the final solution. This approach can also be used for solving similar problems which deal with cylindrical shells and multilayered cylinders having either finite or infinite lengths.

U5-H-5 512C-H 9:30 a.m.

EXPERIMENTAL STUDY OF A SHARP BENDING WAVE-GUIDE CONSTRUCTED IN A SONIC-CRYSTAL SLAB OF AN ARRAY OF SHORT ALUMINUM RODS IN AIR

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We present here promising experimental results on the characteristics of a sharp bending sonic wave-guide constructed in a sonic-crystal slab, which was made of a two-dimensional square-array of aluminum rods, namely scatterers, in air between a pair of parallel metallic sheets of a space smaller than the wavelength.

First, we constructed a two-dimensional sonic crystal of an array of long acrylic-resin rods in air, and observed experimentally a full band-gap [Toyokatsu Miyashita: Jpn. J. Appl. Phys. vol.41, No.5, pp.3170-3175 (2002)]. Next, we realized an alternative two-dimensional sonic crystal, namely a sonic-crystal slab which has a periodic 12 x 16 array of short aluminum rods of a radius of 5.0 mm with a lattice constant of 12.0 mm between a pair of parallel metallic sheets of a 15.0 mm space.

A plane wave, whose wave-fronts are parallel to the rods, is injected to the sonic-crystal slab by a tweeter (Fostex FT7RP) which has a long flat rectangular aperture of 50 mm x 7 mm fitting to the cross-section of the air slab and a plane membrane vibrating with a uniform phase. The sound or ultrasound waves are received by a thin-rod microphone (Earthworks SK-16) of a 5.5 mm diameter with a flat response from 9 Hz to 40 kHz. To perform a precise measurement independent of the inevitable surrounding echoes in a usual laboratory, we irradiated the crystal by a tone burst and measured only the wave component which passed through the crystal and further was in a steady-state. We observed a full band-gap, namely a common band-gap in both [100] and [110] directions of the incident wave-front, between 15.2 kHz and 18.9 kHz, in the normalized frequency between 0.52 and 0.65, with a transmission of smaller than -20 dB. These results agree well with the numerically obtained band-gaps [loc. cit.].

Any scatterer of the above sonic-crystal slab is composed of an inner aluminum rod of a 1.5 mm radius and an outer aluminum collar of maximum 6.0 mm radius, so that any scatterer may change the radius between 1.5 mm and 6.0 mm exchanging the collar. We constructed a sharp bending wave-guide in the crystal eliminating the outer collars in two lines along the wave-guide which bends at right angles. To get a smooth impedance matching, both the inlet and the outlet of the wave-guide are increased in width toward the outside of the crystal.

In the frequency range of the full band-gap, the sound waves were guided effectively from the inlet to the outlet of the wave-guide. Especially at 17 kHz, about the center of the full band-gap, the amplitude ratio of the guided wave at the outlet to the leakage sound, which propagated straight without bending along the wave-guide, was 22.3 dB.

The realization of a sharp-bend wave-guide in the sonic-crystal slab, as is

reported here, indicates a further development to various shapes of sonic waveguides and sonic circuits including directional couplers, ring resonators, filtered couplers, splitters, and so on.
This work was partially supported by the Sound Technology Promotion Foundation in Japan.

U5-H-6 512C-H 9:45 a.m.

A COMPUTATIONAL METHOD TO CALCULATE THE TRANSMIT-RECEIVE MODE ECHO RESPONSES FROM TARGETS OF COMPLEX GEOMETRY

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In this paper a three-dimensional computational method is proposed to calculate the echo responses from finite-sized targets of complex geometry. The method is based on the spatial impulse response and on the discrete representation computational concept. It can predict the form of the echo response from target, considering mode conversion at the reflector surface. The method operates by dividing the transmitted aperture, the reflector surface, and the receiver aperture into elementary areas. The method is divided in three steps. As first step, the velocity potential impulse response is calculated at the reflector surface using the Rayleigh integral. In each of the elementary areas of the reflector, the impulse response function is affected by the corresponding reflection coefficients. In a second step, the reflected velocity potential impulse response is calculated by applying the Rayleigh-Sommerfeld integral to the reflector surface. In a third step, the spatial-average acoustic pressure over the surface of the receiver is determined by a temporal convolution between the excitation signal and the spatial-average reflected velocity potential impulse response. The method is valid for all field regions and can be performed for any excitation waveform radiated from an arbitrary acoustic aperture. A closed-form analytical expression of the spatial-average acoustic pressure over the surface of the receiver has been obtained to describe the echo responses. The number of elementary areas used to discretize the transmitted and receiver apertures and the target limits the precision of the computational method. The effects of target geometry, position, and material on both the amplitude and shape of the echo response were studied. The model was compared to other modeling tools, and excellent agreement between our results and theirs were found. Furthermore, experimental results obtained using broadband transducers together with, for instance, plane and concave cylindrical reflectors (acrylic) in a water medium were compared to the theoretical results. The method can predict the measured echoes accurately.

Session: U6-H

LADDERTYPE FILTERS AND DUPLEXERS

Chair: M. Solal

TEMEX

U6-H-1 512A-F 8:30 a.m.

A MINIATURIZED 3X3 MM^2 SAW ANTENNA DUPLEXER FOR US-PCS BAND WITH TEMPERATURE COMPENSATED $LITAO_3$/SAPPHIRE SUBSTRATE

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This paper presents a temperature-stable and miniaturized SAW antenna duplexer using a temperature compensated 42rotY-X:$LiTaO_3$/Sapphire substrate[1] for the 1.9 GHz US-PCS band. The US-PCS band has only 20 MHz of guard band between Tx and Rx band, and therefore, it requires ultra-steep cut-off characteristics, as well as high power handling capability for the antenna duplexer. In spite of these stringent requirements, the authors have already developed an US-PCS antenna duplexer in the size of 5x5 mm^2, using advanced SAW filter design techniques[2][3]. A newly developed 3x3 mm^2 duplexer has not only better temperature stability due to the new substrate material, but also lower insertion loss, because both Tx and Rx filters have already exhibited sufficient cut-off characteristics to fulfill the US-PCS specifications, therefore the reduction of temperature drift contributes to guarantee the lower insertion loss in the temperature range of -30 to 85 deg. C.

One of the major problems to miniaturize the duplexer is deterioration of power durability due to heat-up of the SAW filter die. Sapphire constituting our temperature-compensated substrate also works as a heat sink because of its larger thermal conductivity of 42 W/mK. It was observed by the infrared sensor that the heat generated in the Tx filter was dispersed throughout the die and this led to decrease the temperature of SAW filter surface. In addition, the Tx filter was designed to suppress the heat-up in the IDT regions. By these techniques, the lifetime of 10000 hours was attained for 1 W of input power at 85 deg.C, which is sufficient for practical use of the cellular phone. In the presentation, the detailed design techniques and experimental results will be discussed.

The temperature-coefficient-of-frequency of a developed SAW duplexer was reduced to -20 ppm/K and -12 ppm/K for Tx and Rx filter, respectively, which is approximately half of the 42rotY-X:$LiTaO_3$ bulk substrate. Because of the small temperature drift, the insertion losses were able to be lower than -3.0 dB and -3.5 dB in the temperature range of -30 to 85 deg.C for Tx and Rx band, respectively. Although several papers have been reported on the PCS antenna duplexer, as far as we know, our duplexer has the smallest size and the best performance.

[1] M. Miura et al., to be presented in 2004 IEEE Intl. UFFC 50th Anniversary Joint Conference. (2004). [2] J. Tsutsumi et al., Proc. IEEE Intl. Freq. Cont. Symp., pp.861-867, (2003). [3] S. Inoue et al., Proc. IEEE Ultrasonics Symp., pp.389-392, (2003).

U6-H-2 512A-F 8:45 a.m.

HIGH-Q SAW RESONATOR WITH SIO2 COAT FOR STABILIZING TEMPERATURE CHARACTERISTIC

R. TAKAYAMA*, H. NAKANISHI, Y. IWASAKI, and T. KAWASAKI, Matsushita Electronic Components Co., Ltd.
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Recently, the characteristics of SAW filter, such as insertion loss, power durability, steepness (Q-factor), have been improved dramatically. However, TCF (Temperature Coefficient of Frequency) of a SAW filter remains as a big problem which has to be improved. The TCF of SAW filter using 36 degree cut LiTaO3 substrate is approximately -45ppm/degree Celsius. Therefore it is difficult to keep good frequency characteristics in the wide temperature range. Especially for US-PCS application, which has narrow cross-band, the frequency shift due to temperature variation becomes more crucial for the duplexer, to which high power is applied, or used in a module, which includes power amplifier that generates heat. Up to now, several methods were proposed and studied to improve the temperature characteristics of SAW filter. One of the well-known methods is coating the SAW device with SiO2, TCF of which is opposite to substrate. This method shows improvement on the TCF of SAW device. However it has never put into practical use, because SiO2 degrades the Q-factors of SAW resonator. In order to overcome this problem, we formed high quality SiO2 layer by advanced sputtering method. In addition, we changed the layer-profile of SiO2 by an improved method and condition of deposition. We have studied how does the layer-profile of SiO2 affect on the characteristics of 1-port resonator that is the constituent element of ladder type filter. For the conventional SiO2-coated SAW resonator, the Q-factor at anti-resonance frequency is degraded as the increase of the SiO2 thickness. The degree of this degradation becomes serious as the thickness of electrodes becomes thick. Regarding the TCF, we noticed the tendency that the TCF becomes worse depending on the thickness of SiO2 layer and electrodes. In this paper, we will show that it is possible to improve the frequency characteristic of the SAW resonator that is coated with SiO2 by optimizing the SiO2 layer-profile. The TCF of this SAW resonator is approximately -20ppm/degree Celsius at anti-resonance frequency. This technology was adopted in our PCS SAW duplexers. We have successfully developed PCS SAW duplexer for PCS application, which can compete with FBAR duplexer in the performance in operating temperature range.

SAW LADDER FILTER WITH WIDE REJECTION BAND ADJACENT TO PASSBAND

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Traditional impedance element (i.e. ladder) filters have excellent passband characteristics with very deep nulls on either side. The low-side null coincides with the resonant frequency of the shunt elements, whereby the signal is shunted to ground through a very low impedance. The high- side null, on the other hand, coincides with the anti-resonant frequency of the series elements, whereby the signal is effectively blocked from the output by a very high impedance. Although these nulls can often be 60-70 dB deep, they are extremely narrow, and the rejection rapidly flies back to only 20-30 dB as frequency moves further away from the passband. This characteristic shape is suitable for some applications, but often it is required that a wider band of frequencies be rejected near the passband. In such cases the designer must either use a different filter topology or must carefully control electrical parasitics within the filter and package so as to cancel out the filters acoustic response over the range of interest. This approach requires accurate modeling, creative layout and packaging, and a lot of luck. In some cases, it is simply not possible to achieve the necessary rejection with a traditional ladder filter.

In this paper, a novel ladder topology is presented which has improved rejection characteristics over a relatively wide band (on the same order as the width of the passband) adjacent to the passband. The rejection is achieved by configuring one section of the ladder as a band-reject filter, whereby the frequency of the shunt element is higher than that of the series element. At the passband frequencies, the band-reject section is significantly mismatched in impedance from the remaining bandpass sections. Thus, if all else remained the same, the presence of the band-reject section would cause gross reflections within the filter and the passband would be dramatically degraded. This problem can be overcome, however, by optimizing the ladder sections adjacent to the band-reject section to form an impedance matching network. The result is a well-matched filter with low insertion loss in the pass band, typical of a traditional ladder filter, along with a highly attenuated band of frequencies just above or just below the passband. The trade-off of this improved rejection is the appearance of a new pole on the far side of the rejection band, away from the passband. This causes a very sharp spike in the filter response which can peak at 10 dB or less before settling back down toward the 20-30 dB rejection of a typical ladder filter. The frequency of this spike can be controlled very well, but unfortunately its presence is inevitable. Nevertheless, for many applications this spike is allowable as long as it is well-positioned in frequency.

This technique has been successfully applied to leaky SAW ladder filters at frequencies up to 1.9 GHz.

U6-H-4 512A-F 9:15 a.m.

SAW DUPLEXERS WITHOUT $\lambda/4$ PHASE SHIFTER FOR CDMA CELLULAR PHONE SYSTEMS

T. ONZUKA*, K. NOGUCHI, S. YOSHIMOTO, and Y. YAMAMOTO, NRS Technologies Inc.
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We have already reported about a front-end SAW duplexer for Japanese PDC 800MHz cellular phone [1]. Wide channel separation of 130MHz between Tx and Rx band is required for the PDC duplexer. We controlled frequencies of pole and zero arbitrary by adding outer inductor and/or capacitor to SAW resonator. By using this technique, the duplexer has the advantage that $\lambda/4$ phase shifter and matching circuit are not needed. Very low loss and high attenuation duplexer for PDC system was realized. This paper describes application of the SAW duplexer which has the narrow channel separation by using above technique.For example US-CDMA, J-CDMA and PCS cellular phone systems have the very narrow channel separation and broad bandwidth. To using the outer inductor and mounting the small area, we must consider electro-magnetic field coupling which is decrease the attenuation and isolation of the duplexer. We fabricated the duplexers of the each system by using our unique technique, and discussed possibility for the low insertion loss and high attenuation and high isolation characteristics. [1] T.Onzuka, S.Yoshimoto and Y.Yamamoto.,SAW Duplexers without $\lambda/4$ phase shifters for PDC cellular phone systems ,in Proc.IEEE Ultrason.Symp.,2003,pp.2101-2104

U6-H-5 512A-F 9:30 a.m.

INVESTIGATION OF SAW W-CDMA ANTENNA DUPLEXER AND GSM-BASED FEM INCLUDING DUPLEXER

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W-CDMA (Wideband Code Division Multiple Access) is one of the third generation (3G) cellular-phone systems [1], and has already been served in Japan. Single-mode phones are used in Japan, however, dual-mode phones will be absolutely required in Europe. This is because both voices and data are transmitted via W-CDMA network in Japan, while in Europe voices will generally be transmitted via GSM network, i.e. EGSM and DCS, especially outside W-CDMA service areas. Therefore, we not only developed a SAW antenna duplexer for W-CDMA but also investigated combination of the duplexer and GSM-based SAW FEM (front-end module) [2]. In this paper, first we will show a configuration of RF circuits for W-CDMA phones taking requirements of 3GPP (3rd Generation

Partnership Project) [1] into consideration. Then, we will present frequency characteristics of the developed SAW antenna duplexer for W-CDMA. We also investigated nonlinear characteristics of the SAW duplexer, because very high off-band blocking characteristics are required for the W-CDMA system, which were not regulated in IS-95/98 based conventional CDMA systems. Therefore, we must use very high-linear switches and also must develop SAW chips with very small non-linear characteristics. Finally, we will show a block diagram of a new FEM, which includes not only switching and filtering functions for GSM-based multi-bands, i.e. EGSM, DCS, GSM850, and PCS, but also duplexer function for W-CDMA. The proposed FEM will be possibly used in dual-mode phones with non-compress-mode operation for W-CDMA and EGSM. 1. 3GPP TS 34.121, V3.3.0 (2000-12). 2. M. Hikita, et al Investigation of merged Rx-differential output for multi-band SAW front-end module, in 2003 IEEE Ultrason. Symp.

U6-H-6 512A-F 9:45 a.m.

A SAW DUPLEXER WITH SUPERIOR TEMPERATURE CHARACTERISTICS FOR US-PCS

M. JAKOB, U. RÖSLER, E. GAROVA-MAYER, G. KOVACS*, and W. RUILE, EPCOS AG.
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The system requirements for US-PCS are very hard to fulfill with conventional SAW filters, since the transition band between Tx and Rx is only about 1 percent wide. Furthermore, current CDMA systems in the PCS band have strong demands concerning isolation and rejection levels. Typical SAW devices on LiTaO3 substrates cannot meet these requirements over the whole operating temperature range, because of the large temperature coefficient of frequency (TCF) of $LiTaO_3$. Coating with dielectric films can be applied to lower the effective TCF; however, since the necessary film thickness is rather high, this causes fundamental changes in the acoustic properties of the material. Using one-port resonators and L-sections as test structures, we have conducted a series of experiments to identify interrelations between the properties of the layer system and the main acoustic parameters like piezoelectric coupling factor, reflectivity, and propagation loss. We have determined the requirements for the realization of a SAW duplexer for the US-PCS system and have selected a suitable layer system. In addition, we demonstrate that the effects of the dielectric layer can be simulated accurately with a standard P-matrix simulator, if the model parameters are adjusted accordingly. Finally, we present a complete SAW duplexer device for the PCS band featuring a TCF of -17 ppm/K.

Session: FE1-H

PIEZOELECTRIC MATERIALS I

Chair: A. Safari

Rutgers University

FE1-H-1 513CD 8:30 a.m.

(Invited)

BISMUTH LAYER-STRUCTURED FERROELECTRIC CERAMICS FOR LEAD-FREE PIEZOELECTRIC APPLICATIONS

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A family of bismuth layer-structured ferroelectrics (BLSF) is attractive materials from viewpoints of applications for electronic functional devices such as piezoelectric actuators, resonators and high-temperature sensors etc. Dielectric, ferroelectric and piezoelectric properties of Sr2Bi4Ti5O18 (S2BT) - Ca2Bi4Ti5O18 (C2BT) solid solution (SCBT) with layer number m=5 were investigated for resonator applications. Ceramic samples were prepared by the conventional ceramic fabrication technique (ordinarily firing, OF) and more the grain oriented samples were fabricated by the hot-forging (HF) method. The Curie temperature, Tc, of S2BT ceramic is 290 °C and becomes higher with increasing the amount of modified C2BT. The electromechanical coupling factor, k33, and piezoelectric constant, d33, of the MnCO3 (0.4wt%) doped S2BT (OF) were 0.15 and 26 pC/N, respectively, and gradually decrease with increasing the amount of modified C2BT. On the other hand, the HF-S2BT ceramic showed relatively high k33 and d33 values of 0.29 and 51 pC/N, respectively. The k33 and d33 of the HF-S2BT could be obtained first time in this study. Furthermore, the mechanical quality factors, Qm, for all of SCBT ceramics show relatively higher values than 4000. Temperature coefficient of the resonance frequency, TC-f, in the (33) mode of SCBT was 89.2 ppm/°C for S2BT and was gradually improved with increasing the amount of modified C2BT. The TC-f of the HF-SCBT is lower than those of the OF ones. The SCBT ceramics are seen as superior candidates for lead-free piezoelectric applications such as ceramic resonators and/or filters.

FE1-H-2 513CD 9:00 a.m.

DIELECTRIC AND PIEZOELECTRIC CHARACTERISTICS OF LEAD-FREE (BI,NA,K)0.5TIO3 SYSTEM CERAMICS AS A FUNCTION OF SR SUBSTITUTION AND THE AMOUNT OF MNO2 ADDITION

J. YOO[1], H. LEE[2], D. OH*[3], Y. JEONG[4], J. HONG[5], and C. LEE[6], [1]Semyung University, [2]Semyung University, [3]Sunny Electronics Corp., [4]KEPRI, [5]Dongseoul College, [6]Chungju National University.
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In this study, in order to develop lead-free piezoelectric ceramics that has the excellent piezoelectric characteristics, Bi0.5(Na0.84K0.16)0.5TiO3 ceramics with morphotropic rhombohedral-tetragonal phase boundary were fabricated with the variations of Sr substitution and the amount of MnO2 addition. And their dielectric and piezoelectric characteristics were investigated. As the amount of Sr substitution increase, crystal structure of Bi0.5(Na0.84K0.16)0.5TiO3 ceramics moved from MPB to rhombohedral gradually, and second phase was not appeared. Sr substitution didn't nearly affect microstructural and physical properties. With the increase of Sr substitution, dielectric constant linearly increased at the rate of 90 per 1mol% and Curie temperature decreased slightly. Also, the temperature dependence curve of dielectric constant was moved to left-ward. When the amount of Sr substitution increased, quality factor decreased and electromechanical coupling factor kp and kt increased by 4mol% and 6mol% Sr substitution, respectively, and then decreased. Bi0.5(Na0.84K0.16)0.5TiO3 ceramics substituted with 4mol% Sr and added with 0.3wt% MnO2 that showed kp of 35.8%, kt of 51.07%, ϵr of 786 and d33 of 179[pC/N], were suitable for piezoelectric device application.
This work was supported by EESRI

FE1-H-3 513CD 9:15 a.m.

PIEZOELECTRIC PROPERTIES OF BIFEO$_3$ - PBTIO$_3$

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Polycrystalline ceramics $(BiFeO_3)_x$ - $(PbTiO_3)_{1-x}$ have been prepared using conventional mixed oxide synthesis. The materials produced have a density of greater than 95% of theoretical and a Curie point in excess of 500°C. XRD analyses show that the sintered compacts are phase pure, and close to the morphotropic phase boundary with a c/a ratio of 1.10 for the tetragonal phase and a tilt angle of 89.635°. The room temperature resistivities of the materials are greater than 5 x 10^{11} Ωm. With $x = 0.65$ values for d_{33} and d_{31} of 90 and 25 pm V^{-1} respectively were measured using a Berlincourt meter; using impedance analysis, a value of 23 pm V^{-1} for d_{31} was measured. These materials may be used as a piezoelectric transducers and sensors at temperatures in excess of 400°C.

FE1-H-4 513CD 9:30 a.m.

ALTERNATIVE LEAD-FREE PIEZOELECTRICS: (K,NA)NBO$_3$ BASED CERAMICS

B. MALIC*[1], J. BERNARD[1], D. JENKO[1], J. HOLC[1], M. KOSEC[1], A. BARZEGAR[2], and D. DAMJANOVIC[2], [1]Jozef Stefan Institute, [2]Ceramics Laboratory, Swiss Federal Institute of Technology EPFL.
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Piezoelectric materials based on $Pb(Zr,Ti)O_3$ solid solution (PZT) have been widely used due to their piezoelectric, pyroelectric and ferroelectric properties. One of the major drawbacks of these materials is a high lead content and therefore a possible ecological hazard. An alternative group of lead-free ferroelectric materials are those based on alkaline niobates. According to the rather scarce literature (e. g. Jaffe et al., Piezoelectric Ceramics, 1971) the functional response of sodium potassium niobate with the K/Na atom ratio of 50/50, close to the morphotropic phase boundary, is satisfactory. One of the major problems of alkaline niobates is sintering to high densities (ibid). An increase in density of $K_{0.5}Na_{0.5}NbO_3$ (KNN 50/50) was obtained by introducing A-site vacanicies in the perovskite lattice as for example by Mg-doping (Kosec, Kolar, 1975) or Ba-doping (Ahn, Schulze, 1987). In this contribution the effect of alkaline-earth (AE) dopants Mg^{2+} and Sr^{2+} on functional response of KNN is studied. Ceramic powders with the general formula $(K_{0.5}Na_{0.5})_{1-2y}AE_yNbO_3$, $y = 0.005$, were prepared by classical ceramic processing. Ceramics were sintered between 1100 and 1115 ° C. The values of 94 - 95 % of theoretical density are obtained for stoichiometric KNN after sintering at 1115 ° C for 2 hours. Both Mg and Sr doping leads to higher densities of about 96-97 % TD. The piezoelectric response of KNN ceramics, the d_{33} coefficient of about 80 pC/N for KNN and 75 pC/N and 95 pC/N for Mg- and Sr-doped KNN, respectively, and k_t values of about 0.40, show that alkaline niobates are ecologically acceptable and biocompatible materials for some piezoelectric applications.
Ministry of Education, Science and Sports of Republic of Slovenia and European Union (LEAF project) are gratefully acknowledged for financial support.

FE1-H-5 513CD 9:45 a.m.

PIEZOELECTRIC/ELECTROSTRICTIVE MULTIMATERIAL PMN-PT MONOMORPH ACTUATORS

A. HALL*, M. ALLAHVERDI, E. K. AKDOGAN, and A. SAFARI, Rutgers University.
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Fused deposition of multi-materials (FDMM), a CAD-based layered manufacturing technique, was utilized to deposit monolithic piezoelectric/electrostrictive multi-material monomorphs. Monolithic multi-material samples, comprised of piezoelectric $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$, 0.65PMN-0.35PT, and electrostrictive 0.9PMN-0.1PT, have been successfully co-fired. Multi-material monomorphs, that are isometric with the co-fired ones, have also been prepared by gluing individual layers, and were used in a comparative study. The dielectric permittivity, displacement, and polarization hysteresis were investigated. The permittivity of the multimaterial sample followed the dielectric mixing laws, showing a dielectric constant of 5,800 at room temperature. The P-E loop of the multimaterial sample exhibited a saturation polarization similar to that of the single material electrostrictive 0.9PMN-0.1PT. Hysteresis was shown to be lower for the monolithic monomorph as compared to the glued monomorph. We

provide an in-depth discussion on the effects of material type and interfacial properties on the displacement characteristics of multi-material monomorphs.
The authors gratefully acknowledge the funding provided by the Office of Naval Research and the State of New Jersey.

Session: FC1-H
PHASE NOISE MEASUREMENT AND REDUCTION TECHNIQUES
Chair: G. Montress
Raytheon Research Division

FC1-H-1 511CF 8:30 a.m.

DIRECT-DIGITAL PHASE NOISE MEASUREMENT

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We have completed a Phase 1 SBIR project to develop technology for direct phase noise measurements. This new approach to phase noise measurements uses fast digital-to-analog converters to digitize the input RF signal and performs all down-conversion and phase detection functions by digital signal processing. It has several significant advantages over analog phase noise measurement techniques: there is no external phase-lock loop, oscillators can be compared at different frequencies, amplitude and phase noise may be measured simultaneously, the spectrum and Allan variance may be computed simultaneously, and complex calibration techniques are eliminated.

We have built prototype phase detector coupled to a fast PCI-X server to collect the data. Data analysis was performed using Matlab and has allowed us to determine the wideband noise floor and the flicker noise of the ADCs. The hardware was operated over the input range of 1 to 30 MHz and 3 ADCs from different manufacturers were evaluated. We found consistent wideband noise levels of approximately -150 dBc/Hz from the ADC electronics and flicker levels of -145 dBc/Hz at a 1 Hz frequency offset from the 5-MHz carrier. The ADC quantization noise was always less than the circuit noise. Using cross correlation, we have achieved 5-MHz noise floors of -155 dBc/Hz at 1 Hz and -170 dBc/Hz broadband.

There are several difficult technical issues with the direct measurement approach. The first is the 30 ps/C temperature coefficient of the ADCs, which can increase the low-frequency noise above the flicker noise level of the ADCs. The second is the high speed processing required to perform the FFT computations in real time. These challenges must be overcome in order to build a practical instrument using this technique.
This work was funded, in part, by the National Institute of Standards and Technology under Order Number SB1341-03-W-0817

FC1-H-2 511CF 8:45 a.m.

PHASE NOISE MEASUREMENT OF LOW-POWER SIGNALS

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Traditionally, phase noise is measured by comparing two signals of the same frequency, one of which is taken as the reference, using a saturated mixer as the phase-to-voltage converter. Typical low-noise double-balanced mixers require a power of 5-15 dBm to saturate. In some cases of interest, none of these signals has sufficient power. In the case of signals distributed over optical fibres, for example, the output power of a photodetector can be -20 dBm or less, requiring further amplification before feeding into the mixer. Yet, amplifiers flicker, which turns into the main measurement limitation at low Fourier frequencies. The flicker noise of actual microwave amplifiers is in the range of -100 to -110 $dBrad^2/Hz$ at f=1 Hz off the carrier.

We have discovered that the amplifier flickering can be strongly reduced by feeding into the amplifiers the sum and the difference of the two signals, instead of merely amplifying them. The two signal must be matched in amplitude and phase for the difference to be close to zero. Neither correlation or averaging are required to reduce the flicker noise, for a clean signal proportional to the instantaneous value of the phase is available in real-time at the mixer output. On the other hand, white noise and other linear additive random fluctuations can not be reduced in this way.

The experimental demonstration goes as follows. First, two signals of frequency ν_0=10 GHz and power P_0=-20 dBm, obtained by splitting the output of a single synthesizer, are amplified and detected. The amplifier noise results in a residual flicker of -106 $dBrad^2/Hz$ at f=1 Hz. Then, the sum and the difference of the same signals are amplified and detected. Using the same components, the residual flicker is of -130 $dBrad^2/Hz$ at f=1 Hz. This improves by 24 dB upon the first configuration.

The analytical proof and the physical interpretation are surprisingly simple.

FC1-H-3 511CF 9:00 a.m.

W-BAND DUAL CHANNEL AM/PM NOISE MEASUREMENT SYSTEM

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We discuss the performance of a W-band (92-96GHz) AM/PM noise measurement system. The system uses two nearly identical channels to measure the AM or PM noise added by an amplifier or any passive component. It is principally designed to measure amplifiers in pulsed mode with a duty cycle of 5% to 100% (CW) at a given pulse repetition frequency. The system is calibrated using a single sideband (SSB) modulator. We describe the details of the dual-channel measurement test set and several design considerations that are essential for accurately extracting device noise from measurement-system noise. The preliminary results on the PM noise floor of the measurement system with CW signal are given in Table 1. It is known that adjusting the delay on both sides of each bridge to be identical causes the PM noise of the reference source to cancel to a high degree. The need for a clean W-band reference source signal is especially important in pulsed measurements because pulsing of the signal through the device under test aliases the broadband noise of the source and raises the noise floor. Presently we are involved in reducing the PM noise of the source, a Gunn oscillator that is phase locked to a cavity-stabilized oscillator and synthesizer at X-band. One goal of this work is to study the effect of input power on the 1/f (flicker) noise of different amplifiers under pulsed as well as continuous mode of operations and also get some information about the Noise Figure (NF) from broadband PM noise. The effect of different amounts of phase delay on the noise performance of device under test is also an important subject of our investigation.

Table 1

Offset Frequency (Hz)	Noise floor, L(f) dBc/Hz
100	-110
1000	-120
10000	-130
100000	-140

FC1-H-4 511CF 9:15 a.m.

DUAL PHOTONIC-DELAY-LINE CROSS CORRELATION METHOD FOR THE MEASUREMENT OF MICROWAVE OSCILLATOR PHASE NOISE

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Measuring the phase noise of low-noise microwave oscillators has always been a challenge. For heterodyne measurement, it is not easy to find low-noise reference microwave oscillators. The delay-line discriminator is the homodyne alternative, which eliminates the need for a low-noise reference oscillator. However, the high loss of electrical delay lines limits the delay to some 100 ns at microwave frequencies, which is too short to characterize high performance oscillators. A better alternative to the microwave line is the photonic delay line. Standard telecommunication fiber SMF-28 has 0.2 dB/km loss. A length of 10 km fiber can be spooled in a very compact package, resulting in about 50 microseconds of delay. To measure microwave signals, we use an electro-optic intensity modulator

to modulate the 1.55-μm signal from a semiconductor laser and a high speed photodetector to recover the microwave signal after the delay fiber. For the photonic delay-line discriminator the noise of microwave amplifiers, optical fibers, and other components limit the achievable noise floor. One way to overcome such a limitation is the cross correlation technique, which was used with rf delay lines some years ago. In our system we can, in principle, eliminate the noise of the components, including the noise of amplifiers and the optical fiber, using cross correlation and averaging. The only component common to the two channels is the power splitter that receives the microwave signal. All other components, including lasers, modulators, amplifiers, photonic delay lines, and the photodetectors are separate. A dual channel FFT analyzer is utilized for cross correlation measurement. Averaging on 200 samples, the noise floor at 10 kHz offset from the 10-GHz carrier is 146 dBc/Hz for 1.14 km delay fiber, and 160 dBc/Hz for 4.46 km. To our knowledge, this is the lowest noise floor reported for the measurement of microwave signals using the homodyne delay-line discriminator technique, and shows more than 20 dB improvement over the single channel delay-line discriminator. Using the dual photonic-delay-line cross correlation technique, we have measured the phase noise of the coupled opto-electronic oscillator (COEO) that was recently developed. The phase noise of the 9.3 GHz COEO at 10 kHz offset was 140 dBc/Hz, which is at least 10 dB better than the best commercial synthesizers, and thus could not be easily characterized in our lab otherwise.
Authors thank John Dick for inspiring discussions, and Shouhua Huang for experimental assistance.

FC1-H-5 511CF 9:30 a.m.

THE PHOTONIC DELAY TECHNIQUE FOR PHASE NOISE MEASUREMENT OF MICROWAVE OSCILLATORS

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In this scheme the phase of the oscillator signal is compared to a delayed copy for decorrelation, and converted into a voltage for further analysis. The technique is based on the use of an optical fiber to provide the delay. This homodyne method is appealing because i) it is simple, ii) it does not require a reference oscillator, and iii) it is suitable to any frequency in a wide range, provided the delay be a non-resonant phenomenon. This feature is relevant to the measurement of certain low-noise oscillators that end up with odd frequency values.

At the state of the art, the optical fiber is the ideal delay element for a number of reasons. First and foremost it exhibits low attenuation (0.2 dB/km at λ=1.55μ), which permits the implementation of a long delay, in excess of 100 μs (20km) in a single step, without amplification. By contrast, coaxial cables could never have been used effectively because of the large attenuation.

For reference, the attenuation of a UT-141 semirigid cable (3.5 mm diameter) is 0.8 dB/m at 10 GHz. This limits the maximum length to some 50 m, thus the delay to 200 ns. Secondly, the fiber shows wide bandwidth, low thermal coefficient (dn/dT=6.85×10^{-6}/K), and reasonable mass and size; for reference, a 10 km winding (50 μs delay) takes 1 kg and 1×10^{-3} m^3. Finally, energy is perfectly confined inside the fiber, for EMC, grounding and shielding are no longer a problem.

Theoretical analysis and experiments shows that a fiber-based instrument features excellent sensitivity in the 10^2 to 10^6 Hz region of Fourier frequency f. At 10 GHz of carrier frequency, the sensitivity is of -120 to -80 $dBrad^2$/Hz at f=1 kHz, depending on the delay τ. Presently, the sensitivity is limited by the $1/f^3$ coefficient that results from the 1/f noise of microwave amplifiers and from the frequency-to-phase conversion inherent in the delay. A sensitivity of -100 $dBrad^2$/Hz is obtained with τ=10 μs (2 km fiber). On the other hand, our method is not suitable to long-term measurement.

As an example of application, we measured the phase noise of a 100 MHz quartz oscillator multiplied to 9.9 GHz, and of a 10.05 GHz photonic oscillator. The latter turned out to be simpler because the it has a λ=1.55 μm modulated output.

Most of our effort is spent in understanding the noise in the optical system, and the interaction between microwaves and optics.

FC1-H-6 511CF 9:45 a.m.

PHASE NOISE SUPPRESSION IN FREQUENCY COMB GENERATORS

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We propose an idea to suppress the flicker (1/f) noise in multiplier based frequency comb generators. Comb generators are often used for frequency multiplication in frequency synthesis. In general, comb generators apply high power to a non-linear element (NLE) such as a step-recovery diode (SRD) to generate harmonics. Flicker, random-walk, and drift of phase through NLE cause significant noise to be projected onto the harmonic-frequency signal, not to mention the multiplicative noise introduced by the high power amplifier driving the NLE. A system can be constructed that compares the fundamental signal before and after it enters the NLE. If the phase perturbations between the fundamental and any particular harmonic can be measured in real time, a feedback or feed forward servo can be implemented to correct the phase noise that is introduced by frequency multiplication. This paper outlines the technique and provides measurements of the residual PM noise between a fundamental source signal and the same fundamental as derived after a power amplifier and NLE.
I would like to acknowledge F.L. Walls for his valuable suggestions.

Session: FC2-H
SENSOR TECHNOLOGY AND INSTRUMENTATION
Chair: R. Lec
Drexel University

FC2-H-1 D10 8:30 a.m.

SAW SENSORS USING ORTHOGONAL FREQUENCY CODING

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The SAW sensor offers advantages in that it is wireless, passive, small and has varying embodiments for varying sensor applications. In addition, there are various ways of encoding the sensed data information for retrieval. Single sensor systems can typically use a single carrier frequency and a simple device embodiment, since tagging is not required. In a multi-sensor environment, it is necessary to both identify the sensor as well as obtain the sensor information. The SAW sensor then becomes both a sensor and a tag. For multi-sensor systems, many embodiments use coded reflectors having a single carrier frequency. Previous work by several authors have shown that there are advantages of using spread spectrum techniques for device interrogation and coding, such as enhanced processing gain and greater interrogation power. This paper will present a spread spectrum approach using orthogonal frequency coding (OFC) for encoding the SAW sensor. The encoding technique is similar to M-ary FSK in terms of its implementation where a transducer or reflector is built with the desired code. A second level of coding using a PN sequence can also be employed. The processing gain offered by spread spectrum increases the range of the system and codes are designed to reduce cross correlation for environments where multiple sensors are employed. In addition, it is shown that the time ambiguity in the autocorrelation due to the OFC is significantly reduced as compared to a single frequency tag having the same code length. The OFC approach is general and should be applicable to many differing SAW sensors for temperature, pressure, liquids, gases, etc. Device embodiments are shown, and a discussion is provided for device design considerations such as the number of chips used, chip length, transducer fractional bandwidth, and chosen piezoelectric material. Measured device results are presented and compared with COM model predictions to demonstrate performance. Devices are then used in computer simulations of multiple transceiver designs and the results are discussed.

FC2-H-2 511DE 8:45 a.m.

MEASUREMENT OF THE EQUIVALENT CIRCUIT PARAMETERS OF CHEMICAL INTERFACE LAYERS ON BULK ACOUSTIC WAVE RESONATORS

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A measurement of the frequency shift induced by a sorbed vapour onto a bulk or surface acoustic wave device is often employed as chemical sensors in the vapour phase. The observed frequency shift in the resonator during exposure to an analyte is often simply ascribed to mass loading of the chemical sensor by the analyte species and the well-known Sauerbrey equation is used to express the relationship between frequency shift and sorbed mass. However, in many instances this is a simplification of the real situation, as the adsorbed analyte produces not only a mass change on the surface of the device, but can also produce viscoelastic changes in the chemical interface layer that will perturb the propagation of the acoustic wave and influence the observed frequency shift. This paper now studies the properties of different chemical interface layers deposited on bulk quartz crystal resonators. These interface layers varied from alkane thiol self-assembled monolayers (SAMs) to different polymer layers. In each case the impedance spectrum of the resonator is determined before deposition of the interface layer in order to calculate the equivalent circuit parameters of the resonator. After deposition of the interface layer, the impedance spectrum is again measured and the modified BVD is modeled in order to extract the circuit parameter introduced by the presence of the layer. The sensor structures are then exposed to different vapour phase analytes and the impedance spectrum again measured and modeled to produce the change in equivalent circuit parameters as a result of the sorbed analyte. These measurements performed on resonators with different coatings reveal very marked differences in the effect of organic vapours. In the case of a resonator coated with a polydimethylsiloxane (PDMS) layer, considerable damping from this lossy layer is found as seen from the large increase in the observed effective series resistance from 8 ohm to approximately 150 ohm. Upon exposure of the sensor to tetrahydrofuran (THF) vapour, the resistance doubles over the concentration range while a shift of approximately 90 ppm is observed in the series resonant frequency. A modeling of the equivalent circuit shows that the inductance increases at same rate as the frequency shift, while the capacitance remains effectively unchanged. In contrast to the response of the lossy PDMS layers, only a small change in the effective series resistance of the resonator is observed when a more rigid polyanaline layers are deposited. These sensor structures are not as sensitive as the PDMS structures and frequency shifts of only 25 ppm are observed over the frequency range. Modeling of the motional parameters indicates that changes in the capacitance as well as the motional inductance are now significant in determining the frequency shift. This is most probably due to the greater effect of the sorbed molecules on the elasticity of the polyanaline film.

FC2-H-3 511DE 9:00 a.m.

ON-CHIP SELF-SENSING FUNCTION OF 4X4 MATRIX MICROMACHINED RESONATING PIEZOELECTRIC MEMBRANES FOR MASS DETECTION APPLICATIONS

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Nowadays, Quartz Crystal Microbalance (QCM) devices are still the most widespread and proven resonant biosensors allowing successful characterization of biomolecular systems in their natural aqueous environment. However, the main limitations of QCMs (like their miniaturization or integration in multisensors arrays) stirred up to propose new miniaturized devices like the flexural plate wave (FPW) that successfully addressed the sensitivity issue at the expense of more challenging electronics when used as biosensors [1]. In this paper, we studied the dynamic behaviour of micromachined piezoelectric membranes as an alternative to the QCMs biosensors. The 44 matrix of piezoelectric membranes has been fabricated by standard micromachining techniques starting with a Silicon-On-Insulator wafer. Each membrane (circular shaped, 150 μm of radius) can be individually addressed for actuation and/or sensing applications through a $PbZr_xTi_{1-x}O_3$ (PZT) 800-nm thick film. We proved elsewhere [2] that similar microfabricated piezoelectric membranes can be used as self-actuated mass detection sensors for real time detection of gold colloid adsorption in liquid by using an external optical detection. Here we show that the same kind of membranes exhibit excellent self-sensing capabilities by using the direct piezoelectric effect of the PZT layer. First, the piezoelectric membranes were glued on a TO8 package with each membrane wire-bounded to the TO8 pins. The open-loop resonant frequencies of several membranes were measured by examining the self-induced charge on the sense electrode using a 4x4 mm^2 proximity electronics circuit including a charge amplifier. Care has been taken to the shielding of the sensing electronics in order to improve the signal-to-noise ratio. We simultaneously performed resonant frequencies measures by means of a dynamic optical interferometer that completely matched the electrical self-sensed resonant spectra. In this case the piezoelectric membranes were actuated in two different ways, either by using an external transducer or by using the self-actuating (reverse piezoelectric effect) capability of each membrane. A finite-element computation with CoventorWare [3] was used to implement the model of the piezoelectric membranes where the real multilayer composite configuration has been taken into account in terms of material properties and residual stresses. Modal and harmonic analysis has been performed and the resonant spectra obtained were in very good agreement with the experimental results. Works are currently under progress in order to simultaneously get self-actuation and self-sensing at the chip level for performing specific biorecognition experiments using similar piezoelectric membranes. [1] B. Cunningham, M. Weinberg, J. Pepper, C. Clapp, R. Bousquet, B. Hugh, R. Kant, C. Daly, E. Hauser, Sens. Actuat. B 73 112

(2001) [2] M. Guirardel, L. Nicu, D. Saya, Y. Tauran, E. Cattan, D. Remiens, C. Bergaud, Japan. J. Appl. Phys. 43 No.1A/B L111 (2004) [3] Coventor Inc., 4001 Weston Parkway, Cary, NC 27513
Authors would like to acknowledge Christiane Duprat from INSA-AIME, Toulouse, for helping us to perform the wire-bounding of our devices.

FC2-H-4 511DE 9:15 a.m.

PACKAGING OF SURFACE ACOUSTIC WAVE (SAW) BASED BIOSENSORS: AN IMPORTANT ISSUE FOR FUTURE BIOMEDICAL APPLICATIONS

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SAW devices basing on horizontally polarized surface shear waves (HPSSW) enable label-free, sensitive and cost-effective detection of biomolecules in real time. Due to their high operating frequencies, SAW sensors have the highest sensitivity of all gravimetric methods. Binding reactions on the sensor surfaces are detected by determining changes in surface wave velocity caused mainly by mass adsorption or viscosity changes in the sensing layer. To create a biosensor, SAW devices were coated with several layers to promote covalent binding of biochemical receptors [1]. Early results have shown the importance of small sampling volumes with low inner surface areas. Especially, the use of bond wires is critical. Beside their instability in liquid streams they severely prevent small sampling cells. In addition, a minimum of mechanical stress by fixing the device is required. The latter is hard to solve since sealing elements usually require a minimum of pressure.

We present two consecutive development stages of further SAW device integration: both use resonator filter based HPSSW devices with gold transducers on 36°YX $LiTaO_3$ substrates. They were especially developed for biosensing purposes and operate at 433.9MHz within oscillators in a resonant mode. The first approach takes advantage of large gold electrodes on the SAW sensors enabling capacitive coupling: They are simply faced down onto an electronic board on isolated contact pads and fixed on a small milled channel within the board allowing the fluid passing only along the SAW path. This configuration thus enables simple sensor replacement and cell volumes of a few μl. However, it has also shown a rather inaccurate sensor calibration which was strongly affected by the pressure on the sensor fixation. The main reason was different capacities of the dielectric coupling resulting in a constant but different phase position of the sensor within its oscillator. From earlier work we knew that exactly this effect is critical [2].

Another new approach avoids this drawback and enables a remarkable higher level of miniaturization: The sensor device is completely packed within a polymeric housing produced by stereo lithographic methods. The result is a polymer chip as a tight and durable package for SAW biosensors which are completely encapsulated within the polymer chip leaving only a small flat channel open along the SAW path. The effective sample volume is only 500 nl per chip! Electric contact of the SAW device is made by evaporated conductive paths buried within the chip. They lead to pads on the chip to be contacted from outside with standard contact springs, respectively. These SAW biosensor chips are widely insensitive towards mechanical stress or phase position changes due to a durable encapsulation and pure ohmic contacts. First measurements applying these sensor chips resulting from adsorption phenomena and immunosensing experiments with bioactive molecules will be shown.

1) K. Lnge et al, Anal. Chem. 75(2003), 5561-66 2) J. Reibel et al, Anal. Chem. 70(1998), 5190-97

Siemens/EPCOS Company in Munich, Germany

FC2-H-5 511DE 9:30 a.m.

A NEW ANALOG OSCILLATOR ELECTRONICS APPLIED TO A PIEZOELECTRIC VIBRATING GYRO

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In the past few years, there has been significant progress in improving performance of micro-mechanical inertial sensors. In this area, ONERA, the French National Establishment for Aerospace Research, in partnership with DGA (the French MoD Procurement Agency), has been developing micro-machined vibrating sensors to use in low-cost and miniaturized inertial measurement unit (IMU) developed for e.g. stabilisation, guidance, and inertial navigation. Presently, two monolithic quartz sensors are developed; a vibrating beam accelerometer "VIA" (Vibrating Inertial Accelerometer) and a vibrating Coriolis type gyrometer "VIG" (Vibration Integrated Gyrometer).

The body of the gyro developed at ONERA is a tuning fork type made of quartz. The flexural vibration mode, which is excited by the oscillator electronics, is in phase quadrature with the torsionnal mode used to detect the coriolis force induced by rotation. Electrical signals don't represent exactly this quadrature because of the inter-electrode capacity and variations of the quality factor. These variations also imply drifts of the oscillation amplitude. In order to increase the sensor's precision and to null drifts and the zero signal induced by mechanical coupling, it is important to quantify the effects of phase and amplitude drifts of the drive mode, and to propose a new oscillator electronics to null them.

This paper deals with a new analog oscillator electronics applied to the piezoelectric vibratory gyroscope developed at ONERA. The equivalent circuit of the gyro and the readout electronics are presented. Then the influence of phase and amplitude drifts of the primary vibration on the angular velocity measurements are discussed theorically and experimentally. Finally, simulations and results of the new analog oscillator electronics including phase and amplitude control loops are shown.

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FC2-H-6 511DE 9:45 a.m.

MINIATUARIZING QUARTZ VIBRATORY GYRO SENSOR WITH HAMMER-HEADED ARMS

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A newly designed vibratory gyro sensor using a quartz crystal was developed for electronic image stabilizing technology in digital camera systems. These systems require low driving voltage for low power consumption and the small size for compact assemble. Conventional gyro sensors for these systems are used the PZT ceramics prism shaped vibrator, which is too large to assemble in resent digital camera system. The rapid miniaturization was achieved of the developed quartz gyro sensor with the 2mm square size vibrator. The crystal impedance of the vibrator was reduced less than 40k ohm using in hammer-headed arms with Vacuum- Sealed package. This can be applied to various mobile electronic systems because larger vibrating displacement can be obtained at lower voltage. As it has been using in the tuning fork of the oscillators, it is easy to fabricate in mass production at low cost, which is required for electronic industry. In this paper, the optimization of the design of the flat gyro sensor is discussed. The vibratory gyro sensor with full hammer-headed shaped resonators is proposed. The flat sensor (0.1mm thick) was fabricated using a quartz crystal showing promising performance for electronic mobile applications.
We would like to express our deepest thanks to Professor Yoshiro Tomikawa in Yamagata University for his useful suggestions. Special thanks are due to M. Tanaka, Y.Yabushita, A.Satomura, K.Iwatsuki for initial work on the angular rate sensor.

Session: U1-I

CONTRAST AGENTS IMAGING
Chair: K. Ferrara
University of California - Davis

U1-I-1 510AC 10:30 a.m.

A TWO-STEP PROCEDURE FOR OPTIMIZATION OF CONTRAST SENSITIVITY AND SPECIFICITY OF POST-BEAMFORMING VOLTERRA FILTERS

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We have previously introduced post-beamforming second order Volterra filter (SOVF) for decomposing the pulse-echo ultrasonic radio-frequency (RF) signal

into its linear and quadratic components. Using singular value decomposition (SVD), an optimal minimum-norm least-squares algorithm for deriving the coefficients of the linear and quadratic kernels of the SOVF was developed and verified. Experimental results, both in vivo and in flow phantoms, has shown that the quadratic kernel of the SOVF offers levels of sensitivity comparable to pulse inversion. However, the agent specificity of the standard SVD-based quadratic kernel is sometimes compromised by sensitivity to nonlinear echoes from tissue. In this paper, we present a two-step algorithm for computing the coefficients of the quadratic kernel leading to reduction of tissue component and increase the specificity while optimizing the sensitivity to the ultrasound contrast agents (UCA). In the first step, quadratic kernels from individual singular modes of the data matrix are compared in terms of their ability of maximize the contrast to tissue ratio (CTR). In the second step, quadratic kernels resulting in the highest CTR values are convolved. In practice this is limited to two or three modes in order to avoid impractically large kernel size. Experimental results from imaging of UCA in flow channels through tissue-mimicking phantoms and in-vivo data demonstrate the advantage of this two-step algorithm. Illustrative Images of the kidney of a juvenile pig were obtained before and after infusion of contrast agent (SonoVue, Bracco, Geneva, Switzerland) at various concentrations. For example, at a concentration of 0.01 ml/kg, B-mode images (3 cycles at 1.56 MHz transmit frequency) show no quantifiable change due to the presence of the contrast agent. PI images without second harmonic (SH) filtering showed 10.2 dB enhancement and evidence of residual tissue components due to motion. SH imaging on PI data produced 14.4 dB enhancement with some loss in resolution. On the other hand, quadratic images obtained using the standard SVD-based and proposed algorithm produced CTR values of 22.4 and 27.5 dB, respectively. Interestingly, the histogram of the quadratic component of the echo signal using the two-step algorithm shows the lowest degree of overlap (or maximum separation) between UCA and tissue regions compared with that of the standard B-mode, PI, and standard SVD-based quadratic kernel. Similar results were obtained from imaging flow phantom under a variety of exposure conditions and UCA concentration levels.

U1-I-2 510AC 10:45 a.m.

SPECTRAL COMPENSATION FOR TISSUE ATTENUATION AND TRANSMIT INTENSITY IN ULTRASONIC DETECTION OF MICROBUBBLES BY HARMONIC METHOD

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Background: Gas-filled microbubbles are highly nonlinear and generate strong harmonic component as they scatter the incident ultrasound. For this reason, microbubbles are used as contrast agent to assess tissue perfusion by harmonic

imaging. This imaging method uses the harmonic component to construct the image. However, the magnitude of the harmonic component in the echo is influenced by the intensity of the transmitted ultrasound and the attenuation of the intervening tissues in the ultrasound path. Thus, the harmonic magnitude by itself may not be a reliable indicator of the presence or absence of microbubbles, and hence, tissue perfusion. In a recent work, we introduced a parameter, Harmonic to Fundamental Ratio (HFR), which is defined as the ratio of harmonic magnitude to the fundamental magnitude, and showed that this parameter improves microbubble detection [J Ultrasound Med 21:249-259] by partially compensating for the attenuation. Here, we present a new parameter that, under ideal condition, completely compensates for the effects of tissue attenuation and transmit intensity for superior microbubble detection. **Methods:** We propose a new parameter called Harmonic to Squared Fundamental Ratio (HSFR). The magnitude of harmonic signal generated by a nonlinear medium (e.g., tissue with microbubbles) is proportional to the square of incident sound pressure. Therefore, HSFR removes the effect of transmit intensity. In tissue, the attenuation coefficient for the harmonic signal is twice that of the fundamental. Thus, HFSR also automatically compensates for frequency dependent attenuation, without the need for measuring the tissue attenuation coefficient. **Experiment:** The target tested is 1cm thick, consisting of either 0.01% Definity solution (contrast agent with microbubbles) or water (as a control). Narrowband ultrasound of 1.3MHz is transmitted through the target and the echo is digitized at 20MHz and used to calculate both HSFR and HFR. A calibrated attenuation pad with attenuation coefficient of 0 (water), 3, or 5dB/MHz is introduced between the transducer and the target. The transmitted pressure is also varied over a seven-fold range. **Results:** For all combinations of attenuation and transmit pressure, the HSFR is -28.3±4dB for the Definity solution, and -50.1±3.9dB for the control, whereas the HFR gives -33.3±4.9dB and -52±7.4dB, respectively. **Conclusion:** Compensation for frequency dependent attenuation and transmit intensity is important for harmonic detection of microbubbles. HSFR is a better parameter than HFR: it increases the mean contrast between microbubble solution and the control, and decreases the variance within each class. More importantly, the compensation in HSFR can be done without knowledge of the interlaying tissues attenuation coefficient or the transmit intensity.
This work is supported by NIH grant R01HL068573.

U1-I-3 510AC 11:00 a.m.

HIGH FREQUENCY NONLINEAR SCATTERING AND IMAGING USING A SUB-MICRON CONTRAST AGENT

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Nonlinear contrast imaging using ultrasound biomicroscopy instrumentation has recently been demonstrated at transmit frequencies (f_{trans}) of up to 30 MHz.

These results, achieved with Definity®, indicated the feasibility of subharmonic imaging (SHI, $0.5f_{trans}$) and ultraharmonic imaging (UHI, $1.5f_{trans}$), while second harmonic imaging (HI, $2f_{trans}$) was ineffective due to the presence of tissue harmonics. Previously, we established that nonlinear scattering at 30 MHz could be stimulated with improved efficiency from bubbles with diameters on the order of 1 micron and below, which were present in a conventional frequency agent (BR14, Bracco Research, Geneva), and isolated by means of mechnical filtering. In this study we investigate nonlinear scattering and imaging of a novel experimental lipid encapsulated agent (BG2423, Bracco Research, Geneva) comprised predominantly of sub-micron bubbles. This work is conducted both with a broadband PVDF transducer (19 MHz center; 8 mm aperture; f#1.6) used in ultrasound biomicroscopy systems, and, in order to assess the feasibility of extending nonlinear contrast imaging to intravascular ultrasound (IVUS) applications, with a 30 MHz single element PZT IVUS transducer. Agent characterization experiments were conducted to assess nonlinear scattering as a function of transmit frequency (20, 30 and 40 MHz), bandwidth (10%, 15%, 25%, 50%) and pressure (~200 kPa to 3 MPa). Additional experiments were conducted to test for the presence of bubble disruption. A substantial bandwidth dependant pressure range was found where it is possible to produce energy in the subharmonic and second harmonic regions in a nondestructive manner. Imaging experiments were then conducted with a bench-top system and a flow phantom. Images were constructed using pulse-inversion techniques from a series of pulse ensembles acquired during continuous mechanical translation. HI and SHI modes were evaluated as a function of transmit amplitude for f_{trans} of 20 and 30 MHz (bandwidths 25 and 50%) using the PVDF transducer. For the IVUS transducer, HI was performed at f_{trans}= 20 MHz, and SHI was performed at 30 and 40 MHz (25% bandwidths). HI was found to produce modest improvements in contrast to tissue signal ratios (CTR) at low transmit amplitudes (up to 7 dB with IVUS HI). In all cases, the SHI mode results show tissue suppression to the noise floor. With the IVUS 40 MHz SHI mode, contrast to noise ratios of up to 16 dB were achieved. This work demonstrates the feasibility of high frequency nonlinear imaging using a sub-micron microbubble agent and indicates the potential of extending nonlinear contrast imaging to intravascular ultrasound applications.
This work was supported by STW and ICIN.

U1-I-4 510AC 11:15 a.m.

HIGH FREQUENCY CONTRAST IMAGING

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Contrast agents enhance echoes from the microvasculature and enable the visualization of flow in smaller vessels. In order to improve the lateral spatial resolution of contrast imaging, we explore the use of transmission with a center frequency at 7.5 MHz and 10 MHz, and reception of echoes with a center

frequency near the resonance frequency of the contrast agent. In order to improve the sensitivity of this method, while maintaining the spatial resolution of the returned tissue echoes, we explore the use of chirp transmission with a matched receiver. An advantage of the method is that the mechanical index is low due to the high frequency driving pulse. The technique takes advantage of nonlinear oscillations of the microbubble when microbubbles are sufficiently driven by the ultrasound pulse. Results of a numerical evaluation of the modified Rayleigh-Plesset equation and in-vitro experiments will be presented. From the radius-time curve of single bubble simulation, the maximal bubble expansion using a 7.5 MHz linear chirp with pressure up to 1 MPa has been tested with equilibrium radii ranging from 0.5 to 2 microns resulting in a maximum relative expansion ratio below 2. A time-frequency analysis of the received pressure shows that a substantial fraction of the low frequency component comes from the ringdown when the driving pulse ends. In the experiments, the response is explored with a center driving frequency of 7.5 MHz. To better detect the low frequency component, we propose to use two confocally aligned transducers at widely separated frequencies, transmitting at 7.5 MHz and receiving at 2.25 MHz. The excitation pulse is a 2-microsecond, Hamming windowed chirp signal with bandwidth ranging from 5.6 MHz to 9.3 MHz and a peak pressure at 7.5 MHz ranging from 0.7 MPa to 2 MPa. The flow phantom used in the experiments consists of a 200-micron diameter cellulose tube embedded in a tissue mimicking phantom at a depth of 1 cm (attenuation of 7 dB/cm at 7.5 MHz). The contrast agent used has a lipid-shell with high molecular weight gas core and is diluted in distilled water to a concentration of no greater than 5000 microbubbles per microliter. The contrast agent was pumped through the phantom at a velocity of 1.2 cm/s and M-mode data were acquired at a PRF of 10 Hz while receiving with the 2.25 MHz transducer. In regions containing the contrast agent, there are significant low frequency components centered at about 3 MHz. The bubble components can be separated from the tissue components using a band pass filter from 1 MHz to 5 MHz applied directly to the radiofrequency data, and the resulting tissue and noise spectral components were found to be 20 dB down compared with microbubble components for peak transmitted pressure of 2 MPa at 7.5 MHz (approximately 1 MPa derated for attenuation). Results for chirp transmission centered at 10 MHz with pressures up to 3 MPa will also be presented and compared to the results obtained at 7.5 MHz. This method may provide the opportunity to detect contrast echoes resulting from a single pulse, and thus may be robust in the presence of tissue motion.
We acknowledge the NIH (EB 00239) for their support.

U1-I-5 510AC 11:30 a.m.
(Invited)
ULTRASOUND CONTRAST IMAGING—A COMPANY PERSPECTIVE

P. J. A. FRINKING*, M. ARDITI, and M. SCHNEIDER, Bracco Research S.A.
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Ultrasound imaging has seen tremendous technological improvements over the last 10 years mainly thanks to rapid developments in digital electronics. This has made possible machines with digital beamformers resulting in improved image quality, and real-time 3D imaging is currently a reality. In parallel, the introduction of ultrasound contrast agents (UCA) more than 10 years ago prompted tremendous research efforts by clinicians, scientists and manufacturers, and also positively influenced the development of ultrasound imaging, even without UCA. With the advent of the so-called second generation contrast agents, and due to a better understanding of the acoustic properties of UCA, new sophisticated contrast-specific imaging techniques helped the field to mature and evolve considerably. It has made ultrasound a serious competitor with other imaging modalities, like CT and MR, for which contrast agents have been used for years. One extremely interesting feature of UCA is the possibility to do quantification or functional imaging. At Bracco Research in Geneva we have developed a destruction-replenishment method based on fundamental physical principles determining the imaging process during the UCA replenishment phase. Consequently, estimates of perfusion can be made independently of instrument settings, e.g. gain, log-compression, etc. Additionally, because of the physical foundation of the method, it is possible to extract morphological information about the organisation of the microvascular network under investigation from a distribution of flow velocities, which is reflected in the shape of the replenishment curve. This might be of importance for the characterisation of neovascular tissue in cancer and ischemic heart disease. The concepts of this new approach have been validated *in-vitro*, and are presently under investigation in the *in-vivo* context. A new and exciting area for ultrasound contrast, which might have an even greater impact on ultrasound imaging, is in molecular imaging. Microbubbles, or the so-called third generation agents, can be targeted to specific tissue types to delineate pathologies which would otherwise be difficult to detect, or can be used for therapeutic purposes such as drug delivery and gene therapy. The most interesting clinical applications will be in cancer and cardiovascular disease, which are the most prevalent causes of death in humans in developed countries. Apart from chemical and biological challenges, there are numerous physical implications on the behavior of the contrast agent microbubbles. With molecular imaging, the bubbles will be close or attached to a surface or interface. The presence of such an interface strongly influences bubble dynamics, changing its acoustic properties. These acoustic properties are currently under investigation with the help of sophisticated equipment, like high speed cameras, with which dynamics of individual bubbles close to an interface can be studied in detail. In summary, we strongly believe that UCA will continue to stimulate innovation in medical ultrasound, in its diagnostic capabilities in a growing number of indications, as well as in therapeutic areas.

Session: U2-I

THERAPY: BRAIN
Chair: E. Ebbini
University of Minnesota

U2-I-1 510BD 10:30 a.m.

LARGE VOLUME BLOOD-BRAIN BARRIER DISRUPTION BY LOW FREQUENCY FOCUSED ULTRASOUND: A METHOD FOR TARGETED DRUG DELIVERY AND MOLECULAR IMAGING

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Previously, we showed that the blood-brain barrier (BBB) can be locally disrupted by pulsed focused ultrasound sonication (frequencies 0.7 and 1.6 MHz) at low pressure amplitude levels if an ultrasound contrast agent containing preformed gas bubbles is injected beforehand. Here, we hypothesize that the BBB disruption can be also induced at lower frequencies that penetrate the skull better, do not suffer significant wave distortion while propagating through the skull, and produce a larger focal spot that is often desirable for targeted drug delivery or molecular imaging. We used a focused ultrasound transducer with a frequency of 0.26 MHz (diameter/radius of curvature 10/8 cm) to sonicate rabbit brains after injecting Optison intravenously. Both sonications through the intact skull and through a craniotomy were performed. The sonications were done under magnetic resonance image (1.5T or 3T) guidance. Burst lengths of 1 and 10 ms were investigated with a repetition rate of 1Hz and duration of sonication of 20 s. The pressure amplitude was varied between 0.14 and 0.9 MPa (acoustic power during the burst 0.09-4.3W). BBB opening was measured by following the MR image signal intensity over time after injecting an MRI contrast agent that does not normally penetrate through the BBB. The animals (34 rabbits) were sacrificed at 4-6h or 28 days after sonication, and the brain was harvested for histology. An additional set of rabbits (4) was sacrificed at 1-60min after sonication to perform an electron microscopy (EM) evaluation. The results showed that focal BBB disruption occurred at a rarefactional pressure amplitude of 0.2 MPa (estimated in the brain) in some cases (20%). At 0.3 MPa, about 90% of the locations were disrupted with 100% of the locations disrupted at 0.4 MPa. The histology did not show brain necrosis or damage in the power range tested. However, there were small extravasations of erythrocytes in 60% of the locations sonicated at the pressure amplitudes of 0.4 MPa, but none at lower pressures. The EM findings indicated that the ultrasound caused transport through the tight junctions and also induced transport through vacuoles.

The survival experiments (9 animals) showed that BBB repair began shortly after sonication. It was reduced but open after 3h and completely closed at 5h. The animals sacrificed at 28 days did not display any noticeable effects. In

these cases, the average enhancement at the sonicated locations in imaging at 28 days was as in control locations in the contralateral side of the brain.

These results demonstrate that the low frequency sonications could induce focal BBB disruption at pressure amplitudes and power values lower than what was found at higher frequencies. Similarly, there was less tissue damage at the higher power values, and the exposure conditions could be selected such that the disruption was induced without even the extravasation of erythrocytes that were shown to be present at higher frequencies. This is an important result for focal drug delivery into the brain.

This work was funded by NIH grants CA76550 and EB000705

U2-I-2 510BD 10:45 a.m.

TRANSCRANIAL MRI-GUIDED FOCUSED ULTRASOUND-INDUCED BLOOD-BRAIN BARRIER OPENING IN RATS

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While the blood-brain barrier (BBB) protects the brain from foreign bodies by preventing the penetration of large molecules, it also inhibits the entry of many therapeutic drugs. Nonlocalized diffuse opening of the BBB permits these drugs to reach their target but can have dose-limiting side effects due to the spread of neurologically active agents within the central nervous system. We previously demonstrated that focused ultrasound (FUS) could locally open the BBB in a rabbit model when a piece of skull is removed and that magnetic resonance imaging (MRI) could be used to guide and monitor the procedure. The present study examined whether the same desired effect of local BBB disruption can be achieved by applying FUS through an intact skull in a rat model.

Twenty-eight male Sprague-Dawley rats ($\sim$0.4 kg) were anesthetized and the hair covering the skull removed. Each rat was laid on the MR table in a standard 3-Tesla scanner so that its skull was acoustically coupled with degassed water and exposed to ultrasound from a single-element focused transducer. The transducer (diameter = 10 cm; radius of curvature = 8 cm; frequency = 1.5 MHz; acoustic efficiency = 60by a positioning device. Four focal locations aimed 5 mm deep in the brain were sonicated at different peak acoustic power levels ranging from 0.06 to 3.0 W. At the start of each sonication, a bolus of ultrasound contrast agent (Optison, Mallinckrodt, Inc., St. Louis, MO) containing microbubbles was injected simultaneously into the tail vein. The sonications were pulsed with a burst length of 10 ms, repetition frequency of 1 Hz, and total duration of 30 s. Contrast-enhanced MR images were obtained before and after sonication to detect focal leakage of the contrast agent through the BBB. The difference in MR signal intensity (SI) before and after the sonications was measured. If the increase in SI at the site of sonication, less the average increase in SI in unexposed tissue, was greater than one standard deviation of SI in unexposed

tissue, the BBB was considered to have been opened in that location. The MR images indicated 100focal coordinates following Optison-enhanced sonication of 0.6 W acoustic power or greater, demonstrating that the BBB was open where focused ultrasound was applied through the skull. The average increase in SI was 6.7at 0.6 W. No significant damage was observed in histological analysis of tissue samples, in agreement with our findings in the rabbit. Finally, our preliminary results indicate a possible spatial dependence of the rat brain's response to applied FUS, the anterior and posterior quadrants exhibiting different thresholds for BBB opening. This study demonstrates that transcranial FUS is effective in inducing focal BBB opening in the rat brain. Subsequent MRI-guided FUS experiments in a rodent model can thus be performed more efficiently without cranial surgery.
This research was funded by NIH Grant No. CA76550.

U2-I-3 510BD 11:00 a.m.

SCHLIEREN OBSERVATION OF THERAPEUTIC FIELD IN WATER SURROUNDED BY CRANIUM RADIATED FROM 500 KHZ ULTRASONIC SECTOR TRANSDUCER

T. AZUMA*[1], K. KAWABATA[1], S. UMEMURA[1], M. OGIHARA[2], K. ASAFUSA[2], J. KUBOTA[2], A. SASAKI[2], and H. FURUHATA[3], [1]Central Research Laboratory, Hitachi, Ltd., [2]Hitachi Medical Corporation, [3]ME Lab. Jikei Univ. School of Med.
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The use of ultrasound at a relatively low frequency, typically lower than 1 MHz, which can penetrate a skull bone more efficiently, is suitable to enhance the effect of thrombolytic drugs such as tissue plasminogen activator. Acoustic cavitation can cause adverse biological effects through inducing huge mechanical stresses and generating chemically active species. The generation of cavitation is affected not only by acoustic intensity and frequency, but also other conditions of an acoustic field, especially standing wave formation. In a standing wave field, a microbubble migrates toward the antinode, where it will increase its size quickly by merging with other migrated microbubbles and by relatively effcient rectified diffusion at an acoustic pressure at the antinode. As soon as the microbubble reaches the resonant size, it may violently collapse, easily even at a relatively low acoustic amplitude, causing huge magnitudes of mechanical stress and temperature. In this study, standing-wave formation in water surrounded by a contoured piece of a human cranium with a transcranial ultrasonic beam at 500 kHz was optically observed using Schlieren imaging. The ultrasonic beam was generated from a prototype sector-scan phased-array transducer, which can transmit an ultrasound beam in various angles, with a fixed transducer position on the skull bone. In Schlieren image at a steering angle of 12 degrees the twice-reflected beam as well as the once-reflected beam by the cranium could be seen. A stripe pattern caused by standing waves was clearly seen near the place of the first reflection and another stripe pattern was also seen near the place of the second reflection. No standing wave patterns were detected in the basically the

same setup with a commercial sector-scan phased-array transducer at 2 MHz. These suggests that standing waves can be formed also in the brain tissue near the place of reflection by transcranial insonation of a human brain at a relatively low ultrasonic frequency, typically less than 1 MHz, and further suggests the possibility of inducing the intracerebral hemorrhages through cavitation in brain tissue thereby. Modulations in ultrasonic frequency, amplitude, and beam angle are being studied to suppress standing-wave formation and will also be discussed.
This work was supported in part by the Health and Labour Sciences Research Grants for Translational Research from the Japanese Ministry of Health, Labor and Welfare.

U2-I-4 510BD 11:15 a.m.

PREDICTION OF THE SKULL OVERHEATING DURING HIGH INTENSITY FOCUSED ULTRASOUND TRANSCRANIAL BRAIN THERAPY

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High Intensity Focused Ultrasound (HIFU) brain therapy is currently highly limited by the strong phase and amplitude aberrations induced by the skull heterogeneities. Recently, several studies have shown that adaptive techniques coupled with high-resolution CT images of the entire skull can achieve a completely non-invasive sharp focusing inside of the brain. CT images were used to predict the propagation of ultrasound in the skull, using density dependent models of speed of sound and attenuation. In this paper, we show that the temperature increase in the skull-bone can also be predicted, which is of great importance to ensure the safety of the treatment. A CT scan of an entire human skull is performed. The ultrasound wave propagation in the skull is computed using a 3D finite differences acoustic software developed in our laboratory. A 3D mapping of the ultrasonic field in the skull is performed, and then coupled with a 3D thermal diffusion code. The increase of temperature in the skull is computed during HIFU treatments simulations. In parallel, experiments are performed in a water bath in the same experimental conditions, using a 280-element array at 1MHz central frequency designed for transskull therapy. Adaptive focusing is achieved thanks to a hydrophone, and HIFU sonications are performed. The temperature variations are measured in several locations including the outer, the inner table and the diplo, using thermocouple sensors. Experimental results are in very good agreement with the simulations: the average difference between experimental results and simulations is less than 1°C. The temperature elevation distribution is strongly heterogeneous, and can locally reach more than 10°C. Moreover, the use of an external water-cooling system allows to limit the average overheating in the skull to 2.5°C. Finally, it is shown that the ratio between the overheating of the skull and the temperature elevation at the focus can be decreased by adjusting the amplitude on each transducer of the therapeutic array.

U2-I-5 510BD 11:30 a.m.

THE USE OF OPTISON TO REDUCE THE POWER REQUIREMENTS FOR FOCUSED ULTRASOUND LESION PRODUCTION IN THE BRAIN: A MRI/HISTOLOGY STUDY IN RABBITS

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In this work, we investigated focused ultrasound exposures in the brain in the presence of an ultrasound contrast agent with MRI and histology. The presence of the microbubbles in the vasculature has been shown to greatly reduce the threshold for tissue damage, which would make focused ultrasound surgery more practical in targets such as the brain that are shielded by bone. Because the lesions induced will depend on the local supply of the agent as well as the acoustic and tissue parameters, being able to monitor the exposures will be crucial.

Fifty-seven locations in the brains of 15 rabbits were targeted with focused ultrasound exposures. The transducer characteristics were: ROC/diameter=8 cm/10 cm; frequency=1.5 MHz. Sonications were performed continuous wave (CW, 23 locations) and at a 50% duty cycle (PRF 1Hz, 34 locations). The acoustic power ranged from 0.35-14W and the sonication duration was 10-20s. Before the sonications, an ultrasound contrast agent (Optison) was injected (0.05 mL/kg, IV). MRI was used to monitor the temperature rise during sonication and to detect tissue effects. Four hours after sonication the brains were removed, fixed, sectioned, and examined under light microscopy (H&E).

The temperature rise was visible in the MR thermometry. Focal heating could be more reliably produced with the sonications with a 50% duty cycle. However, in a few cases hot spots were observed outside the focal region, perhaps due to the presence of large blood vessels. In some cases with the CW sonications, heating at the focal plane rapidly progressed to heating along the entire beam path. Tissue changes were observed in MRI at all power levels tested and matched the shape of the temperature distributions seen in MRI. The damage seen in histology was not the same as has been described for thermal lesions. Effects ranged from small hemorrhages to areas with extensive extravasation containing no distinguishable cells.

The threshold for tissue effects was reduced by approximately a factor of ten below that found in the same experimental conditions without the contrast agent. Pulsing the sonication is needed to avoid pre-focal heating. Even though the tissue effects did not appear to be related to thermal changes, MRI thermometry could detect the temperature distribution created during the sonications, which appeared to be similar to the shape of the lesions as seen in MRI. This ability may be useful to guide such sonications. The use of Optison during the sonications greatly reduces the power needed to produce lesions, which may be useful for focused ultrasound surgery through the intact skull.

This work was funded by NIH grants CA76550 and EB000705

U2-I-6 510BD 11:45 a.m.

ULTRASONIC TRANSCRANIAL BRAIN THERAPY: FIRST IN VIVO CLINICAL INVESTIGATION ON 22 SHEEP USING ADAPTIVE FOCUSING

M. PERNOT[1], J.-F. AUBRY*[1], M. TANTER[1], A.-L. BOCH[2], M. KUJAS[3], and M. FINK[1], [1]Laboratoire Ondes et Acoustique, ESPCI, Université Paris VII, U.M.R. C.N.R.S. 7587, 10 rue Vauquelin, 75005 Paris, France, [2]Service de Neurochirurgie, Groupe Hospitalier Pitié-Salpêtriére, Paris, France, [3]Service d'Anatomie Pathologique Neurologique, Groupe Hospitalier Pitié-Salpêtriére, Paris, France.
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A high power prototype dedicated to trans-skull therapy has been tested in vivo on 22 sheep. The array is made of 280 high power transducers working at 1MHz central frequency and is able to reach 400 bars at focus in water during five seconds with a fifty percent duty cycle. An echographic array connected to a Philips HDI 1000 system has been inserted in the therapeutic array in order to perform real time monitoring of the treatment. In a first series of experiments, 10 sheep were treated and sacrificed immediately after treatment. A complete craniotomy has been performed on half of the treated animal models in order to get a reference model. On the other animals, a minimally invasive surgery has been performed thanks to a time reversal experiment: a hydrophone was inserted at the target inside the brain thanks to a 1mm2 craniotomy. A time reversal experiment was then conducted through the skull bone with the therapeutic array to treat the targeted point. Hyperechogeneicity was clearly visible on the sonographic system for all animals with complete craniotomy. Without craniotomy, the ultrasonic image was distorted but the hydrophone location was visible, allowing a rough positioning of the therapeutic device. A more accurate positioning was then obtained by cross correlating the signals received by a set of elements of the therapeutic device. Thanks to the high power technology of the prototype, trans-skull treatment could be achieved with phase aberration correction and electronic beam steering not only at the geometrical focus but also 2 centimeters away in all directions. In a second series of experiments, 12 animals were divided into three groups and sacrificed respectively one two and three weeks after treatment. The evolution of the targeted region was checked each week thanks to Magnetic Resonance Imaging and CT scans. Finally, histological examination was performed to confirm tissue damage. These in vivo experiments highlight the strong potential of high power transcranial time reversal technology.
This work was supported by a grant from La Fondation de l'Avenir.

Session: U3-I
SINGLE CRYSTAL TRANSDUCER MATERIALS
Chair: C. Oakley
Tetrad Corporation

U3-I-1 511AB 10:30 a.m.

HIGH COUPLING $KNBO_3$ WIDTH-EXTENSIONAL VIBRATORS WITH A POLAR MULTIDOMAIN STRUCTURE

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Potassium niobate ($KNbO_3$) single crystals have high electromechanical coupling factors for various types of vibration modes [1]. The longitudinal piezoelectric coupling factor for the width-extensional mode of thin plates, k_{11}, has been predicted to be as high as 82.4% for the 43.5° rotated Z-cut about the Y-axis. The width-extensional vibrator using this cut would be promising as a Pb-free piezoelectric element of phased-array ultrasonic probes. To experimentally confirm the calculated value we fabricated a width-extensional vibrator using a 45° rotated Z-cut plate about the Y-axis, close to the maximum k_{11} cut. This vibrator had electrodes on its end faces in the width direction. However, the measured value of k_{11} was 71.3%, a little lower than the predicted value. In this paper it is clarified that the lower coupling factor can be ascribed to the tilt of the electric field vector from the major face of the plate, which results from an off-diagonal component of the dielectric tensor. FEM simulations considering this electric field tilt are performed. It is shown that the calculated coupling factor agrees well with the measured value. To prevent the electric field tilt, a polar multidomain structure consisting of two kinds of 90° domains [2] is introduced into the width-extensional vibrator. In such a domain structure obtained by poling the crystal at the phase transition temperature under application of an electric field in the width direction, the electric field vectors do not tilt, because the thickness-direction component of the spontaneous polarization is the same in magnitude and opposite in sign in two kinds of 90° domains. It is demonstrated by FEM simulations that the coupling factor approaches the predicted value (82.4%), as the number of domains formed in the vibrator increases. The measured coupling factor of a width-extensional vibrator with a polar multidomain structure is as high as 79.4%, which is close to the predicted value. An additional advantage of using this domain structure is the low spurious response.
[1] K. Nakamura and Y. Kawamura, IEEE Trans. Ultrason. Ferroelectr. Freq. Control, 47, pp.750-755 (2000) [2] K. Nakamura, T. Tokiwa and Y. Kawamura, J. Appl. Phys., 91, pp.9272-9276 (2002)

U3-I-2 511AB 10:45 a.m.

MULTILAYER PMN-PT SINGLE CRYSTAL TRANSDUCER FOR MEDICAL APPLICATION

S. M. RHIM*[1], H. JUNG[1], and S.-G. LEE[2], [1]HUMANSCAN Co., Ltd., [2]iBULe PHOTONICS Co., Ltd.
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Applications of single crystal for medical ultrasound transducer are studied widely. Especially broad bandwidth and high sensitivity of single crystal transducer is attractive for medical applications. Moreover, because problem of making transducer is almost overcome, commercialization of single crystal transducer is done. However new PZT ceramics having high dielectric constant and multilayer PZT is developed in recent year, so high sensitivity of single crystal transducers strength is threaten. Because the mechanical strength of single crystal is weaker than that of PZT, to make multilayer is somewhat difficult. For 3.0 MHz phased array, the thickness of multilayer single crystal with 2 layers is about 0.4mm and the thickness of each layer is about 0.2mm. If bilayer single crystal wafer is made, the dielectric constant is over 20000. The performance of 3.0 MHz phased array using multilayer PMN-PT single crystal with 2 layers was investigated. Dielectric constant of bilayer PMN-PT single crystal with 2 layers is over 20000 and clamped dielectric constant is over 6000. Electrical coupling factor k33 and piezoelectric constant d33 is similar with single layer PMN-PT. k33 is about 0.92 and d33 is about 1800-2000. k33 for array transducer is about 0.82. The bandwidth of bilayer PMN-PT single crystal transducer is about 100% and this is similar with single layer PMN-PT single crystal transducer. However, the sensitivity of bilayer transducer is about 6dB higher than that of single layer transducer. The impedance of element using bilayer single crystal is half of that of single layer and this is very effective for electrical impedance matching between transducer and ultrasound imaging system.

U3-I-3 511AB 11:00 a.m.

A MULTIROW SINGLE CRYSTAL PHASED ARRAY FOR WIDEBAND ULTRASOUND IMAGING

M. J. ZIPPARO*[1], C. G. OAKLEY[1], D. M. MILLS[2], A. M. DENTINGER[2], and L. S. SMITH[2], [1]Tetrad Corporation, [2]GE Global Research.
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From a theoretical perspective the very high coupling of single crystal materials can provide exceptional bandwidth while maintaining or improving sensitivity relative to arrays which incorporate PZT ceramics. The utility of this bandwidth has been targeted towards applications which include multi-frequency arrays and phased arrays for enhanced harmonic imaging capability. This paper presents array measurements for what is believed to be the first multi-row single crystal array, in this case a 3x64 element 128 channel phased array. The probe was

fabricated with PMN-PT single crystal grown via the Bridgman process into a one inch boule. The crystal used had a composition close to the morphotropic phase boundary, i.e. PMN-32%PT, and demonstrated a coupling of over 90% for a free air k_{33}' array element. Two acoustic matching layers and an acoustic lens were applied to the front of this array. While materials were the same as for a conventional probe, the matching layer and crystal thickness as well as the electrical tuning were optimized to maximize bandwidth. Even though the fabrication process was adjusted for the crystal material, fabrication difficulties caused less than optimal sensitivity and pulse response uniformity. The nominal center frequency measured was 3.2 MHz, and many of the elements had a bandwidth over 100%. We will present both phantom and in vivo images from this multi-row probe along with comparison images from a multi-row ceramic based probe with the same aperture.
Contributions to this work have been funded by ONR and DARPA.

U3-I-4 511AB 11:15 a.m.

BROAD BAND SINGLE CRYSTAL TRANSDUCERS FOR CONTRAST AGENT HARMONIC IMAGING

W. HACKENBERGER*[1], X. JIANG[1], X. GENG[2], A. WINDER[3], and F. FORSBERG[4], [1]TRS Technologies, Inc., [2]Blatek, Inc., [3]J&W Medical, LLC, [4]Thomas Jefferson University Hospital.
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A broadband single element transducer was constructed from single crystal PMN-PT and tested to determine the feasibility of using this material for simultaneous subharmonic and second harmonic imaging. The transducer consisted of a 1-3 PMN-PT/epoxy composite with two quarter wave matching layers and a backing. The transducer face was spherically curved to yield a 50 mm focal point. The transducer had a center frequency of 4.9MHz and -6 dB bandwidth over 130%, but the response decayed very slowly outside the -6 dB band so that useable bandwidth was estimated to be on the order of 200%. Subharmonic and second harmonic responses were tested by driving the transducer with a 3.5 MHz 64-cycle tone burst and recording the impedance spectra of harmonics generated by Optison contrast agent dispersed in water.
NIH Grant #1-R43-RR18016-01

U3-I-5 511AB 11:30 a.m.

CHARACTERIZATION OF VERY HIGH FREQUENCY TRANSDUCERS WITH WIRE TARGET AND HYDROPHONE

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The wire-target technique [1] was used for lateral beam profile measurements in very high frequency range (30-60 MHz). A 9 cm long tungsten wire with a diameter of 8 μm was used as pulse-echo target to measure the lateral beam profiles at the focal points of two transducers, a spherically focused 40 MHz Panametrics transducer with an aperture size of 6.35 mm and a geometrical focal length of 12.7 mm and a lense-focused $LiNbO_3$ 60 MHz transducer fabricated in house with an aperture size of 2 mm and a geometrical focal length around 6.5 mm. For comparison, measurements on these transducers were performed by two small-aperture hydrophones. The first one is a polyvinylidene fluoride trifluoroethylene (PVDF-TrFE) membrane hydrophone developed by Hewlett-Packard, which has a geometric diameter of 37 μm, a measured effective diameter of less than 100 μm and a 3 dB bandwidth of more than 150 MHz. The second one is a needle-type polyvinylidene fluoride (PVDF) hydrophone from Precision Acoustics, which has a 9 μm-thick PVDF element, a 40 μm geometrical aperture and a measured effective diameter of less than 100 μm. The measured 6 dB transmit-receive beam widths from the wire target are 82.3 μm for Panametrics transducer and 107.1 μm for the in-house transducer. The measured 3 dB transmit beam widths from Hewlett Packard hydrophone are 77.4 μm for Panametrics transducer and 92.4 μm for the in-house transducer. For Precision Acoustics hydrophone, the results are 89.6 μm and 103.0 μm respectively. Preliminary experimental results show that the 6 dB two-way beam widths measured by this 8 μm wire-target are comparable to 3 dB transmitted beam widths measured by small-aperture hydrophones.

Compared to small-aperture hydrophones, the wire-target technique is a simpler, more cost-efficient and time-efficient method. Its major advantage however is in the frequency range above 100 MHz in which commercial hydrophones are not yet available.

References: [1] Kay Raum and W.D. OBrien, Pulse-Echo Field Distribution Measurement Technique for High-Frequency Ultrasound Sources, IEEE Trans. Ultrason. Ferroelec. Freq. Contr. ,vol.44(4), pp.810-815, (1997)

Session: U4-I

ACOUSTIC AND OPTICAL SCATTERING

Chair: F. Hickernell
University of Arizona

U4-I-1 513AB 10:30 a.m.

ULTRASONIC FIELD MEASUREMENT IN TEST CELLS COMBINING THE ACOUSTO-OPTIC EFFECT, LASER INTERFEROMETRY & TOMOGRAPHY

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High power, low frequency ultrasound is used in many applications throughout a wide selection of industrial sectors, ranging from food processing to industrial cleaning. One significant difficulty lies in the accurate quantification of the generated acoustic pressure fields using conventional techniques, particularly within relatively small test cell configurations. Limited spatial resolution at low frequencies, disturbance of the field due to probe presence and the need for periodic probe calibration are the principal limitations encountered. One solution, which negates several of the issues mentioned, as well as offering pronounced advantages, involves the optical detection of pressure, through the acousto optic effect, combined with field mapping via tomographic measurement procedures.

The density, and hence the refractive index, of a transparent load medium is dynamically altered by ultrasonic pressure. Given this relationship, the phase component of laser light travelling through a disturbed medium will be subject to a variation proportional to the line integral of acoustic pressure along the light path. By moving the laser in incremental steps along an axis parallel to the beam diameter, a set of projections at various angles representing the induced phase change are formed. If the piezo-optic coefficient of the medium is known, the values of pressure for a cross section of the acoustic field can be evaluated through the implementation of basic tomographic techniques and reconstruction algorithms. A customised scanning facility has been designed and built, incorporating Polytec OFV-303 laser interferometer and OFV-3001 controller, to accommodate the practical implementation of this measurement approach.

This paper describes both the theoretical and experimental investigation of the pressures generated by a 33 kHz Tonpilz device used in conjunction with a high power cylindrical test cell. Firstly, the methodology was validated through an evaluation of the air coupled pressure field generated by the transducer within a screened environment. Field prediction software was utilised to provide a theoretical comparison, with good correlation demonstrated. Next, manipulation of the firing angle of the interferometer, necessary due to refraction issues, was applied in order to create the desired projections within the cylinder. Finite element modelling, using the PZFlex code, is employed to provide simulated pressure field patterns for comparison. The optically measured reconstructed pressure maps demonstrate reasonable correlation with PZFlex predicted profiles. Importantly, this experimental technique demonstrates a relatively high spatial resolution ($\sim$40 μm) and large dynamic range ($\sim$90 dB), which are necessary for accurate ultrasonic field measurement.

U4-I-2 513AB 10:45 a.m.

NONDESTRUCTIVE ELASTICITY EVALUATION OF THIN ADHESIVE LAYERS BY BRILLOUIN SCATTERING

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Elastic wave properties in thin epoxy adhesive layers have been investigated in the GHz range. By applying a Brillouin scattering technique, we have succeeded in nondestructive, non-contact and simultaneous measurements of longitudinal and shear wave velocities in the epoxy adhesive layers, down to 2 micron meter in thickness. From precise velocity measurements, we have clarified the distinctive elastic behaviors in the curing layer. The thin adhesive layers are made of the mixture of curing agent and prepolymer called diglycidyl ether of bisphenol A, which is well known as the base material of epoxy adhesives. The mixture changes from viscous liquid to brittle solid, which is physically considered as a glass transition due to polymerization. In curing layers, the glass transition temperature (T_g) increases from 247.8 K (initial prepolymer value) to the temperatures more than 400K. Brillouin scattering measurements are performed using a JRS type Fabry-Perot interferometer, with an argon ion laser (λ_o=514.5nm). Using 90A scattering optical geometry, the phonon wavelength λ is given by $\lambda=\lambda_o/2^{1/2}$ and the hypersonic wave velocity $v=f\lambda$ depends on the Brillouin shift frequency *f*. Owing to the careful treatment and check of small interferometer drift during measurements, we have achieved 0.1% precision of the observed shift frequency using the weak scattered light from thin adhesive layers. The isothermal curing processes of thin adhesive layers were then investigated changing the curing temperature and mixing ratio of curing agents. The shift frequency of the longitudinal Brillouin peak increased rapidly and finally became constant, reflecting the extent of cure. This result is very similar to the reported longitudinal wave behaviors in the MHz range, except for the effect of frequency dispersion in the glass transition region. Simultaneously, we could observe gradual appearance of shear Brillouin peaks, which showed the vitrification of the layer. In these layers, the amount of the curing agent mixed was much smaller than the epoxy prepolymer, so that the visco-elastic properties during cure seems to be dominated by those of pure prepolymer. The prepolymer itself experiences glass transition due to the temperature. We then suggest to introduce a modified temperature T_n ($= T_c$-T_g), where T_c is the curing or measuring temperature. As a function of T_n, the longitudinal velocities in any curing layers become in good accordance with those in prepolymers. This result shows that one can roughly estimate the velocity in the curing layer at any temperature if T_g of the layer is known. An additional insight is provided by the longitudinal (V_L) and shear wave (V_S) velocities in the layers. In any curing layers, squared values of V_L and V_S showed an identical linear relation, which was in good accordance with that of longitudinal and shear wave velocities in the pure prepolymer layer. The linear relation then exhibits the synchronous behavior of longitudinal and shear moduli, which does not depend on the curing process.

U4-I-3 513AB 11:00 a.m.

LONGITUDINAL ACOUSTIC PROPERTIES MEASUREMENTS OF SOLID SPECIMENS BY THE PLANE-WAVE ULTRASONIC MATERIAL CHARACTERIZATION SYSTEM IN THE UHF RANGE

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We have developed a plane-wave ultrasonic material characterization system in order to accurately measure acoustic properties, viz., velocity, attenuation coefficient, acoustic impedance, and density, of solid, liquid, and biological tissue specimens in the VHF/UHF range. Measurements for solid specimens are performed in the ultrasonic composite transmission line, consisting of a buffer rod with an ultrasonic transducer on one end, a couplant, and a specimen. Pure water is used for the couplant in the VHF range. The measurement frequency range is limited to 300 MHz, due to the large attenuation. In this paper, a method for measuring longitudinal acoustic properties of solid specimens over a higher frequency range is discussed. Specimens were bonded to the buffer rod using salol (phenyl salicylate) to measure longitudinal acoustic properties in the UHF range. Three devices with different operating center frequencies of 200, 600, and 1000 MHz, were fabricated, for measurements up to around 1 GHz. ZnO piezoelectric thin film is used for the transducer. Synthetic silica glass is used as a buffer rod for a 200 MHz device, and Z-cut α-quartz for 600 and 1000 MHz devices. Measurements have been demonstrated for a synthetic silica glass (C-7980, Corning Co.) which exhibit no velocity dispersion in the VHF range and a Pyrex glass (C-7740, Corning Co.) which exhibit velocity dispersion. Velocities of C-7980 were constant at 5929.13$\pm$0.05 (m/s) in 50-1180 MHz. C-7740 exhibited velocity dispersion, from 5542.27 m/s at 50 MHz to 5546.83 m/s at 760 MHz with an increase of 4.56 m/s. Attenuation coefficients of C-7980 were measured to be $\alpha f^2 = 1.1 \times 10^{-16}$ (s^2/m), proportional to the square of the frequency. And, those of C-7740 were proportional to the 1.25 power around 100 MHz and gradually rising to 1.30 power around 550 MHz. Measurement results by this system are very useful for characterizing materials and studying their physical properties, because the frequency characteristics of velocities and attenuation coefficients can be obtained accurately.

U4-I-4 513AB 11:15 a.m.

TUNABLE PHONONIC BAND GAPS OF SURFACE AND BULK ACOUSTIC WAVES IN TWO-DIMENSIONAL PHONONIC CRYSTALS

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The existence of complete band gaps of electromagnetic waves in photonic structures extending throughout the Brillouin zone has demonstrated a variety of fundamental and practical interests. Successful application of photonic crystals has led to a rapidly growing interest in the analogous acoustic effects in periodic elastic structures called the phononic crystals. In this paper, based on the plane wave expansion method [1], dispersion relations of the surface and bulk modes with square lattice in Al/quartz (circular cylinder: Al) and quartz/PMMA (square cylinder: quartz) two-dimensional phononic structures are calculated and discussed. Band gap widths due to different parameters, such as filling fraction, temperature variation and rotation of noncircular rods are analyzed. From the effects of filling fraction and rotating square rods, the optimal band gap widths could be used to design the dimensions and the lattice arrangement of the phononic structures. In regards to the temperature effect, band gap variations of both of the bulk modes and surface modes due to the changing of temperature of the background material and the cylinders from zero to fifty degrees centigrade are calculated and discussed. The results show that the elastic band gaps can be enlarged or reduced by adjusting the filling fraction, the rotating angle of square cylinders, and the temperature of the cylinders or the background material. The effects discussed in this paper can potentially be utilized for fine tuning of the phononic band gap frequency and may serve as a basis for studying the band gaps of SAW and BAW modes in phononic structures.

[1] Wu, Tsung-Tsong, Huang, Zi-Gui and Lin, S.-C., Surface and bulk acoustic waves in two-dimensional phononic crystals consisting of materials with general anisotropy, Physical Review B, to appear (2004).

The authors gratefully acknowledge the financial support received for this research from the National Science Council of Taiwan and from the NTU-ITRI center.

U4-I-5 513AB 11:30 a.m.

FULL BAND GAPS FOR SURFACE ACOUSTIC WAVES IN PIEZOELECTRIC PHONONIC CRYSTALS

V. LAUDE*, M. WILM, S. BENCHABANE, and A. KHELIF, FEMTO-ST.
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Phononic band gap materials are receiving increasing attention since they enable the realization of novel functions such as perfects mirrors, the localization of acoustic energy in defect modes, and very efficient waveguiding. All these functions are accessible in a very reduced space of the order of some acoustic wavelengths. Phononic crystals are similar to photonic crystals but for the peculiarities of elastic as compared to optical waves. Among these, of special interest are the strong anisotropy, the existence of various combinations of shear and longitudinal polarizations, the consideration of surface in addition to bulk waves and their direct excitation by interdigital transducers on piezoelectric materials.

In this paper, we focus on the existence of surface acoustic waves (SAW) in solid/solid and solid/air compositions including at least one piezoelectric material. The phononic crystals we consider are two-dimensional in nature; they are composed of a periodic repetition of solid or hollow cylinders inside a solid matrix, with the cylinders axes normal to the propagation surface. Classical models used to predict the existence of SAW on homogeneous substrates are not applicable in this case. We use a plane-wave-expansion (PWE) method suited to piezoelectric materials to obtain all partial waves. If N harmonics are used in the Fourier series representing the materials constants, 8N partial waves have to be considered as compared to 8 for a homogeneous piezoelectric material. A selection rule is devised to retain only the 4N partial waves that are compatible with a surface excitation. The free and shorted boundary conditions are then satisfied only if certain determinants vanish. The concept of an effective permittivity matrix (EPM) is also introduced. The poles and zeros of the determinant of the EPM reveal the existence of piezoelectrically coupled SAW. A search for these poles and zeros is used to conclude on the existence of full-band-gaps for SAW. The procedure is illustrated with lithium niobate.

U4-I-6 513AB 11:45 a.m.

SOME PECULIARITIES OF ACOUSTOPTICAL INTERACTIONS IN X-RAY RANGE

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Lots of work is devoted to interactions of X-ray beams with elastic waves and vibrations. Firstly it is very useful tool for investigations of acoustic wave propagations in solids, resonator vibrations and so on. Also some interesting physical phenomena as for example x-ray-acoustic resonance allow to improve the x-ray methods of investigation solids. At present report we would like to pay attention on some common features between interaction acoustical waves with electromagnetic waves both optical and x-ray ranges. From this point of view several areas of acoustic-x-ray interaction are represented. I. Area of low frequency elastic waves when elastic wavelength many times exceeded the x-ray beam aperture. X-ray Laue diffraction in germanium and silicon plates with exited longitudinal vibrations (λ=20-40 mm) was investigated. At those conditions in central part of resonator ones can periodically changes uniformly in space the lattice parameters. Simultaneously on periphery part of resonators ones can periodically change gradient of lattice parameters Experimental results demonstrates possibilities: a) to deflect the direction of propagation of x-ray beam b) to make corrections in space structure of x-ray beam II. The analog of optical Raman-Nath diffraction Area when Klein-Cook parameter Q= $2\pi\lambda l/\Lambda 2$ $<<1$ λ-x-ray and Λ -elastic wave wavelength ; l- interactions length. Existing experiment are analyzed and common features with optical Raman-Nath diffraction are established III. The analog of optical Bragg diffraction Area when Klein-Cook parameter Q= $2\pi\lambda l/\Lambda 2$ $>>1$ New effect is proposed

Session: U5-I

IMAGING AND SIGNAL PROCESSING

Chair: J. Saniie

Illinois Institute of Technology

U5-I-1 512C-H 10:30 a.m.

OPTIMIZATION OF AN ARRAY BASED PULSE-ECHO SYSTEM FOR IDENTIFICATION OF REFLECTOR GEOMETRY

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In ultrasound imaging systems, array transducer are used primarily for beam steering and beam focusing, yet are capable of producing a much wider range of fields. This work investigates the use of array transducers for generating the acoustic field, which maximizes the energy of the received signal, after beamforming, for a given reflector geometry. This technique may be applied to object recognition among a limited set of *a priori* specified objects.

A key tool for this work is an accurate and efficient way of calculating the received signal, due to a given reflector, for any pair of transmit and receive array elements. We have developed a broadband modeling method, the *Diffraction Response for Extended Area Method (DREAM)*, where for a reflector tile of modest dimensions - spatial integration is replaced by an equivalent low pass filtering. The *received signal matrix* for a specified reflector (defined as an N x N symmetric matrix of signals, for an array transducer with N elements) is thus found by tessellating the reflector surface into triangular tiles and summing over all tiles.

The N^2 signal elements in the received signal matrix have a good deal of similarity in terms of shape, but the elements differ in terms of their delay with respect to a common time reference. Different reflector geometries result in unique distributions of relative delays among the signal elements, as well as in unique patterns of energy distribution. Choosing the element with the largest energy as a reference signal, and cross-correlating all the other signals with the reference signal, produce an N x N delay matrix that is unique for a given reflector, and which allows identification of the given reflector among an a priori defined set of reflectors.

For practical measurements, it is more convenient to identify the reflector geometry by simply calculating the energy of the received signal. The concept is as follows: If the task is to identify which one out of M possible unique reflectors geometries is present, then M measurements need to be carried out. Each measurement is performed with a transmitted field and a receiver characteristic that optimize the energy of the output signal from the beam former for a given reflector. We have developed several optimization algorithms; one example is the adaptive waveform correlation matrix whereby the $N(N+1)/2$ unique signals in a symmetrical N x N received signal matrix are ordered in terms of descending

energy, and the signals are cross-correlated, aligned and added, starting with the signal with the highest energy. This leads to an N x N optimal delay matrix for each reflector.

The optimization has been carried out with annular array transducers, due to smaller number of array elements. A planar flat reflector, a cylindrical reflector surface, and a sinusoidal reflector surface were chosen as representative reflectors, all with dimensions of 25mm x 25mm. Simulation results have demonstrated that this optimization technique can identify which reflector among a set of specified reflectors is actually present.

The work was supported by the Telemedicine and Advanced Technology Research Center (TATRC), DAMD17-03-2-0006

U5-I-2 512C-H 10:45 a.m.

ULTRASONIC FLAW DETECTION USING FAST LIFTING WAVELET TRANSFORM FOR NDE APPLICATIONS

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Ultrasonic flaw detection and classification in the presence of high scattering microstructure noise (i.e. clutter echoes) is a significant and challenging problem in the nondestructive evaluation (NDE) of materials. Clutter echoes exhibit randomness and are sensitive to frequency bands. However, flaw echoes are less vulnerable to frequency variations. Therefore, frequency diverse signal decomposition can be advantageous in differentiating the flaw information from the clutter echoes. In this work, we analyze signal decomposition properties of discrete wavelet transform (DWT) for enhanced ultrasonic flaw detection. In wavelet analysis, a collection of time-frequency representations of the signal with different resolutions are obtained. Unlike other transforms such as Fourier transform or cosine transform, both time and frequency domain information can be utilized for decorrelating and compacting the flaw echo from clutter echoes. We have explored techniques to benefit from both temporal and spectral properties of DWT for enhancing flaw echo visibility. In particular, the compactness properties of the DWT allow a region of interest to be determined in 2D time-frequency representation which is essential for flaw detection. Flaw-to-clutter ratio enhancement is governed by the degree of the compactness of the flaw echo. 2D moving windows across several frequency bands within this region of interest are utilized to reconstruct a family of signals that bear dominant information from the flaw echo. Order statistics processing of this family of reconstructed signals results in significant flaw-to-clutter ratio enhancement. In this paper, we present the performance analysis of different wavelet kernels with respect to ultrasonic NDE applications and develop the wavelet selection criteria for optimal flaw detection. The clear benefit of using DWT is the capability of fine tuning the wavelet kernel for compacting of the flaw echo information while spreading the clutter energy over a 2D plane. Experimental and simulated data have been used to examine a family of wavelets of different sizes and properties such as orthonormal, symmetric and biorthogonal

for improved clutter suppression. Among many wavelet kernels, we have found that Daubechies-20, Symmlet-10, Coiflet-5, and Vaidyanathan-24 offer greater signal compaction in the time-frequency plane due to high correlation between ultrasonic echoes and wavelet kernels. These wavelets offer flaw-to-clutter ratio enhancement of 6-12 dB when the measured flaw-to-clutter ratio is 0 dB or less. DWT has a clear advantage in flaw-to-clutter ratio enhancement when compared to conventional frequency diverse flaw detection methods such as split-spectrum processing. Furthermore, DWT can be implemented efficiently in hardware for real-time applications. In this study, we will also present an optimal hardware design for DWT using the fast lifting scheme algorithm. Lifting scheme enables high speed, integer-to-integer operation and in-place calculation. This allows an efficient architecture which is optimized for speed, reduced power dissipation and chip size.

U5-I-3 512C-H 11:00 a.m.

PERFORMANCE ASSESSMENT OF A NEW KALMAN FILTER-BASED METHOD FOR ULTRASONIC TIME-OF-FLIGHT ESTIMATION

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There are relevant examples of application fields requiring reliable and speedy measurements of the distance between a device and an external surface. To achieve this goal, the use of ultrasonic transducers is widely exploited. Ultrasonic based distance meters generally estimate the time-of-flight (TOF) of an ultrasonic pulse generated by a proper transducer. In the paper, the authors propose a digital signal processing method based on the use of the discrete extended Kalman filter (DEKF) for TOF estimation [1]. The discrete Kalman filter (KF) is a recursive solution of the problem of estimating the state of a linear stochastic system or process by using measurements that are linear functions if the state. Similar approaches can be extended to the analysis of non linear systems, provided that suitable techniques of linearization about a nominal trajectory are applied. If the nominal trajectory is defined on the fly as the current best estimate of the actual trajectory, the corresponding filter is named DEKF. In recent scientific works [2], the DEKF has been used to improve the accuracy of ultrasonic based location systems of robots. In particular, TOF data provided by several ultrasonic sensors and collected as temporal readings are properly fused thanks to the exploitation of some nice properties of the DEKF. The authors, instead, propose the DEKF as an original tool to overcome the well-known problem of biased estimate occurring when the echo envelope undergoes shape distortions. The novelty of the method mainly relies upon its capability of jointly estimating the whole set of parameters (A_0, α, T, and τ) that characterize the well-known model of echo envelope, A(t): $A(t)=((t-\tau)/T)^{\alpha}*\exp((t-\tau)/T)\ A_0$

accounts for echo amplitude, α and T are peculiar to the specific ultrasonic transducer, and τ is the desired TOF. This way, the achieved TOF estimation inherently accounts for the distortion the ultrasonic echo eventually undergoes, with a consequent positive effect on bias reduction. Details concerning the suggested use of the DEKF and its action in the framework of the adopted measurement procedure will be given in the full paper. Actual research activities is focused on the performance assessment of the proposed digital signal-processing method at varying of typical measurement conditions. In particular, the capability of the method of granting an accurate value of the shape parameters will be used in order to identify the presence of non-planar or non-orthogonal reflection surfaces, able to distort the received echo. Moreover, typical problem of closed tank or reservoir configuration, such reverberation and multiple echoes, will also be taken into account.

[1] M.S.Grewal, A.P.Andrews, Kalman filtering. Theory and practice, Englewood Cliffs, NJ, Prentice Hall, 1993. [2] A.M. Sabatini, A digital signal-processing technique for compensatine ultrasonic sensors, IEEE Trans. On Meas. And Instr., Vol.44, n.4, August 1995, pp. 869-874

U5-I-4 512C-H 11:15 a.m.

ENSEMBLE OF CLASSIFIERS APPROACH FOR NDE DATA FUSION

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Several measurement modalities have been developed over the years for various nondestructive evaluation (NDE) applications, such as ultrasonic, magnetic flux leakage, and eddy current testing, all of which have been used extensively in pipeline defect identification. While it is generally believed that different testing modalities provide complementary information, only a single testing modality is typically used for a given application. This is in part due to lack of effective, computationally feasible data fusion algorithms that are applicable to NDE signals. Such an algorithm capable of data fusion can combine information from two or more different sources of data, giving more insight and confidence to the data analysis than a decision that would otherwise be based on either of the sources alone. We have previously introduced Learn++ as an effective automated classification algorithm that is capable of learning incrementally from new data that may later become available, after a classification system has already been created with the initially available data. The algorithm is based on generating an ensemble of classifiers and appropriately combining the outputs of these classifiers. We have recently discovered that the ensemble of classifiers approach used for incremental learning is directly applicable for data fusion applications. This is because data fusion also involves learning from additional data, albeit with a different set of features. Our approach which can be considered as a decision level fusion is then to employ an ensemble of classifiers strategically generated by using all of the data sources available such that the

complementary pieces of information provided by different datasets are best utilized. The classifier outputs predicting a specific defect type are then combined through weighted majority voting of the classifier outputs, where the weights are determined based on the training or previous performance of each classifier. The defect class that receives the highest weighted vote is finally selected by the ensemble system. Exploiting this conceptual similarity between incremental learning and data fusion, Learn++ was applied to a NDE data fusion application. Specifically, we generated two ensembles of classifiers, one trained on ultrasonic signals, and the other on corresponding magnetic flux leakage signals obtained from the same samples. The signals were obtained from steal samples that contained five classes of discontinuities: crack, pitting, weld, mechanical damage, and no discontinuity. We have observed that the prediction ability of the automated classification system, as measured by the accuracy and reliability of the classification performance on validation data, was significantly improved when the two data sources were combined using Learn++.
This material is based upon work supported by the National Science Foundation under Grant No: ECS-0239090, and is also supported in part by the National Energy Technology Laboratory, US Department of Energy grant no. DE-FC26-02NT41648

U5-I-5 512C-H 11:30 a.m.

BROADBAND ULTRASONIC ATTENUATION MEASUREMENTS USING CODED SWEEP EXCITATIONS

R. P. B. COSTA-FELIX*[1] and J. C. MACHADO[2], [1]National Institute of Metrology, Standardization, and Industrial Quality Inmetro, [2]Biomedical Engineering Program - COPPE/Federal University of Rio de Janeiro, RJ, Brasil.
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The useful bandwidth for measuring ultrasonic attenuation of materials is typically defined as the frequency range over which the amplitude spectrum (AS) of the wave signal is greater than 3 dB in relation to the maximum amplitude of the spectrum. Usually, to cover a broad frequency band, several measurements are performed with different transducers, each one covering a particular range of the desired spectrum. Apart from issues of the equipment availability, the procedure is remarkably time consuming. An experimental procedure was developed in which the 3 dB AS of a system consisting of a transmit/receive pair of ultrasonic transducers was broadened. Originally, the 3 dB AS bandwidth of the system output signal was found to be 1.788 +/ 0.001 MHz, after 30 repeated measurements (12 readings each), when excited with a constant envelope linear sweep (crest factor of 3.4 dB) with flat AS up to 5 MHz. As a next step, a non-linear sweep was codified based on the AS of the system, and used to excite the transmit/receive system, in order to expand the useful AS bandwidth of the output signal. The excitation signal presented a crest factor of 4.2 dB and the output signal useful 3 dB bandwidth was enlarged to 4.57 +/ 0.04 MHz, also obtained after 30 measurements with 12 readings each. Both the linear and the codified sweeps were employed in attenuation measurements of a mixture of

water and glycerol (0.90 glycerol:0.10 water, by weight) at 20.7 +/- 0.1 degrees Celsius. The experimental results for either type of excitation are in agreement, within 0.5 dB, with both the theoretical results for the attenuation as a function of frequency, and with each other. The measured transmission loss ranges from about 1 dB at 0.5 MHz to 14 dB at 4.5 MHz, with a sample length of 6.05 cm. The outstanding distinction was the useful 3 dB bandwidth accomplished with the different excitation signals. Whilst the linear sweep leads to consistent measurements from 1.55 MHz to 3.25 MHz, the coded sweep results are suitable from 0.425 MHz to 4.70 MHz. It is important to note that only one pair of transducers was required to cover the expanded frequency range. The results give an illustration regarding the potential applicability of the specially designed sweeps used within this research on ultrasound metrology.

U5-I-6 512C-H 11:45 a.m.

THEORETICAL AND EXPERIMENTAL STUDY OF TIME REVERSAL IN ANISOTROPY

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It is very important and interesting to overcome the phase distortion caused by the velocity anisotropy. Time Reversal is a novel self-adaptive focusing method that has been applied into many fields since the 80s of the 20th century. Although many works about the time reversal are carried out, the study on the time reversal in anisotropy has seldom been seen. The objective of this paper is to give theoretical and experimental results of the time reversal in anisotropy. The silicon (cubic system) is chosen as the anisotropy material for carrying out the study of the time reversal. The self-adaptive focusing of the time reversal in anisotropy is conducted for the compressional wave field in the cubic crystal silicon. The experimental result, which is coincident with the theoretical result, about the time reversal in anisotropy is obtained for the first time. The focusing gain and the displacement distributions of the time reversal field in the spatial and time ranges are analyzed thoroughly. The theory about the time reversal in anisotropy is proved by the experiments. It is shown that the waves from different elements of the transducer array arrive at the original place of the source simultaneously after the time reversal operation. The waveform distortion caused by the velocity anisotropy can be compensated automatically by the time reversal processing.

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Session: U6-I
SYSTEM AND DEVICE APPLICATIONS
Chair: B. Abbott
Sawtek

U6-I-1 512A-F 10:30 a.m.
(Invited)
SAW IN CHINA

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SAW research and development in China started in early nineteen seventies. Now, most kinds of SAW devices have been developed in China. However, the research, development and mass production fabrication in China is not matched to the huge market. Especially the high frequency devices (GHz level), new generation filters (for example, high specification devices due to accurate simulation and optimization, new structures like multi-track devices, etc.), advanced fabrication technology and package technology with small size device design, etc. are to be developed. Facing great needs, Chinese institutions are thirsted to cooperate with international advanced techniques. The main institutions in China are introduced. The state of the art of research, device development is described through some results of researches and device developments, proceeding in China. They include innovations in fundamental theory, fundamental tools for accurate simulation and device optimization, high speed substrate and cut orientation searching, new structures of devices and design approaches, high quality device developments, and new SAW material researches, etc.
Chinese Natural Science Foundation Grant No. 10074034

U6-I-2 512A-F 11:00 a.m.

ORTHOGONAL FREQUENCY CODING FOR SAW DEVICE APPLICATIONS

D. C. MALOCHA*, D. GALLAGHER, and D. PUCCIO, ECE Dept., University of Central Florida.
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This paper presents the concept of orthogonal frequency coding (OFC) for applications to SAW device technology. OFC is the use of orthogonal frequencies to encode a signal, which spreads the signal bandwidth and is analogous to a fixed M-ary frequency shift key signal. In addition, a pseudo random (PN) sequence can be additionally added for further encoding. The OFC technique provides a wideband spread spectrum signal format with all the inherent advantages obtained from the time-bandwidth product increase over the data bandwidth. The theory of OFC is introduced and discussed. The fundamental equations that define the orthogonal functions, the relationships of the pulse width and chip frequencies, and the key relationships of frequency and time domain are shown.

Frequency and time domain plots of the autocorrelation function are compared between the OFC and an equivalent PN single-carrier code. The combination of the OFC and PN sequence demonstrates the advantage of the combined coding, showing a reduced compressed pulse width as compared to a simple, single-carrier PN sequence. Processing gain versus time-bandwidth product is shown. The application of PN-OFC to SAW devices for use in communications and sensors is introduced. Several SAW device embodiments are presented and both simulated and measured responses are shown. The use of PN-OFC using fixed coded SAW devices should be applicable to many communication systems using spread spectrum. The use of chirped interrogation signals for SAW sensor PN-OFC applications are also introduced. This format provides increased average-transmit-input power, increased signal processing gain and reduced correlated pulse width as compared to a single frequency RF gated burst. The PN-OFC provides all these advantageous for SAW sensors while maintaining the same device length of the equivalent PN sequence alone.

U6-I-3 512A-F 11:15 a.m.

THE NEW APPROACH TO REALIZE SMALL IMBALANCES IN DIFFERENTIAL RX-OUTPUTS FOR SAW FRONT END MODULE

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The direct conversion architecture have been widely adopted to simplify the RF (Radio Frequency) circuit composition and reduce the cost for GSM-based mobile phones. Since, a differential type LNA (Low Noise Amplifier) and a differential type mixer are used in the above-mentioned system, the DMS (Double Mode SAW) filter has been generally adopted for the Rx filter in FEM (Front End Module). However, the DMS filters are rather difficult to achieve the imbalance deviation smaller than +-1.0dB and +-5deg. which will be required for EDGE (Enhanced Data GSM Environment) systems for amplitude and phase, respectively. We have developed balun having accurate balanced characteristics which has unique structure having quarter lambda line for negative phase blanch and an inductor and capacitors for positive phase blanch. Since the quarter lambda line is shielded with ground plate the crosstalk with other circuit in the package can be avoided and this makes the device size small. The impedance of input port of the balun is designed to match the impedance of single ended ladder type SAW filter to make the insertion loss of Rx filter small and the Rx-output balanced impedance is designed to 100 ohm. The balun for both of DCS SAW and PCS SAW are implemented in LTCC (Low Temperature Co-fired Ceramics) layered package with 500 micron thickness. The Ansoft HFSS (High Frequency Structure Simulator) is used to design the FEM characteristics including the balun circuit. Using this technique, we have developed SAW front end module whose typical size is 7.2x5.5x1.25 mm^3 for quad-band and 5.6x5.5x1.25 mm^3 for triple-band. In this paper we will describe the simulation results for the balun circuit, combined characteristics of Rx filter and the balun, and total Rx response of FEM. The experimental results will also be shown.

U6-I-4 512A-F 11:30 a.m.

MODULAR INTEGRATION OF RF SAW FILTERS

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Surface acoustic wave (SAW) devices are fabricated on a piezoelectric substrate and therefore require special packaging considerations. The active area of the SAW die needs to be protected to avoid damage or mass loading to the surface. Although SAW packaging has been shrinking in both footprint and height, there are still limitations to existing packaged SAW devices for modular integration. This paper will describe an advanced packaging approach for SAW devices and illustrate various modules that can take advantage of it. The active area of the filter is packaged at the wafer level by a low profile, hermetic lid. It can thereafter be tested, singulated and integrated along with other devices into a module. Due to this advancement, modules can now realize additional miniaturization.

U6-I-5 512A-F 11:45 a.m.

QUANTITATIVE EVALUATION OF CONGRUENT $LINBO_3$ CRYSTALS USING THE LFB ULTRASONIC MATERIAL CHARACTERIZATION SYSTEM

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The line-focus-beam (LFB) ultrasonic material characterization system has been established to be a very useful system for evaluating $LiNbO_3$ and $LiTaO_3$ crystals/wafers produced for surface acoustic wave (SAW) devices as well as integrated optoelectronic devices, through measurements of the phase velocity of leaky surface acoustic waves (LSAWs) on the water-loaded wafer surfaces, which are directly interrelated to the other chemical and physical properties of the ferroelectric materials.

In this study, the LFB system is applied to characterization of congruent $LiNbO_3$ crystals. To quantitatively interpret variations of measured velocities, we investigates experimental procedure and relationships among LSAW velocities, chemical compositions, densities, lattice constants. First, specimens of X-, Y-, and Z-cut substrates were prepared from three kinds of $LiNbO_3$ single crystals, grown with different compositions of starting materials of 48.0, 48.5, and 49.0 Li_2O-mol%. Measured LSAW velocities were compared with their Li_2O contents, densities, and c-axis lattice constants. The system sensitivities to the Li_2O content and density depended upon the crystalline surfaces and

LSAW propagation directions, and were greatest for the *Y*- axis direction on the *Z*-cut specimen: for Li_2O contents, 0.0224 mol%/(m/s) with a resolution of 0.0013 mol%; for densities, -0.143 (kg/m^3)/(m/s) with a resolution of 0.009 kg/m^3; for lattice constants, -1.31 $\times 10^{-5}$ nm/(m/s) with a resolution of 7.9 $\times 10^{-7}$ nm. Next, characterization of a commercial optical-grade $LiNbO_3$ single crystal, pulled along the *Z* axis with 77-mm diameter and 49-mm length, was conducted by this ultrasonic method. It was evaluated, from the LSAW velocity variations, that this crystal boule was not exactly grown with a true congruent composition, having still a small variation of 0.35 m/s, corresponding to the changes of the Li_2O content of 0.0078 mol%, the density of 0.050 kg/m^3, and the lattice constants of 4.6×10^{-6} nm.

Session: FE1-I

PIEZOELECTRIC MATERIALS II

Chair: S. Pilgrim
Alfred University

FE1-I-1 513CD 10:30 a.m. (Invited)

HIGH PERFORMANCE, HIGH TEMPERATURE PEROVSKITE PIEZOELECTRICS

T. R. SHROUT*, S. ZHANG, R. EITEL, C. STRINGER, and C. A. RANDALL, Penn State University.
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The industrial and scientific communities have expressed the need for sensing and actuation over a broad temperature range. This review presents high temperature piezoelectric materials that are commercially available and those that are under development. Key materials, in order of increasing Curie Temperature (T_c) are $Pb(Zr,TiO)_3$, $PbTiO_3$, $(Pb,Ba)Nb_2O_6$, $Na_{0.5}Bi_{4.5}Ti_4O_{15}$, and $LiNbO_3$. The maximum operation temperature for sensors is limited by T_c combined with the level of sensitivity determined by the piezoelectric voltage coefficient (g) and dielectric loss combined with the level of electrical resistivity. New materials include perovskite layer structured ferroelectric ceramics, which possess the highest known T_cs, and non-ferroelectric single crystals, such as Langasites and Gallium phosphate.

For actuators, high T_c comes with the expense of significantly reduced piezoelectric strain (d_{33}) being further reduced for non-morphotropic phase boundary systems. Recently new high T_c morphotropic phase boundary materials have been developed, as predicted by a perovskite crystal structure tolerance factor relationship. Specifically, compositions based on $(1\text{-}x)BiScO_3$ $(x)PbTiO_3$ exhibit piezoelectric activity comparable to PZT, with T_cs greater than 100°C higher. In the single crystal form, these materials offer d_{31}s $>$ 1000 pC/N and coupling coefficient $>$ 90%. Finally, T_cs $>$ 600°C are projected in lower tolerance $(1\text{-}x)Bi(Me)O_3(x)PbTiO_3$ systems.

FE1-I-2 513CD 11:00 a.m.

PIEZOELECTRICS AND ELECTROSTRICTORS FOR HIGH TEMPERATURE ULTRASONIC DRILLS

W. HACKENBERGER*[1], E. ALBERTA[1], S. SHANG[2], R. EITEL[2], and T. SHROUT[2], [1]TRS Technologies, Inc., [2]The Pennsylvania State University.
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A variety of bismuth-based perovskites were investigated for use as high temperature piezoelectrics and electrostrictors. The targeted application for this work is an ultrsonic, rock-sampling drill to be used on a proposed Venus lander. The operating temperature of this device is expected to be 460 to 480°C. The high temperature resistivity, dielectric, and piezoelectric properties were measured for several bismuth scannate-lead titanate (BS-PT) and bismuth magnesium titanate-lead titante ceramics (BMT-PT) with differing dopants and stoichiometries. For compositions that had their Curie temperatures very near the intended operating temperature, induced piezoelectric properties were measured by applying a DC bias. All piezoelectric properties were determined from resonance techniques. Manganese-doped BS-PT operated as a piezoelectric showed the most promising properties both in terms of high resistivity (10^7 Ohm-cm) and piezoelectric performance ($d_{31} > 100$ pC/N) at 450°C. This material is being tested in a working ultrasonic drill at high temperature.
NASA Contract #NNC04CA92C

FE1-I-3 513CD 11:15 a.m.

CHARGING AND SWITCHING OF FERROELECTRETS: HOW MUCH CAN FERROELECTRETS BEHAVE LIKE FERROELECTRICS?

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Dielectrics with good charge storage capability, so called charge electrets, are non- or weakly-polar materials. Despite their non-polar nature porous charge electrets with internally charged surfaces can exhibit very pronounced piezoelectricity. Such systems have been termed "Ferroelectrets" and they have been receiving growing attention over the last few years. Their puzzling and unexpected features resemble very much those normally known from traditional ferroelectrics: Ferroelectrets are piezo- and pyroelectric, their polarization can be reversed by means of an external field and electrical as well as mechanical hysteresis loops were observed. As conventional ferroelectrics are different and more complicated than ferromagnets, so are ferroelectrets different and more complex than most ferroelectrics. Here we report about the very different charging and switching mechanism in ferroelectrets, both in simple model-systems and in less simple foam structures. These mechanism are crucial and form the basis for the

striking phenomenological similarities to ferroelectrics. We also want to address some of the specific peculiarities and pitfalls related to present ferroelectrets and their characterization. Interfacial charge injection at high electric fields and anelastic non-linearities, for instance, can be the cause for false ferroelectric-like hysteresis effects which do not reflect any polarization reversal. Our contribution is an attempt towards a more comprehensive picture of how much ferroelectrets behave like ferroelectrics.

FE1-I-4 513CD 11:30 a.m. (Invited)

RELAXOR FERROELECTRIC POLYMERS WITH HIGH ELECTROMECHANICAL RESPONSES

Q. M. ZHANG*[1], C. HUANG[1], R. KLEIN[1], F. XIA[1], D.-Y. JEONG[1], K. REN[1], V. BOHNAR[2], and A. LEVSTIK[2], [1]The Pennsylvania State University, [2]Jozef Stefan Institute.
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Recently, it was demonstrated that by introducing random defect fields in ferroelectric poly(vinylided fluoride-trifluoethylene) (P(VDF-TrFE)) polymer, one can convert it to a relaxor ferroelectric material with a high electromechanical responses. It will be shown that the defect modified PVDF polymers exhibit polar-glass freezing transition. The large strain associated with the electric field induced local conformation change between the polar and non-polar bonds is responsible for the observed large electrostrictive strain in the irradiated copolymers. However, for PVDF based terpolymers, the electromechanical response is more of a combined effect of the local nano-polar vector reorientation and field induced conformation change.
This work has been supported by NIH, ONR, and DARPA

Session: FC1-I

TIMESCALES AND TIME TRANSFER

Chair: T. Parker

NIST

FC1-I-1 511CF 10:30 a.m.

TIME COMPARISONS BETWEEN USNO AND PTB: A MODEL FOR THE DETERMINATION OF THE TIME OFFSET BETWEEN GPS TIME AND THE FUTURE GALILEO SYSTEM TIME

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The European satellite navigation system Galileo will have its independent system time, GST, which shall be realized in a so-called Precision Timing Facility PTF and shall be aligned with International Atomic Time TAI. Interoperability of Galileo and GPS shall be assured by, among other measures, broadcasting the actual difference between the two system timescales, GST and TGPS. In the current context we do not discuss the time offset of an integer number of seconds but only the fractional part. The algorithms and methods how this offset will be determined in practice are currently under study. At least two options were identified so far. The time difference could be determined using a dedicated time transfer using the technique of Two-Way Satellite Time and Frequency Transfer, TWSTFT, between PTF and United States Naval Observatory, USNO, USNO providing additionally the offset between its reference time scale, UTC(USNO), and TGPS. In the second approach, a GPS time receiver is operated at PTF and the GPS Galileo Time Offset, GGTO, is determined from the GPS signal as received.

The medium and long-term stability of PTB's reference time scale UTC(PTB) are similar to what is expected for GST. We analysed both methods to determine the difference UTC(PTB)-TGPS making use of data collected between March and October 2003. Two independent TWSTFT links, one using a commercial telecommunication satellite (Ku-band), one using a military communication satellite (X-band), were operated between USNO and PTB. USNO provided the required data UTC(USNO)-TGPS. At PTB, a C/A code single channel single frequency GPS time receiver and a geodetic multichannel GPS receiver are operated. All links and receivers were calibrated and in an ideal world both methods should give the same result. At the current stage of data analysis we notice a difference of 5 ns on average between the TWSTFT and the two GPS SIS results. The differences change by about 3 ns over the study period. In the presentation we give a history of the calibration exercises, we discuss data treatment in more detail: averaging, use of modeled or measured ionosphere in post-processing of the single-channel single frequency data, use of GPS precise ephemerides. A new calibration of the time link USNO-PTB is scheduled for March 2004, and we plan to include the result in the final data analysis.

We acknowledge the support of United States Naval Observatory, maintaining the TWSTFT link to PTB and providing the required GPS data. We also acknowledge the Bundesamt fr Kartographie and Geodsie, Germany, for providing the geodetic GPS receiver to PTB

FC1-I-2 511CF 10:45 a.m.

A NEW TECHNIQUE FOR ESTIMATING FREQUENCY FROM GPS CARRIER-PHASE TIME-TRANSFER DATA

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GPS carrier-phase time transfer offers high frequency stability at short averaging times, approaching a fractional frequency stability of 10^{-15} at averaging times of less than one day. However, this technique suffers from day-boundary offsets that can degrade long-term stability.

The day-boundary offset is a discontinuity in the time-transfer estimates that occurs between the end of one processing batch and the beginning of the next. A processing batch is typically 1-3 days in length, and these steps characteristically range in size from 50 ps to 1 ns, depending on the level of pseudorange noise at the receiver sites. Though techniques exist for estimating and removing these steps, the removal of each step introduces additional uncertainty into the results. In the end, the uncertainty of the difference between two time points depends on the number of steps that have been removed in between them.

The conventional procedure for computing frequency from GPSCPTT data over a multi-day epoch has been to concatenate the batch solutions as described above and then to use the time points from the concatenated series to compute the frequency. We propose a new method in which a frequency is computed directly from each batch solution and then an appropriate average of these frequency values taken in order to obtain a mean frequency value for the epoch of interest.

The primary advantage of this method is that we avoid the introduction of uncertainty that arises from the removal of day-boundary offsets. Other advantages include computational simplicity and greater robustness in the event of a data outage. The disadvantage is that the uncertainty only decreases as one over the square root of the number of independent frequency measurements.

We will compare the frequency values obtained from this new technique to those obtained from the concatenation method and from two-way satellite time transfer. Preliminary results obtained from data recorded in October, 2003 indicate that over a span of 15 days, the three methods agree at $1\text{-}2*10^{-15}$ in fractional frequency.

FC1-I-3 511CF 11:00 a.m.

CONTINUOUS GEODETIC TIME TRANSFER ANALYSIS METHOD

R. DACH*[1], T. SCHILDKNECHT[1], U. HUGENTOBLER[1], and G. DUDLE[2], [1]Astronomical Institute, University of Bern, [2]Swiss Federal Office of Metrology and Accreditation (metas).
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The Astronomical Institute of the University of Berne (AIUB) and the Swiss Federal Office of Metrology and Accreditation (METAS) as well as other groups have demonstrated the capability of using of GPS (Global Positioning System) carrier phase measurements for time transfer. If a number of high performance clocks are connected to geodetic GPS-receivers all of them can be compared with each other within a consistent network solution.

Usually a daily data analysis is performed. Small discontinuities in the resulting time series with a magnitude of up to one nanosecond occur at the boundaries of the daily computation batches. We demonstrate an analysis strategy where these artificial "clock jumps" can be prevented. The solution corresponds (more or less) to a solution for an infinite time interval.

The results from this new analysis strategy will be compared with the time series obtained with independent time transfer techniques. An important issue in the presentation will be the long term stability of this new analysis method.

FC1-I-4 511CF 11:15 a.m.

UNCERTAINTY ESTIMATION ON MULTI-CHANNEL GPS TIME TRANSFER

M. ADDOUCHE*, F. MEYER, and F. VERNOTTE, Observatoire de Besançon.
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The GPS common view technique, using C/A code receivers, is used to realize the TAI (Temps Atomique International) and the TA(F) (Temps Atomique Franais). Clock offsets between laboratory clocks are determined according to a fixed procedure defined by the CCTF (Comité Consultatif du Temps et des Fréquences). This schedule contains a maximum of 89 13-minute long, 16-minute spaced tracks, resulting each day in (ideally) 89 clock offset estimations. The usual method used to compute the daily average of clock offsets is a quadratic least-squares linear interpolation; the time offset uncertainty is obtained by the calculation of the daily standard deviation of the residuals of the interpolated samples. This simplified estimate does not take into account the statistical properties of the different types of noise present in the measurement. We chose in this work to perform the Chebyshev interpolation in order to lead to a formulation of the time transfer uncertainty according to the noise levels present in the GPS track results. This is achieved by the calculation of the covariance matrix of time samples. The results we obtained showed that the empirical uncertainty estimation agrees well with the noise-based uncertainty calculation. In addition to validating the empirical method, our method provides a good estimation of the bounds of the daily standard deviation. However, the dispersion of the uncertainty estimation using the noise level indications shows a bias when data are not equally spaced, typically when scheduled track slots are empty. That is due to the change of the estimated noise level values when we consider the set of incomplete data. Getting rid of this bias can be done either by using a modified schedule filling all 16-minute slots, or, as we did, by using multi channel receivers with which we can take full advantage of the low dispersion property of the noise-based uncertainty estimation method.

FC1-I-5 511CF 11:30 a.m.

COMPARISON BETWEEN GPS AND LORAN PERFORMANCE USING INDOOR AND OUTDOOR LORAN ANTENNAS

J. JACOBY*, C. SCHWEITZER, P. SCHICK, and H. MONSON, Locus, Incorporated.
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Because Loran can function as a GPS backup in multimodal applications, the Loran infrastructure in the United States is undergoing a substantial modernization, and it is progressing towards an enhanced or e Loran system. As a part of this modernization, three new Agilent 5071A cesium clocks were installed at each transmitter, and state-of-the-art time and frequency clock measurement and control equipment (TFE) by Timing Solutions Corporation is being installed, which uses GPS to steer the ensemble averaged Cs clocks to recover UTC (USNO) within 15 nanoseconds at each transmitter. Given that 29 Loran transmitters are located in North America, it is likely that the Loran system now forms the largest distributed primary clock system in the world. When the conversion to e-Loran is complete, the e-Loran system will use time of transmission control similar to GPS, and add a 9th pulse that will distribute UTC, leap second, and other information from each transmitter.

At the present time, Loran stations located near the Great Lakes are undergoing modernization, and it is expected that these stations will be upgraded to the TFE by this summer. Locus is located in the Great Lakes region, and can monitor the transition from old to new control equipment. However, it should be emphasized that the conversion to time-of-transmission control will not take place until the entire modernization program has been complete.

As Loran transmitter technology moves forward, Locus has developed new all-in-view digital receivers that can take advantage of the modernization of the Loran infrastructure and provide much better time and frequency performance than available from older technology devices. For example, recent common view Loran studies using short baselines have demonstrated Stratum 1 frequency performance with less than 1 hour of averaging and 8-25 nanosecond (RMS) time recovery.

In addition to new Loran receiver technology, Locus has developed new magnetic or H-field Loran antenna technology and associated receiver software to process these signals. Using this technology, when an H-field antenna is mounted indoors, it is still possible to track multiple (e.g.10-16) Loran stations.

In order to get an initial appreciation for the performance possible when using indoor Loran antennas and to monitor the progression towards the new e-Loran system, Locus has developed a test system to compare the frequency performance provided by: a GPS receiver with rooftop antenna, a Loran receiver with an outdoor e-field antenna, and a Loran receiver with an indoor H-field antenna. The timing outputs from each of the receivers are measured using a Cs frequency standard as a reference. This setup enables relatively long-term data sets to be collected, so we could also monitor any changes as the Loran transmitters were switched over to the new TFE equipment. This paper will provide an overview of the experimental setup, review results of the frequency performance provided by each system, and summarize any changes observed while Loran stations in the Great Lakes area are upgraded to the new TFE equipment.

Session: FC2-I
FREQUENCY SHIFTS IN CRYSTAL RESONATORS
Chair: D. Stevens
Vectron International

FC2-I-1 511DE 10:30 a.m.

EXAMINATION OF DETAILED FREQUENCY BEHAVIOR OF QUARTZ RESONATORS UNDER LOW DOSE EXPOSURES TO PROTON RADIATION

G. L. WEAVER*[1], M. J. REINHART[1], H. B. SEQUEIRA[1], and W. STAPOR[2],
[1]The Johns Hopkins University Applied Physics Laboratory, [2]Innovative Concepts.
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The behavior of quartz crystal resonators in the radiation environment of space has been a subject of study for decades. Specific, interest arises from the concern for frequency drift in satellite timing systems which must transit through the radiation zone of the South Atlantic Anomaly. The radiation of this zone is characterized by a flux of solar protons in the 40 to 100 MeV energy spectrum, presenting a total accumulated dose of 1 to 5 rads per transit.

Previous work by Suter and Norton asserted that the effect of this radiation to the quartz crystal lattice structure of AT cut resonators was in the form of ionization, similar to that of gamma rays. They cited that the frequency response recorded for any specific resonator varied proportionately with flux level and accumulated dose during low dose exposure. They also postulated that the frequency shifts from low dose ionization would likely recover to pre-exposure conditions since no permanent displacement of atomic lattice structure was believed to occur and no correlation to the aluminum ion contaminate concentration of the quartz was found. Most important they noted specific signatures in the frequency drift patterns peculiar to certain groups of resonators.

Stapor, Cash and Emmons subsequently corroborated the findings of Suter and Norton in SC cut resonators. They additionally noted an apparent systematic reduction of a resonator sensitivity to low dose radiation after subsequent exposure to repeated dose rates. In both studies, the authors posit correlation of a resonators low dose radiation sensitivity to the manufacturing lot while discarding the basic quartz material properties of contamination density, Q and cut angle.

Our work to be presented in this paper further explores these previous discoveries using the detail observed in a recent screening of SC-cut quartz resonators for proton radiation sensitivity selection. Specifically, we will use the peculiar signatures of the observed frequency drifts to test certain qualities of the quartz lattice structure relating to localized mechanical stress in the resonator and the possible influence of microscopic twinning. We will also attempt to correlate lattice quality to possible manufacturing techniques which would likely influence the lot dependence asserted by previous publications. Finally, we will present in-flight data that demonstrates that the long term frequency drift in not degraded by repeated radiation exposures in orbit.

FC2-I-2 511DE 10:45 a.m.

622MHZ HIGH FREQUENCY FUNDAMENTAL COMPOSITE CRYSTAL RESONATOR WITH AN AIR-GAPPED ELECTRODE

M. UMEKI*, T. SATO, H. UEHARA, and M. OKAZAKI, Nihon Dempa Kogyo Co.,Ltd.
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We have developed a 622MHz high frequency fundamental crystal resonator made from a laminated quartz blank with an air-gapped electrode. The quartz blank(1.4mmx1.2mm) is mounted on a 3.2mm x 2.5mm size package.The following is the new crystal resonator's electrical characteristics:

1. Fr (Resonance frequency) : 622MHz 2. CI (Crystal impedance) : 18ohm 3. Q (Quality factor) : 12000 4. L1 (Motional inductance) : 60uH 5. C1 (Motional capacitance) : 1.0fF 6. C0 (Parallel capacitance) : 0.45pF 7. M (Figure of merit) : 26

Presently, as the signal source for the optical digital communication network based on SONET Synchronous Optical NET work) and SDH "Synchronous Digital Hierachy", a VCXO using a 4 times multipled frequency of 155MHz crystal resonator or a VCSO using 622MHz SAW resonator is required. However, these oscillators have problems on phase noise characteristic for further high-density and high-speed communication system. Therefore, a crystal resonator with high stable and reliable which has a 622MHz fundamental-mode has been demanded to build the superior low noise characteristics of VCXO. However, the frequency of the 622MHz fundamental crystal resonator had strong dependency of temperature and drive level. The dependency is due to mass loading effect of electrode accompanied by the thickness of the vibration area. In order to resolve the problem, we developed a new inverted mesa quartz blank with an air-gapped electrode. As a result, we have developed a high stable and reliable 622MHz fundamental crystal resonator. It is very important that the air-gap between electrode and quartz blank was precisely controlled with 0.01um in this resonator. Therefore, we used the advanced technology of photolithography, high accurate wet etching and a laminated wafer. The blank for fundamental crystal resonator was made from the laminated three wafers of 3 inches AT cut crystal. The first layer with a through-hole was to support the thin vibration area. The 2nd layer had a thin vibration area with precise shallow groove. The 3rd layer was designed as an air-gapped electrode.

FC2-I-3 511DE 11:00 a.m.

AN INVESTIGATION INTO THE EFFECTS OF ELECTRODE FILM THICKNESS ON RBA IN HIGH FREQUENCY FUNDAMENTAL MODE CRYSTALS

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The impact of electrode film thickness on the Tc characteristics of high frequency fundamental mode AT-strip crystals has been characterized. In particular we have studied how RBA and inflection temperature vary as the thickness of the gold plated electrode is increased from 0.75 f_1^2 to 1.2 f_1^2. Our characterization encompassed the entire frequency range between 77.76 MHz and 250 MHz. We have also investigated how variations in plating thickness impact Tc behavior in HFF mode crystals when other commonly used metals are utilized. This paper presents our results, compares, and contrasts them with data collected by other authors at lower frequencies. Furthermore we discuss the implications of this data on the industrys ability to make even higher frequency fundamental mode crystals.

FC2-I-4 511DE 11:15 a.m.

FREQUENCY SHIFTS IN CRYSTAL RESONATORS DUE TO INTRINSIC STRESSES IN UNEQUAL THICKNESS ELECTRODES

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A resonator when subject to mechanical stresses changes its resonance frequencies. Intrinsic stress in electrodes deposited on resonators is one source of stresses in resonators [1,2]. In this paper we study frequency shifts in crystal resonators due to intrinsic stresses from electrodes. The first-order perturbation integral as developed by Tiersten for frequency shifts in resonators is used. Frequency shifts in quartz and langasite thickness-shear resonators are calculated. The effect of asymmetric electrodes [3] is examined. Our results on AT and BT cut quartz resonators agree qualitatively with [1]. It is also observed that under the same electrode film stress Y-cut langasite resonators show considerably less frequency shifts than Y-cut quartz resonators.

[1] E. P. EerNisse, Quartz resonator frequency shifts arising from electrode stress, in: Proc. 29th Frequency Control Symp., 1975, pp. 1-4. [2] H. F. Tiersten, B. K. Sinha and T. R. Meeker, Intrinsic stress in thin films deposited on anisotroic substrates and its influence on the natural frequencies of piezoelectric resonators, J. Appl. Phys., vol. 52, pp. 5614-5624, 1981. [3] J. A. Kosinski, Thickness vibrations of flat piezoelectric plates with massy electrodes of unequal thickness, in Proceedings of IEEE Ultrasonics Symposium, 2003, pp. 70-73.
This work was supported by the Army Research Office under DAAD19-01-1-0443.

REDUCTION OF SPURIOUS RESPONSES IN A THICKNESS-TWIST MODE RESONATOR MADE OF CRYSTAL CLASS 32 BY TILTING EDGES

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Rotated-Y-cut quartz resonators vibrating in a thickness-twist (TT) mode have been widely used in oscillators, filters and sensors. The TT mode is a pure shear mode with the displacement parallel to the X axis. If a plate is isotropic, side surfaces normal to the plate and parallel to the X axis is traction free and hence can be cut without disturbing the vibration to make a rectangular strip. This is not the case of anisotropic quartz and such surfaces cause spurious responses due to coupling with other modes.

Mindlin found an exact solution of TT mode in a rotated-Y-cut quartz strip by tilting side surfaces, so that the traction-free condition can be met. Two of the authors noted that its lowest mode retains important features of a large plate and developed miniature AT strip resonators. Tilt angle calculated from the exact solution is for a semi-infinite parallelogram strip at a certain temperature. Hence optimum combinations of width vs thickness ratio, cut angle, tilt angle and the length vs width ratio were determined. Based on this design, six million units are monthly made and the total in the last 30 years exceeds one billion. Whereas one of the authors developed a method for analyzing characteristics of a strip resonator with tilted edges and a finite length.

This paper presents two further works, one for other crystals and another for doubly-rotated-Y-cuts. Gallium Phosphate (GP) and Langasite family (LGS, LGN and LGT) belong to the same crystal class 32 as quartz and useful rotated-Y cuts have been found. Their higher EM coupling and wider usable temperature range (no phase transition) than quartz are useful in applications in wide band or temperature range, but require more control of spurious responses. Our solutions are extended to cover useful cuts of these crystals. For example, in (YXwlt)0/-15.5/0 cut of GP, a tilting of -1.54 eliminates much spurious responses and undesirable shift of turnover temperature. (YXwlt)0/1.08/0 cut of GP with tilt of 10.9 has a good linear f-t over very wide range of temperature. In the case of Langasite family, required tilt is usually larger than that of quartz. For example, (YXwlt)0/-2/0 cut requires the tilt of 18.7. Hence much improvements in spurious reduction over rectangular strips are obtained.

Doubly-rotated-Y-cuts have been used to refine characteristics of rotated Y cuts. The (quasi) TT mode is still dominant, although it is not a pure mode and its displacement is not parallel to X-axis any more. No side surface is traction free. We found, however, much reduction of spurious responses is obtained, if we set edges parallel to the displacement of dominant TT mode and tilt side surfaces parallel to the equiphase plane of coupled FS mode. One of the authors expanded the analytical method to take into account effects of other modes as well as high EM coupling. Marked reduction of spurious responses are obtained in various cuts of Quratz, GP and LGS family.

Session: U1-J
CONTRAST AGENTS: THERAPY
Chair: A. Boukaz
Erasmus M. C.

U1-J-1 510AC 1:30 p.m.

REMOTE MANIPULATION OF CELLS WITH ULTRASOUND AND MICROBUBBLES

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Introduction: Ultrasound in combination with contrast microbubbles has been shown to alter the permeability of cell membranes without affecting cell viability. This permeabilization feature is used to design new drug delivery systems using ultrasound and contrast agents. However, the underlying mechanisms are still unknown. One hypothesis is that oscillating microbubbles cause cell deformation resulting in enhanced cell membrane permeability. In this paper we show the interaction between oscillating microbubbles and cultured cells under a microscope recorded with a fast framing camera at 10 million frames per second.

Method: Optical observations of microbubbles and cultured cells is possible through the use of a standard BX-2 Olympus microscope mounted in front of the fast framing camera Brandaris128. The Brandaris128 is capable of recording a sequence of 128 images with a frame rate up to 25 million frames per second. Pig aorta endothelial cells and Chinese hamster ovary cells were grown on the inside of an OpticellTM container. A diluted suspension of experimental agents BR14 (Bracco Research, Geneva, Switzerland) was added. Ultrasound exposure consisted of a burst of 6 cycles at a frequency of 1 MHz and a P_{-} of 0.9 MPa. During ultrasound transmission, the interactions between BR14 microbubbles and cultured cells were recorded using a frame rate of 10 million frames per second.

Results: The cell membrane deformation is studied through measuring the distance between two fixed points of the cell membranes. The microbubble vibration is quantified by measuring its diameter. We observed that, upon ultrasound arrival and microbubble oscillations, the cell membrane deforms up to a few micrometers in length as a result of the oscillation of the microbubble. The membrane deformation rate changes with the oscillation strength of the microbubble. During the insonification, changes in the cross-sectional distance of the cultured cells were observed due to microbubble vibrations. With endothelial cells, expansion of a 6 mm-microbubble up to 200% caused membrane deformation in radial direction of 3 mm (15%). Depending on the cell type, vibrations of the microbubble and the distance between the microbubble and the cell, the changes in cross-sectional distance of the cells varied form 0 to 25%.

Conclusions: This study reveals the action of an oscillating contrast microbubble on the cell. Using oscillating microbubbles for therapeutic strategies may be a real asset because the oscillations can be controlled externally and hence most likely also that of the endothelium response. The Brandaris 128 provides a powerful means for analyzing interactions between ultrasound-microbubbles and cells. It is known that living cells sense mechanical forces thus there is no doubt that perturbation of the oscillating microbubbles results in profound alterations in the cellular content. These data are the basis for further studies to reveal the functional relationships that lie beyond the remote manipulation of cells and ultrasound microbubble induced permeabilization of the cell membrane.

This project was supported by the Dutch Technology Foundation STW (RKG 5104).

U1-J-2 510AC 1:45 p.m.

COMBINED OPTICAL AND ULTRASONIC MONITORING OF LASER-GENERATED INTRACELLULAR CONTRAST AGENTS: INITIAL CELL CULTURE STUDIES

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We propose that acoustically monitored laser-induced optical breakdown (LIOB) can be used as an important diagnostic and therapeutic tool in living cells. With properly controlled laser parameters, optical breakdown is a minimally invasive means to target a single, transient, acoustically detectable contrast agent within a cell, without affecting its viability. With different laser parameters, optical breakdown can effectively obliterate a target cell. Simultaneous real-time acoustic microscopy can monitor both types of effects. To test this hypothesis, experiments were performed on Chinese hamster ovary (CHO-K1) cells, cultured in an adherent monolayer on an uncoated glass coverslip. To initiate and monitor intracellular photodisruption in real time, we have developed a system integrating an ultrafast laser with optical and acoustical microscopes. A Ti:Sapphire laser beam (λ=796 nm), focused to a 5 μm spot size and pulsed at 18 kHz (100 fs pulse duration), produced optical breakdown. Upon initiation of LIOB, a high-frequency (85 MHz) ultrasonic transducer, confocal with the laser, monitored the resultant bubble formation and dissolution via continuous pulse-echo measurements. During and following laser exposure, the fate of each targeted cell was observed with optical microscopy. By varying laser pulse fluence (from a threshold of 0.5 J/cm^2 to 1.78 J/cm^2) as well as the number of applied pulses, a broad range of intracellular effects was studied. When 20 laser pulses were applied at maximum fluence, a large (15 μm diameter), stable bubble was formed

and the targeted cell was ruptured and completely detached from the substrate. However, with a single laser pulse at threshold fluence, a transient bubble of less than 5 μm diameter was generated and rapidly dissolved, with no visible damage to the cell structure. Target cells in this regime continued to adhere to the substrate (indicating continued viability) and were optically monitored with no apparent changes for several hours after laser exposure. This system has significant benefits over other contrast agents for intracellular applications. Geometric targeting within cells generates acoustically detectable microbubbles without introducing exogenous agents, eliminating reliance on endocytosis and other inherent complications. Furthermore, by incorporating biochemical targeting agents, this system can also be used as a powerful tool for molecular diagnostics (e.g. detecting targeted molecular agents without affecting cell viability) and therapy (e.g. by destroying targeted cells without damaging cells in the vicinity). The laser penetration depth (several mm) is ideal for many superficial and endoscopic applications, and at shallow depth, the beam can be more tightly focused to further reduce the invasiveness of LIOB in cells. A full range of parameters can thus be characterized to define applicability for these intracellular contrast agents.
This work is supported by the Whitaker Foundation, NIH Grants HL-47401 and HL-67647, and NCI/NIH Grant NO1-CO-27173.

U1-J-3 510AC 2:00 p.m.

IN VITRO ACOUSTIC MOLECULAR IMAGING OF TISSUE FACTOR EXPRESSED BY SMOOTH MUSCLE CELLS WITH STABLE LIQUID PERFLUOROCARBON NANOPARTICLE CONTRAST AGENTS

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The success of molecular imaging with targeted contrast agents depends in part upon the agents stability and the specificity of their binding to selected molecular markers. Liquid perfluorocarbon (PFC) nanoparticle (NP) emulsions developed in our laboratory exhibit long half-lives in vivo and markedly enhance the reflectivity of surfaces to which they are bound. In this study we sought to characterize the specificity of targeting of perfluorooctyl bromide (PFOB) NPs to tissue factor (TF), a transmembrane glycoprotein expressed by smooth muscle cells (SMCs) as part of inflammatory response after vessel injury (e.g., angioplasty). Porcine SMCs constitutively expressing TF on the cell surface were cultured on microporous membranes and targeted with PFOB NPs by avidin-biotin binding techniques. Treatment groups included: 1) targeted cell samples exposed sequentially to biotinylated TF antibody/avidin/biotinlyated NPs; 2) non-targeted SMCs exposed to avidin/biotinlyated NPs; 3) control SMC's left untreated. Ultrasonic imaging and quantification of surface reflectivity for each cell group was accomplished by scanning a 25MHz transducer in a grid over the membrane inserts and analyzing the reflected RF signal from the cell-covered

surfaces. Total PFC content for each sample (directly related to NP concentration) was determined independently by gas chromatography. Targeted cells exhibited significantly enhanced surface reflectivity (-22.6±2.0 dB referenced to steel reflector, $p<0.002$) relative to either non-targeted (-29.6±1.1 dB) or control groups (-29.3±1.4 dB). Gas chromatography data indicated that bound PFOB was present in targeted cells at levels nearly six times greater as compared with nontargeted cells. Additionally, bound PFOB levels for the targeted samples correlated directly with the magnitude of surface reflectivity ($r=0.99$; $p<0.03$). In conclusion, PFOB nanoparticles targeted to SMC tissue factor specifically bind to such cells at levels nearly six times greater than to nontargeted cells. The targeted cells exhibit substantially enhanced acoustic reflectivity, thereby confirming the utility of quantitative molecular imaging with ultrasound with the use of a nongaseous nanoparticle contrast agent.

U1-J-4 510AC 2:15 p.m.

IN VIVO ULTRASONIC DETECTION OF ANGIOGENESIS WITH SITE-TARGETED NANOPARTICLE CONTRAST AGENTS USING MEASURE-THEORETIC SIGNAL RECEIVERS

M. S. HUGHES*[1], J. N. MARSH[1], C. S. HALL[2], J. H. ALLEN[1], P. A. BROWN[1], E. K. LACY[1], M. J. SCOTT[1], S. A. WICKLINE[1], and G. M. LANZA[1], [1]Washington University School of Medicine, Cardiovascular Division, [2]Philips Research, USA.
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Angiogenesis or neo-vasculature surrounding a tumor has been postulated as an important marker for the early detection of cancer. The proteins associated with new vessels are sub-resolution for ultrasonic imaging, necessitating the use of contrast agents. In this work we use a liquid, perfluorocarbon nanoparticle previously shown to enhance specific targets in *in vitro* and *in situ* settings. Previous studies focused on the use of conventional signal analysis techniques including signal amplitude, signal energy, and spectral analysis. To explore the possibility of further increasing contrast between targeted bio-markers and untargeted tissue, we applied the theorems and concepts of measure-theoretic (e.g., information theory, thermodynamics) and topological dynamics. We describe the outcome of employing these types of dynamical analyses to ultrasonic data acquired *in vivo* using New Zealand White Rabbits implanted with VX2-tumors and then exposed over the course of two hours to $\alpha_v\beta_3$ integrin-targeted liquid perfluorocarbon nanoparticles. Animal models were anesthetized, and a 7.5 MHz center frequency array held fixed against the left hindquarter directly above the tumor. A single frame was acquired using a modified clinical medical imager (ATL HDI 5000 with RF capture card) prior to injection of $\alpha_v\beta_3$ targeted perfluorocarbon nanoparticles. Subsequently, frames were acquired at 0, 15, 30, 60, and 120 minutes post injection. Each data set consisted of a

single frame of 256 A-lines (8bit, 957 samples, 40 Ms/s). A 32-sample window was moved along each A-line to calculate a single signal receiver value for each window position. A parametric image was then constructed showing the 2-D spatial variation of each of the signal receivers. Subsequent comparison of the resulting family of parametric images was performed using two different methods. In the first, the mean value and standard deviation (σ) of the pixel values in each frame was computed. The area of the image greater than one σ above the mean was computed for the frames acquired at each time. For entropy-based images, the resulting area increases monotonically with time post-injection (R=0.952). Moreover, the area is confluent and collocated with $\alpha_v\beta_3$ expression indicated by histological examination of the extracted tumor. In the second analysis, the pre-injection image was subtracted from all subsequent images; the resulting difference images further reduce background noise and correlate well with histological analysis. Further corroborative evidence of the specificity of the site-targeted contrast agent was provided by experiments using Indium-labeled nanoparticles. Conventional analysis of the same data yields no evidence of enhancement. In this study, we have demonstrated the use of measure-theoretic techniques to evaluate the time course of specific binding of targeted contrast agents *in vivo*. These techniques may be useful for enhancing biomarkers obscured by a relatively large signal from untargeted tissue.

U1-J-5 510AC 2:30 p.m.

ACOUSTIC RADIATION FORCE ENHANCES ADHESION OF MICROBUBBLES TARGETED TO P-SELECTIN

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Recent research has shown that targeted ultrasound contrast microbubbles achieve specific adhesion to regions of intravascular pathology. However, the efficiency of the attachment to molecular targets tends to be low, and substantial non-specific and unintended microbubble adhesion frequently occurs. Previous work has suggested that circulating microbubbles tend to migrate toward the center of the blood vessel, and thus may not achieve contact with the vascular endothelium. Hemodynamic factors in the microcirculation may diminish this problem; however, microbubble contact with the vascular surface in large, high flow vessels may be infrequent, and adhesion in large vessels has not been demonstrated. The efficacy of targeted contrast enhanced ultrasound imaging might be improved by increasing the fraction of transiting microbubbles that bind specifically to the intended target site. Several studies[1,2] have proven that low-intensity acoustic radiation can be used as a mechanism to force free-stream microbubbles toward a surface. In the current work we present evidence that acoustic radiation increases the specific delivery of targeted microbubbles in vitro. Lipid shell microbubbles bearing a monoclonal antibody as a targeting ligand were infused at through a microcapillary flow chamber coated with the pro-inflammatory endothelial protein P-selectin. A 2.0 MHz ultrasonic pulse was applied perpendicular to the flow direction, and microbubble accumulation was observed on the flow chamber surface opposite the transducer. We observed that acoustic pressures between 70 and 170 kPa enhance microbubble adhesion up to 60-fold at microbubble concentrations of 75 to 0.25 mL^{-1}. We found that adhesion was highly dependent upon microbubble concentration, and that acousic pressure mediated the greatest enhancement in adhesion at concentrations within the clinical dosing range. Acoustic pressure enhanced adhesion to P-selectin nearly 80-fold at a wall shear rate of 1244 s^{-1}, suggesting that this mechanism is appropriate for achieving targeted microbubble delivery to atherosclerotic plaques expressed in large vessels.

[1]Dayton P.A., Morgan K.E. Klibanov A.L, Brandenburger G., Nightingale K.R., K.W. Ferrara. 1997. A preliminary evaluation of the effects of primary and secondary radiation forces on acoustic contrast agents. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*. 44: 1264-1277.

[2]Dayton P.A., Klibanov A. Brandenburger G., Ferrara K. 1999. Acoustic radiation force in vivo: a mechanism to assist targeting of microbubbles. *Ultrasound in Medicine and Biology*. 25: 1195-1201.

This work was supported by grants from the NIH.

U1-J-6 510AC 2:45 p.m.

INCREASING BINDING EFFICIENCY OF ULTRASOUND TARGETED AGENTS WITH RADIATION FORCE

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The goal of this work is to demonstrate both theoretically and experimentally that ultrasound radiation force can significantly increase the binding efficiency of targeted contrast agents, without increasing non-specific adhesion of agents to the target surface. Targeted ultrasound contrast agents are microbubbles that have specific binding molecules on their albumin, lipid or polymer shells. These microbubbles can accumulate at their target sites of angiogenesis, inflammation, or thrombus after they are injected into the body. Concentration of these highly echogenic microbubbles in a targeted region can facilitate the detection and evaluation of disease. When a traveling ultrasound wave is absorbed by a microbubble, the momentum associated with the wave generates a primary radiation force. A microbubble driven at or near its resonant frequency experiences a far larger force and a resulting far greater displacement than other particles. We demonstrate that it is possible to displace a microbubble into contact with a vascular endothelium in vitro and therefore increase the binding efficiency of the targeted agents. We report first on the results of a theoretical evaluation of models for bubble oscillation and radiation force. The radial oscillation of a microbubble was determined using a previously developed model, and then displacement and translational velocity were predicted by solving the trajectory

equation of the microbubble. Parameter values were chosen to match our experimental settings and the results were compared with those from experiments. An experiment with an avidin-coated tube and biotin-targeted microbubbles clearly showed the effect of the radiation force on targeted agents in a 200-μm microvessel phantom. For controls without avidin on the tube, agents without biotin, or with targeted agents and vessels but without radiation force, very few agents were bound to the vessel wall. When radiation force was applied, a much larger number of microbubbles (over 20 fold) adhered to the wall. The binding efficiency decreased with increased flow rate or increased center frequency of the driving pulse. Experiments using endothelial cells grown within a vessel also demonstrated a 20-fold increase in binding for the targeted agent when radiation force was applied. Translational velocities determined by a high-speed camera system were in good agreement with those predicted by numerical evaluation, both on the order of mm/s for a driving pressure at approximately 14 kPa. An up to 25 dB increase in returned echo signal amplitude was observed with radiation force enhanced targeting over the case of no radiation force.
We would like to acknowledge the support of NIH R21 EB002952, NIH R21 CA980692, and NIH CA76062. Additionally we thank Terry O. Matsunaga and Patricia Schumann at ImaRx Therapeutics Inc. for providing MRX contrast agents.

Session: U2-J

INTRAVASCULAR IMAGING
Chair: H. Ermert
Ruhr University

U2-J-1 510BD 1:30 p.m.

INTRAVASCULAR ULTRASOUND TISSUE HARMONIC IMAGING IN VIVO

M. E. FRIJLINK*[1], D. E. GOERTZ[1,2], and A. F. W. VAN DER STEEN[1,2],
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Background Tissue Harmonic Imaging (THI) has been shown to increase the image quality of ultrasound images in conventional echocardiography, due in large part to the reduced effects of phase aberration, reverberation and sidelobe artefacts. In a previous study we showed initial results of THI of *in vitro* phantom experiments using a separate intravascular ultrasound (IVUS) transducer. An important application for IVUS is to improve the diagnosis of a diseased coronary artery. At present, mainly rotating single elements IVUS catheters at center frequencies of 30 and 40 MHz are used. In this study we measured the pressures and bandwidth of IVUS catheters, and performed THI with a conventional IVUS catheter in a phantom and in a rabbit aorta *in vivo*.

Methods Hydrophone measurements of IVUS catheters were performed. We assessed the fundamental (20 MHz) and second harmonic (40 MHz) pressure on axis of a Du-MED catheter (f_c 30 MHz) and measured the bandwidths of this Du-MED catheter and a currently clinically used Boston Scientific catheter (f_c 30 MHz) . An IVUS imaging system using a fast-rotating single element was constructed to do phantom experiments and perform *in vivo* imaging. To study the ability of a conventional IVUS catheter to generate the required fundamental pressure to build up a detectable level of propagation harmonics, a tissue mimicking phantom was used. We acquired 2400 RF-lines per rotation, with a rotation speed of five frames per second, in both fundamental (20 and 40 MHz) and harmonic (40 MHz) mode, allowing averaging of neighbouring lines. Finally, harmonic pulse inversion images were formed of cross sections (2400 lines per rotation) of the atherosclerotic aorta of a New Zealand White rabbit *in vivo*.

Results Fundamental peak pressures of up to 2.1 MPa were generated with the Du-MED IVUS catheter. The second harmonic in water built up to 0.25 MPa, corresponding to 18 dB below the fundamental peak pressure. The transmitted power at the second harmonic frequency was 45 dB below fundamental for all excitation voltages.The -6dB bandwidth of the Du-MED catheter was 15 MHz and of the Boston Scientific catheter 20 MHz. The phantom experiment data showed the feasibility of an IVUS catheter to generate and detect the propagation harmonic at 40 MHz. When averaging of 8 neighbouring RF-lines was applied, the harmonic signal to noise ratio (SNR) was about 16 dB. Using THI, we were able to create cross-sectional images of the rabbit aorta *in vivo*.

Conclusion This study shows that *in vivo* THI in IVUS applications is feasible with a conventional single element IVUS catheter.

Supported by STW and NWO

U2-J-2 510BD 1:45 p.m.

COMPUTERIZED SEGMENTATION OF BLOOD AND LUMINAL BORDERS IN INTRAVASCULAR ULTRASOUND

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Intravascular ultrasound (IVUS) provides detailed images of normal and abnormal coronary vessel wall morphology and can be used for measuring the lumen area and plaque burden. A prerequisite for this task is the reliable segmentation of IVUS images and discrimination of blood and tissue. However, at frequencies above 20 MHz the backscatter of blood can approach the same level as backscatter from the vessel wall, which turns the visual identification of blood into a difficult task. In addition, the high amount of data makes a system for automated segmentation strongly desirable. This work presents an automated scheme for the segmentation of blood in IVUS images. Based on the in vivo acquisition of radio frequency (RF) data, spectral parameters as well as first and second order texture parameters were evaluated and classified using neurofuzzy inference systems as higher order classifiers. In vivo acquisitions were

performed in the catheter laboratory during interventional procedures. Data was acquired with a Galaxy IVUS machine (Boston Scientific, CA), using 40 MHz single element transducers. Analog RF data was sampled at 100 MHz and 14 bit resolution with an A/D converter board (Gage 14100, Gage Applied, QC). Consecutive RF frames were stored during intervals of approximately 3 seconds. Tissue describing parameters were estimated directly from RF data after dividing each RF frame into numerous regions of interest to allow spatially resolved classification. Parameters originating from different parameter groups were compared with each other and a neuro-fuzzy inference system was trained on up to eight parameters to distinguish blood from tissue using a multifeature approach. This work presents a new robust approach for the segmentation of blood in IVUS images. The high center frequency (40 MHz) allows the evaluation of blood backscatter properties. The combined analysis of spectral and texture parameters provides an advantage over conventional gradient based segmentation techniques. The in vivo results of the multifeature classifier achieve classifications results of A>0.85 measured as the area under the ROC curve and thus prove the reliability of the presented method for the segmentation of blood and tissue in IVUS.
A project of the Ruhr Center of Excellence for Medical Engineering (KMR), funded by the German Federal Ministry of Education and Research (bmb+f grant No. 13N8079)

U2-J-3 510BD 2:00 p.m.

'BLIND' DATA CALIBRATION OF INTRAVASCULAR ULTRASOUND DATA FOR AUTOMATED TISSUE CHARACTERIZATION

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Coronary atherosclerosis continues to be a leading cause of death in the developed countries. However, the current clinical setting lacks adequate identification or characterization of unstable plaques. Spectral analysis of intravascular ultrasound (IVUS) signals has displayed accuracies over 85% in characterizing various atherosclerotic plaque components. This technique has been developed for in-vivo data analysis providing color-coded tissue maps of arterial-wall. However, current IVUS catheters vary in spectra calculated with data that is acquired from the same target. In a short study it was observed that the mean bandwidth at -6 dB was calculated to be 33% $\pm$ 6% of the fundamental frequency and the mean absolute difference at 30 MHz was 2.57 dB $\pm$ 1.75 dB, when only 5 IVUS catheters were used to image the same plexiglas cylinder. Such variation is detrimental to spectral analysis, thus, necessitating appropriate data calibration. Currently, the catheter transfer function (CTF) is calculated as the spectra of data from a plexiglass cylinder and data is normalized via inverse filtering (IF). This is possible in an experimental setup, but may not be feasible or time-efficient in the clinical environment. Blind deconvolution (BD), on

the other hand, is a method of data normalization when no estimate of CTF is available. Here the convolution model is computed blindly. This study aimed to assess BD for characterizing atherosclerotic tissue. BD is implemented with a recursive algorithm via an iterated window maximization method. In brief, if the common convolution product was to be modified as time-variant, it could be written such that the pulse shape depends on n and a fixed K where the CTF or $h(k,n) = 0$ for $k < 0$ and $k > K$ and $n=1,2,...N$, where $h(.,n)$ is the pulse shape due to a reflector at position n. Here, noise is assumed to be zero mean, Gaussian, white noise, denoted as measurement noise, that is not accounted for in this model. Finally, in order to obtain a computationally efficient solution, the pulse is assumed to be invariant on small intervals. In this study, data were collected ex-vivo from 61 coronary arteries, with 30 MHz IVUS in saline at physiologic pressure. Regions of interest (ROIs), selected from histology, comprised 115 fibrous (F), 63 fibro-lipidic (FL), 56 calcified (C) and 88 lipid-core (LC) regions. ROI spectra were calibrated after BD and compared to those previously reported with IF. Statistical classification schemes were computed with spectral parameters and were used to assess the accuracy of each calibration. The depth of each ROI was also recorded and included as a parameter in addition to the spectral information. Predictive accuracies of these classification schemes were 86.3%, 88.4%, 93.4% and 90.4% for F, FL, C and CN with the training data set and 72.8%, 77.8%, 82.7% and 75.3% with the remaining test data, respectively. The results were comparable to those previously acquired with IF. BD can be further optimized, improving calibration and decreasing computation time.
This work was supported by NIH Grants R01HL069094 and R01HL64686 awarded to DGV.

U2-J-4 510BD 2:15 p.m.

APPLICATION OF ULTRASONIC THERMAL IMAGING IN IVUS SYSTEMS

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The rupture of soft atherosclerotic (vulnerable) plaques in the arteries causes the vast majority of heart attacks. These plaques are characterized by large lipid pools covered by a thin fibrous cap. A new ultrasonic imaging method, ultrasonic thermal imaging, has been developed to estimate temporal strain from displacement images acquired under controlled heating, which has the potential to identify vulnerable arterial plaque. 1-D real-time measurements on tissue samples have demonstrated strong contrast between water-bearing and lipid-bearing tissue, at spatial resolutions of 300μm for a 10MHz transducer and 50μm for an 85MHz transducer. In this paper, we present results of applying this phase-sensitive, correlation-based technique to existing intravascular ultrasound (IVUS) imaging systems. Preliminary phantom experiments from a 10MHz catheter array indicate that thermal effects with a significant temperature rise can distinguish lipid-bearing from water-bearing tissue. Further simulations show good agreement with theoretical prediction and confirm the experimental observation. In practice, probe motion induced artificial strains

are generally comparable to measured temporal strains and thus have to be compensated. Because the lumen cross section of a severely occluded artery is not circular, all computations were performed in the reference frame of the lumens geometric center, which can be accurately estimated using echo signals from the closed lumen surface. Assuming small lumen deformation during data acquisition, this coordinate system is independent of the imaging catheter and consequently referencing to this frame removes artifacts associated with probe motion. Further improvement in tracking accuracy is accomplished by establishing a thermal fitting model. Specifically, we assume temporally uniform heating, i.e., a constant energy deposition rate. Consequently, temperature rise at each point follows a straight line and a least squared error method was employed to fit the computed displacements for each image pixel, resulting in substantial noise reduction. A 10MHz IVUS array was simulated to image peripheral arteries with vulnerable plaque. The array has a fractional bandwidth of 30% and is modeled as a confocal lens with f/number linearly increasing as a function of distance with aperture size equaling the instantaneous aperture of the experimental synthetic aperture system. The plaque was modeled as a 1.5mm thick cylinder against the artery with inner radius of 4.5mm. Given a 1°C temperature rise and 20dB electronic signal-to-noise ratio, the plaque can be resolved at 300μm spatial resolution. In the presence of maximally 200μm random probe motion during heating, the contrast-to-noise ratio (CNR) dropped from 4 to 0.13, leaving the plaque undetectable. Applying motion compensation increased CNR to 1. An additional gain of 1.6 in CNR was achieved using thermal fitting model. These results suggest that motion compensation and thermal fitting are valuable tools to move thermal imaging toward practical clinical applications for vulnerable plaque identification.
This work was supported by NIH grants HL-47401 and HL-67647.

U2-J-5 510BD 2:30 p.m.

INTRAVASCULAR ULTRASOUND PALPOGRAPHY FOR DETERMINING THE AGE OF A THROMBUS: AN ANIMAL STUDY IN VIVO

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Background Vulnerable plaques can lead to thrombus development, which may cause acute coronary syndrome. The age of a thrombus cannot be assessed in vivo with currently available imaging methods. It is well accepted that a thrombus stiffens over time, nevertheless nothing is known about the time course of this process especially in the very early phase of development. Palpography - an IVUS based technique that has been reported at this conference before- assesses the mechanical properties of biological tissue and can be used to measure the stiffness of thrombi in vivo. We hypothesize that the organization process in a thrombus starts early after introduction and that stiffness is increasing over time.

Methods In 7 anesthetic and surgical prepared pigs thrombus formation was introduced in both femoral arteries by applying electrical DC current (90 mA, 9V) to the outer vessel wall. The current caused a vessel injury with the signs of endothelial erosion. Over this erosion a thrombus was formed, which left a lumen through which the blood pressure could act as the driving force to strain the thrombus. Ten thrombi were formed, while in 4 cases the process failed. Before applying the current a 20 MHz phased array intravascular ultrasound catheter (Volcano) was introduced at the location where the thrombus was created. Radio-frequency (RF) data were acquired at 30 frames per second. Data were recorded at 6 time points after thrombus introduction (5, 20, 45, 75, 105, 180 min) Cross-correlation based analysis of the RF data revealed the radial strain of the luminal layer of the thrombus.

Results Initially thrombi are soft and stiffened dramatically in the first 20 minutes with a strain reduction of about 50%. The strain between frames in a thrombus decreased from (0.27 ± 0.16) at 5 minutes through (0.17 ± 0.10) at 20 minutes to (0.11 ± 0.10) after 45 minutes. Further stiffening took considerable more time, but could be observed towards the end of the experiment. The inverse relation between the time and strain over the first 3 hours is highly significant (R^2=0.59; $p < 0.0001$).

Conclusion This is the first time the in vivo development of a thrombus in an artery could be monitored with special emphasis on the organization of the thrombus. A vast parts of the organization process take place within 20 min after thrombus introduction.

This work is financially supported by the Dutch Technology Foundation (STW), the Dutch Science Foundation (NWO) and the Dutch Heart foundation (NHS).

U2-J-6 510BD 2:45 p.m.

ANALYSIS OF BLOOD CLOT FORMATION WITH TRANSIENT ELASTOGRAPHY: SIMILARITY WITH SOL-GEL TRANSITION IN AGAR-GELATIN PHANTOMS

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Blood coagulation plays an important role in many cardiovascular diseases, like atherosclerosis, heart stroke or deep vein thrombosis. The characterization of blood clot mechanical properties is fundamental in determining the appropriate treatment and for understanding the etiology of these pathologies. Recently, transient elastography has shown its efficiency to map the viscoelastic, anisotropic and non-linear properties of soft biological tissues. Here, transient elastography was used as a new rheological technique to recover the viscoelastic shear properties of blood during coagulation and to compare with sol-gel transition in Agar-gelatin phantoms. The 1D shear elasticity probe, composed of a single element 10 MHz ultrasonic transducer mounted on a vibrator, was

applied at the surface of each sample to record 400 echographic lines (at 2 kHz frequency rate). The shear waves were generated (100 Hz) by the front face of the transducer. The longitudinal component of the displacements along the ultrasonic beam was computed from a cross-correlation algorithm between successive ultrasonic signals stored in memory. From the displacement field, the inverse problem approach based on the wave equation was used to recover the shear elasticity (μ) and viscosity (η) of each medium. This method allowed to observe blood clot formation during coagulation. The experiments were performed on 60 ml pig blood samples anticoagulated with EDTA. The coagulation was initiated in vitro at a later time by adding an excess of calcium ions (0.05 g/ml). The elasticity and viscosity were recovered as a function of time (3 h). As shear waves do not propagate in fluid, the elasticity and viscosity assessment became evident at a precise time tg = 12 min (when the liquid blood becomes solid). This time varied by increasing the calcium ion concentration to 0.1 g/ml. From tg (where μB = 54.66 Pa and ηB = 0.33 Pa.s), the elasticity and viscosity evolved as a power-law as a function of time and reached a steady state, when the blood clot became mechanically stable (mB and hB at the plateau were 372.8 ± 36.9 Pa and 0.68 ± 0.05 Pa.s respectively). In addition, experiments were performed on Agar-gelatin phantoms. The sol-gel transition time tg was defined at 25 min (where μG = 48.72 Pa and ηG = 0.22 Pa.s). The variation pattern of both parameters was similar to blood and reached a maximum of 319.6 ± 28.4 Pa and 0.55 ± 0.05 Pa.s, respectively. The results are in good agreement with measurements found in the literature on gelatin mixture. The kinetic of Agar-gelatin gelation was analyzed in term of percolation regime near tg and in term of an homogeneous network far from tg. The analogy between the viscoelastic behavior of the phantoms as a function of time and that of blood clot formation is discussed and is shown to be very close.
This work was supported by grants from the Canadian Institutes of Health Research (# MOP - 36467) and Valorisation-Recherche Québec (structuring group program), and by a research scholarship award from the Fonds de la Recherche en Santé du Québec. The authors would like also to thank Jean Brochu for blood supply.

Session: U3-J

TRANSDUCER MATERIALS
Chair: S. Smith
GE Global Research

U3-J-1 511AB 1:30 p.m.

FERROELECTRETS: HIGHLY ANISOTROPIC ELECTRICALLY CHARGED POLYMER FOAMS FOR ELECTROMECHANICAL TRANSDUCER APPLICATIONS

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Ferroelectrets are anisotropic voided space-charge electrets with internally trapped charges. On ferroelectrets made e.g. from cellular polypropylene, strong electromechanical activity was found. Ferroelectrets are thus promising as active materials for numerous transducer applications, in particular in microphones, headphones and loudspeakers. Typically, ferroelectret foams contain lens-like voids with a length of several ten μm and a width on the order of a few μm to some ten μm. Application of suitable electric fields to such foams leads to mircodischarges inside the voids, accompanied by electroluminescence, to charge separation and finally to charge trapping at the inner void surfaces. The charge layers constitute large (macroscopic) dipoles whose size ("length") is easily changed by an applied mechanical stress or an applied electric field. In ferroelectrets, the symmetry breaking occurs thus on a macroscopic scale, and the change of the dipole size itself is the reason for the strong electromechanical activity. That mechanism distinguishes ferroelectrets from ferroelectric polymers, where the symmetry breaking usually occurs on the microscopic scale, due to the re-orientation of molecular dipoles or domains, and the electromechanical effect is typically caused by a change of the dipole density. From a macroscopic point of view, however, the properties of ferroelectrets are comparable with those of ferroelectrics, but from a microscopic point of view, the physical origin of the very similar effects is completely different. Here, we discuss the preparation and characterization of ferroelectretic cellular polypropylene foams as well as first modelling steps for the mechanical properties of anisotropic foams. The foams itself as well as their electric charging were optimized with respect to the resulting electromechanical activity. By means of controlled void inflation, the resulting dipole size is varied over a broad range. This will also change the mechanical properties, and ferroelectret foams with elastic moduli between 1 and 15 MPa can be prepared. Cellular polypropylene foams with transducer coefficients from 15 to around 500 pC/N, electromechanical coupling factors between 0.02 and 0.1 and thickness-extension resonance frequencies from 500 kHz to 2 MHz were achieved. Last, but not least, we discuss applications-relevant acoustic properties of cellular polypropylene films, such as measured sound-pressure levels of ferroelectret films used as actuators. Relatively flat frequency responses of the sound-pressure were observed, which makes the polymer films attractive also for applications in the so-called super-audio frequency range.

U3-J-2 511AB 1:45 p.m.

FERROELECTRETS: ULTRASONIC TRANSDUCER FOR A BIOMIMETIC SONAR SYSTEM

A. STREICHER*[1], M. KALTENBACHER[1], R. MÜLLER[2], H. PEREMANS[3], and R. LERCH[1], [1]Department of Sensor Technology, [2]Maersk Institute , [3]Antwerp-University Faculty St. Ignatius.
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Inspired by the bat's use of ultrasound as an adequate substitute for vision the CIRCE* (Chiroptera Inspired Robotic CEphaloid) project is building a robotic reproduction of a complete bio sonar system. In order to investigate the sound

as produced by a wide variety of bat species, the transducers for the artificial bat head have to operate at a bandwidth of 20 - 200 kHz and have to match sensitivity (receiver), transmit efficiency (transmitter) as well as the overall insertion loss of living bats. With a resonance-frequency of 300 kHz in thickness mode and a piezoelectric constant d_{33} up to 800 pC/N, a new type of cellular polymer film called ferroelectrets meets these requirements. With this material, a two layer ultrasonic stack transmitter with a diameter of 1.5 cm was developed for emitting a chirp signal with a sound pressure level of more than 90 dB in a distance of 1m. Compared to a single layer transmitter, the resonance frequency of an two layer stack actuator is shifted down to 100 kHz. This frequency shift enables the transmitter half-power bandwidth to be in the range of 30 - 200 kHz. With the same material, an ultrasonic receiver with a diameter of 1cm was designed. The ferroelectric material in combination with a special pre-amplifier allows an equivalent acoustic noise level of 50 dB and a sensitivity of 20mV/Pa. This sensor matches the bandwidth of the transmitter. In addition we investigate the nonlinear acoustic behaviour of the ferroelectric material by applying 3D finite element simulations of various transducer designs. Therewith, we fully solve the piezoelectric partial differential equations including the complex geometric structure of cellular ferroelectric films. In our talk, we will discuss the measurement results for various designs of transmitters and receivers as well as corresponding simulation results.
(Supported by European Commission, LPS Initiative)

U3-J-3 511AB 2:00 p.m.

SEMI-QUANTITATIVE PIEZOELECTRIC ACTIVITY TESTING IN POLYMER LAYERS

C. BROX NILSEN*, C. GREGORY, and J. HATFIELD, University of Manchester Institute of Science and Technology.
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A technique has been developed for measuring output voltages in piezopolymer layers such as polyvinylidene fluoride (PVdF). This technique can be used for comparing piezoelectric polymer layer responses and investigate how changes in manufacture can affect the output voltage of the layers. The method can quickly measure the output voltages as response to pressure waves in a large number of samples and the result of each sample can be seen immediately. The test equipment consists of an ultrasound transmitter with a build in time delay layer with a metal contact under it and a Perspex layer with a metal contact placed below the transmitter. Both the delay layer and receiver have fixed sized metal contacts. The piezoelectric polymer layer to be tested is placed and clamped between the metal contacts on the delay layer on transmitter and the Perspex layer. An ultrasonic pulse wave from the transmitter deforms the clamped piezoelectric polymer sample with a time delay, which then produces a voltage pulse that can be measured by connecting an oscilloscope to the metal contacts. To ensure that the testing is reproducible for all the samples, the area of the metal layers are of fixed size and the tested sample is clamped between the

metal layers with a fixed pressure as it is forced together with two contraction springs. A simple lever arrangement enables the sample to be clamped with great ease. The technique must be seen as semi-quantitative as the values of the output voltage would be different if the area of the metal contacts in the transducers were different. The same applies for the pressure caused by the springs to clamp the sample. These variables along with several others have not been optimised for the transducers to produce the highest output voltage, but this has been sacrificed to make the tester both easy and quick to use. As this measuring technique is reproducible for all the samples, it works very well for comparing layers. When developing ultrasonic layer fabrication techniques it is very useful to see if a given change improves the output voltage.

U3-J-4 511AB 2:15 p.m.

PIEZOELECTRIC MATERIAL NONLINEARITY IDENTIFICATION WITH A MULTIHARMONIC FINITE ELEMENT METHOD

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In the design of piezoelectric devices, numerical simulation plays an increasingly important role. Finite element methods allow for the precise modeling of transducers, including even nonlinear effects, as they typically occur in the large signal behavior. For this purpose, knowledge of the elastic stiffness coefficients, the dielectric coefficients and the piezoelectric coefficients in dependence of the electric field and/or the mechanical strain is required. These material parameters cannot be obtained directly via the IEEE standard 176-1987 in the nonlinear situation, though. Therefore, we present a numerical identification scheme that automatically fits the material parameters according to a comparison of numerical simulations of the full transducer with voltage–current measurements (see [1]) for material parameter identification in a transient formulation. On one hand the used measurements suggest a formulation of the problem in frequency space. On the other hand, even at excitation with fixed frequency, higher harmonics come into play due to the nonlinearity, thus preventing a purely harmonic behaviour of the electric potential and the mechanical displacement. Therefore, we make a so-called multiharmonic Ansatz for these quantities in the piezoelectric system of partial differential equations describing the transducer. The material parameter functions are approximated by polynomials, which allows for considerable simplifications in the formulation. Using Newton's method for successively reducing the misfit between measured and simulated data, we arrive at enhanced data of the searched for material parameters.

Applicability of the proposed methodology is demonstrated by reconstructions of nonlinear parameter curves for several different piezoelectric ceramics. Therewith, for the first time, elastic stiffness coefficients, dielectric coefficients and piezoelectric coefficients in dependence of the electric field strength can

be obtained from voltage–current measurements. A set of nonlinear material parameters for Pz27 (Ferroperm Piezoceramics A/S) is presented.

[1] B.Kaltenbacher, M.Hofer, M.Kaltenbacher, and R.Lerch: Identification of Material Nonlinearities in Piezoelectric Ceramics. In: Proceedings of the IEEE Ultrasonics Symposium 2003, pages 358-361. IEEE, 2003.

U3-J-5 511AB 2:30 p.m.

NEW LOW ACOUSTIC IMPEDANCE PIEZOELECTRIC MATERIAL FOR BROADBAND TRANSDUCER APPLICATIONS

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This paper describes a new ceramic-air piezocomposite material, i.e. porous piezoceramic based on a soft PZT matrix. First, the main processing steps are given, the microstructure is analyzed and the electromechanical parameters are measured, in particular dielectric constant and losses, acoustic wave velocity and mechanical losses, acoustical impedance and thickness mode electromechanical coupling factor. Frequency dependence of these parameters is investigated experimentally [1] using complex impedance measurements at fundamental and harmonic frequencies of the free thickness resonance mode. A significant increase of mechanical losses with frequency is observed, as well as a slight decrease of thickness coupling factor. The composite is then modeled using unit-cell and diffusion approaches [2], and the theoretical results are compared to measurements. The effective connectivity of the composite is investigated through the use of both 3-3 and 3-0 connectivity models, and by microstructure image analysis. Theoretical results are given for porosity volume fractions from 0 to 50% and then compared to measurements on a few samples with different porosity values. It is shown that the air trapped in the ceramic matrix allows a decrease of acoustic impedance by a factor 2 to be achieved in comparison with classical bulk PZT, the electromechanical coupling factors and dielectric constants being close to those of commercial piezoceramics used for ultrasonic transducer applications, namely thickness coupling factor around 50%. Porosity values around 30% are found to offer the best compromise in terms of functional properties and ease of fabrication. Finally, different transducer designs are considered, namely NDE and medical diagnostic probes. The overall performance, sensitivity, bandwidth and electrical impedance of transducers based on this new material are compared to those of bulk PZT based devices. These results demonstrate that when high bandwidth is the main requirement, the new material is particularly well adapted. Finally, the effects of frequency dependence of electromechanical parameters and of internal structure of the material on transducer operation and fabrication process are investigated, and frequency limits are determined. In conclusion it is shown that, due to a

much better acoustic matching to fluids, this composite material is particularly well adapted to applications such as high resolution immersion NDE and medical imaging in the low to mid-frequency range (up to around 10 MHz), underwater acoustics and flow measurements.

1. Comparison of several methods to characterize the high frequency behavior of piezoelectric ceramics for transducer applications by L.P. Tran-Huu-Hue et al. in Ultrasonics 38 (2000) 219-223. 2. Effective electroelastic moduli of 3-3(0-3) piezocomposites by F. Levassort et al. in IEEE Trans. UFFC 46 (1999) 1028-1034.

U3-J-6 511AB 2:45 p.m.

PIEZOELECTRIC CERAMICS WITH HIGH DIELECTRIC CONSTANTS FOR ULTRASONIC MEDICAL TRANSDUCERS

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Complex system ceramics $Pb(Sc_{1/2}Nb_{1/2})$ O_3-$Pb(Mg_{1/3}Nb_{2/3})$ O_3-$Pb(Ni_{1/2}$ $Nb_{1/2})$ O_3-Pb(Zr, Ti) O_3 (PSN-PMN-PNN-PZT) have been synthesized by the conventional technique and the dielectric and piezoelectric properties of the ceramics have been investigated for ultrasonic medical transducers. Recently a large channel numbers of medical array probes and two dimensional array (2D) probes for volumetric imaging attract a big interest because they can bring possibility of data acquisition and visualization in real time. These array probes consist of a large number of small transducer elements with an area of less than 1.0 mm^2. Therefore, high capacitances of the transducers are desired to lower electrical impedances. Although high dielectric constants ($\epsilon_{33}{}^T/\epsilon_0$) type PZT ceramics which have high dielectric constants and coupling factor sliver mode ($\epsilon_{33}{}^T/\epsilon_0$>5,000, $\epsilon_{33}{}^S/\epsilon_0$>2,000, k_{33}'<65%) are produced in many manufactures, the dielectric constants of PZT ceramics are still insufficient for the small size array transducers. On the other hand, we have reported that low molecular mass B-site ions in the lead-perovskite structures are important to realize better dielectric and piezoelectric properties. We focused on the complex system ceramics PSN-PMN-PNN-PZT which consist of light B-site elements. The maximum dielectric constants, $\epsilon_{33}{}^T/\epsilon_0$=7,000 and $\epsilon_{33}{}^S/\epsilon_0$=3,200 were confirmed at, where k_{33}'=69%, d_{33}=820 pC/N and T_c=135 °C were obtained. Pulse echo characteristics were simulated using the Mason model. The high-$\epsilon_{33}{}^T/\epsilon_0$ typed typed ceramic probe showed that about 6dB higher in the echo amplitude comparing to those of the conventional PZT ceramic probe (PZT-5H). In this presentation, electrical properties of the PSN-PMN-PNN-PZT ceramics and performance of phased array probe using the high-$\epsilon_{33}{}^T/\epsilon_0$ typed ceramic will be introduced.

Session: U4-J
ULTRASONIC MOTORS AND ACTUATORS
Chair: T. Maeno
Keio University

U4-J-1 513AB 1:30 p.m.

A NOVEL APPROACH FOR HIGH POWER ULTRASONIC LINEAR MOTORS

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Several positioning tasks demand translatory drive instead of rotary motion. Classically, rotary motors with gears and spindle-mechanisms are used that for. In means of miniaturization and weight reduction new solutions have to be found. One possible approach are translatory direct drives. Conventional electromagnetic linear motors are often disadvantageous because of their volume, weight, producing electromagnetic noise and missing holding force at power-off. A rather new solution are piezoelectric linear drives, but today their power is sufficient only for a strongly limited field of applications. The overall trend is to minimize their production cost as well as their size and thereby it is impossible to reach the needed higher mechanical output.

To achieve drives that are capable e. g. to drive the sunroof of a car or to lift a car's window, multiple miniaturized motors can be combined. But in this case many other questions arise: The electromechanical behaviour of the individual motors differs slightly due to manufacturing and assembly tolerances. The individual motor characteristics are strongly dependent on the driving parameters (frequency, voltage, temperature, pre-stress, etc.) and the driven load. Many applications, e.g. the drive of a sunroof, need some extra-power for special cases like overcoming periodical higher forces (e.g. driving into sealings). Thus, the bundle of motors has to act well organized and at last controlled to get an optimized drive that is not oversized and costly.

Our contribution will be divided into three main parts. Part I describes a novel miniaturized ultrasonic piezoelectric linear motor with a very simple mechanical structure, which can be produced at very low costs. Experimental data will show the characteristics of a single motor. In part II a simplified model for the motor's electromechanical behaviour will be given, that includes effects of parameter deviation, load dependency and the like. In part III control strategies for a single motor as well as for a bundle of motors will be presented.

U4-J-2   513AB   1:45 p.m.

AN ULTRASONIC LINEAR MOTOR USING A RIDGE WAVEGUIDE

M. TOMINAGA*, J. R. FRIEND, R. KAMINAGA, K. NAKAMURA, and S. UEHA, Precision and intelligence Laboratory, Tokyo Insutitute of Technology.
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For the telecommunications industry, multiplexed optical switching remains difficult and is a current topic of study, with most commercial devices using MEMS electrostatic comb actuators. We propose the development of an ultrasonic motor using a traveling wave generated along a ridge waveguide as one method to address current devices' shortcomings. The ridge waveguide,simply a rectangular prismatic projection from a flat substrate, along which waves propagate ultrasonically, may be fabricated alongside other microcomponents as a part of an integrated MEMS device for optical communication. At any point along the waveguide, the traveling-wave vibration is elliptically polarized and will push a slider placed on the waveguide through friction. The use of a flexural waveguide mode enables us to fabricate the ultrasonic linear motor on a substrate alongside other MEMS devices. This study presents three different methods to excite a traveling wave along the ridge waveguide. In the first version, acrylic, which has a large vibration attenuation, was used for a relatively large rectangular waveguide, at 5 mm in width, 15 mm in height, and 500 mm in length. A traveling wave at 21.7 kHz was successfully generated using a single Langevin transducer attached perpendicularly to the waveguide, transmitting standing-wave vibration energy into the waveguide, progressively attenuated and turned into a traveling-wave along the waveguide's length. The wavelength was 28.2 mm, a vibration velocity of 108 mm/s was obtained along the top of the waveguide,and, using a bronze slider placed on the waveguide, a sliding velocity of 33 mm/s was achieved. In the second configuration, a traveling wave was generated at 81.5 kHz by a Langevin transducer attached perpendicularly to a low-loss aluminum ridge waveguide 3 mm wide, 6 mm in height, and 130 mm long; transmitted along the waveguide's length; and absorbed in a viscoelastic terminator. The standing wave ratio, wavelength, and peak vibration velocity of the traveling wave were 2.7, 23.0 mm, and 110 mm/sec, respectively. A slider velocity of 90 mm/s was achieved in this configuration. In the third configuration, two Langevin transducers were attached at either end of the aluminum ridge waveguide from the previous setup, using a phase difference between the drive signals of the transducers to generate a flexural traveling wave along the ridge at 78.5 kHz, the propagation direction of which could be switched via phase control. At an input-signal phase difference of 60 degrees, a traveling wave with a standing wave ratio of 1.96 was achieved. Reversing the traveling-wave/sliding direction, a standing wave ratio of 1.5 was measured at a phase difference of 320 degrees. A slider velocity of 103 mm/s was achieved in either direction. We finish with discussion and early results on miniaturization of this technology to be applied for optical switching, and compare it with current

technology. In particular, the unlimited stroke of the proposed actuator and the flexibility in material choice in its construction will be emphasized.

U4-J-3 513AB 2:00 p.m.

ANALYSIS OF BIDIRECTIONAL VIBRATIONAL TRANSPORT OF SMALL OBJECTS BY PERIODIC WAVE TRAINS OF PULSES

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Travelling-wave transport of small particles or droplets is a promising principle to create biochips that are a broad class of new programmable microdevices capable, as is expected, to give rise to revolutionary changes in tools of modern medicine, molecular biology, micro- and nanochemistry. The aim of the present study is to develop a simple and general theory of the vibrational transport of small objects by periodic travelling-wave pulses, thus providing a new insight into the basic features and principles of such interaction. The theory may be applied to waves of various nature, although the acoustic transport is in the focus of the research. As a motive force for transporting small objects, we consider the combined effect of electric fields upon a charged object and sliding friction. The first mentioned force arises near the surface of piezoelectric substrates with travelling acoustic waves. The inclusion of such a force into consideration is of interest, in particularly, to investigate possibility to implement a new kind of particle-wave interaction, being suggested by us, in the form of "dielectrophoresis with acoustic drive" (recall that dielectrophoresis is used in medicine and microbiology for separating cells with different properties). In the simplest variant of the model under study, the equation of motion for a wave-driven particle is integrated exactly. Using such an exact solution, we show that the rigorous account of a finite value of the wave propagation velocity produces only a small change in the solution, which is obtained by ignoring the coordinate dependence of the wave phase. This allows us to neglect this dependence in more complicated cases or alternatively to use the perturbation theory. We found that a progressive transport of small objects by wave pulses is possible even in the case of zero time-averaged force on the object, that is, in the linear mode of operation. The direction of transport may be both forward and backward with respect to the direction of wave propagation. It is determined by the phase of carrier wave with respect to the beginning of a square wave pulse and so it can be easily changed by switching polarity of the driving pulse. A simple qualitative explanation of these properties is suggested. These our results are in agreement with the theory of dielectrophoresis and the numerical finding by Gartstein and Shaw (1999) who studied "electrostatic wave" transport. For objects driven by shear-horizontal elastic waves (Love waves, Bleustein-Gulyaev waves, SH-modes of plates), transport via sliding friction may occur in the lateral direction. The effect of friction as a deceleration factor leads to a fast violation of the optimal

relationship between the phase of carrier wave and the beginning of pulse. This in turn restricts the length of the wave pulses to obtain useful result. Alternative pulse shapes which fall and rise more gradually are studied and optimal combinations of their parameters are determined.

U4-J-4   513AB   2:15 p.m.

ANALYTICAL AND NUMERICAL MODELING OF AN ULTRASONIC STEPPING MOTOR USING STANDING WAVES

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Piezoelectric motors (usually called ultrasonic) show interesting characteristics, in particular in precise positioning applications, since their large output torque provides a quick response and their structure confers to them a braking force, without energy consumption, which is relatively high. Thus, this paper presents the analysis of an ultrasonic stepping motor using standing waves to create the stator vibration. Initially, the working principle of this type of motor is described. It is based on the phenomena that a tooth of the rotor, pressed against the vibrating stator through a prestressing force, will move to the nodal position of the vibration mode and then will stay there. The structure chosen is a ring where several standing waves are excited one after another to obtain the motion of the rotor. Specifications like the number N of steps (about 300-400), the output torque (20 mNm) and the time t to carry out a step (about 20 ms) are then considered to build an analytical model of the motor in order to be able to characterize the position, speed and torque, according to the selected parameters (results obtained with Matlab). Strategy of modeling is based on the hypothesis that there are a lot of small leaps at the interface between the stator and the rotor and this is the phenomenon taken into account in our study to obtain the characteristics of the motor.

Based on these considerations, the analytical model is then validated by finite element simulations. The different modes of vibration of the motor will be carried out with the aim of determining the resonance frequency of the system for the selected mode. Transient and steady-state responses of the system are obtained. As a function of the voltage applied to the piezoelectric ceramics, the deformation amplitude of the stator is achieved. In addition to these numerical analyses, some practical results on prototypes are presented. Two different stator configurations are observed. Measurements are realized through Speckle interferometry and also with a vibrometer laser. Results obtained show the different modes of vibration of the stator and also allow to determine which is the resonance frequency of the most interesting mode. For example, a n=10 modes vibrating stator and vibration amplitude of 0.11 μm are achieved for a resonance frequency of about 19.7 kHz and a voltage input of 80 V. In parallel, the admittance (amplitude and phase) of the vibrating body is measured by

an impedance analyzer and the results obtained are compared with the FEM simulations and also with the measurements by interferometry. Good agreement between simulation and practical results will then make it possible to validate the analytical model and show if the hypotheses made at the beginning match with the reality. At the end, feasibility and characteristics of such a motor will be discussed.

U4-J-5 513AB 2:30 p.m.

PRECISE POSITION CONTROL OF ULTRASONIC MOTOR USING FUZZY CONTROLLER

H. LI*[1], C. GU[2], and C. ZHAO[1], [1]Nanjing University of Aeronautics and Astronautics, [2]Huazhong University of Science and Technology.
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The features that ultrasonic motors (USMs) can operate in low speed range and lacking a brake, are useful for utilizing as gearless actuators or direct servo drives. Because the USM has a heavy non-linearity and time-varying characteristic, which varies with driving conditions and possesses variable dead-zone with the input voltage, which are problems as an accurate positioning actuator for industrial applications. Therefore, it is important to compensate the non-linearity and time-varying characteristic in order to improve the control performance. A precise position control scheme for ultrasonic motor using fuzzy controller to control the phase difference of the voltages is presented, the principle and construction of the fuzzy-controller is analyzed, and the design method is proposed in this paper. Experimental results validate the proposed scheme. The fuzzy control system for USM is a numberical controller, which utilizing fuzzy set theory and fuzzy reasoning, and it is not necessary to use the mathematical model of the motor, but the determination of inference rules relies on the operator's experience. The system has two inputs: one is the error, which is obtained by comparing the difference from the position command and the actual position obtained by a rotary encoder, which has a resolution of 2500P/R, and other is the rate of the change of the error, and a certain phase difference Φ between the output voltages as the output to drive the motor. The core of the system is a fuzzy controller, which consists of three parts:1)Conversing the actual input to fuzzy quantity (fuzzification);2)Making fuzzy decision by inference rules according to the input;3)Conversing the gained fuzzy decision to accurate controlled quantity (defuzzification).The value of the error is divided into 8 classes: NL, NM, NS, NO, PO, PS, PM, PL, and represented as A. The values of the rate of the change and Φ are divided into 7 classes: NL, NM, NS, O, PS, PM, PL, and represented as B and C respectively. The fuzzy control rules are adopted as a table .The proposed control system is digitally implemented by a DSP (TMS320F240) based microcontroller.The actual value Φ is obtained by the defuzzification of subset C.

This work is sponsored by Key Project of National Natural Science Foundation of China (Project No. 50235010) and National 863 High Tech Space Project(863-2-2-4-6B).

U4-J-6 513AB 2:45 p.m.

DEVELOPMENT OF AN ARRAYED-TYPE MULTI-DEGREE-OF-FREEDOM ULTRASONIC MOTOR BASED ON A SELECTION OF RECIPROCATING VIBRATION MODES

K. OTOKAWA*[1], K. TAKEMURA[2], and T. MAENO[1], [1]Keio University, [2]Tokyo Institute of Technology.
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This paper presents a novel type of multi-degree-of-freedom (MDOF) ultrasonic motor. In recent years, ultrasonic motors are attracting attention as a new type of actuator well suited for MDOF actuation. Ultrasonic motors can be divided into two types, either driven by a single phase and by dual phases. Ultrasonic motors driven by a single phase are easier to downsize and have simpler form than those driven by dual phases, because plural frequencies must correspond to each other completely. However, a single ultrasonic motor driven by a single phase cannot generate MDOF movement. Hence, we propose of a MDOF ultrasonic motor composed of plural vibrators driven by a single phase. First, its principles and structure are designed. This motor has a spherical rotor and four vibrators that are each driven by an independent single vibration mode. Therefore, coupling frequencies and reprocessing is unnecessary. Each vibrator has three patterns of vibration modes that can be changed by adjusting the frequencies (it is 22.048 kHz, 31.106 kHz and 86.252 kHz). The rotor is driven by the total frictional force generated by the four vibrators. The rotor may rotate on three axes by combining different vibration modes. Secondly, we decided the form of the vibrators, the position of protrusions, the layout of the piezoelectric ceramic (PZT) and excitation methods through FEM analysis. Then, we manufactured the motor and confirmed that the rotor could rotate on three axes. Experiments were thus conducted to measure the driving characteristics of the motor. The maximum torque of the rotation on the x-axis was about 15 mN-m. Considering principles of the developed ultrasonic motor, which is driven by rectilinear reciprocating vibration, this result seems to be relatively good. As a result, we developed a novel type of MDOF ultrasonic motor driven by a single phase, which can rotate a spherical rotor on three axes. In the future, this ultrasonic motor will be miniaturized and be able to generate higher torque. The developed ultrasonic motor offers a wide range of applications. The form of the vibrator and rotor is changeable. In addition, it is availableness for miniaturization because of its simple form. And it is cheap to manufacture and easy to manufacture. In the future, this motor may be used for a number of applications, such as adjusting the lens on cameras, and joints of robot arms.
This study was supported in part by Grant-in-Aid for Encouragement of Young Scientists (B) 15760093 of the Ministry of Education, Culture, Sports, Science and Technology of Japan. Authors also would like to thank the staff of Canon Inc. for their help in manufacturing the vibrators and PZT.

Session: U5-J

NDE
Chair: R. Maev
University of Windsor

U5-J-1 512C-H 1:30 p.m.
(Invited)

ULTRASONIC TOMOGRAPHY - APPLICATION TO THE VISUALIZATION OF AIR FLOWS

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In the case of very small acoustic impedance variations in a medium, the imaging of these variations cannot be performed by echography. On the other hand, the transmitted signals may be sufficiently sensitive to these variations to allow the extraction of information about the medium. If the amplitude and time of arrival of the transmitted signals through an air flow can be determined with sufficient accuracy, this information can be used to make images. As these parameters of each individual transmitted signal are the result of the whole history of the acoustic ray along its path, an inversion procedure must be performed. Tomography is achieved by the use of multiple acoustic paths networking the area of investigation. The different inversion methods and their tractability in air flow visualization are discussed. Tomography requires a very precise determination of the amplitude and time of arrival of the acoustical signal. Although piezoelectric transducers provide easily this level of precision when used in immersion in liquids, their use is notoriously difficult when used in air where the huge impedance mismatch requires high excitation voltages and high amplification particularly when pulse mode is used. Furthermore the emitting surface of those transducers must be fairly large in order to launch enough energy. This induces a high directivity impairing their use as a source emitting towards many receivers. To solve the problem, we have developed spark emitters that appear to be particularly well suited to tomography in air. Very stable acoustic pulses, with a wide frequency band (audio frequencies to 1MHz) are generated. The effective bandwidth in a given experiment is then only limited by the attenuation in air. In the stated frequency range, the sources are highly non directive due to the cylindrical symmetry and the small size (few millimeters) of the sound emitting zone. Small-radius capacitive microphones are used as receivers. Emitters and receivers are placed on a rotating wheel. 1200 (for 2D imaging) or 2400 (for 3D) acoustic paths are recorded in a tomography experiment. Stationary components of the velocity and turbulence in the flow fields are obtained using an iterative algorithm and displayed as images. The pixel resolution size is a few centimeters for an investigation zone with a 1.8 m diameter size. Theoretical aspects and the assumptions made are fully discussed.

U5-J-2 512C-H 2:00 p.m.

OPERATING PRINCIPLES OF THE MONOLITHIC CYLINDER GYROSCOPE

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This work outlines the operating principles, design and fabrication of the monolithic cylinder piezoelectric gyroscope. The cylinder gyro is closed at one end and open at the other, the closed end providing a means of attaching the gyro to the supporting structure. The vibrating body is made of Lead Zirconate Titanate and it provides the drive and detection mechanisms via eight electrodes deposited on the surface of the cylinder. A periodic voltage with correct phase applied to driving electrodes drive the cylinder into resonant vibration via piezoelectric action (Primary motion). If the cylinder starts to rotate about its main axis a secondary motion will be produced by Coriolis inertia forces. The Primary and secondary motions of the cylinder are coupled through rigid body rotation about the central axis. The value of the voltage generated at secondary motion electrodes can be measured as an applied rate of turn.The monolithic piezoceramic cylinder is constructed entirely from PZT material and their operation is discussed both theoretically and experimentally. The performance of the prototype gyro under constant and transient angular rates of turn has been tested. The gyro responded very well to fast changes and showed good linearity output up to 800 Deg/Sec. The experimental results showed the potential of this type of sensor as a low cost and fast response gyroscope with application in many areas such as: guided weapons, automotive, navigation , robotics and aerospace.
I would like to thank Prof. J.S. Burdess for his contribution toward this work during 1986-1989 at the Newcastle University.

U5-J-3 512C-H 2:15 p.m.

PRECISION ULTRASONIC MICROMETER POSITION INDICATOR WITH TEMPERATURE COMPENSATION

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This paper discusses a novel ultrasonic system for high precision relative position monitoring. An innovative combination of existing signal processing techniques was implemented to facilitate an accurate, efficient, and automated digital algorithm. A method was derived for physical compensation of temperature dependant water velocity through the design and use of a two-tiered target. A leave-in-place, couplant-free transducer was designed and fabricated for use at elevated temperatures, the details of which will be discussed in presentation form. A prototype was developed according to ultrasonic wave propagation principles in order to produce multiple roundtrip reflections from a water immersed target. The digital automated processing includes gate tracking algorithms, reference correlations, and Hilbert transformed envelopes which helped facilitate a phase

stability of 1-3 ns. This type of phase stability allowed for a precision of $\lambda/150$ (1 μm at 10 MHz) in relative target positioning. Analysis was conducted at 23^{0}C and 77^{0}C with velocity measurements taken over this range in order to qualify the systems capability of position indication at elevated temperatures. Repeated target movements on the order of 100 μm were measured with approximately 0.1% mean square deviation from average over a displacement range of 1 mm at both temperatures.

U5-J-4 512C-H 2:30 p.m.

ON THE SENSITIVITY OF CORROSION AND FATIGUE DAMAGE DETECTION USING GUIDED ULTRASONIC WAVES

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Technical machinery and systems are subject to varying or cyclic service loads and environmental influences, like adverse weather conditions. Such operation conditions can lead to the development of faults during the lifecycle of the structure, e.g., fatigue cracks and severe corrosion damage in offshore oil platforms and ship hulls. This damage can lead to malfunction and ultimately failure, endangering lives and the environment. The corrosion damage often appears as large area thickness reduction in the vicinity of frames, stiffeners, and welds on the hull, while fatigue cracks develop in areas of stress concentration. An important problem for the monitoring of the integrity of such structures using non-destructive testing (NDT) methods is the accessibility of critical areas, e.g., the space between the plates of a double-hull tanker.

Fast inspection of large areas of plate-like structures can be achieved employing guided ultrasonic waves. Guided ultrasonic wave testing often utilizes a lower frequency region than standard ultrasonic testing (UT), usually in the order of several hundred kHz. The excited wave has a mode shape through the thickness of the structure and can propagate over large distances along the structure. Such measurements have been successfully performed on pipelines, where propagation distances of up to hundreds of meters were realized. This allows the fast and cost-efficient monitoring of difficult-to-access structures from a single sensor location.

The sensitivity of the measurement method to typical structural defects is studied experimentally and theoretically. The reflection and mode conversion of the employed guided ultrasonic wave at model defects and structural features is calculated numerically employing a three-dimensional finite element code and verified in laboratory experiments. Corrosion damage often results in large area thickness reduction and is modelled as a circular part-through hole. The scattering and mode conversion of the first antisymmetric wave mode A0 at such defects is studied. Good agreement with measurement results in the laboratory is found and the sensitivity of the guided wave measurement to such a kind of defect can be predicted.

For the practical long-term monitoring of structural integrity, a permanently attached guided ultrasonic wave array prototype has been designed and built. The array consists of a ring of piezoelectric transducer elements for excitation and reception of the guided wave. The development of the compact array device for the inspection of large areas, array operation, and data processing schemes are described, and measurement results shown.

U5-J-5 512C-H 2:45 p.m.

NONLINEAR INTERACTION OF ULTRASOUND WITH AN UNBOUNDED ROUGH INTERFACE

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Kissing bonds are one of the specific flaw types in friction stir welds and, in many cases, they are difficult to detect using linear ultrasound. Under the insonification of intensive ultrasound, however, they show nonlinear behavior. This nonlinearity has been exploited to detect such deficient bonds. A kissing bond can be treated as an imperfect interface between rough surfaces in contact (an imperfect rough interface). Motivated by the practical problem, a theoretical model has been developed for the nonlinear interaction of ultrasound with an imperfect rough planar interface. The model is established based on elastodynamic theory. It is a first-order differential equation governing the relation between the interface opening (or thickness) and the ultrasonic (dynamic) force. The relation in general is nonlinear, but it is easy to implement numerically. The solution to the equation is the interface opening, a function of time directly related to the transmitted and reflected nonlinear waves from the interface. The model can be used to deal with various planar interfaces, like smooth interfaces, rough interfaces with either linear or nonlinear relation between Hertzian contact force and interface opening, and rough interfaces with a hysteretic response to ultrasonic load. For smooth interfaces, rough interfaces with linear relation between Hertzian contact force and interface opening, and rough interfaces with piecewise linear bistability (causing hyteresis), the analytical solutions are available. The proposed model has also been applied to the prediction of the experimental data from Barnard's work [1] for a single interface that was made by compressing two aluminum cylinders together. The results show that it gives a better prediction than the Richardson's theory [2] (for predicting the nonlinearity from a smooth interface) that gives the overestimated amplitude ratio of the second harmonic to the fundamental.

[1] D. J. Barnard, et al, J. Nondestr. Eval., Vol. 16, pp. 7789, 1997. [2] J. M. Richardson, Int. J. Engng. Sci. Vol. 17, pp. 8385, 1979.

This work was sponsored by the Swedish Nuclear Fuel and Waste Management Co. (SKB)

Session: U6-J
SAW MATERIALS AND PROPAGATION
Chair: M. Periera da Cunha
University of Maine

U6-J-1 512A-F 1:30 p.m.

EXISTENCE OF HARMONIC METAL THICKNESS MODE PROPAGATION FOR LONGITUDINAL LEAKY WAVES

M. SOLAL*[1], T. MAKKONEN[2], R. LARDAT[1], V. P. PLESSKY[3], W. STEICHEN[1], and M. M. SALOMAA[2], [1]TEMEX Microsonics, [2]Materials Physics Laboratory, Helsinki University of Technology, [3]GVR Trade SA.
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In [1], an approximate model for longitudinal leaky waves propagation was described. This model was based on the assumption that this wave was due to a coupling by the substrate between quarter wavelength resonance modes of the successive electrodes in a grating. Based on this assumption, we tried to find out if similar behavior is possible by coupling other electrodes resonance modes like harmonic of the original quarter wavelength modes. It is shown that longitudinal leaky waves can exist on YZ lithium niobate not only in the vicinity of thickness of Al electrodes equal to 8% of the electrical period but also for thickness multiplied by 3 or 5, i.e. for which the operating frequency is in the vicinity of the 3rd and 5th harmonic electrode resonance modes. This possibility was verified by FEM/BEM simulations and confirmed as by test devices. Experimental results and simulations, confirming the original assumption of [1], are reported and discussed. It is also shown by using FEM/BEM simulations that the LL-waves do exist in split finger configuration (in IDT with 4 electrodes per period) showing strong resonance properties. It illustrates that the strong reflections and the Bragg stopband observed in standard 2 electrode-per-lambda IDT are not necessary for existence of LL-waves.

[1] V. Plessky et al., Proc. 2001 IEEE Ultrasonics Symposium, pp. 239-242.

This research has been carried out in the framework or the French-Finnish Eureka project E! 2442 SUMO.

U6-J-2 512A-F 1:45 p.m.

OPTIMIZED CUT OF LITHIUM NIOBATE FOR HVPSAW FILTERS WITH DIFFERENT METALIZATION RATIO OF ELEMENT RESONATORS

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High velocity pseudo-surface waves (HVPSAW) can be very useful for increasing operating frequencies of resonator filters. In general, HVPSAW is more strongly

attenuated than low-velocity PSAW, but with proper choice of a substrate orientation and electrode thickness propagation loss can be reduced. Previously it was reported [1] that HVPSAW with negligible propagation loss exists in $LiNbO_3$ orientation with Euler angles (0°, 81°, 90°) if periodic grating of Al electrodes has normalized thickness about 8.3% of HVPSAW wavelength. These orientation and electrode thickness provide high Q-factor at resonant frequency. To minimize propagation loss at any other frequency, for example at anti-resonance, different combination of crystal cut and electrode thickness is required. Generally, a composite device structure of ladder filter includes several element resonators, some of which determine the level of rejection in the stopband and others provide steep passband edges. A specific requirement to propagation loss of each element resonator depends on the device structure but commonly minimum propagation loss is required either at resonance, at anti-resonance, or in between. Thus, it is impossible to optimize simultaneously all element resonators, if they are fabricated on the same substrate with the same electrode thickness and metalization ratio. In the present paper, the propagation loss of HVPSAW propagating in orientations of $LiNbO_3$ with Euler angles (0°, μ, 90°) with periodic Al grating has been numerically analyzed as function of three parameters - angle μ, elecrode thickness and metalization ratio. It was found that there is no combination of these parameters giving non-attenuated HVPSAW simultaneously at resonant and anti-resonant frequencies. However, there is a wide area, within which the propagation losses at resonance and at anti-resonance are simultaneously less than 0.001 dB/λ. This area is located approximately between orientations (0°, 78.5°, 90°) and (0°, 81°, 90°), with normalized Al thickness varying between 7.9% to 8.75%, and metalization ratio varying between 0.4 and 0.8. Orientation (0°, 80°, 90°) can be considered as the best choice of orientation to provide low propagation loss within wide interval of Al thicknesses. For example, with thickness 8.3%, the optimal metalization ratios, which minimize propagation loss at resonance and at anti-resonance, were determined as 0.64 and 0.5, respectively. Thus we demonstrated that metallization ratios of individual resonators within one resonator filter can be varied to allow the propagation loss for each individual resonator to be minimized at predetermined individual frequencies and provide improved performance of HVPSAW filter. [1] A.Isobe, M.Hikita, and K.Asai, IEEE Trans. Ultrason., Ferroelect., Freq. Control, 1999, v.46, No 4, pp. 849-855.

U6-J-3 512A-F 2:00 p.m.

EVALUATION OF MATERIAL CONSTANTS AND SAW PROPERTIES IN $LACA_4O(BO_3)_3$ SINGLE CRYSTALS

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Rare-earth calcium oxoborates, $RCa_4O(BO_3)_3$ (R = La-Lu, Y; RCOB) single crystals exhibit excellent non-linear optical properties and can be grown by Czochralski (Cz) technique[1]. We have paid attention to piezoelectric properties of the RCOB crystals. In this study, we prepared RCOB (R = La, LaCOB) crystals using the Cz technique and evaluated the material constants and SAW properties. From our previous report[2], the relationship between the morphology of the grown crystal and crystallographic *abc* - rectangular *XYZ* axes was revealed. This knowledge is very useful to prepare substrates for piezoelectric measurements. The LaCOB crystals belong to the monoclinic symmetry (point group *m*). The total number of material constants which should be determined is 27. They consist of 4 dielectric, 10 piezoelectric, and 13 elastic compliance constants (ϵ_{ij}, d_{ij}, and s_{ij}, respectively). We could suggest substrates in order to determine these constants using length-extensional (transverse effect), thickness-extensional (longitudinal-effect) and thickness-shear modes. Twenty four of 27 constants were determined until now, e.g., ϵ_{11}, ϵ_{22}, ϵ_{33}, ϵ_{13} at 10 kHz were 9.7, 14.3, 9.7, -1.24 and d_{11}, d_{32} were 2.3, -2.3 pC/N at room temperature, respectively. Their 1st order temperature coefficients were 56.3, -273.6, 135.8, -258.4 and -408.3, 409.6 ppm/K, respectively. SAW and Pseudo-SAW (PSAW) on the *X*-, *Y*- and *Z*-cut substrates of LaCOB crystal were characterized. Maximum coupling factor ($k^2 = 0.6\%$) was observed on the *Z*-cut crystal at the *Y*-axis propagation. Relatively low temperature coefficient of time delay (48 ppm/K) was observed on the *Y*-cut crystal at the *Z*-axis propagation. These feature suggested the LaCOB crystal will become performance-competitive with existing $Li_2B_4O_7$ and $La_3Ga_5SiO_{14}$ crystals.

Reference [1] J.J.Adams, C.A.Ebbers, K.I.Schaffers, and S.A.Payne: *Opt.Lett.,* 26, 217-219, (2001) [2] H.Takeda, H.Sako, H.Shmizu, K.Kodama, M.Nishida, H.Nakao, T.Nishida, S.Okamura, T.Shikita, T.Shiosaki: *Jpn.I.Appl.Phys.,* 42, 6081-6085, (2003)

U6-J-4 512A-F 2:15 p.m.

PROPERTIES OF RADIO FREQUENCY RAYLEIGH WAVES ON LANGASITE AT ELEVATED TEMPERATURES

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Langasite ($La_3Ga_5SiO_{14}$) is a piezoelectric substrate crystal of the calcium-gallogermanate group. These single crystals have a moderate piezoelectric coupling, crystal cuts with zero power flow angle and wafers with a diameter of up to 4 are available. Moreover the material is high temperature resistive. Thus it is a suitable substrate for surface acoustic wave (SAW) sensors operating in harsh environments. Such SAW sensors are passive devices having the capability of wireless interrogation, basically achieved at radio frequencies (RF). In this paper the RF properties of Rayleigh waves being operated at high temperatures on

Langasite crystal cuts with Euler Angles of (0°, 138.5°, 26.6°) and (0°, 30.1°, 26.6°) are investigated. By evaluating the frequency response of SAW test devices the SAW velocity, the coupling factor and the propagation attenuation have been determined experimentally in a temperature range from 20 °C to 500 °C. The SAW devices could be operated up to frequencies of 3 GHz. However, considering a future sensor application a limiting factor is a strong increase of the acoustic losses both with frequency and temperature.

U6-J-5 512A-F 2:30 p.m.

ANALYSIS OF THE SAW PROPAGATION IN LANGASITE CRYSTAL BY X-RAY TOPOGRAPHY

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The development of acousto-electronic devices based on the SAW has been very active in the fields of filters, resonators, convolvers, etc., which are widely used in telecommunication systems. Application of new piezoelectric materials (langasite, langatate, etc.) is accompanied by an increased need for precise characterization of acoustic wave field propagation. The process of the SAW excitation and propagation can be investigated using X-ray diffraction and topography methods because X-ray radiation is very sensitive to the distortions of crystal lattice modulated by SAW. X-ray diffraction and topography methods permit to visualize the acoustic wave field on the crystal surface and to measure the SAW amplitude, attenuation and SAW penetration depth inside the crystal. In present paper we report the investigation of the SAW propagation in the X-, Y- and (022)-cuts of a langasite crystal using X-ray topography method. Usually, the X-ray topography method is used for visualization of the traveling SAW propagation at synchrotron radiation source. For visualization of the traveling SAW it is necessary to synchronize the process of the SAW excitation with temporal structure of synchrotron radiation. Here, we present the simple X-ray topography technique for visualization and investiagation of standing SAW wave fields in langasite crystal using laboratory X-ray source. The principle of X-ray visualization is determined by antinodes structure of the standing SAW. The nodes of the standing SAW are motionless and locate in the plane of crystal surface, and antinodes act as concave focusing mirrors and carry out the X-ray focusing in the focal plane placed at the distance D from the crystal surface (D=λ^2sin$^2\Theta_B/8\pi^2$/s up¿h, where λ is the SAW wavelength, Θ_B is the Bragg incident angle of X-ray radiation, h is the SAW amplitude). The period of X-ray topography image of the standing SAW is two time smaller than the SAW wavelength, because one wavelength consists from two nodes and two antinodes. X-ray topography visualization of acoustic wave field was used for measurements of the power flow angles in various langasite cuts (X-cut: PFA=6.3°; Y-cut: PFA=0°; (022)-cut: PFA=21°). The method of X-ray topography has allowed to observe the diffraction phenomena in acoustic beam

due to the SAW diffraction on the IDT aperture. Also the method of X-ray topography was used to study the process of the SAW interaction with crystal structure defects. It is shown, that growth banding and block structure do not render influence on the process of the SAW propagation while the presence of the decorated F-centers leads to decreasing of the SAW velocity and to distortion of the wave front. As well as the presence of the twins in the crystal leads to the distortion of the SAW wave field, which is due with the SAW diffraction and refraction by twins.
This work has been supported by Russian Fondation for Basic Research (Contract No. 02-02-22006)

U6-J-6 512A-F 2:45 p.m.

ACOUSTIC WAVES ON PLANE INTERFACES IN PIEZOELECTRIC BI-CRYSTALLINE STRUCTURES OF SPECIFIC TYPES

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The theory has been developed of the acoustic waves guided by the interface inside a piezoelectric medium. The uniform interfaces of two types have been considered. 1) Infinitesimally thin metallic layer inserted into homogeneous piezoelectric crystal of arbitrary symmetry. 2) Rigidly bonded crystals whose piezoelectric coefficients differ by sign while the other material constants are identical, when referred to a common coordinate system. The latter structure can be constructed from two parts of the same crystal, one of which must be appropriately rotated relative to the other before they are cut along the equivalent plane and brought in contact; one can also use the left- and right-hand crystal types of the same substance. Previous analytic considerations had been confined to explicit calculations for SH-polarized interface acoustic waves (IAW) travelling along special directions related to the element of crystallographic symmetry. In this work, without any reference to crystallographic symmetry we prove a number of theorems on the existence of generically polarized IAW propagating slower than bulk waves. In particular, a sufficient condition for the existence of such "slow" IAW has been derived. The propagation of leaky IAW has been investigated. A special attention has been paid to the analysis of the situation when the imaginary component of the leaky IAW velocity vanishes, resulting in the appearance of non-attenuating IAW travelling faster than the slow transverse bulk wave. The coefficient of electromechanical coupling has been numerically estimated for "slow" and leaky IAW on interface 2) in $LiNbO_3$ and $LiTaO_3$ structures. A comprehensive study has been made of the bulk wave reflection from interfaces 1) and 2). Analytical expressions for the coefficients of mode conversion have been derived. An analysis has been carried out of specific singularities arising at the angles of incidence corresponding to the resonance excitation of leaky IAW. The conditions for the occurrence of the resonance total reflection

have been established. The computations performed for LiNbO3 and LiTaO3 illustrate general conclusions.

A. Darinskii thanks Deutsche Forschungsgemeinschaft (grant 436 RUS 113/645/3-2) and Russian Foundation for Basic Research for financial support.

Session: FE1-J

CAPACITORS AND DIELECTRICS

Chair: J. Capurso
Ferroelectric Material Systems

FE1-J-1 513CD 1:30 p.m. (Invited)

THE NATURE OF LARGE DIELECTRIC CONSTANT OF RELAXORS

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Ferroelectrics with partially disordered structure exhibit diffuse phase transitions. They are solid solutions with non-uniform allocation of structural ions. Relaxors are type of diffused transition crystals that distinctive feature is extraordinary softening in dielectric and elastic properties over a wide range of temperatures. This property underlies many technical applications: non-hysteresis actuators, non-linear optical devices, piezo-filters, etc. To distinguish relaxor among other ferroelectrics, microscopic or optical investigations are employed. In this report a macroscopic test-method is proposed to draw a line between the relaxor and usual disordered ferroelectric solid solution. By the dielectric spectroscopy (0.11E11 Hz) in a broad temperature interval a family of ϵ*(ν,T)=ϵ'(ν,T)+iϵ"(ν,T) curves are obtained. The spectra of relaxor are compared with the spectra of classic displace and order-disorder types ferroelectrics, and with the spectra of ferroelectric solid solutions with diffused phase transition such as Ba(Ti,Sn)O3 or Pb(Ti,Zz)O3, etc. A frequency dependence of ϵ'-temperature maximum (Tmaxϵ) is analyzed. Customary ferroelectric is defined by sharp ϵ'(T)-maximum at the Curie temperature TC=Tmaxϵ, and no frequency shift of this maximum is seen. In disordered ferroelectrics parameter Tmaxϵ increases with frequency rise. Usual ferroelectric solid solution with diffused phase transition shows slick linear rise in the Tmaxϵ(logν)-dependence. It is first noticed that key feature of relaxor ferroelectric is a broken or bifurcated Tmaxϵ(logν)-line. Relaxor of PMN type shows the broken-line increase in Tϵ'max(logν)-dependence while relaxor of KLT type (K1-xLixTaO3) demonstrates the bifurcation of this line. The main reason why the Tmaxϵ(logν) dependence becomes broken or bifurcated is a coexistence in the relaxor at least two different types of polar clusters that occupy the adjoining nano-scale regions in crystal. Only this cannot explain peculiar to the relaxor large permittivity (ϵ 1E4-1E5) that is observed at minor electric field over a broad temperature interval. If the relaxor would be a simple composite of low and high frequency adjoining polar clusters, the ϵ-value should be formed predominantly by the

clusters that have reduced ϵ at a given temperature so as the ϵ-size of relaxor cannot be such a big. Previously large ϵmax of this nature is seen only in the narrow temperature interval near ferroelectric Curie point, and this sharp ϵ-peak is explained as a fundamental property of phase transition. It is considered that relaxor ϵ is large due to non-homogeneous distribution of electric field: applied field is concentrated in "low-ϵ" clusters. Dielectric polarizability of those clusters increases. The spatial wave of non-linear polarization diffuses in relaxor with acoustic mode velocity, so a strong dispersion is seen in relaxor just above frequency of 1E5 Hz.

FE1-J-2 513CD 2:00 p.m.

INTEGRATED HIGH ENERGY DENSITY PLZT BASED CAPACITORS

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The primary goal of this work is to investigate the feasibility of integrating robust dielectric components of minimal volume into an electronics package. The advantages of system integration include low cost, as well as increased reliability. To this end, multi-layer capacitors were fabricated using an aerosol deposition apparatus to deposit electroactive ceramic material directly onto an alumina substrate. This technique was used to fabricate uniform ceramic layers $30 - 100\mu$m in thickness. Due to interactions between the alumina substrate and the dielectric layer during sintering, a buffer layer between the dielectric layer and alumina substrate was used to control Pb loss in the active layers. High Zr content $(Pb,La,Zr,Ti)O_2$ (PLZT) ceramics were investigated as candidate materials for this application due to their relatively high dielectric constant, low loss, and high breakdown strength. Chemically synthesized powders were evaluated for their low sintering temperature, which minimizes the PLZT/alumina interaction. Doping the PLZT with silver has also been investigated in this work, as it has also been shown to reduce the sintering temperature. Silver doping has the added benefit of substantially lowering the dissipation factor of the material (DF $<$0.006) over a temperature range greater than 100°C.
Sandia is a multiprogram laboratory operated by Sandia Corp., a Lockheed Martin Company, for the U.S. Department of Energy, under contract No. DE-ACO4-94AL85000.

FE1-J-3 513CD 2:15 p.m.

LASER CRYSTALLIZED BISMUTH ZINC NIOBATE THIN FILMS

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The rapid development of communication technologies, especially mobile communication systems, is facilitated by miniaturization of devices. Integrated decoupling capacitors and microwave resonatores are of interest for such systems. Dielectric materials for these applications must possess medium or high permittivity, low temperature coefficients of capacitance (TCCs) and low loss tangent values. For this purpose, bismuth zinc niobate (BZN) thin films with different composition have been studied, and it has been demonstrated that $Bi_{1.5}$ $Zn_{1.0}$ $Nb_{1.5}$ O_7 , $Bi_{1.5}$ $Zn_{0.5}$ $Nb_{1.5}$ $O_{6.5}$, and Bi_2 $Zn_{2/3}$ $Nb_{4/3}$ O_7 films deposited by metalorganic decomposition (MOD) methods have many of the required electrical properties[1, 2, 3]. However, typically, the annealing temperature must be higher than 650 ° C to get well crystallied BZN films, which makes integration with polymeric substrates problematic. To reduce the annealing temperature, pulsed laser annealing (PLA) was employed using a defocused 248 nm laser beam. Well crystallized $Bi_{1.5}$ $Zn_{0.5}$ $Nb_{1.5}$ $O_{6.5}$ films have been successfully obtained by PLA at a laser energy density of 34 mJ/cm^2 and substrate temperatures around 400 °C. Electrical measurements showed that the PLA $Bi_{1.5}$ $Zn_{0.5}$ $Nb_{1.5}$ $O_{6.5}$ films (laser energy of 34 mJ/cm^2 , T_{sub} = 400°C) have a relative permittivity as high as 178, with low loss tangents and a TCC of 285 ppm/° C. The dielectric constant of the PLA $Bi_{1.5}$ $Zn_{0.5}$ $Nb_{1.5}$ $O_{6.5}$ films decreased with bias field, while the loss tangent changed very very little. The dielectric constant changed 5% under a bias of 676 KV/cm; a higher tunability is expected when higher bias is applied to the samples. The dielectric properties of the PLA $Bi_{1.5}$ $Zn_{0.5}$ $Nb_{1.5}$ $O_{6.5}$ films annealed at 400 ° C are comparable to those of RTA $Bi_{1.5}$ $Zn_{0.5}$ $Nb_{1.5}$ $O_{6.5}$ films annealed at 650 ° C. The low annealing temperature with PLA technique make integration with polymeric substrates possible; results of studies towards this will be reported.

References 1. Wei Ren, Susan Trolier-Mckinstry, Clive A. Randall and Thomas R. Shrout, J. Appl. Phys. 89, 767 (2001). 2. R. L. Thayer, C. A. Randall, and S. Troler-Mckinstry, J. Appl. Phys. 94, 1941 (2003). 3. Jiwei Lu and Susanne Stemmer, Appl. Phys. Lett. 83, 2411 (2003).

FE1-J-4 513CD 2:30 p.m.

HIGH DIELECTRIC CONSTANT ALL-POLYMER COMPOSITES

C. HUANG*, F. XIA, H. LI, M. POH, and Q. M. ZHANG, The Pennsylvania State University.
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Although several recently developed electro-responsive polymers exhibit very high strain response induced by electric stimulus, the electric fields required to generate such a high electromechanical response are quite high (>100 MV/m to induce a strain response with the elastic energy density higher than 0.1 J/cm^3) which limits the applications of these polymers. One fundamental reason for the need of high electric field to generate high strain with high elastic energy density is the relatively low dielectric constant of these polymers. In order to

reduce the applied field level while maintaining high electromechanical response in the electro-responsible polymers, the dielectric constant should be raised substantially above the current level (all below 50). In this presentation, several approaches are introduced and demonstrated which show that all-polymer composites, based on ultrahigh dielectric constant organic solids and percolative phenomenon, can lead to all-polymer blends to high dielectric constant. For example, in a CuPc-PVDF terpolymer blend, a dielectric constant of more than 300 has been achieved. In a three-component dielectric-percolative composite, a dielectric constant of more than 1000 has been achieved. As a result, the field level required to induce high electromechanical strain is substantially lowered. That is, a more than 9% strain with the elastic energy density of 0.4 J/cm^3 can be induced under an electric field of 20 MV/m. Experimental data also show that in these composite systems, there exist strain enhancement effects which can be due to the interface effects between the constituents in these composites
This work was supported by NIH, ONR, and DARPA

FE1-J-5   513CD   2:45 p.m.

STRUCTURE AND PROPERTIES OF HIGH DIELECTRIC CONSTANT $CACU_3TI_4O_{12}$ CERAMICS

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Due to continuous demand for miniaturization of electronics, there is an interest to develop capacitor ceramics with higher dielectric constant and for some capacitors the temperature coefficient of capacitance of $<$15%. Recently, it has been reported that the perovskite $CaCu_3Ti_4O_{12}$, has a very high dielectric constant with values of 10,000 for polycrystalline and 80,000 for single crystals. It has a cubic structure and no phase transitions down to 35 K. This material is, therefore, a promising capacitance material.

In this work, the structure and dielectric properties of $CaCu_3Ti_4O_{12}$ ceramics have been investigated. The material was synthesized both by the conventional ceramic method and by a modified glycine nitrate process. The ceramics obtained exhibit a cubic perovskite structure. Dielectric constants up to 50,000 and dielectric losses of around 0.04 at 1 kHz have been observed at room temperature. The temperature and frequency dependence of the dielectric properties have also been investigated. The effect of processing and microstructure on the dielectric properties will be discussed.

Session: U1-K

VASCULAR IMAGING
Chair: J. Greenleaf
Mayo Clinic

U1-K-1 510AC 3:30 p.m.

HIGH-FREQUENCY ULTRASOUND CHARACTERIZATION OF PULMONARY ARTERY WALL UNDER NORMOTENSIVE AND HYPERTENSIVE CONDITIONS

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Diagnosis of secondary pediatric pulmonary hypertension is often difficult because no single test permits complete evaluation. Improved understanding of the effects of hypertension on ultrasonic (US) properties of the pulmonary artery (PA) wall could lead to earlier detection. High-frequency US *in vitro* measurements were performed on fresh and fixed, excised PA walls from control and hypoxic knockout Long-Evans rat models to determine if US properties differed between groups. The study reported here is part of a broader effort that also includes mechanical measurements of the PA specimens using a bubble-inflation technique. US measurements were performed prior to and following mechanical measurements to determine the effects of mechanical testing on US properties of the tissue. Control (n_C=2) and hypoxic knockout (n_H=1) rat models were sacrificed at 13 and 12 weeks of age, respectively. The knockout rat line was genetically modified so that a greater propensity for developing hypertension existed. PA specimens (main trunk, left and right branches) were excised following sacrifice and stored in a 0 °C nutritive solution until measurement. Each artery section was cut along the longitudinal axis, and opened intima-side up for measurement. Specimens were clamped on a stainless steel fixture. Measurements on fresh tissue occurred within 24 hours of animal sacrifice. We used an acoustic microscope system that included a 50 MHz polymer-film transducer, a 150 MHz square-wave pulser/receiver, a 1 GHz digitizer, and a 3-axis gantry system. Data acquisition and motion control were automated. Specimens were immersed in a 37 °C nutritive solution bath. Ultrasound backscattered from the fixture was digitized with (i.e., shadowed) and without (i.e., unshadowed) tissue intervening, and stored to computer for off-line analysis. Mechanical measurements of the specimens were then performed, followed by a second set of US measurements. Specimens were then placed in a fixative solution for at least 24 hours. US measurements were performed on fixed tissue immersed in a 37 °C deionized water bath. Thickness and speed of sound (SOS) of each PA specimen was determined from time-of-flight measurements of the front and back tissue walls and the shadowed and unshadowed reflector. Slope-of-attenuation was determined by Fourier analysis of the backscattered signals from the shadowed

and unshadowed reflector over a bandwidth of (25 to 50) MHz. Preliminary results indicate mechanical testing affects the SOS only modestly (<5 %), but can cause up to a 20 % decrease in the slope-of-attenuation (0.5 dB/cm/MHz). Fixation of tissue causes an increase in the SOS of up to 15 % (200 m/s), and a further decrease in the slope-of-attenuation of up to 50 % (1 dB/cm/MHz). Consequently, US characterization of the PA specimens must be performed prior to mechanical testing. Measurements on this small population do not yet permit conclusions on the effect of hypertension on the US properties of the PA wall, and additional testing is planned to address this issue.

The author would like to thank Chris McCowan at the National Institute of Standards and Technology (NIST) Materials Reliability Division (MRD) and Kelley Colvin at the University of Colorado Health Sciences Center for assistance with tissue specimen preparation. The author would also like to thank Lonn Rodine at NIST MRD for design of the tissue specimen fixture.

U1-K-2 510AC 3:45 p.m.

IMPROVED ACCURACY OF VASCULAR WALL SHEAR RATE MEASUREMENTS

J. K. TSOU*[1], J. LIU[1], C. PELLOT-BARAKAT[1,2], and M. F. INSANA[1], [1]University of California, Davis, [2]INSERM.
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Wall shear rate (WSR) is the derivative of blood velocity with respect to vessel radius. Low and oscillating WSR has been identified as a necessary factor for increasing endothelial cell (EC) permeability leading to arterial wall remodeling and atherosclerosis. WSR is as difficult to estimate as it is important for assessing health risk. It is the greatest at the EC surface where blood velocity is minimum. Consequently accurate WSR estimates require both high spatial resolution and high sensitivity to slow-flow velocities. Conventional velocity estimators involve narrowband pulses and autocorrelation estimators or broadband pulses and crosscorrelation (CC) estimators. Both approaches yield noisy estimates or blur the sharp velocity gradient at the wall because of the long Doppler pulse or CC window required for the low echo SNR conditions. Hence conventional techniques often generate large bias and variance for WSR estimates. We propose a time-domain method designed to simultaneously achieve high spatial resolution and high sensitivity for slow flow. The approach is to transmit a phase-modulated code to increase echo SNR and then apply a specially designed Wiener filter to the received echoes. Finally CC estimators are used to estimate velocity and thus WSR.

The method was designed by analyzing echo simulations that model steady laminar flow in muscle tissue. A 10 MHz transducer (60% bandwidth) scanned a random medium to generate echo simulations sampled at 60 MHz. Phantom measurements were also acquired to validate results obtained with simulated data. A graphite-gelatin phantom with a 6.4 mm diameter flow channel was supplied with constant flow (Vmax =10 cm/s). RF echo data were recorded from a Siemens Antares using the ultrasound research interface and 7.3 MHz Doppler pulses. Broadband pulsed acquisition was obtained using a lab scanner with a 10 MHz, f/1.5, annular array and dynamic receive focusing. Echoes from transmitted 10-bit optimal codes were compressed using inverse filters. The Wiener filter was designed in part from the impulse response recorded with a fine line target phantom.

Simulation results show unfiltered narrowband pulses generate the greatest WSR bias (44%) while the bias for single-cycle pulses and compressed 10-bit optimal coded pulses are approximately 20%. Variance was fixed throughout. Applying the Wiener filter, noise reduction expanded the 6dB echo bandwidth for broadband and coded pulses from 6 to 12 MHz. Larger bandwidth permits use of smaller CC windows that are able to detect the sharp gradients in WSR profiles. Consequently WSR bias was reduced from 20% to 12% (one cycle pulse) and 8% (coded pulses). As expected, Wiener filtering provided little improvement for narrowband pulses (WSR bias =36%). Flow phantom studies generally supported simulation results whenever the impulse response was accurately modeled.

A combination of coded excitation and Wiener filtering applied to broadband velocity estimation produced a four-fold decrease in WSR bias for fixed variance. The improved accuracy extends the use of ultrasound to new areas in the study of atherosclerosis.

U1-K-3 510AC 4:00 p.m.

COMPARISON OF ULTRASOUND RADIATION FORCE AND FLUID PRESSURE GENERATED WAVES IN ARTERIAL VESSELS

X. ZHANG*, R. R. KINNICK, M. FATEMI, and J. F. GREENLEAF, Mayo Clinic College of Medicine.
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Background: Pulse wave velocity (PWV) is widely used for estimating the stiffness of an artery. It is well known that a stiffened artery can be associated with various diseases and with aging. Usually, PWV is measured using the "foot-to-foot" method. The "foot" of the pressure wave is not clear due to reflected waves and blood noise. Also, PWV is an average indicator of artery stiffness between the two measuring points, and therefore does not identify local stiffness variations. In a series of recent studies, we investigated bending waves in the arterial wall using low frequency localized ultrasound radiation force and measured the wave velocity along the arterial wall [X. Zhang et al., Proc. 2003 Ultrason. Symp., 1883-1886], [X. Zhang et al., Proc. 2004 SPIE, Medical Imaging]. The wave velocity can be measured accurately over a few millimeters.

Objective: The pulse wave is generated by blood pressure so that it is a fluid-born pressure wave. The bending wave we generate directly on the arterial wall is due to the wave propagation of the wall itself so that we can call it a structure-born wave. The objective of this paper is to address the mechanism of these two kinds of waves.

Method: The pressure wave in a tube is generated with a specially designed apparatus for this research. The apparatus consists of a small pressure chamber having a rubber membrane on one side that is driven by an electrodynamic shaker. The bending wave is generated directly on the tube with the localized radiation force of ultrasound. The wave velocities of both waves are measured with established methods. An arterial phantom was constructed with a 24 cm length of 5 mm outer diameter latex tubing. The tube was pressurized with water and surrounded with tissue-mimicking gelatin. Wave velocity was measured over frequency from 50 to 150 Hz.

Results: The results show the different mechanism of the two waves. The pressure wave velocity is higher than the bending wave velocity in this frequency range. The pressure wave velocity is measured 46 m/s at 50 Hz which decreases with frequency while the bending wave velocity is measured 11 m/s which increases with frequency.

Conclusion: Dispersion of wave velocity over frequency was found for both the pressure wave and bending wave. This is very important because conventional pulse wave velocity measurement does not consider the dispersion. The bending wave shows some advantages over the pressure wave. The complex Young's modulus of the artery can be computed from models of the wave propagation modes.

This study is supported by grant EB 02640 from the National Institutes of Health

U1-K-4 510AC 4:15 p.m.

3D SIMULATIONS OF DIFFERENCE FREQUENCY EFFECTS ON A BLOOD VESSEL IN ULTRASOUND-STIMULATED VIBRO-ACOUSTOGRAPHY

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Changes in mechanical properties of tissues can indicate evolving abnormalities. Therefore, several techniques have been developed to evaluate elastic properties of materials. These techniques are based on either mechanical or acoustical stimulation. If the elasticity parameters change, also the natural frequencies and internal vibrations of biological structure change. In ultrasound-stimulated vibro-acoustography (USVA) [1] two focused ultrasound fields that have a joint focal region produce highly localized stimulating force. The harmonic radiation force is produced using fields at slightly different frequencies. This localized harmonic force causes oscillatory displacements into the target at the difference frequency. The vibration depends on the stimulation force and elastic properties and structure of target. Previous simulation studies of USVA [2] have been computed in a simple cylindrically symmetric geometry modeling the stimulating force by a point load placed in the geometrical focal point and directed to the center axis of the stimulating fields. In our simulations the real three dimensional

distribution of the radiation force at the focal region is used. Displacements in soft tissues are simulated using the finite element method. All simulations have been computed in a three dimensional geometry that consists of a vessel perpendicular to the larger cylinder whose longitudinal axis points to x direction. That domain is used to represent the blood vessel surrounded by soft tissues. Hooke's law is used to describe the deformations of the materials. The center axis of the stimulation field is the same as the longitudinal axis of the cylinder and the geometrical joint focal point is placed in the middle of the vessel wall located closed to the transducer. The effects of the difference frequency to the displacements are simulated using different frequencies and material parameters. The range of difference frequencies is 0.2-1 kHz. The stiffness of the surrounding tissue is 24 kPa while the stiffness of the vessel wall is varied between 60 kPa and 120 kPa. All of the other parameters are kept constant for the surrounding tissue and the vessel. The results show that the frequency and amplitude of displacements are proportional to the excitation frequency and material parameters of the target. It can be seen from the simulations that the response is highly dependent on the eigenfrequencies of the target. The strongest response is reached when the excitation is at the eigenfrequency and if the stiffness of a vessel is changed the response decreases. [1] M. Fatemi and J. F. Greenleaf. Ultrasound-stimulated vibro-acoustic spectrography. Science, 280:82-85, 1998. [2] E. Konofagou, J. Thierman, and K. Hynynen. A focused ultrasound method for syncronous diagnostic and therapeutic applications - a simulation study. Physics in Medicine and Biology, 46:2967-2984, 2001.
This work has been supported by The Academy of Finland (54065) and The Finnish Cultural Foundation of Northern Savo.

U1-K-5 510AC 4:30 p.m.

DETECTION OF SHEAR WAVE PROPAGATION IN AN ARTERY USING PULSE ECHO ULTRASOUND AND KALMAN FILTERING

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Background: Oscillatory radiation force from ultrasound can be used to excite monochromatic waves on an artery. The wave propagation speed is related to the elasticity and viscosity of the artery, and can be estimated from the phase change over a short distance traveled [X. Zhang et al., Proc. 2003 Ultrason. Symp., 1883-1886]. In earlier phantom experiments, a laser vibrometer was used as a detection method because the motion of the artery is very small (submicron). We have proposed a novel method using pulse echo ultrasound and Kalman filtering to detect such small harmonic motions, which facilitates these measurements in opaque tissues [Y. Zheng et al., Proc. 2003 Ultrason. Symp., 18121815]. In this work, we apply this pulse echo method to detection vibration on an artery phantom and estimate the shear wave velocity. **Methods:** Ultrasound pulses are repetitively transmitted to a desired location to detect

the tissue harmonic motion that is expressed as an oscillatory phase shift in received echoes. A quadrature detector extracts the vibration signal from the echoes. The vibration signal is modeled by a 2nd order differential equation with random amplitude and phase, which are estimated by Kalman filter with minimum mean squared error. **Experiment:** A rubber tube embedded in a gelatin phantom is used to simulate an artery. A focused ultrasound transducer introduces oscillatory radiation force confined to a point on the tube. Ultrasound pulses are transmitted from another transducer (5 MHz center frequency) at a PRF of 4 kHz to detect the vibration of the tube. One hundred echoes are digitized at 40 MHz to estimate the vibration phase. The distance between the excitation and detection points is varied from 10 to 20 mm, with 1 mm increment, to evaluate phase changes. The same experiment is tested on a pig carotid artery embedded in gel containing graphite as scattering particles. The artery is vibrated at 200 Hz and the detection point is 10 to 15 mm away from the excitation point. **Results:** Linear regression gives a slope of 9.72, 13.56, 15.34, and 16.49 degrees/mm (all with $R^2 \geq 0.99$) for shear waves of 200, 300, 400, and 500 Hz on the tube. The results lead to estimated shear wave speeds of 7.4, 7.96, 9.39, and 10.91 m/s, respectively. The amplitude of the vibration is as low as 0.4 μm. The shear wave speed of the artery is 4.0$\pm$0.58 m/s at 200 Hz, which is comparable to the result of 3.9 m/s measured by Zhang et al.. **Conclusion:** Shear wave in an artery induced by the ultrasound radiation force can be effectively detected by pulse echo ultrasound and Kalman filtering.
This work is supported in part by grant EB02640 from National Institute of Health.

U1-K-6 510AC 4:45 p.m.

TRANSCUTANEOUS MEASUREMENT OF VISCOELASTICITY OF ARTERIAL WALL BY APPLICATION OF REMOTE ACTUATION

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Background: To characterize tissues in atherosclerotic plaque, we have developed a method, the *phased tracking method* [H. Kanai, IEEE Trans. UFFC, 43, 1996; H. Kanai, Circulation, 107, 2003], for measurement of the strain (change in wall thickness) and elasticity with transcutaneous ultrasound. However, some types of tissue may be difficult to be discriminated based only on the elasticity because of the small differences in their elasticity values. For more precise tissue characterization, we aim to measure the viscous property by applying remote actuation to generate changes in internal pressure at multiple frequencies. In this paper, the viscosity constants of an extracted human femoral artery and three human carotid arteries were measured by *in vitro* and *in vivo* experiments.

Methods: In an experimental setup with a water tank, the change in pressure inside an extracted human femoral artery was generated with an actuator by compressing a rubber balloon placed at a position of 40 cm away from the ultrasonic probe. Resulting changes in internal pressure and wall thickness were measured by a pressure sensor and ultrasound, respectively.

For *in vivo* measurement, we constructed a system for changing the actuation frequency heartbeat by heartbeat. The remote actuation was applied at the brachial artery and the change in wall thickness of the carotid artery was measured with ultrasound. The change in blood pressure was measured at the radial artery with an applanation tonometer.

The elastic modulus at each actuation frequency, which corresponds to the absolute value of the complex elastic modulus, was obtained from amplitudes of changes in internal pressure and wall thickness estimated by applying FFT to these waveforms.

Results: In *in vitro* experiments using an extracted human femoral artery, the elastic modulus increased linearly from 0.6 MPa (5 Hz) to 1.5 MPa (13 Hz) with actuation frequency. Such a frequency characteristic can be explained by the Voigt model in this frequency range. By assuming the Voigt model as an viscoelastic model of the wall, the viscosity constant was estimated as 18 kPa·s by minimizing the difference between the measured frequency characteristic and the Voigt model.

In *in vivo* experiments, the elastic modulus of the carotid artery of a 30-year-old male increased from 140 kPa (10 Hz) to 250 kPa (13 Hz) with actuation frequency. Frequency characteristics were also measured for other two subjects and the viscosity constants of 30, 24, and 22-year-old males were determined to be 6.0, 1.6, and 6.5 kPa·s, respectively.

Discussion and Conclusion: In the literature [B. M. Learoyd, Circ. Res., 18, 1966], viscosity constants of the human femoral and carotid arteries are measured as 11 kPa·s and 5 kPa·s, respectively, by *in vitro* mechanical testing. These values are in good agreement with those measured by the proposed method. From these results, the remote actuation combined with our *phased tracking method* has potential for noninvasive measurement of regional viscoelastic properties.

Session: U2-K

BEAMFORMING II
Chair: W. Walker
University of Virginia

U2-K-1 510BD 3:30 p.m.

NEARFIELD CODING AND SPATIAL PROCESSING FOR ULTRASOUND IMAGING

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OBJECTIVE: Aperture growth and dynamic receive focusing are array processing techniques that give high quality ultrasound images with an approximately constant f-number. For a given maximum receive aperture size, this work demonstrates that the nearfield point-spread function (psf) formed by receive focusing beyond the zone of interest actually has more spatial frequency bandwidth than the psf formed by receive focusing at the scattering point. This means that spatial resolution and signal-to-noise (SNR) can potentially be improved over traditional dynamic focusing and aperture growth techniques. The nearfield psf is large and banana-shaped, and the wavefront curvature gives a lateral modulation similar to a chirp. This is one example of a larger than unity time-bandwidth lateral coding scheme. To recover the spatial resolution information, RF filtering must be applied. One simple (but sub-optimal) way of doing this is by matched or mismatched filtering.

METHODS: We use simulations and experiments to demonstrate and implement the nearfield imaging technique. A research interface on a Siemens Antares ultrasound scanner gives us the opportunity to turn off dynamic receive focusing and aperture growth functions, while specifying the transmit focus, receive focus, and receive f#. System psfs were measured at 2 cm depth and 6.69 MHz transmit frequency and compared well with simulations using ultrasound simulation software. The transmit focus is set at 4 cm, and we compare psfs and images from receive foci at 2 and 4 cm respectively. The receive f# was set at 2.1 and the apodization was turned off. We demonstrate the nearfield imaging principle by scanning phantoms with 2 and 5 mm hyper-echoic and hypo-echoic inclusions. Analytic expressions derived from statistical decision theory are shown to be instrumental for evaluating the design of coding techniques for diagnostic detection tasks.

RESULTS AND CONCLUSIONS: K-space analysis of measured and simulated psfs revealed that nearfield psfs have 69% more bandwidth and almost twice as much mean power-spectral density than those with dynamic receive focusing for a fixed receive aperture. Nearfield phantom images before filtering show almost no visible clue of inclusions, but after filtering, the images are sharp, high contrast, and have finer lateral spatial resolution than images obtained from using dynamic focusing (for the same f#). The results suggest that nearfield coding can improve spatial resolution and signal-to-noise (SNR) over traditional dynamic focusing and aperture growth techniques for a fixed receive f#. Future work should investigate the effects of phase aberration, improved ways of RF processing, and techniques for designing other spatial codes.

U2-K-2 510BD 3:45 p.m.

TWO-DIMENSIONAL BLIND ITERATIVE DECONVOLUTION OF MEDICAL ULTRASOUND IMAGES

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Introduction The fairly low spatial resolution is one of the major limiting factors in the clinical usefulness of medical ultrasound B-mode images. This is still true, eventhough the spatial image resolution of high end ultrasound scanners has been substantially improved in the last decade.

The most important limiting factor in deconvolution has been the necessity to estimate the point spread function (PSF) from the recorded radiofrequency data. The reason is that the PSF changes with position in a tissue dependent manner. The PSF has to be estimated in two dimensions (2D) because it is not separable in the spatial coordinates. The only successful estimation method so far has been based on filtering in the 2D cepstrum domain, also called homomorphic liftering.

The 2D homomorphic liftering assumes that the PSF and the function of the tissue scatterers reside in separate bands of the 2D cepstrum domain. This approximation, together with unavoidable inaccuracies of the 2D homomorphic transform, lead to errors in the PSF estimates.

Method Here, the 2D-cepstrum separability assumption above is removed by using homomorphic filtering only to initialize the subsequent iterative deconvolution algorithm. However, the initial estimate is still important because all practical iterative algorithms will always converge to a local optimum.

Two iterative blind deconvolution algorithms have been implemented and adapted to radiofrequency signals. The first is the classical iterative blind deconvolution (IBD) scheme, where the PSF and the deconvolved image are alternately estimated in an iteration loop based on their current estimates. Spatial and frequency domain constraints and corrections were implied in each iteration, given by the knowledge of the support regions, lateral symmetry assumption of the PSF, Wiener filtering and Van Cittert deconvolution with reblurring. The second algorithm is iterative maximum likelihood blind deconvolution with optimization based on the expectation-maximization algorithm and constraints of known support regions. Both methods were applied to the whole B-mode images, meaning that only the space invariant component of the PSF was considered.

Results The algorithms were tested on phantom and clinical images. Both visually and quantitatively, the spatial resolution was slightly increased by homomorphic deconvolution (factor of improvement 1.1 to 1.9) and further improved by the iterative algorithm (factor of improvement 1.9 to 5.2). Both iterative deconvolution algorithm gave comparable results.

Conclusion The presented contribution shows the potential of iterative blind deconvolution methods to further improve homomorphic deconvolution and produce high-resolution ultrasound images.

The project has been supported by the Grant Agency of the Czech Republic (grant no. 102/02/0890), the Czech Ministry of Education, Youth and Sports (grant no. 1K03017) and the Norwegian Research Council.

U2-K-3 510BD 4:00 p.m.

A FLEXIBLE ALGORITHM FOR LAYOUT-OPTIMIZED SPARSE CMUT ARRAYS

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Optimization of array layouts for ultrasonic imaging has been a research topic for several decades. The task is to find layouts giving optimal image quality with a reduced number of active elements. The research is motivated from the ability to reduce the cost and complexity of ultrasonic systems. Recently, cMUT array technology has made possible the production of 2D arrays with large flexibility on element size and position. For such arrays, an optimal number, form and placement of elements would give a minimal cost system with an optimal image quality.

To optimize 2D layouts, heuristic optimization algorithms are most commonly used. Most such algorithms are iterative and computing intensive. To minimize the computational burden, sub-algorithms based on the fast Fourier transform (FFT) are often used to calculate the array response in each iteration. FFT-based algorithms put hard constraints to the problems which can be solved with respect to possible element grids and the shape of elements.

In this paper, a flexible simulated annealing algorithm for array layout optimization is presented. In each iteration, the array response of the layout candidate is evaluated using a differential update based on the response in the previous iteration. This is highly effective compared to an FFT-based algorithm. The computational burden to calculate the response is for each iteration only 2*N complex additions, N being the number of evaluation points. For an M x M element array, N is typically chosen as 4-25 times M x M.

In addition to being fast, the algorithm is flexible.There is no limitation in possible element positions. Elements can be freely placed in space on any given grid, and, additionally, clusters of elements can be governed by specialized rules. An example of a 2D array could be a ring array, and a specialized rule could be that the minimum number of elements within a ring should be at least a specified number. For a given array, the underlying grid size could be arbitrary. The algorithm can also handle overlapping element grids. In this way, the grid size can be smaller than the pitch of an element, but the algorithm assures that physical elements do not overlap in space. Moreover, the algorithm does not assume point elements, but handles individual element form and size as well as individual element directivity functions without additional computational burden. The response is calculated for a given focus at any range, i.e. near-field or far-field, and if a symmetry constraint is applied, computational burden is further reduced. For 2D arrays, 2-fold symmetry gives a factor 2 in reduction and 4-fold symmetry gives a factor 4 in reduction. The algorithm can be further extended to perform weight-optimization and pulsed excitation.

Two designs of possible cMUT arrays with minimal sidelobe level are presented. The first is a sparse ring array having increasing element sizes for increasing ring radii. The second is a sparse hex-grid layout optimized with λ / 2 and λ / 10 grid size for which square, circular and hexagonal element shapes are tested.

U2-K-4 510BD 4:15 p.m.

RECTILINEAR 3-D ULTRASOUND USING SYNTHETIC APERTURE TECHNIQUES

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In previous work, we investigated sparse 2-D array design for real-time rectilinear volumetric imaging of targets near the transducer such as the breast and carotid artery. In our continuing efforts to improve 3-D rectilinear ultrasound, we present a new design using a simplified interconnect architecture, switching scheme, and synthetic aperture methods. The main benefit of this design is the interconnect where an expensive multilayer flex circuit is no longer required. The interconnect uses a row-column addressing scheme to enable different groups of elements. Over multiple transmissions, this design is capable of synthesizing a 256 x 256 = 65,536 element fully sampled 2-D linear array. Using a sparse synthetic transmit aperture, a column or several columns of elements are bussed together so that a cylindrical wavefront is emitted into the field. In receive, the echoes from individual elements along a row are recorded by the system receive channels. Different columns and rows are selected in subsequent transmissions, and the echoes are then recorded from these transmit events to synthesize a fully sampled array. We have performed computer simulations of a 10 MHz 64 x 64 2-D synthetic array subaperture to determine the radiation pattern. For an F/2 aperture, the on-axis case (x,y,z) = (0,0,15) mm showed a narrow beam down to -45 dB. In the azimuth direction, on-axis lateral beamwidths at -6, -20, and -40 dB were 0.32 mm , 0.66 mm, and 1.4 mm, respectively. As a tradeoff, elevational beamwidths were wider with on-axis beamwidths of 0.35 mm, 1.5 mm, and 6.6 mm for the same corresponding dB levels.

U2-K-5 510BD 4:30 p.m.

CURVED TWO-DIMENSIONAL ARRAYS IN ULTRASOUND

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The cost of ultrasonic systems scales to the number of elements in the transmitter and receiver. Often there are also technical difficulties in connecting a high number of elements and cables to the array. It is therefore favorable to reduce the number of elements without loss in imaging quality.

In this work, we have classified which sparse 2D arrays show improvement in peak sidelobe level when curved in one direction, and quantified the effect through simulations. Curving in two directions has not been studied as it would follow the surface of a sphere, which is not viable because of difficulties in production. For the imaging quality three measures of performance have been used. The main focus has been on the peak sidelobe level, which indicates the array's signal-to-noise ratio. The other two measures are beamwidth and integrated sidelobe ratio (ISLR).

The class of arrays found is a subset of sparsed designs which have previously been shown to be promising for ultrasonic imaging. The improvement has been accomplished by studying the location of grating lobes, and how they are affected by curvature of the array. The location of grating lobes is a function of the periodicity of the array. Curving yields improvement since the periodicity in the projection of the array (according to the Fourier projection-slice theorem) is broken, and the grating lobes are smoothed. Though, too much curving yields an array for which the projection tends to that of a random array. Thus, for the class of arrays found the peak sidelobe level as a function of curvature attains distinct minimums. These minimums are found by simulation.

Simulations were done on several arrays containing 48 x 48 elements with 0.6 λ pitch at a center frequency of 3 MHz. These were sparsed by up to a factor of 1 / 4. For each array the pulse-echo response was calculated for values of the radius of curvature (ROC) ranging from 10 to 1000 mm. All the designs showed a minimum with respect to peak sidelobe level at around ROC = 40 mm. At these minimums, reductions in the peak sidelobe level of up to 6 dB (from -57 dB to -63 dB) were recorded compared to the corresponding flat array. It was also confirmed that the increased beamwidth was insignificant, and the ISLR only showed increased values for extreme curvatures (typical at less than ROC = 20 mm). At the optimal curvature the increase in ISLR was less than 0.4 dB. Steering of the array also preserved the improved peak sidelobe level, as well as changes in the focal length.

U2-K-6 510BD 4:45 p.m.

A 3X3 MATRIX BEAMFORMER OF PARTIALLY OVERLAPPING BEAMS USING A 1.5D ARRAY FOR REAL TIME CROSS-CORRELATION IMAGING (CCI)- A NUMERICAL VALIDATION

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We are currently developing a Real Time engine for cross-correlation imaging to be utilized in various approaches to elastography and 3D -flow detection. To overcome the problems associated with out of plane scatter displacement, the concept of a 3x3 beamformer matrix is presented and numerically evaluated.

The basic idea is the formation of overlapping parallel beams in the elevational as well as in the azimuthal direction. While standard multiple receive beam techniques are utilized to form beam overlap in the azimuthal direction a translation aperture approach is explored in this study to obtain the desired elevation beam overlap. The array consisting of 64 l/2 - spaced elements in the azimuthal direction and 5 MHz center-frequency is considered specifically for cardiac strain imaging. To define the 3x3 partially overlapping beam matrix extensive beam simulations were performed using Field II [1]. Based on these results we propose a 1.5 D array with 12 rows of 1 mm pitch equally spaced across the array elevation aperture. In transmission, the whole array forms a slightly de-focussed beam providing a reasonable SNR for all off-center receive beams. Even without dynamic receive focusing the 6dB beam overlap (combined) beam width is approx. 2 mm and extends approx. 30 mm in depth while the transmit and fixed receive focus is kept at 80 mm depth. The overlapping beam volume is easily steered into azimuthal off axis angles. Using Field II to create a flow simulation phantom, initial testing reveals a 10 % accuracy for velocity estimates based on a simple line-subtracting anti-clutter filter. The beamformer hardware consists of a 3 x 64 channel bank of TGC and ADC. The three data streams are then further divided into 3 groups forming the three azimuth beams. The beamforming concept is verified bit and cycle true using the Simulink and Xilinx System Generator hardware simulation tool and the beamformer implementation into a Virtex II pro FPGA is shown. [1] J.A. Jensen: Field: A Program for Simulating Ultrasound Systems, Paper presented at the 10th Nordic-Baltic Conference on Biomedical Imaging Published in Medical & Biological Engineering & Computing, pp. 351-353, Volume 34, Supplement 1, Part 1, 1996.

Session: U3-K

TRANSDUCERS II
Chair: J. Tsujino
University of Kanagawa

U3-K-1 511AB 3:30 p.m.

ULTRASONIC LAMB WAVE NDE SYSTEM USING AN AIR-COUPLED CONCAVE ARRAY TRANSDUCER

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Rapid and non contact ultrasonic NDE techniques are of great industrial interest. This paper describes an air-coupled ultrasonic inspection system based on concave linear arrays working on pitch-catch configuration. The system has been designed for real-time characterisation of sheet and plate manufactured materials such as paper and resin-fibre composites. The proposed system is based on

air-coupled Lamb wave excitation and reception that performs a rapid measurement of the optimum input angle of the incident beam impinging the material surface. No mechanical parts are used for tuning the plate wave excitation with the angle, doing that electronically by steering the acoustic beam. This solution increases the exploration velocity and the measurement repeatability and system reliability. The main contributions are related to the utilization of a 0.8 MHz ultrasonic air coupled concave array transducer. This transducer, using only 32 elements, is able to generate a 2.5 square cm size flat wave front, steering up to 26 degrees with 1.6 degree resolution, keeping the distance of wave flight and the impact point constant. The angular resolution can be improved up to 0.2 degrees using a novel micro-deflection technique, without any increment of the system complexity. The paper describes the fundamental concepts involved in the rapid scan air coupled Lamb waves characterisation technique, the block diagram of the system, the transducer structure and morphology and the delay time values determination for wave front flatness and micro-deflection. A study about received signal amplitude error determination due to the temporal discretisation in the wave front generation and recovery is also presented.
This work has been supported by the research project DPI2001-2156 of the Ministry of Science and Technology of Spain.

U3-K-2 511AB 3:45 p.m.

INVESTIGATION INTO THE NON-LINEAR RESPONSE FROM ACTIVE ULTRASONIC MONITORING SYSTEMS FOR APPLICATION IN THE PHARMACEUTICAL INDUSTRY

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Within the pharmaceutical and food industries, ultrasonic monitoring systems are an attractive measurement technique as they can be configured to operate non-invasively and are relatively inexpensive. A number of commercial ultrasonic systems are available for monitoring of both off-line and on-line processes and are used to determine parameters such as particle size and concentration. These techniques are based on pitch and catch technology that requires transmission of the acoustic wave through the sample. However, in many applications the physical nature of the material involved prevents acoustic transmission measurements and more useful process information can be achieved through study of wideband ultrasonic backscatter.

This paper describes an experimental programme to evaluate the generation a non-linear response from chemical particles suspended in a fluid medium using an ultrasonic monitoring system and determining how this information relates to the process under investigation. The non-linear response generated from the particulates produces both sub- and super-harmonics, both of which can be related directly to the presence of the suspended particles. To investigate the potential

of this monitoring approach, a customised test cell has been built incorporating an commercial ultrasonic transducer and polyvinylidene fluoride (PVDF) hydrophone receiving elements. The use of wideband membrane hydrophones allows for a sensitive reception of sub, second and higher order harmonics and importantly, has little impact on the incident sound field as its specific acoustic impedance is close to water. The experimental programme utilised a number of commercial ultrasonic transducers to operate at fundamental operating frequencies over the range 500kHz to 10MHz. Linear and frequency modulated chirp sequences have been used to excite the ultrasonic transducer and the wideband nature of this excitation is intended to cover a relatively wide range of resonant modes within the suspended particles. In addition, pseudorandom sequences have been used to improve the signal to noise ratio through cross-correlation processing. Furthermore, the signal processing also involves matched filtering, such that the identification of harmonic response data across a wide band of frequencies is both rapid and straightforward.

Initially, an inert system, comprising micro crystalline cellulose particules (20 - 180 μm) suspended in distilled water, was investigated to provide confidence in the validity of the approach. A model reaction was also investigated comprising itaconic acid particles in a 1-butanol solution. The itaconic acid was sieved into three sample batches: less than 250 μm; between 250 - 500 μm; and 500 - 850 μm. Non-linear responses were measured for both the inert and reactive systems. It was found that the intensity of the measured second harmonic frequency response was related to the particle size distribution of the itaconic acid.

U3-K-3 511AB 4:00 p.m.

MINIATURE, HIGH EFFICIENCY TRANSDUCERS FOR USE IN ULTRASONIC FLOW METERS

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This paper is concerned with the development of novel, miniature, high efficiency transducers for use in ultrasonic flow meters. In the transmission type of ultrasonic flow meter, two transducers are placed on opposite walls of a pipe through which the fluid is flowing [1]. Acoustic waves generated by one transducer travel through the fluid and reach the other transducer. The time taken by the acoustic wave to travel from one transducer to the other, the transit time, is a function of the flow velocity of the fluid. Thus, by measuring this time, one can determine the fluid velocity and other relevant flow parameters. The transducers can either be placed inside the pipe (wetted transducers) or outside the pipe (clamp-on transducers). This paper is concerned with transducers placed inside the pipe. One of the problems of currently available transducers is that they are generally large in size and protrude a considerable distance inward from the pipe wall and into the path of the flowing fluid. This causes several problems

such as disturbance of flow stream resulting in erroneous flow data, fouling of transducer due to accumulation of rags, debris, etc.

We show that a flat, planar transducer that has minimal protrusion into the pipe can be realized based on conversion of surface acoustic waves (SAWs) to bulk acoustic waves (BAWs) and vice versa [2]. The transducer is essentially a thin plate of a suitable piezoelectric material whose SAW velocity is greater than velocity of BAWs in the fluid. Under these conditions a SAW propagating in the substrate will radiate a BAW in the fluid at an angle θ given by the equation $\theta = \cos^{-1}(v_B/v_S)$, where v_B = BAW velocity in the fluid, and v_S = SAW velocity in the substrate. A similar device is used on the other wall of the pipe. Here bulk wave incident from the fluid generates a SAW on the substrate. Conventional intedigital transducers (IDTs) are used to generate and detect SAWs in the substrate. We will show that with proper design very efficient conversion of SAW to BAW and vice versa can be achieved. For example, using lead zirconate titanate (PZT) as the piezoelectric material and water as the fluid, total conversion loss (SAW to BAW and back from BAW to SAW) of less than 3 dB has been obtained. Another approach to realize a flat, planar transducer is to use the coupling between plate acoustic waves and bulk acoustic waves. Total conversion loss of less than 2.5 dB has been obtained by using the fundamental anti symmetric plate wave mode (A_0 mode) in 128 Y-X lithium niobate and bulk wave in water. An important advantage of plate waves is that since wave energy is present on both plate surfaces, the IDT can be on the surface opposite from that which is in contact with the fluid.

[1] L. C. Lynnworth, Ultrasonic Measurements for Process Control, Academic Press, 1989. [2] S. G. Joshi and B. D. Zaitsev, Low Profile Transducer for Flow Meters, U.S. Patent 6,609,430, Issued Aug. 26, 2003.

U3-K-4 511AB 4:15 p.m.

EFFICIENT GENERATION AND MEASUREMENT OF GUIDED TORSIONAL WAVES USING MAGNETOSTRICTIVE NICKEL PATCHES

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The guided-wave technology becomes a powerful tool for the non-destructive inspection of cylindrical waveguides such as pipes and tubes. Since guided waves can travel over several meters without significant attenuation, a large portion of a waveguide can be efficiently inspected. For waveguide inspection, various wave modes such as longitudinal, torsional, and flexural modes can be employed, but the non-dispersive first branch of the torsional wave mode is the most attractive. However, the torsional wave itself is difficult to generate compared to the longitudinal waves, so it has been used only in limited applications. Motivated by this, we are concerned with the efficient generation and measurement of torsional waves in a waveguide. The specific objective in this investigation is to develop a new method to generate and measure the torsional waves using

the magnestostrictive nickel patches, equivalently, the configuration of a new magnetostrictive transducer. The magnetostriction effect or the Joule effect is the phenomenon in which a piece of ferromagnetic material elongates or shrinks when it is placed under a magnetic field. The inverse magnetostriction effect or the Villari effect is the reverse phenomenon of the Joule effect. Although the magnetostrictive transducers (including sensors) have been applied and studied in many cases, the transducer has been investigated only recently by Kwun for the generation of torsional waves and its application for damage detection. Kwuns transducer consists of a nickel strip and a solenoid coil surrounding the strip. The strip is bonded circumferentially to a test specimen such as a pipe, and a permanent magnet is rubbed on the nickel strip for pre-magnetization. Though his transducer has been successful, there exists the problem of adjusting the alternating current which is sent through the solenoid coil to generate torsional waves. In addition, the nickel strip always needs be pre-magnetized before the transducer is used. Therefore, the transducer is not suitable for long-term on-line monitoring of underground pipes. To overcome the above-mentioned drawbacks, we propose a new transducer configuration using several pieces of nickel strips attached to the test specimen at the orientation of 45 degrees from the axis of the test specimen. The orientation angle change has a significant impact on the transducer characteristics; pre-magnetization is not needed and the generated wave mode is insensitive to the magnitude of the current input to the solenoid coil. The sensitivity of the proposed transducer improves when a bias magnetic field is applied. The damage location estimation in aluminum pipes was considered as a practical application. For experiments, narrow-band Gaussian pulses with the center frequencies ranging from 20 kHz to 300 kHz were used.

U3-K-5 511AB 4:30 p.m.

A 5MHZ PIEZOCOMPOSITE ULTRASOUND ARRAY FOR OPERATION IN HIGH TEMPERATURES AND HARSH ENVIRONMENT

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In non-destructive testing (NDT) applications, ultrasound arrays able to withstand high temperatures (100°C) and harsh environment (high pressure, chemical resistance) are required to perform the in-situ characterisation of materials, process monitoring and in-service inspection. This article presents a 32-element 5MHz transducer specifically designed for this type of applications. First, the design of the whole transducer is presented, then 1-3 piezocomposite configuration with improved performances is demonstrated and systematic study of the thermal behaviour of the different layers of the transducer is conducted. For the active layer, different configuration are studied including piezocomposites with different piezoelectric ceramic, filler material or ceramic volumic fraction. Thus

dielectric , piezoelectric and electroacoustic parameters are measured as a function of the temperature as well as the thermal conductivity. Using these results candidates for the targeted arrays are chosen. For passive (matching layers and backing) materials thermal conductivity as a function of the temperature and their main properties (acoustic impedance are disclosed.

Finally, the transducer is connected to a 32-element coaxial cable and integrated in a stainless steel housing. Resistance of the whole transducer to standard chemical agents is evaluated. Pressure and temperature cycles are applied to the transducer and the electro-acoustical performances are reported in the article, from cycle to cycle and complete characterisation of the transducer at 100°C is provided.

U3-K-6 511AB 4:45 p.m.

CONFIGURATIONS OF 40 KHZ ULTRASONIC COMPLEX VIBRATION SOURCES WITH COMPLEX TRANSVERSE VIBRATION RODS AND A DISK WITH MULTIPLE TRANSDUCERS

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The ultrasonic complex vibration systems with elliptical to circular locus are effective and essential for new high power applications in various industries. Configuration of a 40 kHz complex vibration source with a complex transverse vibration rod with a welding tip part and a disk with four bolt-clamped Langevin type longitudinal transducers (BLT) and welding characteristics of aluminum and aluminum alloy plates using complex vibration systems are studied. Outer diameters of the 40 kHz complex vibration sources are 191 to 195 mm which are about half of the diameter 395 mm of the 27 kHz vibration source that was developed previously. The complex transverse vibration disks (JISA5056 and SUS304) vibrate in (2, 1) mode that has two circular nodal lines and one radial nodal line and two BLT transducers of 30 mm diameter are installed symmetrically opposite sides of radial nodal line. The two transducers of are driven in anti-phase vibration mode using a 500 W static induction transistor power amplifier and a transformer whose transform ratio is 1:1:1. The other two transducers are installed in 90° direction to the former transducers. The two transducer pairs are driven in 90° vibration phase difference using two transformers, two power amplifiers and an arbitrary waveform generator with two output voltages of phase difference 90°. A stepped complex transverse vibration rod with a welding tip is installed in the center of the disk and is driven in circular vibration locus at the free edge of the rod (welding tip). Quality factors of the complex vibration systems are over 1200 and welding tip vibration amplitude over 10 μm (peak-to-zero value) is obtained under driving voltage of 200 Vrms. Using the ultrasonic complex vibration sources, various aluminum and aluminum alloy plate specimens were welded. Aluminum plate specimens

of 0.3 mm thickness and 1.0 mm thickness were welded with weld strength almost equal to the material strength under welding tip vibration amplitude of 1.0 μm which is very smaller than that required for conventional system with linear vibration locus. Aluminum alloy plates (JISA5052P) of 1.0 mm thickness were welded with weld strength almost equal to the material strength using welding tip vibration amplitude of 3.5 μm. Using ultrasonic complex vibration welding systems, ultrasonic welding of various metal plates becomes possible which is almost impossible using a conventional system with linear vibration. It have been shown that, using a complex vibration weld tip, weld area and weld strength become larger than that obtained using a conventional system and independent of the welding position.

Session: U4-K
ULTRASONIC MOTORS AND ACTUATORS II
Chair: M. Kurosawa
Tokyo Institute of Technology

U4-K-1 513AB 3:30 p.m.

A CYLINDRICAL MICRO ULTRASONIC MOTOR USING A MICRO-MACHINED BULK PIEZOELECTRIC TRANSDUCER

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In this paper, micro ultrasonic motors using micro-machined cylindrical bulk piezoelectric vibrators are introduced. There have been various kinds of micro actuators for micro systems. Among them, ultrasonic motors are promising actuators for micro mechanism applications like micro robots or microsurgery equipments. Cylindrical shaped bulk piezoelectric vibrator, a diameter of 0.8 mm and 2.2 mm, was developed as a stator transducer for traveling wave type ultrasonic motors. Since the stator transducer was fixed at the end of the cylinder, it is easy to support the vibrator and the structure of the motor was not complicated. This is important for micro ultrasonic motor because it is difficult to support the vibrator when the vibrator was miniaturized. The cylindrical ceramics was formed to be a pipe and step like shape by micro machining process. In addition, nickel was plated as electrodes on the surface and inside of the pipe. After the polarization process, the nickel film was divided to four electrodes by the laser beam cutting. Four electrodes on the surface of the cylinder type vibrator were used for the oscillation of the vibrator. The deformed shape and the resonance frequency were estimated by using the finite element method. The operating vibration mode was the fundamental bending mode. The vibration properties of the stator transducers were evaluated. At the resonance frequency of 70 kHz, the bending direction vibration amplitude at the end of the cylindrical

vibrator was 152 $nm_{o\text{-}p}$ at the driving voltage 5 $V_{p\text{-}p}$. The vibration velocity was not exceed 0.7 m/s. The rotational direction could be controlled by changing the polarity of the driving voltage. To evaluate the relationship between the applied voltage to the stator transducer, pre-load values, and the revolution speed, we used pre-load mechanism using a coil spring and a rotor. We have succeeded in driving this stator and could measure the revolution speed. The maximum revolution per minute was 8600 at the driving voltage of 40 $V_{p\text{-}p}$. The relationship between the output torque and pre-load values was also evaluated. The output torque was measured by using a load-cell. The measured output torque was 0.03 μNm when the pre-load value was 5 mN. A micro ultrasonic motor with pre-load mechanism was also fabricated. The motor was designed by the modal analysis using the finite element method. The diameter of the motor with pre-load mechanism was 2.0 mm, and the height was 5.9 mm. A rotor, whose diameter was 0.8 mm, was pressed to the end of the stator vibrator by using a spring whose diameter was 0.8 mm. An output shaft was united with the rotor, and the diameter of the shaft was 0.4 mm. We have succeeded in driving this motor and could measure the revolution speed. The maximum revolution per minute was 2500 at the driving voltage of 40 $V_{p\text{-}p}$.
This work was supported by the Mazda Foundation, and by the Cooperation of Innovative Technology and Advanced Research in Evolutional Area (CITY AREA) of the Ministry of Education, Culture, Sports, Science and Technology.

U4-K-2 513AB 3:45 p.m.

DESIGN AND TESTING OF A 4-MM^3 BIDIRECTIONAL LINEAR MICROFIN ACTUATOR

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The push for smaller and smaller actuators and sensors is the motivation for our research on micromotion devices. In this research, we describe the design and testing of a piezoelectric linear microactuator, consisting of a 6061T6 aluminum vibrator, machined using electrodischarge machining and fastened to a specially-stepped PZT (lead zirconium titanate) element. Two fins are atop the vibrator body at oblique angles and in contact with a slider. The vibrator is designed so that elliptical motion is excited at the end of each fin. Thrust is generated by the elliptical motion of the fin through friction force.

The key to the design is the use of two different masses on the tips of each fin to cause each fin to have slightly different flexural resonance frequencies. The vibrator is driven by a single-phase generator, and the moving direction can be changed by shifting the driving frequency from one fin resonance to the other. The longitudinal resonance of the PZT element is designed to lie between the flexural resonances of the fins.

We made several 3.25 mm $\times$ 0.5 mm $\times$ 2.6 mm prototypes. Through the measurement of their impedance and vibration velocity characteristics, the desired motion in the vibrator was shown to be present, with 1.25 m/s vibration velocity being generated in the fin tips at the operating resonances. Finally, using a highly-polished phosphor bronze slider, the motor operating characteristics were determined. At a driving frequency of 522 kHz, the motor moves to the right, while at 500 kHz it moves to the left. Measured data shows the peak sliding velocity and force to be over 20 cm/s and 0.15 N, respectively, giving a force density of 37.5 N/m^3 for this actuator.

The authors close with a description of a even smaller design, 0.25 mm $\times$ 0.25 mm $\times$ 0.5 mm, they have assembled and are preparing to test.

U4-K-3 513AB 4:00 p.m.

NUMERICAL STUDY ON SCATTERING OF RAYLEIGH WAVE BY SILICON SLIDER PROJECTIONS FOR SAW MOTOR

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From a numerical simulation, it has been shown that phase velocity difference of the Rayleigh wave between a stator and a slider causes low efficiency of a surface acoustic wave motor. The stator was 128 degree y-rotated $LiNbO_3$ and the slider was silicon. The frequency was 10 MHz, so that the wave length in LN was about 400 micron.

Surface acoustic wave motor has already shown a superior potential such as high speed up to 1.5 m/s, large thrust more than 12 N, high resolution down to 0.5 nm and so on. However, the efficiency from the electrical input to mechanical output is still low. To improve the efficiency, an energy circulation driving method has proposed and demonstrated. For the energy circulation drive, forward scattering beneath a silicon slider was found to be a problem, due to the change of phase relation.

By numerical experiment, scattering mechanism was investigated. Two dimensional FEM analysis in time domain was carried out to simulate the wave propagation from driving points through a pre-loaded silicon slider. The silicon slider has 20 micron diameter projections in intervals of 40 micron with 4 mm long. It has been pointed out that prestress in propagation medium causes the phase velocity change. Hence, the prestress condition due to the silicon slider projections was estimated. It was found that the phase change by the prestress was negligibly small, in spite of large equivalent pre-load value of 50 N in 4 x 4 mm square area.

For possibility of numerical simulation in finite time, the model was simplified to be simple boundary condition from actual physical model. The boundary condition between the stator and the slider was fixed to non-slip and non-takeoff. In this condition, wave phase change beneath the 4 mm long slider was about 9 radian.

U4-K-4 513AB 4:15 p.m.

VERY FAST SCANNING PROBE FOR OPHTHALMIC ECOGRAPHY USING AN ULTRASOUND MOTOR

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High frequency transducers, up to 35-50 MHz, are now used in ophthalmic echography to image fine eye structures. Phased array techniques are not practically applicable at so high frequency due to the small dimensions required for the single transducer element. Mechanical scanning is the only practical alternative. Mechanical scanning probes based on electromagnetic motors have a limited frame rate, up to 8-10 Hz, while a good feedback between probe positioning and operator image evaluation requires a refresh-rate of 15-30 frames per second. In this work, we present the design and the experimental characterization of the prototype of a fast scanning probe for ophthalmic echography, based on an small ultrasound motor previously developed. The prototype produces high resolution echographic images reaching a scanning rate of 15 frames per second, with very silent operation.

U4-K-5 513AB 4:30 p.m.

SINGLE CRYSTAL ULTRASONIC MOTOR FOR CRYOGENIC ACTUATIONS

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A novel single crystal piezomotor is presented in this paper for large stroke, high precision, and cryogenic actuations with capability of position set-hold at power-off. Regular PZT actuator/motor shows almost 0 motion at cryogenic environment, and electromagnetic motor consumes significant power which is not desired in many applications. The concept to be reported will advance the state-of-art cryogenic actuations considering that the excellent cryogenic properties (with d_{33} and d_{31} at 30K similar or higher than that of PZT at room temperature) and the great electromechanical coupling of single crystal piezoelectrics, and the novel design of the wobbling mode piezomotor with 33 mode single ring stacks instead of the conventional 31 mode plates for excitation. The cryogenic properties of PMN-PT and PZN-PT single crystals with <001> cut for 33 mode application, d_{32}-cut for 31 application and <110> cut for shear mode application have been investigated indicating excellent piezoelectric properties at temperatures down to 20 K. The 33 mode PMN-PT ring stacks with OD of 10 mm and ID of 3.5 mm is used as ultrasonic drivers. The effective d33

of this ring stack is about 1900 pC/N at room temperature leading to significantly improved wave amplitude comparing to PZT counterpart. FEA modeling considering the special piezoelectric and elastic properties of single crystals and the cryogenic environment is conducted using ATILA FEM software. A fine screw is used for linear motion translation and the expected maximum stroke is 10mm with response time of ms. The positioning resolution is around 10 nm and operation temperature range is 20K to 300K. The developed single crystal ultrasonic motor will be fully tested at both room temperature and cryogenic temperature and more results will be reported in the full paper.

The single crystal ultrasonic motor is presented for the first time for cryogenic actuations with large stroke, high precision, position set-hold at power-off characteristics which are desired for NASA adaptive optics, deployable truss structures, antenna tuning, and positioning.

This work is sponsored by NASA under contract NNC04CA87C. The authors would like to thank Dr. Benjamin C Platt from JPL for technical monitor on this project.

U4-K-6 513AB 4:45 p.m.

AN AUTONOMOUS SELF-POWERED ACOUSTIC TRANSMITTER USING RADIOACTIVE THIN FILMS

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We present a radioactively powered acoustic transmitter for wireless sensor nodes. The acoustic transmitter presented here integrates a piezoelectric acoustic transducer with a self-reciprocating radioisotope-powered piezoelectric unimorph actuator for long-life (10s of years) autonomous transmission operation. We have previously reported a radioisotope powered self-reciprocating cantilever [1], a directly charged piezoelectric beam (not a unimorph) that produces a RF pulse every reciprocation cycle [2] and a piezoelectric unimorph structure that efficiently converts the radiated kinetic energy into electrical energy [3] The radiated β-particles from the radioisotope are used to direct-charge an air-gap capacitor structure, formed by the collector plate at the tip of a piezoelectric unimorph cantilever beam and the thin-film radioisotope source plate placed directly underneath the collector. The collector plate eventually makes contact with the source due to the resulting the electrostatic force, discharging the air-gap capacitor and releasing the cantilever. The sudden release excites the unimorph mechanical impulse response, causing the cantilever to oscillate. The mechanical vibrations induce charges in the piezoelectric section of the monomorph, which are used to drive the acoustic transmitter. The stored mechanical energy is first converted into electrical energy by the piezoelectric unimorph and then into radiated acoustic energy in the external piezoelectric section. Eventually, the vibrations die out and a new cycle begins for the self-reciprocating actuator. Prototype transmitters were fabricated and tested to demonstrate functionality. The piezoelectric unimorph actuators were fabricated by solder bonding laser-cut PZT [4] plates to silicon beams. This monomorph was placed over a 4 millicurie/cm^2 Ni-63 (half-life=100.1 years) source and placed under vacuum (10-20 mTorr). The piezoelectric acoustic transducer was fabricated by electroplating nickel on laser-cut PZT (lead zirconate titanate) structures. It was placed outside the vacuum chamber and the displacement was monitored. At the end of every reciprocation cycle, pulse motion of 10 μm amplitude, with energy in the very low frequency of 17 Hz to the high frequency range of MHz was observed.

[1] Li et al., Digest of Technical Papers, Transducers'01, Vol. 1, pp: 744-47 [2] Li et al., Digest of Technical Papers, Transducers'03, Vol. 1, pp: 53-56 [3] Duggirala et al., to be presented at Hilton Head 03. [4] Duggirala et al., Digest of Technical Papers, Transducers'03, Vol. 2, pp: 1554-57

Session: U6-K

ADVANCED TECHNIQUES
Chair: B. Potter
Vectron International

U6-K-1 512A-F 3:30 p.m.

TEMPERATURE COMPENSATED LITAO$_3$ /SAPPHIRE BONDED SAW SUBSTRATE WITH LOW LOSS AND HIGH COUPLING FACTOR SUITABLE FOR US-PCS APPLICATION

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Temperature compensated SAW substrate with low loss and high coupling factor was developed by using direct bonding techniques. Conventional temperature compensating method of thick SiO_2 film on a piezoelectric substrate causes considerable insertion loss and the decline of coupling factor and requires extremely strict control of SiO_2 thickness. On the other hand, our direct bonding method has merits to keep the same coupling factor and propagation loss as the original piezoelectric substrate and need not strict control of substrate thickness. Temperature compensating method using direct bonding techniques requires support substrate with small thermal expansion coefficient, large elastic coefficients and large resistivity. Our temperature compensated SAW substrates were fabricated by direct-bonding $LiTaO_3$ substrate and Sapphire substrate. Sapphire is one of the ideal materials for the support substrate. Thickness of the piezoelectric substrate has also large influence on the temperature characteristics and spurious responses caused by reflection of BAW at the bonding interface. We found appropriate thickness of $LiTaO_3$ with good temperature performance and no spurious responses. As a result, good performance and high productivity were realized by using $LiTaO_3$ /Sapphire bonded substrate and US-PCS SAW duplexer with small temperature coefficient of frequency was developed.

U6-K-2 512A-F 3:45 p.m.

LOW RESISTANCE QUARTZ RESONATORS FOR AUTOMOTIVE APPLICATIONS WITHOUT SPURIOUS MODES

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The performance of one-port resonators is often affected by spurious transversal modes which in particular around the fundamental antiresonance are troublesome. In this work we demonstrate that by employing the fundamental antisymmetric instead of the fundamental symmetric waveguide mode to carry the main acoustic resonance, a suppression of these spurious resonances is obtained. The approach is particularily useful in applications where design considerations do not permit to form a single mode waveguide by reduction of aperture.

As example a one-port resonator on quartz supporting 5 transversal modes is investigated. The resonator exhibits undesired resonances closely above the fundamental antiresonance. The recently presented 2D P-matrix simulator [1] accurately describes this impedance characteristic. Employing the simulator a suitable antisymmetric resonator configuration was derived which efficiently suppresses the spurious resonances.

Insight into the role transversal modes play in forming the resonator's impedance characteristic is obtained by a decomposition of the resonator function into the contributions of the single transversal modes, by visualizations of the wavefield and a consideration of dispersion relations of the transversal modes.

[1] Markus Mayer, Andreas Bergmann, Günter Kovacs, Karl Wagner "A Powerful Novel Method for the Simulation of Waveguiding in SAW Devices, 2003 IEEE Ultrasonics Symposium, pp. 205-209

U6-K-3 512A-F 4:00 p.m.

ULTRA WIDEBAND LOVE WAVE DEVICES IN GHZ RANGE ON CU-GRATING/ROTATED-YX-LINBO$_3$-SUBSTRATE STRUCTURE

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This paper discusses the application of Love mode propagating on Cu-grating/ rotated YX-LiNbO$_3$-substrate structure for the development of ultra-wideband and low-loss RF SAW filters. It is known that the velocity of SH type SAWs on rotated YX-LiNbO$_3$ can be reduced by depositing thick electrodes such as Au, Ag and Al on the propagation surface, which makes SH type SAWs with large K^2 a non-leaky guided mode (hereafter, the guided SH type SAWs discussed are called Love mode). In the present study, heavy and hard Cu was chosen as an

electrode material instead of conventional Au, Ag and Al. Theoretical analysis shows that resonators with small capacitance ratio could be realised using Cu gratings of the thickness of several percent relative to the wavelength. When Au or Ag is employed as grating electrode materials, the required thickness becomes too thin for practical devices, whereas it becomes too thick when Al is employed. This suggests that Cu would be very promising to enhance the producibility of devices, while ohmic loss is considered not to badly increase because of the large electrical conductivity of Cu. It is also indicated that by properly choosing the substrate rotation angle, the spurious response due to Rayleigh mode would be suppressed without badly affecting Love mode characteristics. Next, IDT-type one-port SAW resonators were fabricated on the Cu-grating/15°YX-$LiNbO_3$-substrate structure, and a very small capacitance ratio of 3.7 and quality factor Q of 128 were obtained. Two ladder-type SAW filter were designed and fabricated. For the 751 MHz device, the minimum insertion loss of 0.9 dB and fractional -3 dB bandwidth of 14 % were simultaneously obtained. On the other hand, for the 1.7 GHz device, the minimum insertion loss of 0.6 dB and fractional -3 dB bandwidth of 15 % were obtained. These results clearly revealed potential of the Cu-grating/15°YX-$LiNbO_3$-substrate structure for developing ultra-wideband and low-loss RF SAW filters, though further investigation is necessary to improve total device performances.

U6-K-4 512A-F 4:15 p.m.

THEORETICAL AND EXPERIMENTAL RESULTS OF UNIDIRECTIONAL INTERDIGITAL TRANSDUCERS USING GRATING SAW SUBSTRATES AND NEW RESONATORS USING λ-PERIOD REFLECTORS

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Surface acoustic wave (SAW) filters employing a conventional interdigital transducer (IDT) show an inherent minimum insertion loss of 6 dB and a strong passband ripple for a low loss filter. In order to avoid these flaws, many types of unidirectional interdigital transducers are proposed. These unidirectional transducers have a small transducer efficiency. Therefore it is difficult to obtain wide band and low loss filters. In this paper we describe a new single phase unidirectional transducer (UDT) with about $\lambda/4$ electrode width of the best transducer efficiency. The new UDTs are fabricated on the very thin dielectric grating or the very shallow groove grating SAW substrates with $\lambda/2$ periods or λ periods. The electromechanical couplings (k2) of electrodes on SiO2 gratings decrease rapidly for film thickness. Therefore the good properties of UDT are obtained for the very thin thickness of SiO2 (about 0.06μm at 500MHz with electrode thickness of Al of 0.15μm). Also the very thin grooves have a large reflection coefficients of SAW and good UDTs are obtained. The calculation results showed wide band low loss filters below 1dB insertion loss. The experimental results showed below 1.0dB insertion loss with a wide band at 500MHz. The UDT can realize the 2dB insertion loss filters at 5GHz using a conventional fine lithography technologies. Also we show new SAW resonators using the admittance and susceptance changes with around λ period reflectors for high frequency filters. The exprimental results with quality factor of over 3000 have the good agreements to theoretical ones. The experimental results also show small spurious responses compared with conventional $\lambda/2$ period resonators.

U6-K-5 512A-F 4:30 p.m.

PHASE SENSITIVE OPTICAL MEASUREMENTS AND NUMERICAL SIMULATIONS OF A FAN-SHAPED FILTER

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Acoustic field profiles within a fan-shaped SAW filter have been studied with our new phase sensitive heterodyne laser interferometer. The laser interferometer features a tightly focused sample beam, a high-frequency optical detector and a high-resolution x-y-z sample translation stage. The heterodyne detection enables to determine the absolute amplitude of the surface vibration without calibrations. Care has been taken to simultaneously acquire both the absolute amplitude and phase maps of the acoustic field under study [1].

The sample is a two track 374 MHz fan-shaped filter on 112° $LiTaO_3$. The two tracks are identical in design and parallel to each other with the launching IDTs electrically connected in series. The launching IDTs are designed to be unidirectional. When the filter is driven at the center frequency, acoustic beams are formed at the center of the launching IDTs where the finger period matches the drive frequency. In addition, both main beams feature side lobes, as expected.

The measured phase and amplitude data of the acoustic field clearly show the nonzero power-flow angle of the substrate. Furthermore, there exists a phase difference between the main beam and the side lobes which is clearly visible in the measured phase data. To characterize the performance of the IDTs, the unidirectivity of the launching IDTs and the absorption at the output transducers are studied. The measured results are compared with detailed numerical simulations.

[1] K. Kokkonen, J. V. Knuuttila, V. P. Plessky and M. M. Salomaa, Phase-Sensitive Absolute-Amplitude Measurements of Surface Waves Using Heterodyne Interferometry, Proc. IEEE Ultrason. Symp., 2003, pp. 1145–1148.

This research has been carried out in the framework of the Eureka project E! 2442 SUMO. We are grateful to Marc Solal and William Steichen for valuable discussions.

U6-K-6 512A-F 4:45 p.m.

A STUDY OF ELECTROSTATIC DISCHARGE EFFECTS OF THE SAW PATTERN BY THE FDTD METHOD

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The purpose of this paper is to estimate the influences of the electrostatic discharge (ESD) of the SAW patterns by the full-wave approach based on finite-difference time-domain method (FDTD). The results can help producers design the guard pads on the SAW substrate to protect IDT from the ESD destruction. As the types of the SAW filters become more, the IDT sometimes has to be designed in a more complex and thinner pattern that will suffer from more serious electrostatic discharge challenges. An effective simulation method taking these phenomena into account is thus important for the designers to increase the reliability of the SAW filters and reduce the time to market. Earlier attempts in the literature used the finite element method, such as the High Frequency Structure Simulator (HFSS), to simulate the electromagnetic effects on the packaged SAW devices. However, the ESD issues are caused by the discharge of the accumulative electric charges that is a transient response in time-domain. Therefore, the HFSS based on the frequency-domain method is not suitable to simulate these effects. For this reason, the time-domain algorithm, the FDTD method, combined with equivalent current source approach and the model of the resistor is carefully used to investigate the ESD problems. According to the ESD standard of MIL-STD-883C method 3015.7, the value of equivalent capacitance and discharge resistance of human-body can be regarded as 100pF and 1.5k ohm. The equivalent current source method combined with the Spice model can effectively simulate the source of ESD and directly integrate with FDTD to calculate the values of the electric and magnetic fields in the calculated space alternately. By the Amperes law the distributions of the current on the SAW pattern can be obtained to analyze the relations between the shapes of the pads and the ability to attract extra charge, so as to design the guard pads to protect IDT more efficiently. Our approach has been applied to simple geometries on the SAW substrate and then the electromagnetic fields and the current distributions are observed concentrated around the edges and the sharp shapes that can be used to judge the degree of dangers. Finally, the investigation is extended to include several protective patterns by point discharge to reveal the efficiency of the protection.

The authors gratefully acknowledge the help of TAI-SAW Technology in useful discussions.

Session: FE1-K

MATERIALS PROCESSING
Chair: M. Creedon
Ferroelectronic Materials Systems

FE1-K-1 513CD 3:30 p.m.

SOLID STATE CONVERSION GRAIN GROWTH OF PIEZOELECTRIC SINGLE CRYSTALS

S. KWON*[1], W. HACKENBERGER[1], P. REHRIG[1], J. B. LEE[2], T. M. HEO[2], D. H. KIM[2], and H.-Y. LEE[2,3], [1]TRS Technologies, [2]Ceracomp Co. Ltd., [3]Sunmoon University.
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Solid-state single crystal growth (SSCG) involves the growth of a single crystal into a fine-grained matrix. SSCG process is driven by the difference in surface free energies of the advancing crystal plane and the matrix grains across a thin liquid layer during thermal processing. This process is an attractive method for fabricating piezoelectric single crystals because of its advantages in cost-effectiveness and suitability for mass production. It has been shown that many piezoelectric single crystals including $BaTiO_3$, $Ba(Ti,Zr)O_3$, and PMN-PT ($PbMg_{1/3}Nb_{2/3}O_3$-$PbTiO_3$) can be grown to a significant size and thus the SSCG method has been proven to be an effective way of growing single crystals. The recent results related to development of the SSCG process and characterization of SSCG single crystals, specially focusing on PMN-PT and will be presented. The grain size of precursor ceramics and processing parameters such as sintering atmosphere of the ceramic matrix and growth temperature of crystal will be correlated with the growth kinetics and quality of grown single crystal. The piezoelectric and dielectric properties of single crystals grown by the SSCG method will be compared with the values measured from single crystals fabricated by the Bridgman method. The feasibility of using SSCG for the growth of high Tc piezoelectric materials such as $BiScO_3$-$PbTiO_3$ will be also presented. The fundamental steps in templated grain growth, such as hetero epitaxial nucleation and growth, are examined in 36$BiScO_3$-64$PbTiO_3$ ceramics using $SrTiO_3$ and $BaTiO_3$ as template materials. The amount of excess PbO is correlated with the growth distance when $BaTiO_3$ single crystals are used as templates. More than 100 mm of growth was observed at 1150°C after 16 hr heat treatment for this system. When tabular $SrTiO_3$ particles are used as template materials, elongated grains 10 times larger than matrix grains were observed.

This work is sponsored by DARPA (contract number N00014-03-0327)

FE1-K-2 513CD 3:45 p.m.

FABRICATION OF PIEZOELECTRIC SINGLE CRYSTALS WITHOUT MELTING STEP OF MAJOR COMPONENTS

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Some piezoelectric single crystals (PMN-PT, PZN-PT, and PIN-PMN-PT, etc.) with very high electromechanical coupling factors (k_{33}>0.9), piezoelectric constants (d_{33}>2,000), and piezoelectric strains (>0.6%) have great potential in the applications of actuator and transducer. Recently the solid-state single crystal growth (SSCG) method has been applied to fabrication of the piezoelectric single crystals. In the SSCG process single crystals grow in polycrystalline precursors by grain growth mechanism without melting of major components. Since the SSCG process is basically same to normal sintering process, the SSCG process is very simple, cost-effective, and thus suitable to mass production of the piezoelectric single crystals. In the previous investigations single crystals of $BaTiO_3$, $Ba(Ti,Zr)O_3$, and PMN-PT were successfully grown up to 2 inches by the SSCG method. It was also reported that high Tc piezoelectric single crystals of PZT, PMN-PT-PZ, and PIN-PMN-PT were fabricated up to 1 inch. These results demonstrated that the SSCG process would be a primary single crystal growth method for piezoelectrics and relaxors.

In this presentation we will present recent progresses in SSCG process of piezoelectric single crystals and characterization of piezoelectric properties of the SSCG single crystals. By using the SSCG process, complex-shaped or near-net-shaped single crystals can be fabricated without machining of single crystals by machining or shaping polycrystalline precursors before a crystal growth step. Complex-shaped single crystals grown by the SSCG process will be also presented in this presentation. Some SSCG single crystals can be used as single crystal substrates for SSCG process as well as thin film growth of ferroelectric materials. Especially PZT single crystalline thin films were successfully grown on SSCG $Ba(Ti,Zr)O_3$ single crystal substrates by hydrothermal process. The growth rate and crystal quality of PZT single crystalline thin films on the $Ba(Ti,Zr)O_3$ single crystal substrates will be discussed and compared with those on commercially available $SrTiO_3$ single crystal substrates.

FE1-K-3 513CD 4:00 p.m.

MICROSTRUCTURE AND PIEZOELECTRIC PROPERTIES OF <001> FIBER TEXTURED PB(MG1/3NB 1/3)O3-PBTIO3 CERAMICS

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Textured PMN-PT ceramics were synthesised by homo-epitaxial template grain growth (HTGG) using PMN-PT nano-particles and cubic templates. Samples are prepared using doctor Blade method and sintered in controlled atmosphere. Orientation of the templates was obtained during tape casting. Textured Tape Cast Ceramics display quasi complete (001) texture (f=0.99) in the cubic phase. The (111) pole figure reveals (001) fibre texture in accordance with optical observation. The texture was obtained in all the volume and only small misorientation was observed. The samples were analysed by Raman spectroscopy and imaging. Relationships between Raman parameters such as band component centre of gravity and area versus composition (x) is proposed. Smart Raman imaging shows that the final composition is very close to that of the matrix. Formation of short-range ordered B/B domains is expected.

Piezoelectric properties measured at low level using RIE method show that coupling efficiency of tape cast textured ceramics (kp =0.69, d33= 600pC/N) are about twice of tape cast random ceramics but only 20% better than random optimised disk ceramic. Regarding low misorientation of the high textured ceramics, we conclude that poling process and ferroelectric domain reorganisation have to be extensively studied to clarify behaviour of textured ceramics.
This work was supported in part by "PYRAMID" project under European Fifth Framework Programme.

FE1-K-4 513CD 4:15 p.m.

NOVEL TRANSDUCERS BY LAYERED MANUFACTURING AND DIRECT-WRITE TECHNOLOGY

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Novel design transducers have been prototyped using Layered Manufacturing. Multimaterials actuators with piezoelectric and electrostrictive compositions in the Pb(Mg1/3Nb2/3)O3-PbTiO3 system (90/10 and 65/35 PMN-PT) were made and successfully fired. The dielectric and electromechanical behavior of monomorph and spiral actuators with symmetric and asymmetric electrodes were studied. Multimaterial spiral actuators exhibited improved displacement relative to single material (piezoelectric) spirals with same dimensions. Similar behavior was observed for the transducers with asymmetric electrodes where a thin (35 microns) steel shim was attached to the inner side of the spirals. Currently, transducers with concave and convex tubular geometry are under investigation in collaboration with Penn State University. Grain oriented PMN-0.35PT ceramics were also prepared using tape casting and fused deposition techniques. Platelet SrTiO3 templates, synthesized via molten salt technique, were incorporated into fine PMN-PT matrix to obtain oriented microstructures with a Lotgering factor of 50%. A new non-lead based composition in the system of (Bi1/2Na1/2)TiO3-(Bi1/2K1/2)TiO3-BaTiO3 (BNT-BKT-BT) system is currently under investigation. A thickness coupling factor of 45%, dielectric constant of 850, and d33 of about 150 pC/N were measured for the ternary composition. Preliminary results

on texturing of the BNT-BKT-BT with SrTiO3 templates show a Lotgering factor of 73% in the (00l) direction upon heat treatment of the sample at 1170°C for 2h in oxygen atmosphere. Thick films of doped PZT with and without additives (PbO, lithium bismuth oxide, and borosilicate glass) have been prepared using a Direct-Write technology (MicropenTM) on alumina substrates. Lithium bismuth oxide exhibited a positive effect on the microstructure and electrical properties of the PZT thick films sintered at relatively low temperatures. In addition, BaxSr1-xTiO3 thick films with x=0.4, 0.5, and 0.6 have been produced for microwave applications. The effects of sintering temperature (1300-1350°C) on the microstructure and the extent of reaction at the substrate/thick film have been examined. Properties such as dielectric constant, percent tunability, and loss are currently under being studied.
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FE1-K-5 513CD 4:30 p.m.

FERROELECTRIC AND RELAXOR FERROELECTRIC MATERIALS BY NEW SOL-GEL ROUTES

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This paper reports the development of new soft chemistry techniques for the synthesis of ferroelectrics and relaxor ferroelectrics. Solid solutions of the relaxor ferroelectric lead magnesium niobate lead titanate, (1-x)$Pb(Mg_{1/3}Nb_{2/3})O_3$ x$PbTiO_3$ [(1-x)PMNxPT, x = 0.10 and 0.35] have successfully been synthesized, via a polyethylene glycol-based new sol-gel method, in the form of dense ceramics of pure perovskite phase with good dielectric properties. This synthetic route results in a very stable sol which makes it very promising for thin film deposition. Ferroelectric layered perovskites, $SrBi_2Ta_2O_9$ (SBT) and $Bi_4Ti_3O_{12}$ (BIT), have also been prepared using a similar sol-gel process. Pure SBT ceramics were obtained by the sol-gel route and by a precipitation technique. The stability of the sol has allowed us to make the thin films of SBT with a pure perovskite phase at a relatively low temperature of 750 °C. The dielectric and ferroelectric properties of the ferroelectric ceramics and thin films have been characterized and discussed in relation with the synthetic and processing conditions with a view to improving the quality and performance of the materials.

FE1-K-6 513CD 4:45 p.m.

PROCESSING AND APPLICATION OF FERROIC GLASS CERAMICS

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Various ferroelectric and ferromagnetic glass ceramics have been developed to meet increasingly complicated requirements of electronic devices. In many cases, very complicated and comprehensive requirements of electric, magnetic, optic and mechanic behaviors are of much importance to specific applications. The processing requirements to the materials such as co-firing with other materials and/or electrodes, sometimes dominates the selection of materials. Glass ceramics are introduced to meet such special requirements. Most major ferroelectrics and ferromagnetics can be prepared as glass ceramics by using sol-gel technology. The glass content of the glass ceramics can be adjusted in very wide range from less than a few percent to more than ninety percent. The size of ferroic crystallites can be controlled in the range from nanometer to micrometer sizes. The electric, magnetic and optic behaviors of the glass ceramics will mostly inherit from the crystalline components, while the mechanical and processing behaviors will be mostly depending on the glass components. The electric, magnetic, optic, elastic, and thermal behaviors of the glass ceramics can be tailored in much wider range compare to the crystalline counter parts. The ferroic glass ceramic can be prepared in the form of bulk ceramics, thick and thin films. The preparation, behavior and application as electronic devices will be discussed in this talk.