* Author presenting Paper

Session: U1-C
CONTRAST AGENTS - FUNDAMENTALS
Chair: N. De Jong
Erasmus

U1-C-1 510AC 10:30 a.m. (Invited)

CONTRAST AGENTS

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In the past decade, microbubble contrast agents have evolved from a technical curiosity into a new clinical modality for ultrasound imaging. Among other achievements, microbubbles can be credited with the first real time images of myocardial perfusion that have been made by medical imaging. The agents themselves are now into their second generation, dominated by the use of perfluorocarbon gases and thin, flexible shells. The first synthetic shell agents using polymers designed to decouple the physical stability of the bubble from its acoustic behavior are near to clinical availability; work is now underway to associate these constructs with targeting ligands as well as drugs, genes, and other biological agents that will eventually be delivered using bubbles.

The effort to image microbubbles has warded advances in imaging technology that expand beyond contrast studies; tissue harmonic imaging has become a standard method in the clinic, often used in preference to conventional linear imaging of organ structures. For microbubble detection, the challenge of detecting bubbles without disrupting them, while rejecting both the tissue echo and the echo from the propagation harmonic has stimulated significant innovation in imaging strategies. Most approaches include sequences of pulses, with periodic modulation of amplitude or phase, or both, followed by some form of Doppler detection. Their success relies on an understanding of the behavior of bubbles in an acoustic field, an area that has benefitted from the recent advent of extremely fast cameras. In particular, the mechanisms of bubble disruption are only now beginning to be understood. These are important not only because they underlie the most sensitive method to detect a bubble, but because disruption followed by reperfusion offers a unique opportunity to quantify microvascular flow and volume. These quantitative flow measurements do, however, depend on assumptions about vascular geometry and indicator concentration and are at present less well validated than they should be. Finally, the issue of the very low concentration of microbubbles (usually less than 100 per ml of tissue) and the unknown subpopulation that undergoes resonant oscillation and hence are detectable, has yet to be addressed. One approach that will be shown involves tracking individual bubbles, allowing them to create striking, map-like images of microvascular structure.

U1-C-2 510AC 11:00 a.m.

MICROBUBBLE SURFACE MODES

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Bubbles insonified by ultrasound will generally exhibit a radial oscillation mode. In addition, surface waves can be generated through instabilities at the interface of the liquid medium and the gaseous content of the bubble. These so-called surface modes have been studied extensively for millimeter-sized droplets and bubbles. Here, we investigate surface waves generated by ultrasound excitation of individual micron-sized bubbles. Single air bubbles with diameters ranging from 30 μm to 120 μm were generated in a regulated co-flow micropipette injector. The injector allowed for a controlled production of microbubbles, both in diameter and in separation distance. The bubbles were left to rise to the test section at a downstream distance of 4 cm from the injector. The bubbles were insonified with a pulse of ultrasound from a flat transducer consisting of a burst of 8 cycles at a frequency of 130 kHz. The acoustic pressure leading to the production of surface mode oscillations was ranging from 37 kPa up to 150 kPa. We also investigated phospholipid-coated microbubbles (Sonovue, Bracco) contained in a 150 μm diameter fiber which were subjected to ultrasound from a focused transducer at frequencies of 1 to 4 MHz. The experiments were conducted with mechanical indices in the range of 0.1-0.6. The microbubble dynamics was recorded with an ultra high-speed camera at a frame rate of up to 16 million frames per second. It was observed that the free microbubbles developed surface vibrations after several volume oscillations. The preferred mode vibration was linearly related to the bubble size, where a mode $n = 3$ was observed for an 80 μm diameter bubble while a surface vibration up to mode $n = 7$ was observed for a 120 μm diameter bubble. In addition, it was found that the surface wave oscillations occur with a periodicity at the half subharmonic of the transmit frequency. This is consistent with previous theoretical and experimental investigations of free millimeter sized bubbles. For encapsulated bubbles it was found that surface mode vibrations are generated even at low M.I.. For example, a 4.1 μm Sonovue bubble exhibits a mode $n = 3$ surface vibration when insonified with a frequency of 4 Mhz at a pressure of 100 kPa. The encapsulated bubbles also predominantly oscillate at the half subharmonic, therefore these new observations of contrast agent behavior may lead to an improved understanding of the generation of acoustically observable subharmonic energy. In addition, surface modes may provide insight into shell properties, acoustic steaming close to the bubble and bubble fragmentation and destruction.

U1-C-3 510AC 11:15 a.m.

AIR BUBBLE OSCILLATIONS IN AN ULTRASOUND FIELD: THEORETICAL AND OPTICAL RESULTS

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Introduction: The study of bubble oscillations in an acoustic field is a fundamental subject to better understand physical phenomena. This can find applications in acoustic cavitation, gaseous emboli and ultrasound contrast agents. Many studies have been conducted to develop a theoretical model that describes the radial motion of the bubble radius. These models have been widely investigated numerically or analytically and have brought fruitful information about the bubble behavior. The aim of this study was to qualitatively and quantitatively compare the results obtained with optical recordings and a theoretical model of bubble dynamics. Methods: The bubble oscillations were optically recorded using the ultrafast digital camera, BRANDARIS. The radius-time curves are directly computed from 128 video frames with a high temporal and spatial resolution. Individual air bubbles with a resting diameter ranging from 26μm up to 100 μm were generated in a flow micropipette and explored in this study. Ultrasound consisted of an 8-cycle pulse at a frequency of 130 kHz generating an acoustic pressure between 10 kPa and 150 kPa. Optical recordings were performed at 1.2 MHz frame rate. The time and frequency responses of the bubble radial motion were compared to the Keller model. Results: For low acoustic pressures, the amplitude of the bubble oscillations at the fundamental and second harmonic frequency is maximal for an air bubble with a resting radius of 24 μm, which corresponds to the theoretical resonance size at 130 kHz. The oscillations decay in strength for bubbles above and below the resonance. The comparison between the experimental and the simulated time and frequency responses of the bubble shows globally a very good agreement both qualitatively and quantitatively and for all bubble sizes. The theoretical model correctly reproduced the nonlinear features of the bubble oscillations observed optically. Both the model and the experiments showed that the second harmonic generation is maximal for resonant bubbles and for bubbles with half resonance size, whereas bubbles above the resonance size required much higher acoustic pressures to oscillate nonlinearly. For bubbles close to twice resonance size ($r=48\mu$m), the predicted subharmonic oscillations agreed well with the measurements for relatively low driving levels. However above a certain acoustic threshold and depending on their size, the bubbles were induced into non-volumetric motion where surface modes appear. In this case the model was unable to predict the subharmonic component accurately. Conclusions: Keller model can be used to accurately predict the linear and nonlinear scattering of gas bubbles. One of the applications is the prediction of the behavior of gaseous microemboli in an ultrasound field.

U1-C-4 510AC 11:30 a.m.

NOVEL METHOD OF MICRO BUBBLE MANIPULATION BY SELF ORGANIZATION IN ULTRASONIC WAVE

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Ultrasonic wave assisted micro bubble manipulation is a promising technology, for example, in future drug delivery system. Several methods have been proposed in order to manipulate the micro bubbles, however, these methods assume that the bubbles receive sufficient acoustic radiation force for producing the required bubble motion. This may not be satisfied in some future applications, because the bubble has hard shell in order to prevent the internal gas rectified diffusion or the bubble has multiple shells in order to carry material, such as drug, as a payload. These shells suppress the volumetric oscillation of bubbles resulting in decrease of received force in bubble manipulation. In this paper, novel method of ultrasonic wave assisted micro bubble manipulation is proposed. We use self organization of seed bubbles in order to manipulate the target bubbles whose volumetric oscillation is too small to manipulate by themselves. If the seed bubbles flow into the ultrasonic wave field, they start to oscillate radiating the secondary ultrasonic waves around them. The secondary waves interact with the incident wave generating the Bjerknes force between the neighboring bubbles. If the force is an attractive one, the bubbles are self organized to make bubble aggregation and the aggregated bubbles are trapped at adequate positions inside the ultrasonic wave field. Then the target bubbles flow into this area, relatively large Bjerknes force field around the seed bubbles traps the target bubbles making bi-layered bubbles mass (inner layer is seed bubbles and the outer layer is the target bubbles). The bi-layered bubbles mass has enough sensitivity to the ultrasonic wave, it is possible to manipulate the target bubbles, as payloads of the seed bubbles. The Bjerknes force between the seed bubbles and the target bubble is derived theoretically and the required conditions to build up the bi-layered bubbles are evaluated. The experiments are carried out using PVC shell bubbles with mean radius of 10 mm (seed bubbles) and the bubbles with multiple micro holes over hard shell (target bubbles). The ultrasonic wave frequency is 2.5 MHz and the peak acoustic pressure is 100 kPa. Two concave ultrasonic wave transducers are used in order to produce lateral shifting ultrasonic wave field. When only the target bubbles flow into the ultrasonic wave field, any bubble aggregations are not observed. However, if the seed bubbles are introduced to make aggregated bubbles before the target bubbles, the target bubbles are trapped as bi-layered bubbles. As an example of bi-layered bubble manipulation, lateral movement of the bubble is demonstrated by shifting the phase of two ultrasonic waves.

U1-C-5 510AC 11:45 a.m.

MONITORING THE PULSE-TO-PULSE EVOLUTION OF MICROBUBBLE CLOUDS USING LIGHT SCATTERING

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Measurements of the dynamical response of ultrasound contrast agents to diagnostic and therapeutic ultrasound pulses have been accomplished with light scattering. Previously, we showed how a simple light-scattering approach can be used to resolve the instantaneous motion of single microbubbles and provide information about the bubble evolution over many acoustic cycles. We applied this same technique to monitor the evolution of clouds of Optison microbubbles subjected to pulsed ultrasound from a diagnostic ultrasound system. A diluted suspension of Optison microbubbles was injected into a solution containing water and a slight amount of xanthan gum gel. The gel was such that the solution was slightly more viscous than without the gel, allowing for the bubble cloud to slow and stabilize soon after injection. A 30-mW laser beam passed through the suspension, scattering off multiple bubbles. A lens and aperture set at 80 degrees from forward scattering concentrated the signal onto a photodetector. A diagnostic imaging system (Philips HDI5000, with a C5-2 probe) was focused at the region of bubbles and laser beam. Bubble oscillations were measured by focusing the light scattered by the microbubbles onto the photodetector. Data was collected with a fast oscilloscope set up to capture instantaneous bubble oscillation data for 40 consecutive ultrasound pulses. During insonation, bubble oscillations could be observed as sinusoidal changes in the scattered light signal. At low MI settings, bubble oscillations were relatively linear. In some cases, we observed an increase in the background light scatter amplitude, suggesting that bubble coalescence or gas diffusion occurred. At higher MI settings, the motion was nonlinear. Bubble fragmentation could be observed as the background light scattered signal decreased significantly from pulse to pulse. Power spectral density analysis showed broadband behavior, suggesting that bubble activity was inertial.

We are grateful to Philips and especially Mike Averkiou for the HDI5000 and for numerous discussions, and to NIH, 8RO1 EB00350-2.

Session: U2-C

BEAMFORMING I
Chair: K. Thomenius
GE

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

SPATIAL AND TEMPORAL STABILITY OF TISSUE INDUCED ABERRATION

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The limited number of working, real-time adaptive imaging systems currently employ near-field phase correction techniques. Near-field models may not be the most ideal representation of true aberration, however, their correction techniques are desirable because of their simple implementation and their ability to be executed in real-time. Aberrator stability is important to adaptive imaging because it defines the limitations of the near-field correction techniques as they are applied to the clinical environment. Spatial aberrator stability defines the size of the isoplanatic patch and determines the required spatial update of the aberration profile. Temporal aberrator stability defines the length of time for which the aberration profile is valid. For a near-field aberrator under ideal scanning conditions, spatial and temporal stability are infinite. However, transducer/tissue motion, target heterogeneity, noise, and tissue acoustic velocity and attenuation variations removed from the transducer face all contribute to decreased stability. We have measured the spatial and temporal stability of aberration in breast, thyroid, and abdominal imaging. Individual channel data was acquired on a Siemens Antares scanner using the Ultrasound Research Interface (URI) and a 9 MHz, 1.75-D transducer (Tetrad Corp., Englewood, CO). Two-dimensional aberrations were measured over space and time and correlated to determine the extent of the aberrator stability. While the temporal coherence of the aberration is expected to maintain a correlation coefficient of 1, decorrelation due to operator/patient motion and noise decreased aberrator correlation to 0.82, 0.72, and 0.65 in breast, abdomen, and thyroid tissue, respectively, within 0.5 seconds and leveled off to 0.75, 0.62, and 0.67 after 1.5 seconds. Larger decorrelations from motion are expected in the thyroid due to the proximity of the carotid artery. The measured spatial decorrelation of the aberrator is primarily affected by SNR and motion. For breast tissue, we measured significant spatial stability in aberration, with neighboring profiles correlating between 72% and 94%. Abdominal tissue exhibited lower spatial stability than breast tissue due to increased motion and decreased SNR and had neighboring aberrator correlations ranging from 0.71 to 0.82. Aberrations in the thyroid showed smaller spatial stability than breast or abdomen with correlations ranging from 0.43 to 0.74 for neighboring aberrations. We compared these results with controlled simulation and phantom experiments to discern the effects of noise, SNR, and

motion on aberrator stability. We discuss the implications of aberrator stability as they apply to real-time adaptive imaging.

This work is supported by NIH grant RO1-CA43334 with technical support from Siemens Medical Solutions, USA.

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

A NEW ADAPTIVE IMAGING TECHNIQUE USING OPTIMAL APERTURE SIZE

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Focusing errors caused by sound-velocity inhomogeneities in human tissue, also known as phase aberrations, reduce coherence of the received signals. Low coherence results in high sidelobes in the radiation pattern and degrades contrast resolution. Several adaptive imaging techniques have been proposed in the past to compensate for such errors. Among them, the correlation based techniques have been widely adopted, but its performance is primarily limited by the elevational aberrator integration error of a one-dimensional array. Another approach is based on adaptive removal of undesired sidelobe contributions utilizing multiple receive beams. Although this approach does not require elevational sampling of the aperture, its computation requirements prohibit its real-time implementation. In this paper, an efficient adaptive imaging technique using optimal receive aperture size is proposed. The technique determines the optimal aperture size based on the coherence factor, which is defined as the ratio of the coherent energy to the incoherent energy. The coherence factor quantifies coherence of the received array signals, and a threshold can be set to distinguish a mainlobe signal from sidelobes. With the thresholding, the receive aperture size (i.e., the number of active receive channels) at each imaging position can be optimally determined so that the final array sum is maximum for the mainlobe and minimal for the sidelobe. Consequently, focusing errors can be reduced and image quality degradation resulting from undesired sidelobe contributions can be compensated. Efficacy of the proposed technique was demonstrated by simulations and experimental array data. A time delay error profile with a 5 mm correlation length and a 71 ns maximum delay error was simulated. Simulated beam plots showed that the sidelobes were effectively suppressed, even when no aberration was present. Generally speaking, the sidelobe reduction was 5-15 dB and 7.3 dB contrast improvement was demonstrated with an anechoic cyst. Results from experimental array data of a tissue mimicking phantom indicated a 40% improvement in contrast-to-noise ratio for no aberration and a 130% improvement for severe aberrations. It is clearly shown that the proposed technique effectively reduces sidelobes and decreases speckle variance. It is also shown that the proposed technique outperforms other adaptive imaging techniques in image quality improvement while requiring less computations. Methods and results of the proposed adaptive imaging technique will be presented. Effects

of the signal-to-noise ratio as well as its computational complexity will also be discussed.
Support from Siemens Ultrasound is greatly appreciated.

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

HIGH RESOLUTION ULTRASONIC BRAIN IMAGING: NON INVASIVE ADAPTIVE FOCUSING BASED ON TWIN-ARRAYS

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Ultrasonic imaging systems assume a constant acoustic velocity in human tissues in the beamforming process. However, in the case of brain imaging, strong skull aberrations induce a spreading in the main lobe and an increase in the sidelobes level. This limits considerably ultrasonic brain imaging applications. It has been shown that a very accurate focusing could be achieved through a human skull by using an inverse filter technique. This method, based on a set of acoustic sensors located inside the brain, demonstrated invasively that it was possible to achieve high resolution brain imaging. We developed a non invasive ultrasonic method based on two arrays located on each side of the head. Each array focuses on the other one in order to deduce the aberrations induced by each side of the skull bone. Basically, the amplitude distortions induced by one given skull bone are deduced by performing a time reversal experiment on each element of the array located close to this skull bone: the square root of the amplitude received on each element corresponds to the amplitude distortion induced by the piece of skull in front of this element. Similarly, phase aberrations are deduced by comparing different focusing on each element of the array. In fact, time reversal ping pong through the entire skull allows to separate the influence of each skull bone. Once the influence of each skull bone has been evaluated, the propagation operators through each skull bone are calculated and inverted in order to perform a non invasive inverse filter focusing. This non invasive technique lowers the secondary lobe level up to 15dB compared to a non corrected cylindrical focusing, as shown on experimental directivity patterns acquired through a human skull. The impact of this improvement in the focusing quality is shown on ultrasonic images of cyst models reconstructed with this non invasive technique: cysts are not visible without aberration correction, whereas they are clearly visible on the images reconstructed with the focusing technique presented in this paper.
This work was supported by grant QLG1-CT-2002-01518 (UMEDS: Ultrasonographic Monitoring and Early Diagnosis of Stroke) from the European Commission.

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

RESOLUTION IMPROVEMENT OF POINT TARGETS THROUGH REAL-TIME PHASE ABERRATION CORRECTION: IN VIVO RESULTS

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We report on improved resolution of suspected microcalcifications and other point-like structures in the human breast in vivo using a phase aberration correction algorithm implemented in real time on a Siemens Antares ultrasound scanner. Images of point-like targets in 10 volunteers showed an average reduction in width of 23%.

Ten patients receiving treatment at the Duke University Medical Center volunteered for this study. Patients were scanned with a purpose-built 9MHz, 8x96 1.75D array transducer. Individual-element RF signals for a single image A-line were extracted from the Antares beamformer and loaded into the system computer. After compensating for geometric delays the aberration profile was estimated by cross correlation of signals using a least-squares algorithm over a 3x5 element neighborhood. The delays estimated were used to modify the transmit and receive beamformer delays. The correction profile was applied to all A-lines of the image. The time between reception of the RF echo and application of the correction profile was approximately 1.5 seconds. The scanners video output was recorded to DVD for offline analysis.

Single video frames captured at times just before and just after application of aberration correction were compared. Two to three targets per image were examined. The targets were near the center of the image, where the aberration profile was calculated. The change in point-image width was estimated with sub-pixel precision by comparing upsampled image lines at a threshold of 50%. The average reduction in point-image width was 23%. The average brightness increase was 4.5%. We postulate that this relatively small improvement in brightness is due back-end image processing, i.e. logarithmic compression. Offline processing of individual-element RF data captured on the same patients shows a pre-log compression increase in envelope amplitude of 39% after off-line aberration correction using the same algorithm. We discuss these results and their implication for clinical imaging using phase-aberration correction

This work was supported by NIH Grant R01-CA43334. We gratefully acknowledge the support of Siemens Medical Solutions, USA for their equipment and support.

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

REFOCUSING DUAL-MODE ULTRASOUND ARRAYS IN THE PRESENCE OF STRONGLY SCATTERING OBSTACLES

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One of the main advantages of phased arrays as HIFU applicators is the feasibility of optimization of power deposition at the target(s) while minimizing the power deposition at strongly scattering obstacles. Dual-mode ultrasound arrays (DMuA) are considered for this application, where the imaging capabilities of the applicator are used in the optimization of the targeting process. The optimization procedure is based on the use of single-transmit focus (STF) imaging, in which a single transmit imaging beam employing the same delays as the intended therapeutic focus is used. Full dynamic receive focusing is used to form images of the target region. STF imaging has been shown to offer a very sensitive imaging tool for visualization of HIFU-induced lesions (due to inherent registration between the coordinates of both therapeutic and imaging foci). Another important advantage of sub-threshold STF imaging before lesion formation is that strongly scattering structures that may obstruct the therapeutic beam can be easily identified. This allows for refocusing algorithm for optimization of power delivered to the target(s) while minimizing the incident power at the obstructing obstacle(s). In this paper, we present experimental results of a DMuA refocusing algorithm that selects the control points from the target(s) and the ribs visible in the STF image. The new phases and amplitudes (for HIFU beam) or focusing delays (for adaptive focusing) are obtained by solving a constrained optimization problem that minimizes the direct incidence of acoustic power at the ribs as it optimizes the power delivered to the target. A 64-element 1 MHz DMuA prototype was used to refocus on a fine needle thermocouple within a tissue-mimicking phantom near the geometric focus. Four Plexiglas 1.2 cm diameter ribs were placed in front of the target (as seen from the DMuA prototype). Thermocouples were positioned on the ribs on the DMuA side in the imaging/therapy plane. The temperature at the target and the ribs were recorded before, during and after 3 s HIFU exposure for the following cases: 1) geometric focusing, 2) refocusing without considering the presence of the ribs, and 3) refocusing with accounting for the ribs. The input electrical power to the system was kept practically the same and the ratios of temperature at the target and the ribs per W/sq. cm of input were recorded. For example, in one experiment, two ribs were visible in the STF image obtained with the geometric focus. When this beam was used for heating, the temperature to power ratios were 0.47, 0.21, and 0.1 at the target and two ribs, respectively. When the DMuA was refocused using the proposed optimization algorithm, the ratios were 6.4, 0.5, and 0.22. This illustrates a 5-dB increase in intensity gain at the target with respect to the most significant obstacle. We have also recorded corresponding increase in target intensity with respect to this rib in the STF image using the refocused beam (from 11 dB to 5 dB below the rib intensity). A complete discussion of this form of image-based feedback for refocusing will be given.

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

SYNTHETIC APERTURE ANGULAR SCATTER IMAGING

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Angular scatter imaging has been proposed as a new source of image contrast in medical ultrasound and as a parameter for tissue characterization. While angular scatter has been researched for nearly twenty years, only recently have techniques been presented to acquire coherent data at multiple scattering angles. These methods utilize the Translating Apertures Algorithm (TAA) by moving the transmit and receive apertures in equal and opposite directions between interrogations, to maintain a nearly identical point spread function (psf) as new scattering angles are interrogated. Ideally, the only variations seen are the result of intrinsic variations in scattering by the target. Unfortunately such ideal behavior is only possible at the system focus. Furthermore, when the TAA is applied using large focused apertures, multiple scattering angles are interrogated in each acquisition, blurring the system resolution in the scattering angle dimension.

We propose a new method of acquiring angular scatter data that combines the TAA with synthetic aperture methods to coherently acquire angular scatter information with high resolution in both space and scattering angle. This method, which we term Synthetic Aperture Angular Scatter (SAAS) Imaging effectively applies the TAA to single array elements and then focuses data synthetically to form high resolution images at precisely defined scattering angles. Not only does SAAS achieve high spatial and angular resolution, but it also avoids the limited depth of field that constrains the TAA.

One challenge in implementing SAAS is the strict spatial sampling requirement imposed on the transducer array. While one wavelength sampling is adequate for linear arrays with conventional beamforming, the requirements for SAAS are twice as strict, requiring half wavelength sampling for linear arrays. We describe a modified approach to SAAS that gives up some angular resolution in return for a reduced spatial sampling requirement. We describe this technique in k-space and provide an intuitive explanation of its behavior. We present simulation results showing that the modified SAAS reduces grating by a factor of greater than 100 (-40 dB).

We have implemented SAAS on a GE Logiq 700MR system. We imaged a 20 μm steel wire target and an RMI tissue mimicking phantom using both the original and modified SAAS. The wire target data shows a reduction in grating lobes from -23dB to below the noise floor (-50dB). The RMI tissue mimicking phantom images show high speckle correlation across angles ranging from 180° (backscatter) to 156° while maintaining a large depth of field and excellent spatial resolution. We applied the modified SAAS to form angular scatter images of a 3-wire phantom (cotton, nylon, steel) and in vivo human thyroid. These images show that angular scatter clearly offers new image information unavailable in conventional b-mode images. These results suggest that angular scatter imaging may have applications in the breast, thyroid, and peripheral vasculature.
The authors acknowledge technical support from GE Global Research and grant support from the U.S. Army CDMRP in Breast Cancer.

Session: U3-C

CMUT MODELING
Chair: Y. Roh
Kyungpook National University

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

A SIMPLE DISTRIBUTED MODEL FOR C-MUT

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Capacitive micromachined transducers are now considered to show a high technological potential to make high performance air-coupled or water-coupled transducers. Precise modelling of their behaviour have to made during the design process prior to engineering and after for the experience feedback. The influence, in terms of final performances, of both the geometrical parameters and mechanical properties of the c-MUT layers have to be known. Geometrical parameters include size and thickness of the diaphragm, electrode and gap, mechanical properties mainly being flexural rigidity and residual stress linked to the manufacturing process. Different modelling approaches can be found in literature from the most simple one : 1D mass-spring analysis, up to large scale computing using finite elements models (FEM) for calculation of the electrical and the mechanical fields including the radiated acoustic field. Our objective has been to build up a calculation process in between these two extremes : accurate enough for being used in design engineering and avoiding massive electromechanical FEM. In our approach, the moving part of the c-MUT is considered as an axisymetrical plate which both flexural rigidity and volumic mass depend on the radial co-ordinate. This can then, take into account the sizes and the profiles of the electrode diaphragm. Because of the gap small size, the electrical force distribution is easy to link to the electrode profile. Then, the usual equation describing a pre-stressed plate under a known force distribution [1] is used and sampled. Firstly, the static c-MUT profile is found according to the bias voltage. This is done through an iterative process since the electrical forces are non linear with displacements. Of course, non convergence tells that the collapse voltage has been reached. Linearisation of the dynamic equations around the static equilibrium gives a pair of coupled matrix equation linking mechanical and electrical vectors. Solving that leads to the determination of the suited figures like resonant and antiresonant frequencies or the internal parameters of the equivalent circuit for the c-MUT. One of the important issues to be considered is the coupling with the radiated field of the hundred of cells which are used to create one array element. The collective function, as well as the analysis of inter element cross-coupling can be taken into account through the adequate choice of matrix for fluid loading. For seek of validation, one simple calculation process has been checked with FEM published results [2] trying to produce master curves like C(V/Vcollapse) and kt(V/Vcollapse) where C, kt, V and Vcollapse are the

static capacitance, the coupling coefficient, the bias voltage and the collapse voltage. Moreover, simulation results have been confronted with experimental data issued from the characterisation of c-MUT with different geometries.

[1] A. Caronti and al., IEEE-UFFC, vol. 49-2, pp 159-168, 2002. [2] G. G. Yaralioglu and al., IEEE-UFFC, vol. 50-4, pp 449-556, 2003.

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

DYNAMIC FEM ANALYSIS OF MULTIPLE CMUT CELLS IN IMMERSION

B. BAYRAM*, G. G. YARALIOGLU, A. S. ERGUN, and B. T. KHURI-YAKUB, Stanford University.
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This paper reports on the modeling of immersion capacitive micromachined ultrasonic transducer (CMUT) membranes using finite element analysis. A dynamic analysis of CMUT has been performed using commercially available finite element software LS-DYNA. Our 3-D model includes a square-shaped silicon membrane, which rests on silicon substrate. The model also includes a fluid medium over the membrane. The membrane is insulated and supported at the edges by silicon oxide. Symmetry boundary conditions on the planes surrounding the model are applied such that the single cell is infinitely replicated in the membrane plane. Absorbing boundary conditions on the plane terminating the fluid eliminate the reflected waves to act as an infinite medium. Contact surfaces are defined on the bottom of the membrane and on the top of the insulation layer to model the collapse of the membrane. CMUTs are biased with a DC voltage and excited by a rectangular pulse or an AC voltage. Depending on the amplitudes of these voltages relative to the device collapse and snapback voltages, the devices operate in the conventional, in the collapsed or in the collapse-snapback regime.

Using the described model, dynamic analysis has been performed. The membrane is 32 um wide and 0.75 um thick. Initially, the substrate is clamped. The collapse and the snapback voltages of the membrane have been calculated to be 55 V and 40 V, respectively. The membrane has been biased to operate in three different regimes. In the conventional regime, the bias voltage (30 V) has been kept below the collapse voltage and the membrane has been excited without contacting the substrate. In this case, 30 kPa/V output pressure and 100% bandwidth have been calculated. In the collapsed regime, the bias voltage has been set to 65 V. Our calculations showed 113 kPa/V output pressure which is higher than that of the first case. In the collapse-snapback regime, the membrane operated in and out of collapse by selecting bias voltage (45 V) and excitation pulse amplitude (20 V) applied to the membrane. This regime yielded the highest output pressure. Finally, the substrate is included in the analysis and the effect of wave coupling into the silicon substrate is investigated. The inclusion of the substrate resulted in the reflected waves coming from the backside of the substrate on the output waveform. Periodicity of the single cell and substrate thickness has been adjusted to minimize the reflected waves.

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

ANALYTICAL CALCULATION OF COLLAPSE VOLTAGE OF CMUT MEMBRANE

A. NIKOOZADEH*, B. BAYRAM, G. G. YARALIOGLU, and B. T. KHURI-YAKUB, Stanford University.
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The collapse voltage of a capacitive micromachined ultrasonic transducer (CMUT) is an important parameter since it determines the operation point of the device. Therefore, it is crucial to calculate and control this parameter. As a first order approach, one can use parallel plate approximation where the average membrane displacement is modeled by a parallel plate motion. In this approach, applied voltage between the plate and the bottom electrode creates electrostatic forces and a spring that is holding the plate counter balances these forces. For this configuration, the collapse of the plate onto the substrate occurs when the electrostatic force gradient overcomes the restoring mechanical force. The calculation based on this approximation usually yields calculated collapse voltage 25 percent higher than the actual collapse voltage. More accurate calculation involves finite element analysis. However, FEM analysis requires iteration between electrostatic and mechanical solution and the computation time is usually on the orders of hours depending on the required accuracy. In this paper, we propose a fast numerical algorithm for the calculation of collapse voltage. The algorithm uses parallel plate method and analytical solution for the plate equation. First, it is assumed that the electrode region is divided into small segments or small capacitors. The force between the top electrode and the bottom electrode is calculated by using parallel plate approximation at each segment. This yields a force distribution over the electrode. Using the plate theory, one can easily calculate the membrane deflection corresponding to the previously calculated force distribution. In the next step, the forces at each segment are updated according to the calculated membrane deflection. This algorithm is iterated until the center of the membrane, where the displacement is maximum, converges within the error limits. Therefore the algorithm yields the membrane deflection for a given voltage. The collapse voltage then is calculated using binary search. When the bias voltage is higher than the collapse voltage, the displacement of the center of the membrane diverges quickly. This can be used as a criterion to decide whether the applied voltage is above or below the collapse voltage. We compared the algorithm results with FEM analysis. We found that 50 segments are enough to calculate the collapse voltage with 0.1 percent accuracy in couple of seconds whereas FEM analysis runs 12 hours. The proposed algorithm is also suitable for the inclusion of any external force distribution on the membrane that might exist such as atmospheric pressure.

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

MODELING AND DESIGN OF CMUTS USING HIGHER ORDER VIBRATION MODES FOR HARMONIC IMAGING

N. HALL*, J. MCLEAN, and F. L. DEGERTEKIN, G.W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology.
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Capacitive micromachined ultrasonic transducer (cMUT) design has so far relied on the first mode of the cMUT membrane which most resembles piston-like motion. However, experiments show that when a transducer with a symmetric electrode is excited with a broad band signal, the received spectrum has several frequency bands due to the first and higher order symmetric vibration modes of the membrane separated with nulls corresponding to the anti-symmetric modes. For example, our measurements on a cMUT array fabricated for intravascular imaging with elements made of 32μm diameter, 1.2μm thick uniform silicon nitride membranes show that the transducer has its first peak at 12MHz and a second resonance peak around 43MHz, which is only 8dB below. In this paper, we discuss the modeling and design of cMUTs to take advantage of these higher order vibration modes of the transducer membrane. We use this concept to design harmonic cMUTs, where the thickness distribution of the membrane is adjusted so that the modal resonance frequencies are harmonically related. These transducers can be used in applications such as tissue harmonic and contrast agent imaging. Our finite element analysis shows that the strain energy distribution and the fluid loading are critical in determining the optimum membrane shape. For example, the 3rd and 5th modes of a 0.5μm thick 50μm uniform silicon nitride membrane in immersion can be moved from 4MHz and 14MHz to 7.1MHz and 15.7MHz, respectively, by adding a 1μm thick, 10μm wide layer over the region where the 3rd mode has maximum strain energy. We will present detailed simulation results on optimization of both the cMUT membrane and the electrode shape for practical arrays for harmonic imaging.

U3-C-5 511AB 11:30 a.m.
(Invited)

ACCURATE MODELING OF CMUTS

R. LERCH[1], M. KALTENBACHER*[1], M. HOFER[1], and H. LANDES[2], [1]University of Erlangen, [2]WisSoft.
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In recent years, capacitive micromachined ultrasound transducers (CMUTs) have emerged as an alternative to piezoelectric transducers. The well known process steps, also used in semiconductor technology, allow a cheap and reproducible fabrication, and, furthermore, an integration with electronics. Additionally, CMUTs have a wider bandwidth compared to piezoelectric transducers, and, therefore, deliver a better resolution in ultrasound imaging equipments.

The design of micromachined transducers strongly depends on the availability of appropriate computer aided engineering (CAE) tools, since the fabrication of each prototype is quite costly. Precise computer simulations are needed to analyze and furthermore optimize the dynamic behavior and efficiency of such transducers. We have developed a CAE environment for the computer simulation of CMUTs. The schemes are based on the Finite Element (FE) method and take all relevant nonlinearities geometric nonlinearity of the mechanical structures, electrostatic force, moving body in an electrostatic field) and couplings between the different physical fields (electrostatic, mechanical and acoustical fields) into account. Therewith, the full pulse-echo mode of CMUTs can be computed and the relevant quantities such as electric transducer impedance, sensitivity and dynamic range are provided.

The presentation will start with an overlook of former and current research activities concerning the modeling of CMUTs. In a next step, we will give a short overview of our simulation scheme, which allows us to perform 2D and 3D simulations of different CMUT-designs. We emphasis the necessity of a fully nonlinear coupled simulation by comparing results, e.g. by determining the snap in bias voltage, to simulations with a linear behavior. Finally, we compare our simulations to measurements. Here, we focus on the determination of the snap in voltage, the crosstalk and the pulse-echo behavior of CMUTs. Futher on, we show the general applicability of our scheme by comparing measured and simulated sound properties of micromachined microphones in the audio range.

Session: U4-C

BAW RESONATOR ANALYSIS, MAGNETIC INTERACTIONS

Chair: K. Lakin
TFR Technologies, Inc.

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

APPLICATION OF A DC BIAS TO REDUCE ACCELERATION SENSITIVITY IN QUARTZ RESONATORS

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Random vibrations will induce frequency changes in a quartz resonator. This short term instability of the resonant frequency is caused by inertia strains in the energy trapped area of the quartz resonator. The largest random vibration induced inertia strains occur when the plate resonator is accelerated out of its plane, that is in the general direction of its plate normal. Such strains are predominantly plate bending strains, especially those caused by low frequency random vibrations. This paper demonstrates the use of a dc bias voltage to piezoelectrically stiffened the plate resonator, and also to reduce the plate bending strains caused by random vibrations. Incremental Lagrangian equations were

derived and solved to show the effects of the inertia strains on resonant frequency of a quartz resonator. Finite element models are used to show the effects of a dc bias voltage on the resonant frequency. The frequency change is about 2 to 10 parts per million of frequency change for a dc bias of 50 volts depending on the placement and geometry of the electrodes, and on the plate geometry. The phenomenon may be useful for ultra stable quartz resonators. Since the effects of low frequency random vibrations are the most difficult to control, this dc bias method,which can be implemented at low frequencies,may be quite useful. A forced vibration finite element model is used to demonstrate the effects on the fundamental thickness shear mode frequency of a quartz resonator due to a dc bias voltage changing polarity at a frequency of 50 Hz.
Funding by NAVSYS Inc. is gratefully acknowledged.

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

DEDICATED FINITE ELEMENTS FOR ELECTRODE THIN FILMS ON QUARTZ RESONATORS

S. SRIVASTAVA*[1], Y.-K. YONG[1], M. TANAKA[2], and T. IMAI[2], [1]Rutgers University, [2]Seiko Epson, Inc.
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The electrode thin films of a quartz resonator deserve particular attention in a three-dimensional finite element analysis because they give rise to (1) electrical boundary conditions at the electrode-quartz interface, (2) mass loading effects and (3) stiffness effects. Since the films are usually on the quartz surface, their stresses are relatively low in magnitude. In dynamic analyses in which we ask for natural frequencies and mode shapes, there is an urgent need to reduce the number of degrees of freedom because the major difficulty is the expense of computing eigenvalues and eigenvectors. The reduction of number of degrees of freedom is detrimental to accuracy, but negligibly so if properly used. In this paper we develop and show the results of dedicated finite elements for electrode thin films on quartz resonators. The subtle effects of the electrical boundary conditions on the frequency-temperature curves of an AT-cut plate are presented. Two strategies for modeling the electrode thin films and their numerical results are presented. These modeling strategies for the electrode films are important in the finite element modeling of both low and high frequency quartz resonators because (1) they help avoid the inherent effects of elements with poor aspect ratios in thin films, and (2) they greatly reduce the number of degrees in the finite element models. The films are conductors, hence they form an electric equipotential surface at the film to quartz interface where the electric potential is a specified known value in forced vibration problems and short-circuit eigenvalue problems. For an open circuit eigenvalue problem, the electric potential is unknown. The electrode films also contribute mechanically to the quartz plate in terms of additional stiffness and mass. One strategy for the mechanical modeling of very thin films is to neglect their stiffness and include only the mass effects. In this strategy, no additional degrees of freedom are needed for the film if the mass of such a film is added to the mass degrees of

freedom at the film to quartz interface. Results in terms of frequency spectra are presented to show that the strategy is quite accurate for very thin electrode films. For thicker electrode films, their stiffness effects, in addition to the mass effects, must be included to yield accurate frequency spectra. The second strategy is to perform Guyan static condensation of the mechanical degrees of freedom of the electrodes into the degrees of freedom at the film to quartz interface. Results in terms of frequency spectra are presented to show that the second strategy is accurate for both thin and thick electrode films.
Funding by DARPA and SPAWAR is gratefully acknowledged. Clark Nguyen is the program manager.

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

OPTIMIZATION OF FRAME-LIKE FILM BULK ACOUSTIC RESONATORS FOR SUPPRESSION OF SPURIOUS LATERAL MODES USING FINITE ELEMENT METHOD

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Wireless networks are growing rapidly. Their applications include cellular phone, satellite communication and wireless local area networks. Because of the trend of miniaturization, film bulk acoustic resonator (FBAR) has become a key technology in the applications of RF filters. FBAR comprises of a piezoelectric layer sandwiched between two electronically conductive layers that serves as electrodes. The portion of the piezoelectric film included between the overlap of the electrodes forms an acoustic cavity. The primary vibration mode of this cavity is that in which sound waves propagate in a longitudinal direction perpendicular to the plane of the electrodes. Unfortunately, the electric field also excites other spurious lateral vibration modes that correspond to sound waves traveling parallel to the plane of the electrodes and reflecting off the walls of the acoustic cavity or the various discontinuities at the edges of the electrodes or the resonator structure. These spurious lateral resonances near the main resonance of the resonator will show up as ripple in the pass band of the filter. Frame-like FBARs have been proposed to eliminate the generation of the spurious lateral modes. The frame-like FBAR structure comprises a frame-like zone confining a center area. The width and thickness of the frame-like zone area are arranged so that the displacement relating to the piezoelectrically excited strongest resonance mode is substantially uniform in the center area. In such a structure, the spurious resonances have often only a weak coupling. In this paper we apply finite element method to investigate the effect of the frame-like FBAR on the suppression of the lateral modes and find the optimal design of the frame-like zone area. The simulation results for different frequency ranges and different electrode materials are presented.

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

PREDICTION OF BAW RESONATOR PERFORMANCE USING EXPERIMENTAL AND NUMERICAL METHODS

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Numerical simulations are valuable for a fast and cost efficient development and optimization of microelectronic devices, yet experimental verification is crucial. We present a hierarchical optimization strategy for solidly mounted BAW resonators. It is based on the 1D transmission line model (Mason-model) and higher dimensional FEM approaches. The Mason model is an excellent method to construct the resonator layer stacks with respect to the desired resonance frequency and coupling constants, but can neither predict the Q-values nor spurious resonances. We therefore employ coupled electro-acoustic FEM simulations to investigate the displacement distribution of possible resonance modes and the confinement of the mechanical energy, thus facilitating the design optimization with respect to a maximum Q and a minimum content of spurious modes. The simulator CAPA [1] has proven to be a suitable tool for that purpose. To get reliable results, an adequate choice of the mechanical boundary conditions is of crucial importance, in order to suppress artificial reflections at the boundaries of the simulation domain. For a series of different resonator designs, we demonstrate the variation of Q and the overall spurious mode content and discuss specific modes, such as the main resonance mode, the modes generated in the boundary region and the modes related to standing waves in the acoustic mirror. The calculated results are confirmed by electrical measurements and laser interferometry. Typical technological features such as processing related non-uniform thickness of an electrode across the resonator are covered by introducing arbitrarily shaped interfaces into the FEM simulation model. The origin of deformed impedance curves around series resonance frequency is analyzed. We discuss the impact of interface roughness on the Q-factor and the purity of the resonance.

[1] R. Lerch, Simulation of Piezoelectric Devices by Two- and Three-Dimensional Finite Elements, IEEE Trans. on Ultras., Ferroel., and Freq. Control, Vol. 3, 1990, pp. 233-247

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

EXCITABILITY OF ULTRASOUND GENERATED BY MAGNETOSTRICTION

V. J. SÁNCHEZ-MORCILLO*, J. REDONDO, V. ESPINOSA, and F. CAMARENA, Departamento de Física Aplicada, Escuela Politécnica Superior de Gandía, Universidad Politécnica de Valencia.
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The parametric generation of ultrasound resulting from magnetoelastic interactions in the core of a ferromagnetic material driven by an alternating magnetic field is an active subject of research in nonlinear acoustics, and the basis of important applications, such as acoustic wave phase conjugation. For the theoretical description of this system, a dynamical model taking into account both magnetic and acoustic nonlinearities has been proposed, and the pumping threshold value for parametric generation and the intensities in the stationary regime of operation have been obtained in the resonant case [1]. In this work we have extended the model to include non-resonant (detuned) excitation, and we have performed the stability analysis of the stationary solutions in the bistable regime. The analysis reveals the existence of oscillatory solutions, which are a consequence of a Hopf bifurcation in the system. The dynamics of the fields is quasi-harmonic near the bifurcation point. Decreasing the pumping a more complex scenario is observed. First, the acoustic field experiences self-pulsations, i.e., the ultrasound is emitted in the form of bursts of high amplitude with a large separation in time. This behaviour occurs when the pumping magnetic field value is above but near the threshold of parametric generation of ultrasound. Below the threshold, where the parametric wave is not excited, we observe a dynamical behaviour which is called excitability: weak perturbations of the equilibrium (null) solution, but above a given threshold value, are highly amplified, and the medium emits an acoustic pulse which relaxes to the equilibrium state. Excitability is a well known phenomenon in physiology and chemistry, and explains, e.g. the propagation of electric signals in neurons. Recently, excitability has been also found in some laser models. Following [2], in terms of dynamical systems theory, a system is called excitable when (i) the unperturbed system is at stable equilibrium, (ii) a perturbation above the excitability threshold triggers a large excursion (in phase space) from the stable equilibrium, and (iii) the system then settles back to the attractor in what is called the refractory phase, after which the system can be excited again. Our numerical analysis of the model shows all these features, demonstrating the excitable character of the system. The main parameter for the occurrence of these effects is the ratio of the different nonlinearity coefficients, the circuit resonant frequency shift (due to the magnetic nonlinearity) and the parametric self-action of acoustic waves. We have estimated that the value of this parameter in the excitable regime is in accordance with experimentally achievable values.

[1] Streltsov V.N, BRAS Physics/Supplement, Physics of Vibrations 61, 228 (1997) [2] Murray J.D. Mathematical biology. Springer (1990)

This work is supported by the Spanish DGICYT under project BMF2002-04369-C04-04

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

SIMULATION OF MAGNETOSTATIC SOLITON GENERATION AND PROPAGATION IN THIN YIG FILMS USING EQUIVALENT CIRCUIT TECHNIQUE

T. KOIKE*[1], R. MARCELLI[2], and G. BARTOLUCCI[3], [1]Tamagawa University Research Institute, [2]CNR-PSM, Rome Section, Microwave Microsystems Technology, [3]Dept. of Electronic Engineering, University of Roma "Tor Vergata".
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Nonlinear magnetostatic wave (MSW) propagation in thin YIG films has attracted great attention for its potential use in microwave and millimeter wave signal processing [1]. Although we already developed a very effective equivalent circuit method to design linear devices [2] and discussed the soliton generation using equivalent circuit approach [3], the remaining problem is how to combine these concepts for the soliton generation and propagation under various experimental conditions. In this paper, we first discuss a combined equivalent circuit technique to simulate the soliton generation and propagation at the same time. In the circuit, a nonlinear soliton generation section and a linear propagation section are connected using an ideal impedance matching transformer. When the input pulse is introduced in the nonlinear section, the soliton is formed if a proper length is chosen. After the formation of the soliton in the nonlinear section, it propagates in the linear propagation section since the power level is greatly reduced. Although the simulated results are very sensitive to the choices of various parameters in the combined equivalent circuit, they show very good agreement with the observed soliton behavior. We also find that we can even simulate the formation and propagation of nonlinear, soliton-like waves by the same equivalent circuit. Finally, the simulated results and the related experimental results [4][5] are compared and discussed in detail. The analysis of this paper is very important for the design of potential nonlinear signal processing MSW devices in the near future. [1] R. Marcelli and S. A. Nikitov: Nonlinear Microwave Signal Processing, NATO Workshop, Roma (1995). [2] T. Koike and M. Ohba: Electrical Engineering in Japan, Vol. 112, No. 7, pp.102-110, Scripta Technica, Inc. (1993) [3] T. Koike, H. Ebihara, R. Marcelli, and G. Bartolucci: Proc. 8th International Conf. on Ferrites (ICF8), pp.962-963, Kyoto (2000). [4] T. Koike: 1998 International Ultrasonics Symp. Proc., pp.1223-1226 (1998). [5] T. Koike, R. Marcelli, Y. Filimonov, S. A. Nikitov, and G. Bartolucci: European Microwave Week 2002, Proc. European Microwave Conf. (EUMC2002), pp.25-28, Milan (2002).

Session: U5-C

DMS FILTER
Chair: C. Ruppel
EPCOS AG

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

DMS-FILTERS WITH REDUCED RESISTIVE LOSSES

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Resistive losses in the metal fingers of an acoustic track are an essential loss mechanism limiting the electrical performance of RF SAW filters. Conventionally, the finite finger resistance is often modeled by adding a lumped resistor in series to the exiting IDTs. While this is a reasonable approximation for long one-port resonators in a ladder-type filter, this model has some serious limitations when applied to more general structures such as DMS tracks. In particular, it assumes the same effective voltage drop along all fingers connected to the same busbar. However, the acoustic field distribution and hence the finger currents are strongly inhomogeneous in the IDTs of a DMS track. Furthermore, this simple model neglects resistive losses in the reflector gratings.

In this paper, we will present two alternative models for finite finger resistance which are rid of the above mentioned limitations. The more comprehensive one assumes an individual, continuous function for current and voltage of each finger. By dividing the track into infinitesimal transversal strips, we obtain a system of coupled differential equations which can be integrated analytically. Applying the proper boundary conditions at the upper and the lower finger ends, we obtain the nodal admittance matrix of the acoustic track. While this is a quite rigorous approach to model the finger resistance, it can be CPU time and memory consumptive for tracks with many fingers. Therefore, we developed and will also present a second model, which uses an equivalent resistance network for each finger and is a very good approximation for small and moderate values of the finger resistance.

The accuracy of both models will be demonstrated and compared to experimental results for an exemplary DMS filter. Using this example, we will also show the limitations of the conventional model, which does not account for an inhomogeneous current distribution and neglects resistive losses in reflector fingers.

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

A LOW-LOSS AND WIDE-BAND DMS FILTER USING PITCH-MODULATED IDT & REFLECTOR STRUCTURES

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Conventionally, a longitudinally coupled double-mode SAW (DMS) resonator filter has large insertion loss compared with a ladder type SAW filter. This paper discusses about the mechanism of the loss for DMS design and about reducing the loss. Conventional DMS design filter is adjusting for the distance of IDT electrodes to realize the pass-band characteristics. However this design method appeared the structural discontinuities. To analyze the loss mechanism for DMS design, the loss was calculated by using the FEM/BEM simulation, which is in consideration of the scattering bulk loss. In this paper, we focus on the reducing the scattering bulk loss. In the past, the QARP structure was well known to reduce the scattering bulk loss by avoiding the electrodes discontinuity. However, it had a demerit for the wider pass-band characteristics of DMS filter design. We proposed Pitch-Modulated IDT & Reflector structure to realize the low-loss and wider pass-band characteristics for DMS filters. This method is to use IDT internal reflection positively and to cancel the radiated bulk waves. By

using Pitch-Modulated IDT & Reflector structure, about 1.0dB improvement of pass-band insertion loss was realized in the RF-DMS filter in GHz range compared with conventional design.

The authors wish to thank M.Ueda, Y.Kuroda, O.Ikata, and M.Koshino for their assistance.

U5-C-3 512C-H 11:00 a.m. (Invited)

EVOLUTION OF THE SAW TRANSDUCER FOR COMMUNICATION SYSTEMS

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This paper will review the evolution of SAW transducer technology for communication systems. Applications of TV sets, radars, satellite communications, mobile phones and a wealth of others have driven a diversity of transducer embodiments. Some of the diverse sets of transducers include: weighted bidirectional, multi-phase unidirectional, single phase unidirectional, chirped, coded, slanted, resonant and others. Scientists and engineers continually push the limits on materials, device design and manufacturing, leading to lower loss, broader bandwidths, smaller size and lower cost devices. Over the past 3 decades competing technologies have rose to challenge SAW devices, such as CCDs, ceramic filters, film bulk wave devices, MEMs and others, however, SAW transducer technology has been remarkably robust in adapting to system needs and continues to fill vital positions in communication transceivers. Connections between past military requirements, commercial communication systems and current consumer applications have driven the transducer technology in varied directions culminating in today's diverse, application specific devices. This paper will take an historical view of the SAW transducer's diverse embodiments, practical implementations, and innovative problem solutions, principally through the eyes of the UFFC society publications.

U5-C-4 512C-H 11:30 a.m.

EXPERIMENTAL RESULTS FOR A LONGITUDINALLY COUPLED 5-IDT RESONATOR FILTER WITH DISTRIBUTED GAPS

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Longitudinally coupled resonator filters (CRFs) with more than two transducers (IDTs) provide a means of achieving a wide passband, low losses, high rejection levels, and unbalanced-balanced operation. At high frequencies ($\sim$2 GHz), the resistive losses arising from the relatively wide aperture of CRFs increase and

may degrade the performance. Reducing the insertion loss in 1.8-2.2 GHz devices remains a challenging problem. One possible solution – connecting two tracks in parallel and reducing the aperture – was studied in [1]. However, if the structure contains more than three IDTs, the topology of the connections becomes very complicated or even impossible on the wafer level. One-track filters with five transducers have been shown to provide an improved performance at high frequencies [2, 3]. A 5-IDT device features several advantages over, e.g., 3-IDT devices, such as a wider achievable passband and reduced resistive losses due to the smaller optimal aperture. For 5-IDT CRFs, the parallel connection of two tracks is not straightforward, and other means of reducing the insertion loss must be found. In this paper, we show that replacing the gaps between the transducers with distributed gaps reduces the insertion loss of the device. In a distributed gap, the filter structure is synchronous and the phase change is realized adding short transducer sections between the main transducers in total, we have 13 IDTs. This reduces the insertion loss as the scattering from the gap and the radiation into bulk waves is reduced. The metallized-gap devices discussed in [2] and [3] feature a maximum insertion loss of -2 dB in the passband at 1842 MHz. Here we present devices with distributed gaps on 42°-LiTaO3 at 1842 MHz. A wide bandwidth of 4.5% and -40 dB suppressions are achieved, with a minimum insertion less than -1 dB in the best devices, and maximum insertion loss of -1.2 dB in the passband. The passband is very flat, with <1 dB ripple. We also discuss the layout of the contact pads and connections and its effect on the device performance and balance characteristics. At high frequencies, the effect of the capacitance between the contact pads increases, and may strongly affect the response of the device. Therefore, the layout of the device must be chosen such that the parasitic capacitances arising from the connections and contact pads are minimized. Longitudinally-coupled 5-IDT resonator filters with distributed gaps are an interesting alternative for achieving an extremely low loss in 2-GHz devices.

[1] J. Meltaus, V. P. Plessky, A. Gortchakov, S. Hrm, and M. M. Salomaa, Proc.2003 IEEE Ultrason. Symp., pp. 2073-2076. [2] M. Koshino, K. Kanasaki, N. Akahori, R. Chujyo, and Y. Ebata, Proc. 2000 IEEE Ultrason. Symp., pp. 387-390. [3] S. Ichikawa, H. Kanasaki, N. Akahori, M. Koshino, and Y. Ebata, Proc. 2001 IEEE Ultrason. Symp., pp. 101-106.

J. Meltaus thanks the Finnish Cultural Foundation for supporting her work. The authors thank P. Brown for measuring the devices.

Session: U6-C

BAW SENSORS
Chair: J. Vetelino
University of Maine

U6-C-1 512A-F 10:30 a.m.

ELECTRODE OPTIMIZATION FOR A LATERAL FIELD EXCITED ACOUSTIC WAVE SENSOR

L. A. FRENCH[1], C. YORK*[1], M. MEISSNER[2], G. BERNHARDT[1], M. PEREIRA DA CUNHA[1], and J. F. VETELINO[1], [1]Laboratory for Surface Science and Technology, [2]Institute for Micro- and Sensor Systems, Sensors & Measurement Technology Group.
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Lateral field excited (LFE) acoustic wave sensors on AT-cut quartz are being investigated for use in liquid sensing applications [1]. In contrast to the standard quartz crystal microbalance (QCM) in which the transverse shear mode (TSM) is excited by electrodes on the sensing and reference surfaces, the TSM in the LFE sensors is excited by placing the electrodes only on the reference surface of the crystal leaving the sensing surface free. The free sensing surface allows the LFE sensors to be more sensitive to electrical and mechanical property changes of the liquid than the standard QCM. As a result of the lateral field excitation the ensonified region is primarily located between the unmetallized sensing and reference surfaces. This is in contrast to the standard QCM in which the ensonified region is located primarily between the metallized sensing and reference surfaces. However, in designing the electrode configuration for optimal excitation of the TSM, several other factors have to be considered. These include electrode orientation, which defines the direction of the exciting electric field, the geometric shape of the electrodes and the electrode gap width. Another critical factor relates to the fact that the liquid environment requires that the sensing surface of the LFE sensor be sealed in a liquid-tight package to prevent the electrodes from being exposed to the fluid being monitored. Preliminary measurements have shown that the package influences the mode profile on the sensing surface of the crystal. The electrode geometries examined are half moon structures with varying radii and gap separations and a wrap around structure in which the sides of the quartz wafer are metallized. The electrode designs are evaluated by measuring each sensor's admittance and resonant frequency when exposed to a variety of liquids with different mechanical and electrical properties and comparing to the results obtained using a standard QCM. A candidate electrode configuration is determined which minimizes the package influences and at the same time allows maximum sensitivity to the mechanical and electrical properties of the liquid being monitored.

1) Hu, Yihe, Lester A. French Jr., Kristen Radecsky, Mauricio Pereira da Cunha, Paul Millard, and John F. Vetelino. "A Lateral Field Excited Acoustic

Wave Sensor." *2003 IEEE International Ultrasonics Symposium Proceedings* (2003): 46-51.
This work is supported by NSF grant 0330100.

U6-C-2 512A-F 10:45 a.m.

KINETIC REACTION MONITORING OF ACIDIFIED MILK GELS WITH A QUARTZ RESONATOR

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The optimized development of acidified milk gels materials like yogurts requires a tight control of the kinetic reaction of the gelation process. Different parameters such as the viscoelastic parameters, the gelation time or the activation energy may be used to characterize this process. In this paper an investigation of these parameters by an ultrasonic technique using shear mode quartz resonator sensors has been developed. Using a suitable model this technique gives access to the accurate gelation time and the shear complex modulus G evolution during a gelation process. Furthermore, the activation energy of the gelation processes can be deduced from by looking at the gelation time for different temperatures. The acidified milk gels investigated are obtained by using instant non fat dry milk and an acid precursor, the glucono-delta-lactone (GDL) provided by Danone Corporation. The gelation process is monitored by a 6 MHz AT-cut quartz crystal immersed in the milk solution kept at constant temperature. In order to get a tight temporal evolution of the yogurt process, its mechanical impedance time evolution is deduced from the measurement of the quartz electrical impedance every 10 seconds. The temporal evolution during gelation process of the elastic G and viscous G moduli are then monitored for different temperatures (15 to 45°C) and for two quantities of GDL (13 and 26 g/L). In this paper, a new definition of the gelation time is proposed. This time corresponds to the instant when the material in the liquid phase, is no more a Newtonian liquid. Therefore a suitable lumped element model is proposed. This model takes into account the mass loading effect in order to link the quartz additional electrical impedance to the material viscoelastic parameters G' and G". The accurate gelation time tg is then defined as the time when the values of the real and imaginary parts of this additional impedance (respectively noted R(t) and X(t)) become different. This model is used for different yogurts. In all cases a strong variation of G' and G" is measured after tg. In the liquid phase, G' is equal to zero and R(t) equals X(t). The following table shows the gelation time measured using $R(t) \neq X(t)$ criteri (see table). We note an acceleration of the gelation process when the temperature increases. The evolution of tg as a function of temperature can be fitted by an exponential law. This result is in good agreement with the Arrhenius relationship. The apparent activation energy constant (Ea) obtained for 13 g/L and 26 g/L of GDL are respectively 106 kJ/mol and 91 kJ/mol. The magnitude order of Ea consistent with the values usually obtained for such soft gels. For a given GDL value, the final values of G' and G" increase too

with the temperature but tends to a constant limit for high temperatures. The quartz sensor model used allows an accurate measurement of the viscoelastic parameters in a wide dynamical range (500-200,000 Pa). By its nondestructive character and its simplicity of measurement, this technique is a first step to make an online rheometer.

Gelation time for different experimental conditions

Gelation time (min)	15°C	25°C	30°C	37°C	45°C
13 g/L of GDL	600	160	80	25	10
26 g/L of GDL	130	50	24	12	3.5

Denis PAQUET Danone Vitapole 91767 Palaiseau Cedex France

U6-C-3 512A-F 11:00 a.m.

WIDEBAND GELATION MONITORING BY QUARTZ MICROBALANCE IN PULSE MODE

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Classical viscoelastic measurement setup with a quartz crystal microbalance uses a steady state input signal in order to measure the complex equivalent electrical parameters. Using a network analyzer, this method enables the measurement of the equivalent impedance around the first resonance peak of the quartz within a tiny frequency range (typically 10KHz around a 6MHz resonance frequency). However, due to the network analyzer acquisition time, such a setup cannot make two successive acquisitions in less than 15s for one resonance peak. Moreover the quartz modes are detected up to the 5 harmonics, but not beyond. In the present paper, the quartz is excited by a short pulse and its time impulse response is recorded. This kind of excitation allows us to record higher resonance peaks (up to the 20th order) and to reduce drastically the acquisition time enabling up to 100 acquisitions by second. The quartz crystal microbalance (6MHz AT-cut) is excited by a pulse Matec generation board TB1000 (output signal amplitude is 10V). The acquisition board is an Acqiris 12bit 200Ms/s The sol-gel (SG) material studied is a silica based material elaborated under basic catalyst. Based on inorganic polymerisation of molecular precursors, the sol-gel process involves the evolution of a polymer from a colloidal suspension (sol) to the formation of a network enclosing a continuous liquid phase (gel). Depending on the initial chemical concentrations, the reaction speed can be imposed, enabling us to design on demand fast to slow gels, with respectively gelation time of 1 minute to 1 day. The two kinds of gels have been monitored with the pulse experimental setup. In both experiments, the 500 impulse responses have been recorded during the whole gelation process. In order to extract the resonance peaks frequencies and the associated widths, two kind of identifications are studied. In the frequency domain, the chirpz transform is used in order to locally zoom the spectrum before the peaks identification. In the time domain, the Prony method is used. Both methods are compared. In both cases, due to the quartz cut design, the odd modes are dominant in the low frequency domain (up to

20MHz), whereas in the high frequency domain (between 20MHz and 100MHz), both even and odd modes have the same contribution in the resonance spectra. In order to recover the time evolution of the mechanical parameters of the gel, a general model linked to the Lamb wave modes is proposed and discussed.

U6-C-4 512A-F 11:15 a.m.

USE OF A QUARTZ CRYSTAL RESONATOR TO STUDY THE CELL ADHESION PROCESS ON OCULAR BIOACTIVE POLYMERS

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The thickness shear mode quartz crystal resonator has been used as a sensitive sensor in various electrochemical and biological applications. This technique based on the transverse propagation of an acoustic shear wave generated through a piezoelectric quartz resonator provides a non destructive and powerful means for probing changes at solid-solid or solid-liquid interfaces. Therefore, it can be used to characterize cell-polymer interactions developed during the cell adhesion process. In the present work, we explored the potential use of the technique to evidence the inhibiting properties of bioactive polymers to fibroblast McCoy adhesion processes. These bioactive polymers are developed to be used a intraocular lens able to prevent the secondary cataract phenomenon. Thin films of various bioactive polymers exhibiting either carboxylate or/and sulfonate functional groups were deposited on the quartz surface by spin coating. An analyzer (HP 4595A) connected to quartz electrodes allowed measurements of the electrical admittance versus time via an IEEE 488 card by both a PC computer and software using HPVEE language. Bioactive PMMA based terpolymers, referenced BP27, BP31, BP32, BP33a, were synthesized by radical copolymerization of methyl methacrylate (MMA), methacrylic acid (MA) and sodium styrene sulfonate (NaSS). The analysis of 1H NMR spectra allowed the determination of the chemical composition of synthesized polymers. McCoy cells were then seeded onto surfaces at a concentration of 2.5 104 cells/ml and cultured on each polymer for different times varying from 1 to 8 hours. Cell adhesion process on these surfaces was investigated both by the quartz resonator technique and by cell counting (Multisizer III - Counter from Beckman) after trypsin detachment. Measurements of the time variation of the electrical motional resistance were performed as the quartz crystal resonator was coated with the polymer and cell suspensions. The observed resistance on a quartz without polymer was identical to that observed on PMMA (control polymer) or copolymers BP31 and BP32 bearing only one functional carboxylate or sulfonate groups. BP27 and BP33a bearing sulfonate and carboxylate groups present inhibiting properties of McCoy fibroblastic cells adhesion when compared to non

functionalized polymer PMMA and polymers bearing only one of these functional groups. The results obtained by both cell counting and with the quartz resonator were in good agreement. The data show that the resistance induced by cell adhesion depends on the chemical composition of the polymer. BP27 and BP33a polymers are excellent candidates when inhibition of cell adhesion and proliferation is needed. This project is currently been extended to the study of the osteoblast cells on chemical treated titanium surfaces for orthopedic prosthesis.
This work is supported by the french research administration in the "Action Concertée Incitative" program

U6-C-5 512A-F 11:30 a.m.

SENSITIVITY ENHANCEMENT OF QCM BIOSENOR WITH POLYMER TREATMENT

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Biosensors with rapid and highly sensitive detection capabilities of various biomolecules are of great demand in the field of life sciences. Acoustic wave sensors have been widely used for detection of various chemical and biological species in liquid media. Binding of a substance onto the resonating membrane surface causes a decrease in the acoustic wave velocity, which is related to the resonant frequency of the device. This principle has been extensively used in case of a Quartz Crystal Microbalance (QCM) wherein a shift in the resonant frequency can be attributed to the mass bound on the sensor membrane. In this work we have used an AT-cut quartz crystal with a resonant frequency of 5MHz (with active area of 1.37 cm2 and frequency/mass coefficient of 0.057 Hz/ng/cm2) to study the immobilization of monoclonal mouse Immunoglobulin G (IgG) antibody on Gold substrates. Various surface modification techniques have been applied to the substrate and the antibody coverage in each case were closely monitored and recorded with Atomic Force Microscopy (AFM) and QCM. Bare gold substrates were modified with (3-Aminopropyl) triethoxysilane (3-APTES) followed by subsequent immobilization of Protein A and IgG. The coverage of the antibody on these substrates was compared to the substrates coated with a thin film of polystyrene (35nm) before modifying with 3-APTES. We have found that the coverage in the case of the substrates with polystyrene film was much better than the other as observed with the AFM. The QCM results also show a resonant frequency shift of 160 Hz for the crystal without polystyrene and a shift of 280 Hz for the crystal with polystyrene proving a better binding of antibodies to the substrates with polystyrene. Immobilization techniques have also been studied on silicon substrates with AFM. The AFM images revealed heart shaped IgG molecules to be immobilized onto the surface. As in the gold substrates, the binding of the antibodies to the substrates was found to be higher when coated with polystyrene. The detailed discussion of the sensitivity enhancement of acoustic sensors will be presented.

This material is based upon work supported by the U.S. Department of Defense under Grant No. W81XWH-04-1-0250.

U6-C-6 512A-F 11:45 a.m.

QUARTZ THICKNESS SHEAR MODE RESONATOR AS A FUNCTIONAL BIOSENSOR FOR MONITORING LIVING CELL BEHAVIOR UNDER CONTROLLED BIOLOGICAL ENVIRONMENTS

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Functional biosensors using living cells or tissues as the biological interfaces for signal transduction has experienced a rapidly growing interest in recent years, especially in the areas related to bacterial and viral analysis, cellular and molecular pharmacology, environment monitoring, and anti-bioterrorism. Acoustic wave devices coated with living cells represent one effective functional biosensing approach for the detection or monitoring of medically relevant cell behaviors under controlled biological conditions. In such a biosensor it is highly desirable that through direct interaction between acoustic resonators with cells, the sensor itself has a capability to monitor cell-pertinent interfacial processes such as attachment, contraction, and proliferation in real time. In this study, we investigate the use of quartz thickness shear mode (TSM) resonators to monitor the behavior of human patellar tendon fibroblasts (HPTFs). The quartz resonator we used is an AT-cut crystal coated with ITO transparent electrodes on both sides so that we can combine the device with a fluorescent microscope to form a sensor platform. The time dependent information of cell behavior is obtained by monitoring the resonant frequency shift Δf and the motional resistance change ΔR in real-time. The HPTFs morphology or profile is also monitored simultaneously to correlate with the quantitative sensor responses. TGF-β1 and TGF-β3, which can significantly alter the contraction behavior of HPTFs, are used to manipulate the cell activities on the sensor surface. Detailed experimental setup and experimental results will be presented in the paper. It will be demonstrated that the functional biosensor system with combination of acoustic wave resonators, appropriate biocompatible interface, livings cells, mini-incubator and optical microscopy provides a fast, yet quantitative functional biosensing approach for cell adhesion, contraction and other behaviors under controlled biological conditions in real time.

This research is partially supported by University of Pittsburgh small grant funding.

Session: FE1-C

THIN FILM II
Chair: N. Setter
EPFL

FE1-C-1 513CD 10:30 a.m.

IMPROVEMENT OF ULTRA-THIN PB(ZR,TI)O3 FILMS BY CONTROLLING INTERFACE WITH NOVEL METAL ELECTRODE FOR HIGH-DENSITY FERROELECTRIC MEMORY APPLICATION BY MOCVD

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Future applications for electronic devices, especially mobile ones, demand increasingly larger memories, lower operating voltage, lower power consumption and higher performance. For these reasons, not only stand-alone FeRAM (Ferroelectric Random Access Memory) using conventional DRAM (Dynamic Random Access Memory) process but also embedded FeRAM should be utilized since it exhibits both performance and potential cost advantages when compared to standard embedded semiconductor memories such as DRAM, Flash memory, and SRAM(Static Random Access Memory). For system-on-chip applications, embedded FeRAM possibly has the potential to be a universal memory solution, replacing all of the above except for high speed SRAM. However, before realizing these memory devices, FeRAM with ferroelectric capacitor has some issues, such as ferroelectric thin film process, device integration process, and device electrical reliability. Thin film technology is the key to device scaling for integrated embedded and stand-alone FeRAM. Therefore, in this study, we focus on improvement of the ferroelectric capacitor controlling the ferroelectric thin film and bottom electrode for this memory application. From our recent preliminary results of retention loss, PZT films deposited by MOCVD show better properties than those grown by CSD(Chemical Solution Deposition) because it may be better interface in these films. In addition, the scaling effects in PZT thin films is known to be alleviated on oxide electrodes, and several reports have been suggested from both the intrinsic and extrinsic points of view. For 30 100nm Pb(Zr,Ti)O3 thin films deposited by LDS-MOCVD (Liquid Delivery System-Metal Organic Chemical Vapor Deposition), we controlled the interface layer by changing process condition such as, gas, pressure, temperature, precursor. We observe the effect of varying the bottom electrode such as oxide family and novel alloy, in which we observe a different behavior of the interface layer in PZT capacitors by measuring SIMS and HR-TEM technology. The ferroelectric capacitors with ultra-thin PZT films could be improved by controlling the interface layer between PZT and electrode. It is believed that these results could provide a possibility for commercializing embedded or stand-alone FeRAM in high-density ferroelectric memory applications.

FE1-C-2 513CD 10:45 a.m.

ENHANCED RETENTION PROPERTY OF PB(ZR,TI)O3 THIN FILM BY APPLYING PBTIO3 SEED LAYER

B.-J. BAE*, K.-M. LEE, S.-D. NAM, J.-E. LIM, C.-M. LEE, S.-O. PARK, U.-I. CHUNG, and J.-T. MOON, Process Development Team, Semiconductor R&D Division, Samsung Electronics Co.
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Metal organic chemical vapor deposition (MOCVD) of Pb(ZrxTi1-x)O3 (PZT) using liquid delivery system (LDS) has been developed for the application of high density ferroelectric memory device. The polycrystalline PZT films have been grown onto the Ir bottom electrode layers using Pb(thd)2, Zr(thd)2(OPri)2 and Ti(thd)2(OPri)2 in octane as MO precursors in the oxygen atmosphere at 550°. The ferroelectric property of the Ir/IrO2/PZT/Ir capacitors has been examined. A 100-nm-thick PZT(111) film showed a 2Pr of about 40 μC/cm2 with a 2Vc of 1.0V at at an applied voltage of 2.7 V. PZT(111) films applying PbTiO3 seed layer were baked at 150°, and their retention properties have been compared to those of the films without seed layer. Detailed results on the growth condition of PbTiO3 seed layer will be presented.

FE1-C-3 513CD 11:00 a.m.

ARTIFICIAL FERROELECTRICITY IN PARAELECTRIC SUPERLATTICES

T. TSURUMI*, T. HARIGAI, D. TANAKA, H. KAKEMOTO, and S. WADA, Tokyo Institute of Technology.
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Strontium titanate/strontium zirconate superlattices were fabricated by molecular beam epitaxy method. Crystallographic orientation and crystallinity of the deposited thin films were analyzed by in situ RHEED observations and reciprocal space maps in XRD. The clear oscillation of the specular intensity of RHEED during the growth of superlattices was routinely observed and the period of this oscillation corresponded to the deposition of one unit cell. XRD profiles exhibited the satellite peaks of superlattices. Reciprocal space maps show strained lattice structure. These results indicated that two-dimensinal layer-by-layer growth was achieved in the deposition. Interdidital electrodes with 5 micron spacing between each electrode were formed by electron beam lithography technique. The small electrode size was important to measure the dielectric properties of ultra-thin films. The electromagnetic analysis was carried out to determine the dielectric permittivity of thin films on a dielectric substrate. The dielectric permittivity and its frequency dependence was changed with the structure of superlattices even though they had the same averaged chemical composition and thickness. It was found from the measurement of polarization vs. electric field curves that some

superlattices shows clear ferroelectricity in spite that both strontium titanate and strontium zirconate were paraelectric material.

FE1-C-4 513CD 11:15 a.m.

EPITAXIAL BISCO$_3$ THIN FILMS

S. TROLIER-MCKINSTRY*[1], M. BIEGALSKI[1], D. SCHLOM[1], J. WANG[2], I. TAKEUSHI[2], and R. RAMESH[2], [1]Materials Research Institute, Penn State, [2]University of Maryland.
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$BiScO_3$ is interesting as an end-member in high transition temperature piezoelectrics. It is, however, very difficult to stabilize as a perovskite, so relatively little is known about its properties. In this work, epitaxial $BiScO_3$ thin films were grown on $BiFeO_3$-buffered/$SrRuO_3$/ (100) $SrTiO_3$ by pulsed laser deposition. The resulting films had out of plane lattice parameters of 4.137Angstroms, a reasonable match with the reported a lattice parameter. The crystallinity of the films is good, with full width at half maximum of 0.58° in ω (004 peak), 0.80° in Φ (222 peak) and 0.28° in θ. The resulting films are good electrical insulators. There is no evidence of significant hysteresis (either ferroelectric or antiferroelectric) at room temperature up to the breakdown strength of the films. Results on the temperature dependence of the properties will also be presented.

FE1-C-5 513CD 11:30 a.m.

LOW TEMPERATURE ALN THIN FILMS GROWTH FOR INTEGRATED CIRCUIT COMPATIBLE SURFACE AND BULK ACOUSTIC WAVE DEVICES

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Aluminium nitride (AlN) has been considered as an attractive thin film piezoelectric material for integrated circuit (IC) compatible surface acoustic wave (SAW) devices. This compatibility requires a deposition process in relatively low temperature. In this work, c-axis oriented aluminium nitride thin films on silicon substrates were deposited by reactive RF magnetron sputtering method at various substrate temperature (without heating 400°C) with the same thickness (1,4 μm). We have previously realised a systematic study of the other growth experimental parameters (power, gas mixture, pressure) to optimise the high piezoelectric coupling AlN thin films. The structural, morphological and optical properties of AlN films were investigated by X-ray diffraction (XRD), field emission scanning electron microscope (FESEM), atomic force microscopy (AFM) and Fourier transform infrared absorbance spectroscopy (FTIR). It was found that the AlN films showed the same highly (002) preferred orientation with low full with of half maximum (FWHM) of rocking curve, which is about

2° for all the films elaborated in various temperatures. The optical properties of these films analysed by FTIR exhibit an absorption bands attributed to vibrational modes of Al-N bonds, in particular E1(TO) at 678cm^{-1} and A1(TO) at 620cm^{-1}. No shift of peaks in FTIR spectra was observed as well as XRD spectra, which are, indicate the constant residual stress in the AlN films determined about 1,5GPa. The surface roughness of AlN films determined by AFM is less than 1nm for the film grown at low temperature which is very suitable SAW devices achievement. The grains size which is directly linked to surface roughness was measured from XRD spectra and exhibits an average value of 30nm. The AlN film realised without substrate heating presents the same optical and structural properties than those realised at high temperature (400°C) for the specific experimental growth deposition which we optimised. However, the surface roughness exhibits a lower value for the film deposited at low temperature. This result is very important and means that films with good crystalline quality, low roughness surface can be processed at low temperature. To evaluate elastic properties of deposited AlN films, AlN/silicon SAW devices were performed and characterized. Experimental results show that realised structure exhibits a good frequency response and practical values of electromechanical coupling coefficient (K^2) and temperature coefficient of frequency (TCF). The SAW velocity value (5200m/s) deduced from frequency response is in accordance with theoretically expected one. This result proves the good crystalline quality of AlN films grown at low temperature.

FE1-C-6 513CD 11:45 a.m.

EFFECT OF 3-D STATE OF STRAIN ON THE ELASTO-DIELECTRIC PROPERTIES OF PARAELECTRIC BST THIN FILMS ON NDGAO$_3$

W. K. SIMON*, E. K. AKDOGAN, and A. SAFARI, Rutgers University - Dept. of Ceramic and Materials Engineering.
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We have measured the 3-D state of strain, and the 2-D state of stress, using triple-axis high-resolution X-ray diffractometry, in $Ba_{0.60}Sr_{0.40}TiO_3$ thin films on <100> oriented $NdGaO_3$ substrates that were synthesized by pulsed-laser deposition. Nanostructural features such as topography, as evaluated with AFM and FESEM, were found to be thickness dependent. X-ray analyses by pole figures and rocking curves have shown consistently <110> textured films with high crystallinity. The evolution of the state of strain (in-plane anisotropic strain and out of plane strain) in the films texture was monitored in the thickness range 20-1200 nm, and the (3 x 3) strain tensor was obtained as a function of film thickness. We provide an in-depth discussion of the effects of 3-D state of strain and 2-D state of stress on the elasto-dielectric properties such as permittivity, tunability and loss factor, which were measured in the range 0.1-20 GHz. We also discuss the effect of the 3-D state of strain on paraelectric phase stability, the potential effect of the superposition of the electrostrictive strain created the by

the bias-field on the 3-D state of strain, and the effects on the elasto-dielectrics properties thereof.
The authors gratefully acknowledge the funding provided by the Howatt Foundation.

Session: FC1-C
MINIATURE ATOMIC CLOCKS
Chair: E. Rubiola
LPMIA

FC1-C-1 511CF 10:30 a.m.
(Invited)
A MICROFABRICATED ATOMIC FREQUENCY REFERENCE

S. KNAPPE*[1], L.-A. LIEW[2], P. SCHWINDT[1,3], V. SHAH[1,3], J. MORELAND[2], L. HOLLBERG[1], and J. KITCHING[1], [1]Time and Frequency Division, National Institute of Standards and Technology, [2]Electromagnetics Division, National Institute of Standards and Technology, [3]Department of Physics, University of Colorado.
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In this paper we describe a physics package of an atomic frequency reference constructed with MEMS microfabrication techniques. The device has a volume of 9.5 mm^3, consumes less than 75 mW of power and has a fractional frequency instability of 3×10^{-10} at one second of integration. The design enables wafer-level fabrication of many physics-packages simultaneously with the same process sequence, potentially reducing fabrication costs.

The frequency reference is based on microwave spectroscopy using coherent population trapping in a cesium vapor, which allows for a simplified experimental setup. Laser light resonant with the atoms, is modulated near a frequency equal to half of the ground-state hyperfine splitting, which produces a narrow bright line in the transmitted spectrum. The frequency of the modulation can then be locked to the hyperfine frequency of the atoms using a feedback-loop. The vapor cell containing the cesium atoms and a mixture of buffer gases at suitable pressures consist of a cavity etched into a silicon wafer and two glass windows anodically bonded on either side[1,2]. The windows are heated to 80°C by transparent film heaters made of indium-tin-oxide (ITO), deposited onto a glass substrate and bonded onto the cell windows. This cell sub-assembly is then integrated with an optics sub-assembly, which collimates, filters, and polarizes the light, in addition to a laser and a photodiode to form the completed physics package.

The performance of the miniature device will be addressed as well as the dependence of the frequency instability on parameters such as laser intensity, cell temperature, RF power, and buffer gases. Devices such as the one described here will likely enable atomic frequency references to be used in applications such as wireless communications, where small size, low-cost, low-power devices are required.

[1] S. Knappe, et al., *Atomic vapor cells for miniature frequency references*, Proceedings of the 2003 IEEE Frequency Control Symposium and PDA Exhibition jointly with the 17th European Frequency and Time Forum, pp. 31.

[2] L. Liew, et al., *Microfabricated alkali atom vapor cells*, accepted for publication, Appl. Phys. Lett.

FC1-C-2 511CF 11:00 a.m.

PRACTICAL REALIZATION OF A PASSIVE COHERENT POPULATION TRAPPING FREQUENCY STANDARD

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The present paper describes the practical realization and characteristics of a small, totally autonomous passive frequency standard based on the coherent population trapping phenomenon (CPT). This phenomenon has opened avenues in the implementation of new types of atomic frequency standards using alkali metal atoms. In the passive approach, CPT offers definite advantages when compared to the classical approach used up to now in the implementation of optically pumped Rb frequency standards [1]. CPT advantages include size, signal amplitude, line width, reduced light shift, optical laser pumping efficiency and the absence of a microwave cavity. The present paper provides first a short description of the basic principles used in the implementation of a frequency standard using CPT. These include for example, CPT excitation technique, detection of fluorescence and transmission signals, light shift, presence of optical pumping and atom trapping. Second, the properties of a typical CPT optical system relative to basic physical characteristics, such as contrast, resonance line width, and background noise are given. An evaluation of frequency stability is made based on these characteristics. Finally, an overall description of a frequency standard based of the above principles is provided, including block diagrams of the optical control CPT resonance system and of the digital control electronics. The characteristics of the frequency standard relative to general functionality and frequency stability are given, as measured on several units.

[1] J. Vanier, M. Levine, D. Janssen and M. Delaney, "On the use of optical pumping and coherent population trapping techniques in the implementation of atomic frequency standards", IEEE Trans. Instrum. & Meas. IM 52, pp. 822-831, 2003.

FC1-C-3 511CF 11:15 a.m.

NARROW LINEWIDTH COHERENT POPULATION TRAPPING SIGNALS IN SMALL VAPOR CELLS FOR CHIP SCALE ATOMIC CLOCK APPLICATION

M. ZHU*[1], L. S. CUTLER[1], J. E. BERBERIAN[1], J. F. DENATALE[2], P. A. STUPAR[2], and C. TSAI[2], [1]Agilent Laboratories, [2]Rockwell Scientific Co.
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Small vapor cells are desirable for the Chip Scale Atomic Clock (CSAC) applications. We measured CPT (Coherent-Population-Trapping) signal linewidths in both rubidium vapor cells and cesium vapor cells. Using a micro-machined absorption cell (diameter = 1.7 mm, length = 2 mm), we demonstrated sub-kHz linewidth (FWHM) of the clock transition in the 133Cs atom (|F = 3, mF =0> |F = 4, mF =0>). The intrinsic linewidth (FWHM = 777 Hz) agrees with the calculated results. We will present our results in detail.
Work supported by DARPA

FC1-C-4   511CF   11:30 a.m.

ALL OPTICAL ATOMIC CLOCK ON A CHIP

D. STREKALOV, A. SAVCHENKOV, N. YU, A. MATSKO, and L. MALEKI*, Jet Propulsion Laboratory.
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The opto-electronic oscillator (OEO) [1] is a generic architecture based on the direct conversion of light energy into spectrally pure microwave signals. The stability, and accuracy of this device is determined by that of the energy storage element in the feedback loop, which in the most basic configuration, is a fiber delay line. Replacing the delay of the fiber with an atomic cell can lead to transfer of stability and accuracy of the atomic resonance to the OEO. With this configuration, an atomic clock with a self-contained, high performance local oscillator, powered directly by light is realizable.

In this paper we will describe such an architecture, and discuss in detail an approach for configuring the OEO architecture as a chip scale atomic clock. The key to the reduction of the size of the atomic vapor based OEO is in the use of a resonant lithium niobate modulator based on high Q whispering gallery (WGM) modes, capable of providing sidebands at the clock frequency. Such a microresonator has been demonstrated at JPL [2], and can function both as the microwave filter and the modulator. The efficiency of the modulator is also an important factor that allows operation with a small (a few mW) amount of microwave drive power, thus eliminating the need for a high power amplifier. We will describe preliminary results based on the operation of a clock consisting of a laser, the WGM modulator, and a mm-scale Rb cell, and present its stability performance. We will also describe future modifications needed to meet the goals of the DARPA Chip Scale Atomic Clock program.

[1] X. Steve Yao and Lute Maleki, "Optoelectronic microwave oscillator," Journal of Optical Society of America-B, 13, 1725 (1996). [2] V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, and L. Maleki, "Sub-Micro Watt Photonic Microwave Receiver," Photonics Technology Letters, 14, 1602 (2002).
The work in this research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract from NASA, and with support from DARPA CSAC Program.

Session: FC2-C

MANUFACTURING TECHNOLOGY
Chair: M. Nusbaum
Saronix Corporation

FC2-C-1 511DE 10:30 a.m.
(Invited)
LATTICE DAMAGES IN QUARTZ CRYSTAL BLANKS — INFLUENCE ON THE RESONATOR PROPERTIES AND ON THE X-RAY MEASUREMENT

E. SEYDEL*[1], H. BERGER[2], G. HILDEBRANDT[2], and H. BRADACZEK[2],
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Lattice damages on the surface (caused by processing) or in the volume (caused by the growing process) influence the electrical properties of the crystal resonator. The surface damage effects the Q-Values (resonance resistance and motional capacitance), the temperature behaviour (especially activity dips) and the ageing [1]. Lattice defects in the volume effect the parameters in a similar way. In this contribution, model calculations of the influence of surface and volume defects on the resonator properties, especially the temperature-frequency behaviour, are presented. Therefore, it is necessary to control sufficiently all the processes beginning with the crystal growing up to the final resonator. If there are different blank suppliers, the blanks have to be checked and selected for surface and volume defects before further production steps. However, standard methods applied up to now, like IR-transmission random tests after growing, can detect only extended defects. The degree of damage caused by the various kind of surface processing can be measured by means of X-ray diffraction methods. The halfwidths of the X-ray reflection curves as well as the reflection intensities depend considerably on the processing state. These parameters can be measured using the EFG Angle-Sorting Machines. To utilise the additional information, a slightly extended evaluation program has to be used. Modifying the measuring arrangement the broadening of the reflection curves due to crystal defects can be measured more sensitively. The evaluation and correction procedure of the cutting-angle determination presumes that the widths of the reflection curves are constant and known. If the reflection curves are broadened by defects and the broadening is not measured, a systematic error of the measured cutting angle may occur. However, this error will be shown to be negligible in most cases. There exist X-ray testing methods for the detection of volume defects. The conception of corresponding X-ray devices suited for the checking of quartz blanks will be discussed shortly. All these relations are also principally valid for other crystalline materials and the methods which will be discussed can be applied to those as well.

[1] E. Seydel, The Influence of the Surface Structure on the Vibration Amplitude and the Equivalent Electrical Data of Quartz Crystals—a Theoretical Overview, Proc. 14th Europ. Frequ. Time Forum, pp.103-107, 2000.

FC2-C-2 511DE 11:00 a.m.

THE TECHNIQUE DEVELOPMENT OF CRYSTALS AND OSCILLATORS IN CHINA AND THEIR MARKET SITUATION

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Recent years the manufacture quantity and requirement of crystals and oscillators in China increased quickly because of the developments of industries, communication, science, transportation and computers. This paper introduces the manufacture, research and the characteristics of the technique development about the crystals and oscillators in recent 10 years in China. Along with the request from industry, science and market, the amount of companies which make and research crystals and oscillators increased from several to more than 300 in recent 20 years in China. The manufacture technology and equipment also are improved a lot. Because of the market and technique reasons, more than 75% companies can only make 49u, 49us, um crystals, and so on. The most accuracy crystals made in China are of glass packages. Now more and more companies pay attention to build the production line to make the cold weld crystals in China, and one or two companies have built the line. The most of accurate crystals are AT cut and some of them are SC cut. The specifications of the crystals are introduced here. Regarding the crystal oscillator manufacture technique, TCXO includes the different TCXO, DTCXO and MCXO. Integrated TCXO and DTCXO have been made in the different companies, and the frequency-temperature stability of them can be from 2ppm to 0.5 ppm in a wide temperature range. The other specifications are also introduced. OCXOs are mainly based on glass holder crystals, and some of them utilize cold weld crystals imported from America and other countries. Specifications of some of OCXOs are almost the same as that of the foreign OCXO. The main design techniques in China are based on experiments. However, in recent years, the special design software is used for the oscillator design, and some advanced instruments and equipment are used. The specifications of different OCXOs are introduced here. The market situation of crystals and oscillators are also introduced.

FC2-C-3 511DE 11:15 a.m.

MULTISTAGE CHEMICAL ETCHING FOR HIGH-PRECISION ADJUSTMENT OF RESONANCE FREQUENCIES IN UHF FUNDAMENTAL QUARTZ RESONATORS

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In an inverted-mesa AT-cut resonator that excites a UHF fundamental thickness vibration, the resonance frequency shifts greatly with changes in the thickness of the vibrating area. Therefore, in order to obtain a target resonance frequency, it is necessary to adjust the thickness of the vibrating area with nanometer precision or better. I report a chemical etching process that achieves uniform-thickness vibrating areas of multiple resonators in a single wafer. By using this process, the resonance frequencies of 41 resonators in the wafer were adjusted to 622 $\pm$ 1.5 MHz, which correspond to thicknesses 2.7 μm $\pm$ 6 nm of the vibrating areas. The process consists of five stages, combining high-rate etching suitable for mass production and low-rate etching for fine adjustment. First, a polished wafer 80 μm thick was soaked in ammonium hydrogen fluoride saturated solution at 85°C. The etching rate was 25 nm/s. At this stage, the wafer, having patterns previously formed by photolithography, was etched to simultaneously produce a number of inverted-mesa blanks. Each blank had an X-length of 900 μm and a Z'-length of 1300 μm. The vibrating area at the center of each blank had an X-length of 320 μm and a Z'-length of 250 μm. The thickness of each vibrating area was 11 μm. The difference between the maximum thickness and the minimum thickness in the vibrating areas (called the distribution) was 171 nm. In the second stage, the thickness of the vibrating area on each blank was individually adjusted to 9.7 μm with a programmable etching apparatus. The etchant used was hydrofluoric acid 13% diluted solution at 21°C, and the etching rate was 0.2 nm/s. By this individual adjustment, the distribution was reduced to 23 nm. In the third stage, all blanks were etched together with the same conditions as in the first stage. In the fourth stage, the wafer was dipped into hydrofluoric acid 23% diluted solution at 21°C. All blanks were finely etched at a rate of 1.5 nm/s until the thicknesses of the vibrating areas reached 2.7 μm; the distribution was increased to 63 nm. In the fifth stage, each blank in the wafer was individually etched using the same method as in the second stage. As a result, a distribution of 12 nm was obtained. This process contributes to reduced mass-loading variations, because the amount of required final adjustment by changing an electrode thickness after mounting is decreased.

FC2-C-4 511DE 11:30 a.m.

PROCESS MONITORING VIA SELF-SENSING TRANSDUCERS

J. WALLASCHEK*[1], M. BRÖKELMANN[1], and H. HESSE[2], [1]Heinz Nixdorf Institut, University of Paderborn, [2]Hesse & Knipps GmbH.
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Process monitoring is an important issue in ultrasonics. Many manufacturing technologies, like e.g. ultrasonic welding, wire bonding, or the like, use sensory information for the control of the process. Most often sensor signals are used to operate the system at resonance.

Increasing demands on quality have lead to the requirement that ultrasonic processes are being monitored permanently. Especially in microelectronic manufacturing technologies like wire bonding, on-line process monitoring systems can help to improve the overall manufacturing quality.

In this paper we first describe how piezoelectric transducers can be used both as an actuator and a sensor at the same time. We then present a framework for the mathematical analysis of self-sensing transducers, based on an electromechanical model. We will point out, how this model can be used to optimise the actuator and sensor characteristics of the overall system. Finally, a self-sensing transducer for wire bonding will be presented, which is capable to provide signals that can be used to evaluate the quality of a wire bond in an on-line modus.

Session: U1-D
CONTRAST AGENTS - CHARACTERIZATION
Chair: P. Burns
University of Toronto

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

NEW CONTRAST IMAGING METHOD USING DOUBLE FREQUENCY EXPOSURE

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We present in this study results of a new imaging technique, capable to detect echoes from microbubbles (MB) and eliminate those emanating from non-oscillating structures (tissue). The method is based on mixing 2 signals, a low frequency signal called the conditioner signal (CS) and a high frequency signal called the detection signal (DS). Principle: The CS is used to modulate the size of MB by making them vibrate. It alters the size of MB between its compression and rarefaction phases. Thus the CS makes the MB expand in its rarefaction phase and shrink in its compression phase. During these two phases of the CS, the DS is transmitted to image the MB. Hence, the DS will sense the same bubble but at two different stages: small and large. During the expansion phase, a larger bubble is insonified with the DS and during the shrinkage phase, a smaller bubble is insonified with the DS. Thus the response of the MB to the DS will be different from positive to negative cycles of the CS. However the response of non-oscillating scatterers (such as tissue) will be identical in both phases of CS. This finding will increase the distinction between MB and tissue usually termed contrast to tissue ratio (CTR). Method: Simulations were carried out using the modified Herring equation using 1 cycle at 0.5MHz and MI of 0.15 (CS) and 7 cycles at 3.5 MHz and MI$<$0.1 (DS). The new method was evaluated against pulse inversion. In addition, Ultra-fast optical observations of contrast MB were carried out using Brandaris. Two different transducers were used transmitting CS at 0.5MHz and MI $<$0.2 and DS at 3.5MHz and MI$<$0.1. The optical

observations were carried out at a frame rate of 14 MHz and 128 successive frames were recorded. A Sonovue MB of 4μm diameter was observed oscillating under the effects of both CS and DS. Results: The simulation results showed that the double frequency exposure increases the CTR by more than 10dB compared to "standard" pulse inversion. The optical results showed that when the 0.5MHz CS amplitude is low, the vibration of the bubble during this period is weak and its diameter doesnt change significantly between the compression and rarefaction phases. Consequently its response at 3.5MHz is approximately equal between the 2 phases. For larger CS amplitude, stronger vibrations of the bubble are observed. The bubble diameter compresses to about 3μm and expands up to 6μm. During these phases, the 3.5 MHz DS interrogates thus the same bubble but that has a variable size. This is clearly demonstrated in the bubble vibrations at 3.5MHz during the positive and negative cycles of the 0.5 MHz CS. The decorrelation between the compression and expansion phases of CS in the 3.5MHz bubble response is significantly high to be used as a parameter to detect contrast MB and discriminate it from tissues. Conclusions: The results demonstrate the feasibility of this approach in improving the CTR compared to current contrast detection methods.

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

THE RESONANCE FREQUENCY OF INDIVIDUAL BUBBLES OF SONOVUE

S. VAN DER MEER*[1], M. VERSLUIS[1], C. T. CHIN[2], D. LOHSE[1], and N. DE JONG[1,2], [1]University of Twente, [2]Erasmus MC.
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Background: An ultrasound contrast agent (UCA) is a liquid containing small, encapsulated microbubbles. A general property is its size distribution as measured e.g. with a coulter counter, resulting in a mean size and the range. For Sonovue, e.g., the mean size is 3 micrometer, while 95 % of the bubbles are smaller than 10 micrometer. Acoustic characterization is done on a representative sample of the UCA, containing many microbubbles, resulting in scattering and attenuation properties as a function of the frequency. From this data the resonance behavior of the sample can be deduced. As the sample contains many microbubbles no direct conclusion can be drawn for individual bubbles. Goal: To develop a method to study the acoustical behavior of individual bubbles in an UCA. As the resonance is an important property of these UCAs, the goal is to develop a method to optically measure the resonance frequency of individual bubbles, including the size and the shell properties of the bubble. Method: Individual bubbles were visualized under a microscope and insonified with ultrasound generated with a broadband single element transducer. Each individual bubble was investigated with a sequential burst of 10 cycles, at 12 different center frequencies between 1.5 MHz and 5 MHz. The acoustic pressure was 200 kPa and programmed to be equal for all frequencies. The oscillation dynamics of the individual bubbles were recorded with a fast framing camera, the Brandaris 128, running in segmented mode at a frame rate of 15 Mfps, acquiring 64 frames

per acoustic frequency component. The total procedure took approximately 1 s. From the images the radius-time curves for each individual bubble were measured for each frequency component. From the R-t curve the maximum radius was determined and normalized to the resting radius, resulting in the relative expansion Rmax/R0. Result: The relative expansion was measured as a function of the frequency for individual bubbles between 1 and 6 micrometer and their resonance behavior observed. It was found that bubbles with a diameter of 4.0, 2.9 and 2.1 micrometer show a resonance frequency of 2.0, 2.7 and 4 MHz, respectively. Theoretical calculations based on free gas bubbles result in values which were 10, 15 and 20 % lower, respectively, suggesting a size-dependent influence of the shell. Conclusion: We have shown that acoustic characterization of individual bubbles is possible, which may lead to improved theoretical models for contrast agent behavior, development of new UCAs and optimized ultrasound imaging methods.

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

EXPERIMENTAL AND THEORETICAL CONTRAST AGENT MICROBUBBLE COLLAPSE THRESHOLD

A. Y. AMMI*[1], J. MAMOU[2], S. L. BRIDAL[1], and W. D. O'BRIEN, JR[2], [1]Laboratoire d'Imagerie Parametrique CNRS UMR 7623, [2]Bioacoustics Research Laboratory, Department of Electrical and Computer Engineering, University of Illinois.
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One of the central questions concerning the dynamics of ultrasound contrast agents microbubbles is under what conditions they collapse. In particular, how can ultrasonic excitation signals be modified to better control microbubble destruction? The answer to this question would provide a step forward toward non-invasive ultrasonic-guided drug delivery. Thus, our objectives are to experimentally evaluate microbubble collapse threshold as a function of ultrasound excitation and to model the movement of the bubble wall under these threshold conditions to identify indices (radial variation, peak velocity etc.) that may be predictive of bubble collapse. Transmit and receive transducers were positioned with their foci overlapping to form a passive cavitation detection system (PCDS). Transmitters have center frequencies of 1, 3 and 5 MHz. A 13-MHz focused transducer is used for detection. Optison microbubbles were gently mixed in a water tank with a pump at a dilution selected so that, on average, only a single bubble was within the focal region at any given time. For each excitation signal, 100 received time traces were recorded (100 MHz sampling, 8 bits). Frequency-domain analysis of the backscattered signals was performed to detect bubble collapse. Spectra were compensated for nonlinearly due to the propagation of the excitation signal. Bubble collapse was identified by the appearance of broadband noise between the harmonics. The collapse threshold was evaluated as a function of the excitation frequency, number of cycles, and pressure. The bubble wall movement (velocity, acceleration, and radial evolution) was modeled for such an excitation signal using the modified Herring equation. For example,

with a 3-MHz 3-cycle burst, the lowest compressional (rarefactional) pressure leading to collapse was 3.4 MPa (1.8 MPa). The corresponding simulation showed that, under these conditions of excitation, the bubble expanded to three times its initial radius and the wall velocity reached 49.23 m/s. Such techniques for the determination of destruction thresholds can be useful for comparison between different agents, minimization of destruction during imaging sequences and assuring destruction for therapeutic applications. Comparison of experimental results with theoretical models for bubble-wall movement should lead to a clearer understanding of the role of contrast agent dynamics in bubble destruction. (Work supported by the cooperative project for biomedical engineering between the University of Illinois at Urbana-Champaign, USA and the Centre National de la Recherche Scientifique, France.)

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

ACOUSTIC DETECTION OF CONTROLLED LIOB BUBBLE CREATION IN TISSUE-MIMICKING GELATIN PHANTOMS

C. TSE*[1], M. J. ZOHDY[1], J. Y. YE[2], T. B. NORRIS[2], L. P. BALOGH[3], K. W. HOLLMAN[1], and M. O'DONNELL[1], [1]University of Michigan, Biomedical Engineering Department, [2]University of Michigan, Center for Ultrafast Optical Science, [3]University of Michigan, Center for Biologic Nanotechnology.
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Laser induced optical breakdown (LIOB), based on nonlinear absorption, enables energy deposition on micron and submicron spatial scales and produces precise cell and tissue effects in a number of medical and biological systems. LIOB occurs only where the breakdown threshold is exceeded, and can be manipulated both geometrically and biochemically to selectively target areas within tissues while minimizing thermal and mechanical damage to surrounding material. Measurable effects of localized breakdown, shock wave emission and microbubble formation, signal targeted areas and generate an object for sensitive acoustic detection and potential manipulation. In this study, we show that by varying specific optical parameters, the size and stability of LIOB bubbles may be highly controlled. To monitor LIOB bubble characteristics in collagen gel phantoms of different concentrations, we use a high-frequency (>50MHz) ultrasound microscopy system which detects shock wave generation at the focus of an ultrafast pulsed laser source and simultaneously probes resulting microbubbles through pulse-echo recordings. Successive recordings taken before, during, and after laser exposure illustrate bubble creation and dissolution dynamics. Bubbles with a range of sizes, lifetimes and dissolution behaviors are produced by varying pulse fluence (0.7-2.1 J/cm^2), number of laser pulses (30500 pulses), and the period between pulses (0.05510 msec). Considering maximum integrated backscatter as a measure of bubble size, and bubble lifetime and backscatter decay rate as measures of bubble stability, we observe that both bubble size and stability are nonlinearly related to total laser exposure, and may be independently controlled

with fluence and pulsing. Both increases in pulse fluence and pulse number can lengthen bubble lifetime from tens to hundreds of milliseconds and decrease the rate of bubble dissolution 7-fold, but a bubble of particular stability does not necessarily have to be of a particular size. For instance, at a pulse repetition rate of 18kHz, a 276 ms lifetime bubble created and stabilized with 300 pulses at near-threshold fluence (0.7 J/cm^2 /pulse) has 8dB reduced integrated backscatter (i.e. reduced size) as compared to an identical lifetime bubble created and stabilized by 30 pulses at above-threshold fluence (1.8 J/cm^2 /pulse). Pulse period and number may be varied to deposit energy in a specific temporal manner, affecting and balancing the natural bubble dissolution rate. Furthermore, for a given set of optical parameters, bubbles of similar size can be created in gelatin phantoms of varying stiffness (2.5 10 w/w %), but are up to 4-times more stable in the stiffest gelatin for pulses at 3-times threshold fluence. Stability can be maintained only above a threshold size, however, below which dissolution rate rapidly increases, causing bubble collapse. Controllable creation of LIOB bubbles demonstrates the utility of these bubbles as *site-activated* ultrasound contrast agents.
This project is supported by NIH grants HL-47401 and HL-67647 and the Whitaker Foundation.

U1-D-5 510AC 2:30 p.m.
(Invited)
U2: COMBINED ULTRASONIC MICROSCOPY AND ULTRAFAST OPTICS FOR MOLECULAR IMAGING AND THERAPY

M. O'DONNELL*[1], C. TSE[1], M. ZOHDY[1], T. ERPELDING[1], and K. HOLLMAN[1], [1]Biomedical Engineering Department, [2]Electrical Engineering & Computer Science Department, [3]Internal Medicine Department.
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Imaging specific molecular pathways is the goal of molecular imaging. Similarly, disrupting aberrant pathways is the goal of molecular therapy. Since the energies associated with molecular interactions are so small, methods are needed to amplify them for detection with conventional optical, magnetic, or acoustic systems. We have investigated an approach to molecular detection in which a nanoscale object similar in size to important biological macromolecules is transduced by a femtosecond laser pulse into a microscale object directly detectable with MRI or ultrasound. Our specific embodiment uses ultrafast optics to transduce a nanoparticle into a microbubble. Nonlinear absorption of an ultrafast light pulse, with high peak intensity but negligible pulse energy, can disrupt a material in a highly localized way via laser-induced optical breakdown (LIOB). This process simultaneously induces a broadband shock wave and produces a microbubble within the disruption site. Dendrimers are highly branched macromolecules serving as nearly ideal templates to form dendrimer nanocomposite (DNC) particles. By trapping metallic domains in DNCs, the LIOB threshold of the organic host in water and tissue can be considerably decreased. In previous studies, we have shown that the LIOB threshold in water can be lowered by

about a factor of 50 using DNCs. These particles can also be targeted to specific cell receptors able to internalize them into desired cell types for localized photodisruption. Of particular interest are folate targeted DNCs for molecular imaging and therapy of squamous cell cancer. Squamous cell carcinoma is the second most common skin cancer, afflicting more than 200,000 Americans each year. It is an ideal candidate for targeted drug therapies for several reasons. First, primary treatment is surgical. Since these cancers are most likely in areas exposed to the sun, surgical solutions can often be disfiguring and/or very expensive. Second, primary cells within squamous cell cancers greatly overexpress folate receptors internalizing folate to satisfy the increased energy demands of the transformed cell. Conseqeuntly, a small folate targeting agent encorporated into a DNC can be highly specific. Finally, since these cancers are primarily superficial, high-resolution optical and ultrasonic methods may be able to monitor molecular diagnosis and therapy. In this study, we use ultrasonic microscopy to monitor LIOB. We present results suggesting that targeted photodisruption can operate in two regimes: one near threshold in which LIOB can be controlled to produce detectable microbubbles with little cellular injury (i.e., minimally invasive); the second at a different set of parameters where LIOB can be highly destructive, killing labeled cells for therapy. If both regimes can be established, then ultrasonic detection of DNC-promoted photodisruption can provide a sensitive tool for site-targeted molecular imaging and therapy of squamous cell cancers.
Support from the Whitaker Foundation and the National Institutes of Health (HL-47401 and HL-67647) is gratefully acknowledged.

Session: U2-D

VASCULAR ELASTICITY I
Chair: K. Nightingale
Duke University

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

CLINICAL EVALUATION OF 3D INTRAVASCULAR ULTRASOUND PALPOGRAPHY FOR VULNERABLE PLAQUE DETECTION

A. F. W. VAN DER STEEN*[1,2], J. A. SCHAAR[1,2], F. MASTIK[1], C. L. DE KORTE[1], and P. W. SERRUYS[1], [1]Biomedical Engineering Thorax Centre Erasmus Medical Centre Rotterdam The Netherlands, [2]Interuniversity Cardiology Institute of the Netherlands.
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Background 3D palpography is a technique that is capable of measuring radial strain in an atherosclerotic plaque. The development of this technique has been reported at this conference. It had been hypothesizes and has been shown in vitro that high strain spot in plaques are indicators for vulnerable atherosclerotic plaques. In this paper the first clinical experience is described. Reproducibility in patients and the relation between number of high strain spots and clinical presentation of the patient are discussed.

Methods 3D palpograms are acquired in patients during percutaneous transluminal coronary angioplasty (PTCA) procedures. For this goal a Volcano InVision echo apparatus was equipped with an rf-output. Intravascular rf-ultrasound data are acquired with a PC based acquisition system. Frames acquired at end-diastole are taken to determine the palpograms. A pull back of 1 mm/s was used to acquire data of a full segment of a vessel in 3D. The systemic pressure is used to strain the tissue. This strain is determined using cross-correlation analysis of sequential frames. In 12 patients a total of 14 3D palpograms were acquired twice at the same location. Palpograms were displayed as map representing the continuous strain distribution of the vessel wall. The maps were subdivided in regions covering 3 mm by 22.5 degrees. The median strain of the corresponding regions of first and the second recording were compared. Furthermore we performed 3 D palpography in 55 patients that were divided into three groups based on clinical presentation (stable or unstable angina, acute myocardial infarction). In patients with myocardial infarction the non-culprit vessel was studied. The number of high strain spots, which are related to vulnerable plaques, are counted and related to clinical appearance.

Results For reproducibility 512 regions were compared using orthogonal regression. The R2 of the model is 0.89 with a $p < 0.0001$, revealing a good reproducibility. Stable patient group (n=19) had 0.7 ± 0.5 high strain spots, the unstable group 1.7 ± 0.4 and the post myocardial infarction 2.0 ± 0.8. There was a significant difference between the stable vs. unstable group ($p<0.001$) and stable vs. post MI group ($p<0.0001$). No difference was seen between the unstable group and post MI group ($p<0.056$).

Conclusion Palpography can be used to assess vulnerable plaques in human. This pilot study revealed a clear association between clinical presentation and the amount of vulnerable plaques. However, additional validation has to be performed to assess the predictive value of the technique to identify vulnerable patients.

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

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

ASSESSMENT OF VULNERABLE CORONARY PLAQUE BY INTRAVASCULAR ELASTICITY IMAGING

T. SHIINA*[1], N. NITTA[2], H. ENDO[1], and M. YAMAGISHI[3], [1]Institute of Information Sciences and Electronics, Univ. of Tsukuba, [2]Institute for Human Science and Biomedical Engineering, National Institute of Advanced Industrial Science and Technology, [3]National Cardiovascular Center.
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Assessment of vulnerable coronary plaque is an essential procedure for prevention of the acute ischemic syndromes due to plaque rapture. In order to assess any risk factors of plaque rapture such as the lipid rich plaque and the vulnerability

of fibrous cap, the intravascular elasticity imaging by intravascular ultrasound (IVUS) is an useful technique different from the conventional IVUS echograms because the plaque compositions such as lipid, fibrosis and calcification can be viscerally assessed by the difference of tissue stiffness. We previously reported the usefulness of intravascular elasticity (strain) imaging based on our method which had a high ability to precisely detect strain over a large dynamic range from RF data acquired during interventional procedures.

However, the spatial resolution and accuracy of the intravascular strain imaging became blurred when catheter rotation induced by heart beat was severe. Then, for the purpose of obtaining more fine and accurate assessments of any plaques under interventional conditions, we newly propose the strain power imaging by analyzing the time-varying strain profiles. For each point or ROI on the instantaneous strain images obtained between consecutive pairs of echograms, strain profiles as a function of time are obtained by two-dimensionally tracking the ROI. Next, the strain power around heart beat frequency is calculated from the power spectrum of the strain profiles over a single cardiac cycle. As a result, the high-resolution and stable strain power image is obtained.

Moreover, for achieving the movie show of strain power images, a special A/D converter with huge deep memory was developed. The performance of this method was evaluated using coronary interventional data acquired with 40MHz catheter, by this A/D converter at a frame rate of 30Hz during 20sec using 240MHz sampling, the 1.6GB memory allowing the capture of 600 images of 1024 scan lines for an investigation depth of 5 mm. In vivo tests were conducted to several patients suffering from the vulnerable coronary plaque with lipid rich plaque. Results showed that the vulnerable plaques were discriminated by strain power imaging at high contrast and high resolution different from the conventional methods. Therefore, the potential of this method to the detection of vulnerable plaques was revealed.

This research is partly supported by grants of National Cardiovascular Center

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

YOUNG'S MODULUS RECONSTRUCTION FOR ASSESSING VULNERABLE ATHEROSCLEROTIC PLAQUE COMPOSITION IN VIVO

R. A. BALDEWSING*[1], J. A. SCHAAR[1,2], F. MASTIK[1], C. W. J. OOMENS[3], and A. F. W. VAN DER STEEN[1,2], [1]Biomedical Engineering, Thoraxcenter, Erasmus Medical Center Rotterdam, [2]Interuniversity Cardiology Institue of the Netherlands (ICIN), [3]Materials Technology, Biomedical Engineering, Eindhoven University of Technology.
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Background and Goal Assessment of vulnerable atherosclerotic plaque composition by calculating a Youngs modulus image allows monitoring of atherosclerosis. Currently, IntraVascular UltraSound (IVUS) elastography generates elastograms, i.e. arterial radial strain images. We have developed a method to reconstruct a Youngs modulus image from an elastogram. This paper describes the assessment of vulnerable plaque composition by applying that method on elastograms that were (a) simulated, (b) measured *in vitro* and (c) measured *in vivo* from a patient.

Materials Two computer-simulated plaques, a plaque-mimicking phantom and two human coronary plaques (*in vitro* and *in vivo*) were used.

Methods Finite element models were used to simulate elastograms for two plaque geometries, both having a lipid pool covered by a cap; one geometry was defined by circles, the other by tracing arterial histology. For the phantom and coronary arteries, elastograms were processed from radio-frequency data obtained with a 20-MHz 64-element phased array IVUS catheter. Multiple *in vivo* elastograms, obtained during the diastolic phase of a cardiac cycle were catheter motion was minimal, were averaged into one *in vivo* compounded elastogram to increase the SNR. Reconstruction was done by a minimization algorithm. It minimizes the Root-Mean-Squared (RMS) error between the elastogram calculated with a Parametric Finite Element Model (PFEM) representation of a vulnerable plaque, and a simulated or measured elastogram by iteratively updating the PFEM material and geometry parameters. These PFEM parameters define a media region containing a lipid pool covered by a cap; these three regions have a constant Youngs modulus and their borders are defined by circles.

Results All reconstructions approximated the geometry and material properties of the real plaque composition. After the reconstruction, the RMS errors [%] of the two computer-simulated and three measured elastograms were respectively 0.011, 0.16, 0.0056, 0.21, and 0.0033.

Conclusions This method can reconstruct Youngs modulus images from simulated and measured elastograms of vulnerable atherosclerotic plaques. These results find application in the diagnosis and therapy monitoring of atherosclerosis *in vivo*.

Supported by the Dutch Technology Foundation (STW) and the Netherlands Organization for Scientific Research (NWO).

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

NON-INVASIVE HIGH-FREQUENCY VASCULAR ULTRASOUND ELASTOGRAPHY: IN-VITRO PHANTOM INVESTIGATIONS

R. L. MAURICE*[1], M. DARONAT[1], S. F. FOSTER[2], and G. CLOUTIER[1], [1]University of Montreal Hospital, [2]Sunny Brook and Women's College Health Sciences Centre.
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Non-invasive vascular elastography (NIVE) was recently introduced to characterize mechanical properties of superficial arteries. In this paper, the feasibility of NIVE and its applicability in the context of high-frequency ultrasound is investigated. The experiments were performed in vitro on vessel-mimicking phantoms of 1.5-mm lumen diameter and 2.2-mm wall thickness. Polyvinyl alcohol cryogel (PVA-C) was used to create two double-layer vessels with different mechanical properties (1-2 and 2-4 freeze-thaw cycles, respectively). In both cases,

the stiffness of the inner layer was made softer (1 and 2 freeze-thaw cycles, respectively). Radial stress was applied within the lumen of the phantoms by inducing incremental static pressure steps with a column of a flowing mixture of water-glycerol. The vessels were insonified at 32 MHz with an ultrasound biomicroscope (Visualsonics, Toronto, Canada) to provide sequences of radio-frequency (RF) ultrasound raw data. The Lagrangian speckle model estimator (LSME) was used to assess the 2D-strain tensors, and the composite Von Mises elastograms were computed. Additionally, a new implementation of the LSME was introduced. It was based on the optical flow equations, since speckle can be considered as a material property; deformation parameters were estimated using an inversion algorithm. Results, reported for the 1-2-cycles PVA-C phantom, clearly delimited both layers. VM elastograms were computed with 5 mmHg gradient steps for intraluminal pressures ranging from 10 to 40 mmHg. The method was found to be reproducible and accurate, showing a maximum strain around 1.8 % for the inner wall in each case. The elastic modulus for the inner layer, made of 1 freeze-thaw cycle PVA-C, was estimated at 30 kPa. Results, reported for the 2-4-cycles PVA-C phantom, also clearly allowed identifying both layers. Whereas a maximum strain close to 1.2 % was observed, a 46 kPa elastic modulus was estimated for the inner 2-cycles PVA-C layer; this measure is in concordance with the literature (Fromageau et al., IEEE-UFFC, 2003). Those results were supported by numerical simulations of the kinetics associated with the double-layer vessel wall using the Ansys finite-element software, and using the Matlab software to simulate dynamic sequences of RF data. In conclusion, the feasibility of NIVE and its applicability using high-frequency ultrasound were confirmed. Additionally, the new implementation of the LSME considerably improved the algorithm performances in term of processing time. The use of the method for the purpose of studying small vessels in humans and in genetically-engineered rodents is discussed.

The authors gratefully acknowledge Mr. Cédric Schmitt for helping in numerical simulations with Ansys. This work was supported by grants from the Natural Sciences and Engineering Research Council of Canada (#138570-01) and Valorisation-Recherche Québec (structuring group program). The salary of Dr Cloutier is partially supported by a research scholarship award from the Fonds de la Recherche en Santé du Québec. The ultrasound biomicroscope was purchased through the support of the Foundation of the University of Montreal Hospital.

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

ESTIMATION OF 2D DISPLACEMENT AND STRAIN FIELD IN HIGH FREQUENCY ULTRASOUND BASED ELASTOGRAPHY

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High frequency ultrasound based elastography can be utilized for tissue elasticity imaging at a microscopic level. Mechanical strain fields inside the tissue are calculated as the spatial derivatives of estimated displacement fields. In this work, a technique for the estimation of 2D displacement fields, i.e. axial and lateral

displacements in the imaging plane, is presented. The developed method was applied to assess skin elasticity and to analyze non-uniform rotational distortions (NURD) in intravascular ultrasound (IVUS) with rotating single element transducers. We have developed a 20 MHz skin elastography system with a mechanically scanned single element transducer (44 μm / 139 μm minimum axial / lateral resolution). Echo signal frames are acquired during the application of a stepwise increased vacuum at the skin surface, causing suction. For the assessment of local strains inside the tissue, the skin surface is segmented and the echo signals are first aligned relative to the segmented contours. Because the deformation of the skin can be complex under the described conditions, elongations as well as compressions can occur. Therefore, we propose to consider positive and negative displacements in the signal processing. Local axial displacements are then estimated by applying a phase sensitive correlation approach, analyzing the phase of the complex cross correlation function of analytical radio frequency (rf) echo signals. In a second approach, local axial and lateral displacements are analyzed tracking speckle in B-mode image frames. An efficient estimation approach was implemented, analyzing the phase difference between B-mode image spectra. Displacements are estimated in adjacent windows over depth, starting from the skin surface, and estimated displacements in consecutive windows are accumulated. Strains are calculated determining the slopes of linear regression fits to the accumulated displacements. We propose to calculate the cross correlation coefficients of echo signals and B-mode images as measures for the reliability of the strain estimates in each window. Results of in vivo measurements on healthy skin, burn scars and nevi are presented. Axial and lateral strain images show that the strains in the dermis and the subcutaneous fat are significantly different. Strains in burn scars and nevi were found to be relatively large compared to the surrounding tissue. Applying steps of 12 mbar pressure change at the skin surface between two consecutive echo signal frames, maximum strains of about 1.5% were measured. The proposed 2D displacement estimation approach was also applied to analyze NURD in IVUS. Experiments were performed with 40 MHz IVUS catheters (Atlantis pro, Boston Scientific, USA). Results of phantom measurements and of coronary arteries in vitro are presented, showing that lateral subpixel shifts between A-line pairs occur, which can be reliably estimated. The developed approach was shown to be feasible in high frequency ultrasound applications.
The work is supported by the Federal Ministry of Education and Research, Germany (BMBF), grant 13N8079.

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

ARTERIAL ELASTIC MODULUS RECONSTRUCTION FROM IN-VIVO STRAIN IMAGE USING ARTERIAL PRESSURE EQUALIZATION

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A non-invasive free-hand ultrasound scanning procedure was performed to apply external force, comparable to the force generated in measuring a subject's blood pressure, to achieve higher strains by equalizing the internal arterial baseline pressure. When the applied pressure matched the internal baseline diastolic pressure, intramural strain and strain rate increased by a factor of 10 over a cardiac cycle. An elastic modulus reconstruction procedure was developed to estimate the nonlinear elastic properties of the vascular wall from intramural strain measurements. A simple model is used in which elastic modulus E_1 of the artery wall is related to elastic modulus E_2 of surrounding tissue by $E_1+K_2E_2=K_1[\Delta p/\Delta\epsilon]$ where $K_1$and K_2 are geometric factors, Δp is pulse pressure and $\Delta\epsilon$ is intercardiac strain (*i.e.*, change in strain from systole to diastole). Within an offset proportional to E_2, it is possible to reconstruct the arterial elastic modulus as a function of mean arterial strain from the ratio $[\Delta p/\Delta\epsilon]$. Both *ex-* and *in-vivo* measurements conducted in this study, as well as a large body of previous literature, suggest that the nonlinear change in arterial elastic modulus with preload can be modeled as an exponential function, $E=E_0e^{\alpha\epsilon}$, where α is a dimensionless constant describing the degree of nonlinearity. Consequently, a simple linear least squares fit to the natural log of the estimated elastic modulus as a function of preload can fully characterize the vessel walls nonlinear mechanical properties. If the elastic modulus of the surrounding muscle, E_2 , can be considered small compared to the arterial elastic modulus, the intercept E_0will determine the undistended (*i.e.*, zero preload) *in-vivo* arterial elastic modulus. If the change in elastic modulus with preload is small for surrounding tissue compared to that of the artery wall, however, then the slope of this curve (*i.e.*, nonlinear coefficient α) will be correctly reconstructed independent of the elastic modulus of the surrounding medium. For a normal human subject, the intercept E_0 ranges from 14.7 kPa to 16.5 kPa (mean$\pm$one standard deviation of logarithmic fit), and the slope α is 2.9$\pm$0.1. The intercept ranges from 153.2 kPa to 193.7 kPa (mean$\pm$one standard deviation of logarithmic fit), and the slope α is 4.0$\pm$ 0.6 for a subject with known vascular disease. The undistended elastic modulus of the diseased subject is over ten times that of the normal subject. Since the surrounding tissue modulus may be comparable between subjects, overestimation for the diseased subject is much less pronounced than that for the normal subject. The undistended modulus E_0 and nonlinear coefficient α can serve as strong indicators of *in-vivo* arterial stiffness.

Work supported in part by NIH grants HL-47401, HL-67647, HL-68658 and a grant from the Renal Research Institute.

Session: U3-D

CMUT APPLICATIONS

Chair: C. Daft

Sensant Corp.

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

(Invited)

MEDICAL IMAGING WITH CAPACITIVE MICROMACHINED ULTRASOUND TRANSDUCER (CMUT) ARRAYS

D. M. MILLS*, GE Global Research Center, Niskayuna, NY.

In recent years, several groups have shown images made with capacitive micromachined ultrasound transducers (cMUTs). This new transducer technology has emerged as a leading research area because these devices are non-resonant and can be integrated together with signal processing electronics. We will review real time imaging performed with early silicon nitride devices. Then, we will present new results from a wafer bonded cMUT probe produced and tested in our lab. These wafer bonded cMUTs show a fractional bandwidth of 130% (3–13 MHz), that covers almost the entire frequency range of interest for medical ultrasound. Further discussion will outline some of the challenges involved and potential solutions for integrating cMUT arrays with medical imagers. A review of some of the models from the literature will also be given as a means to optimizing the cMUT design and impedance matching.

U3-D-2 511AB 2:00 p.m.

INTEGRATED ULTRASONIC IMAGING SYSTEMS BASED ON CMUT ARRAYS: RECENT PROGRESS

O. ORALKAN*[1], X. ZHUANG[1], I. O. WYGANT[1], D. YEH[1], A. NIKOOZADEH[1], A. S. ERGUN[1], M. KARAMAN[2], and B. T. KHURI-YAKUB[1], [1]E. L. Ginzton Laboratory, Stanford University, [2]Dept. of Electronics Eng., Isik University.
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In ultrasonic imaging applications with large number of channels, e.g. volumetric imaging, and with strict area constraints, e.g. intravascular imaging, integration of the ultrasonic transducer array with supporting electronics is required to decrease the number of interconnects between the transducer array and the signal processing unit to a manageable level. This approach also minimizes the parasitics, improves the sensitivity and preserves the transducer bandwidth.

This paper describes a miniature real-time volumetric ultrasonic imaging system designed to fit in an endoscopic channel to assist image-guided, minimally-invasive procedures, and reports the recent progress toward the implementation of the described system. The proposed system employs a 16x16 2-D CMUT array and uses the phased array beamforming approach to alleviate the front-end hardware complexity of the system without sacrificing substantially from

the achievable frame rate and the image quality. The key components for the realization of such a system are the 2-D CMUT array and the frontend electronic circuits.

In order to demonstrate the aforementioned advantages of integration of transducer arrays with frontend electronic circuits, we have designed a custom integrated circuit (IC) comprising a pulse driver, a T/R switch, and a wide-band low-noise preamplifier. This IC was fabricated in a 0.25-μm standard CMOS process and wire-bonded to a 320-um x 320-um 2-D CMUT array element for the demonstration of pulse-echo operation. The CMUT was immersed in vegetable oil, so that an oil-air interface was formed 1.2 mm away from the transducer. A 5-V, 25-ns unipolar pulse was used to excite the transducer. The received echo signals present a frequency spectrum centered at 11 MHz with a 6-dB bandwidth of 15 MHz.

Our general approach to system integration employs flip-chip bonding of electronic circuits to 2-D transducer arrays. Therefore we adapted a Au-In flip-chip bonding process to integrate the 2-D CMUT arrays with ICs fabricated in a foundry. To develop this process, we fabricated fanout structures on silicon and bonded these test dice to 2-D CMUT arrays with through-wafer via interconnects. This process requires gold metallization on the back-side pads of the CMUT array, and indium bumps on the bond pads of the silicon die. The bond pads on the samples used in this experiment are 50-um in diameter. The samples are aligned prior to bonding, and undergo a maximum temperature of 150°C and a pressure of 20 g/bump during the process. The measured series resistance per bump is in the 1-2 Ohm range, and 100% yield is obtained for a total number of 32 bumps.

The results obtained in this study demonstrate the feasibility of the proposed integrated ultrasonic imaging system by illustrating the implementation of 2-D CMUT arrays, frontend electronic circuits and the flip-chip bonding process individually. Our current efforts concentrate on the integration of an array of frontend T/R circuits with 2-D arrays, and the hardware implementation of the described beamformer to obtain practical imaging results.

This work has been supported by the National Institutes of Health.

U3-D-3 511AB 2:15 p.m.

A CMUT LINEAR ARRAY USED AS ECHOGRAPHIC PROBE: FABRICATION, CHARACTERIZATION, AND IMAGES

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Piezoelectric ultrasonic transducers are widely used in echographic systems both for NDE and medical applications. Piezoelectric transducer technology, developed in the last 30 years, is nowadays a mature technology which gives bandwidths as high as 70-80% and a good sensitivity; nevertheless, it is expensive and presents some restrictions in the transducer geometry design and cabling especially for 2D arrays. The electrostatic principle is an alternative to the piezoelectric effect for ultrasonic transducer. In recent years, Khuri-Yakub et al. have introduced a new generation of capacitive ultrasonic transducers (cMUTs). These devices consist of a 2D array of miniaturized electrostatic cells electrically connected in parallel and driven in phase, using surface micromachining. For operation in the MHz range the lateral dimensions of each cell are on the order of tens of microns and for sufficient sensitivity the number is on the order of thousands. In past works, we described the cMUT micromachining technology developed in our laboratories; further, we discussed the design criteria and the analytical and numerical (FEM approach) model used to foresee the performances of this kind of transducers. In this work we demonstrate, with experimental evidences, the practical possibility to use our technology to realize multi-element probes able to be employed in commercial echographic systems for medical diagnostics. We report the design, the fabrication process, and the characterization of a 64-elements cMUT array. Using this transducer, we developed a probe for application in medical imaging. The probe was used in conjunction with a commercial echographic system to obtain images from echographic phantoms and from in vivo human body. Good echographic images of a test object and of internal organs of human body were obtained, demonstrating the practical possibility to use the technology developed in our laboratories to make cMUT echographic probes.

U3-D-4 511AB 2:30 p.m.

HIGH-FREQUENCY CMUT ARRAYS FOR HIGH-RESOLUTION MEDICAL IMAGING: PRELIMINARY RESULTS

O. ORALKAN*, S. T. HANSEN, A. S. ERGUN, and B. T. KHURI-YAKUB, E. L. Ginzton Laboratory, Stanford University.
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Diagnostic ultrasonic imaging systems used in some medical applications such as dermatology, ophthalmology and intravascular imaging are required to provide very high resolution. These systems operating in the frequency range greater than 20 MHz are often realized using mechanically scanned single focused transducer elements. Although arrays are desired to implement dynamic focusing and to improve frame rates, the fabrication of these arrays is challenging due to limitations in existing transducer technologies. Capacitive micromachined ultrasonic transducer (CMUT) technology takes advantage of integrated circuit fabrication techniques to achieve very small device dimensions required for high frequency operation.

In this study, we have designed and fabricated several 1-D CMUT arrays to operate in the 10 to 60 MHz frequency range. The 1-D arrays described in this paper have a total die size of 1.8 mm x 3.0 mm, and consist of 64 individually addressable elements with a pitch of 36 um. Each element consists of 110 circular membranes made of silicon nitride. The arrays are fabricated using the conventional sacrificial layer surface micromachining process. The arrays have been characterized in air and in immersion by electrical impedance and pulse-echo measurements. The first type of these arrays consists of membranes, which are 5 um in radius and exhibit a resonant frequency of 59 MHz in air. The capacitance of a single element is 1.3 pF. For immersion pulse-echo measurements, a single array element is wire-bonded to a custom-designed integrated circuit comprising a pulse driver, a low-noise preamplifier and a T/R switch. The CMUT array element is biased at 100 V, and excited with a 5-V, 12-ns unipolar pulse and echo signals from a plane reflector at 1-mm depth are recorded. The integrated preamplifier has a 50-MHz bandwidth when used with the described transducer element. The received echo signal exhibits a 35% fractional bandwidth centered at 44 MHz. The bandwidth limitation is due to the receiving electronics as confirmed by simulations. The second type of arrays used in this study are made of membranes with 6-um radius and have a resonant frequency of 47 MHz in air. This array element is also characterized in pulse-echo operation with the described electronic circuit. A single element operating in oil exhibits a 70% fractional bandwidth around 30 MHz, when biased at 100 V and excited with a 5-V, 15-ns unipolar pulse. The SNR for the received echo signal is 35 dB in a 50-MHz measurement bandwidth with no averaging. The measured frequency response does not show any indication of lateral cross coupling.

The results obtained in this study show that ultrasonic transducer arrays operating in high frequencies can be fabricated using the CMUT technology. These results also demonstrate that close integration of custom electronics and transducer arrays improve the overall sensitivity and preserve the bandwidth. Transducer arrays operating in the demonstrated frequency ranges are also suitable for small animal studies as well as clinical applications.

This work has been supported by the National Institutes of Health.

U3-D-5 511AB 2:45 p.m.

CMUT RING ARRAYS FOR FORWARD-LOOKING INTRAVASCULAR IMAGING: PRELIMINARY RESULTS

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Cardiovascular diseases are the number one cause of death in the United States. Currently, contrast angiography, which only images the vessel lumen and not the vessel tissue, is the predominant imaging technique to guide the therapy of coronary artery disease. Intravascular ultrasound (IVUS) has recently become a valuable diagnostic tool for many intravascular interventions. IVUS provides morphological descriptions of arteries, and enables a precise quantification of atherosclerotic coronary disease providing accurate information regarding the cross-sectional area and diameter of diseased vessels. However, current 1-D side-looking IVUS probes do not have forward viewing capability to guide interventions. A ring array structure can provide 3-D images in the forward direction ahead of the catheter tip.

In this study, we have designed and fabricated CMUT annular ring arrays for use in the proposed device. The ring array described in this paper is 1 mm in radius, and consists of 64 individually addressable elements. Each element consists of 9 circular membranes made of silicon nitride. The total area occupied by a single array element is 100 um x 100 um. The array is fabricated using the conventional sacrificial layer surface micromachining process. The silicon annulus is formed using deep reactive ion etching, so that a guiding wire can be placed through the center. The array has been characterized in air and in immersion by electrical impedance and pulse-echo measurements. The resonant frequency in air is 17.8 MHz, and the capacitance of a single element is 0.3 pF. For pulse-echo measurements, a single array element is wire-bonded to a custom-designed integrated circuit comprising a pulse driver, a low-noise preamplifier and a T/R switch. The CMUT array element is biased at 35 V, and excited with a 5-V, 45-ns unipolar pulse and echo signals from a plane reflector at 2-mm depth are recorded. The received echo signal has a 114% fractional bandwidth centered at 9.7 MHz. This array element can be operated in the collapse mode by setting the DC bias voltage at 100 V. In this case, a 5-V, 20-ns unipolar pulse excitation results in an echo signal with a 72% fractional bandwidth around 22 MHz. The echo amplitude in collapse mode is three times the amplitude in the conventional mode of operation. In collapse mode, the SNR of the received echo signal from a single element is 23 dB in a 50-MHz measurement bandwidth with no averaging.

The preliminary results reported in this paper underscore that annular ring arrays fabricated using CMUT technology and integrated with custom electronic circuits would be a suitable choice for the realization of forward looking intravascular ultrasonic imaging systems. These results also indicate that the ability to switch the operating frequency by changing the mode of operation offers a unique flexibility to switch from low- to high-resolution imaging mode when necessary.

This work has been supported by the National Institutes of Health.

Session: U4-D

THIN FILM BAW RESONATORS AND FILTERS

Chair: J. Vig
US Army

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

WIDE BANDWIDTH THIN FILM BAW FILTERS

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Wide bandwidth filters are of interest in current and emerging wireless system applications for use in IF circuits or as front-end filters. Filters for the new GPS M code and for wireless LAN are required to have bandwidths in excess of 4% of center frequency. Filter bandwidths are limited in conventional ladder filters by the inherent bandwidth of the piezoelectric resonator. Techniques to increase resonator bandwidth include the use of specialized electrode metallization, such as tungsten, or the use of series inductors to lower the series resonant frequency relative to the parallel resonant frequency. Another technique is to eliminate Co through the use of a "roofing" inductor or by eliminating Co as a factor by using acoustically coupled resonators. Low cost manufacturing for high volume applications suggests that small die are desirable and miniaturization requirements begin to preclude the use of on die inductors. The coupled resonator filter offers small die size for low cost wafer scale manufacturing and is capable of a fractional bandwidth in excess of 4% without the need for inductor tuning. This paper will describe design and fabrication methods for obtaining wide bandwidth filters for GPS and wireless LAN applications using coupled resonator filters. Experimental results will be presented as well.

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

NARROW BAND BULK ACOUSTIC WAVE RESONATORS AND FILTERS

H.-P. LOEBL*[1], R. F. MILSOM[2], C. METZMACHER[1], A. TUINHOUT[3], and P. LOK[3], [1]Philips Research Laboratories, [2]Philips Research Laboratories, [3]Philips Discrete Semiconductors, MSI.
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Bulk acoustic wave (BAW) filters are competing successfully in the range of 900 MHz to 10 GHz with SAW filters. USPCS and UMTS filters require a bandwidth of 60 MHz at approximately 2 GHz (fractional BW $\Delta f/f \approx 3\%$) /1/. This can be realized by optimum design and high quality piezoelectric AlN which allows values of figure of merit k2Q up to 100. On the other hand, relatively narrow-band solidly-mounted BAW filters can also be made. A typical example has approximately 6 MHz bandwidth with centre frequency of approximately 1GHz (fractional BW $\Delta f/f \approx 0.5\%$). The resonators required for narrow-band filters can be designed to have extremely good temperature characteristics (down to -2 ppm/K) and high Q (>1000), which makes such devices interesting for new applications. The paper discusses both broad-band and narrow-band solidly-mounted BAW filters. It is shown that a combination of accurate measurement and simulation using both 1D and 2D analytical models of resonators and filters can lead to more optimised designs. For example, this approach can help to determine accurate values of important material parameters (e.g. elastic constants), and also lead to an improved understanding and therefore reduction of acoustic loss /2/.

/1/ Low-Level Effects in SBARS and their Application to Device Optimization, H.P.Loebl, C.Metzmacher, R.F.Milsom, 2003 IEEE Ultrasonics Symposium, p.182.

/2/ 2D Model of Solidly-Mounted and Membrane BAW Devices, R.F. Milsom, H-P. Loebl, C. Metzmacher, P. Lok, A. Tuinhout, F. van Straten, 2003 IEEE Ultrasonics Symposium, p.1802.

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

SINGLE-TO-BALANCED FILTERS FOR MOBILE PHONES USING COUPLED RESONATOR BAW TECHNOLOGY

G. G. FATTINGER*, J. KAITILA, W. NESSLER, and R. AIGNER, Infineon Technologies AG.
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The dominant trend in mobile communication is the reduction of cost and size of the components. Bulk-Acoustic-Wave (BAW) filters are ideally suited to replace conventional RF-filters for all major cell phone standards such as GSM, CDMA and WCDMA. The main advantages are a performance which is unmatched by SAW filters, very low manufacturing costs and the availability of a Wafer-Level-Package. The Coupled Resonator Filter (CRF) is a new type of Bulk-Acoustic-Wave (BAW) device in which two piezoresonators are stacked on top of each other in a way that a certain degree of acoustic interaction occurs. A remarkable property of the CRF is that the filter bandwidth is not only controlled by the inherent bandwidth of the piezoelectric coupling mechanism, but also by the degree of coupling between the two resonators. CRFs feature complete galvanic isolation between input and output and thus enable to offer BAW filters with mode-conversion (single-ended to balanced) as well as impedance transformation. Major cell phone standards like GSM or W-CDMA are pushing the need for filter devices featuring mode conversion because the LNAs are integrated into the Transceiver ICs and typically have balanced inputs. The current BAW filter technology with ladder and lattice topology can only provide either single-ended or balanced filters but no mode conversion. In order to establish BAW as a mainstream filter technology the capability for mode conversion is mandatory. Therefore CRFs are a promising candidate to overcome the limitations of both, SAW filters and conventional filter-balun combinations. SAW filters have severe problems with ESD robustness and powerhandling. At high frequencies the fabrication of SAWs gets increasingly difficult and SAWs require hermetic ceramic packages. CRF BAW filters have extremely small size, they can achieve ESD ratings 10x better than SAW and they handle power extremely well. In this paper, the basic concept underlying these devices will be reviewed. Manufacturing issues will be discussed. A sensitivity analysis regarding important layer thicknesses has been performed, the results and their impact on the process flow will be reviewed. Subsequently, experimental results of mode converting CRFs for GSM applications operating at 1.8 GHz manufactured at Infineon Technologies will be presented. As this band is the one with the most stringent requirements regarding bandwidth and insertion loss the results proof that all relevant receive filter can be made using CRF BAWs. Moreover the performed single-to-balanced

measurements will be discussed. For the balanced port, those results demonstrate an excellent phase imbalance of less then 5 degrees and an amplitude imbalance smaller than 0.5 dB, which is obtained by a symmetrical design. The temperature coefficient of frequency (TCF) has been measured in the range of -55°C to +200°C. Due to the compensating effect of Si-Oxide in the CRF stack the values obtained are in a range of -11 ppm/K which is factor 4 better than in SAW filter.

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

A NOVEL DESIGN TECHNIQUE & THE DEMONSTRATION OF A 2.0 MM X 1.6 MM CHIP-ON-BOARD PCS TX BAND PASS FILTER WITH STEEP LOW AND HIGH FREQUENCY ROLLOFFS HAVING HIGH REJECTION IN THE PCS RX & IMAGE BANDS

D. FELD*, P. BRADLEY, B. YU, and D. LEE, Agilent Technologies.
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The inherently high Q's and low temperature drifts of Thin Film Bulk Acoustic (FBAR) resonators is an enabler in producing a 60 MHz wide band pass filter with a 1880 MHz center frequency having <8.0 MHz low-frequency rolloff (from 3.5 dB to 25 dB) and <9.0 MHz high-frequency rolloff (from 3.5 dB to 35 dB) respectively. We present a novel design technique required to produce such a filter packaged in a 2.0 mm x 1.6 mm chip-on-board package. Such a high performance filter, which occupies a tiny volume, is demanded by some handset manufacturers to provide > 35 dB Rx band rejection while also providing > 25 dB of rejection in the image band (directly below the pass band) over an operating temperature range of -30 C to +85 C. Our design techniques allow us to meet both of these stringent rejection requirements while also meeting a wide band rejection requirement of 20 dB (to 6.0 Ghz) and having a VSWR of 2:1. We also discuss the process control requirements needed to produce such a filter with high yields.

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

3.8MM X 3.8MM PCS-CDMA DUPLEXER INCORPORATING THIN FILM RESONATOR TECHNOLOGY

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Bulk Acoustic Wave (BAW) technology based on piezoelectric thin films has recently emerged as a preferred technology for the realization of miniaturized high performance RF filters and duplexers to be used in wireless applications

like mobile phones. We present a duplexer for PCS-CDMA applications with a footprint of 3.8mm x 3.8mm and a height of 1.2 mm. The duplexer consists of a transmit (TX) and a receive (RX) filter, both mounted as bare dies on a low temperature co-fired ceramic (LTCC) multilayer substrate containing additional matching elements. The filters are realized using solidly mounted resonator (SMR) technology, where an acoustic mirror separates the active resonator part from the substrate. Duplexer packaging is based on the EPCOS proprietary CSSPlus technology developed for the miniaturization of chip sized SAW packages with a cavity between the package and the acoustically active filter areas. The front-end technology for realizing the bulk acoustic wave filters mainly uses standard 200 mm CMOS technology and a sputtering process for AlN piezoelectric thin films with a very high thickness uniformity over the wafer. The duplexer is fully matched to 50 Ohm with low insertion attenuation in the passbands, a superior stopband characteristic up to 10 GHz, and a temperature coefficient of frequency (TCF) of –15 ppm/K.

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

NEW ELECTRODE MATERIALS FOR LOW-LOSS AND HIGH-Q FBAR FILTERS

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We have developed new electrode materials suitable for AlN based FBAR. This new electrode material makes the quality factor (Q) and electro-mechanical coupling coefficient (K2) of FBAR higher. Consequently, we have been able to achieve the low-loss and the steep cut-off filters using these high performances FBAR. Recently, FBAR technologies attract a lot of attention as RF devices for wireless communication systems. SAW filters are feared to become inadequate for high frequency operation, due to high electrode resistivity and power handling capability. On the other hand, ceramic filters have the disadvantage of large size and broad cut-off characteristics. FBAR filters have a possibility of overcoming these limits of the current filters, and provide miniature, low-loss, steep cut-off and high frequency operation filters. The selection of electrode material is of great importance for high performances FBAR filters, due to the property of electrode material greatly influence Q and K2 of FBAR. Molybdenum has been widely used as the electrode material so far. However, the higher the operation frequency is, the severer the requirements for electrode materials of FBAR become. In this work, the necessary conditions for electrode materials were investigated in simulations and experiments. The one result indicated that low electrical resistivity and high acoustic impedance are required for electrode materials. In addition, deposition conditions of c-axis oriented AlN thin film on new electrode materials and power handling capability are also examined. Eventually, we found the appropriate electrode material, which meets the strict requirements. By using this new electrode material, resonators of the unloaded

resonant Q of 4010 and the effective K2 of 6.3 % at 5100 MHz were obtained. Furthermore, we applied these excellent high performance FBAR to ladder-type FBAR filters for 5 GHz WLAN applications. As a result, we achieved the low-loss of 2 dB and the steep cut-off FBAR filters.

Session: U5-D
SAW DEVICES AND PROPAGATION
Chair: P. Smith
McMaster University

U5-D-1 512C-H 1:30 p.m.

PERFORMANCES OF SHORT REFLECTORS ON 128° $LiNbO_3$

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We study numerically the phase of SAWs reflected by or transmitted through short reflectors comprising only 1-3 aluminium electrodes on 128° YX-cut $LiNbO_3$. We also try to find the best possible geometry for the reflectors to achieve the minimum of ratio of the energy lost due to the scattering of the waves into the bulk to that of the reflected SAW. The electrodes have a finite thickness and they are either open-circuited or grounded. The center-to-center distance between adjacent electrodes d corresponds roughly either to half of the characteristic wavelength d $\sim \lambda_0/2$ or to d $\sim \lambda_0$, for the reflectors operating at the fundamental and second harmonic modes, respectively. We use FEM/BEM software [1] for numerical experiments with a tailored 3-IDT test structure, simulating experimental conditions with an incident wave and reflected and transmitted SAWs. Employing a procedure for enhancement of time resolution in conjunction with the fast Fourier transform (FFT) and time-gating, calculation of the Y-parameters in a reasonably wide frequency range allows us to determine the phase of the reflection and transmission coefficients. Our quantitative results suggest that the phase change attributed to the reflection depends on both the relative electrode thickness ($h/\lambda_0 =$ 2-8%) and the metallisation ratio ($a/p =$ 0.2-0.8). The phase of the reflection coefficient is not necessarily close to $\pm 90°$. The deviation of the phase difference between reflection and transmission coefficients in our symmetric system is an important parameter directly related to energy losses. Thus, for proper design of SAW devices incorporating several reflectors in the same acoustical channel, employing the nominally $\lambda_0/4$- and $\lambda_0/2$-wide electrodes studied, a tight control of phase characteristics is necessary. However, for single electrodes, according to our simulations, a combination of varying magnitude of reflectivity with invariant phase can be found for practical electrode thicknesses and metallisation ratios.

[1] J. Ribbe, "On the coupling of integral equations and finite elements / Fourier modes for the simulation of piezoelectric surface acoustic wave components, PhD Thesis, CMAP / Ecole Polytechnique, 2002.
The authors are grateful to Clinton Hartmann for enlightening discussions and William Steichen at Temex Microsonics SA for conferring TRANSD (FEB/BEM-based simulator for the analysis of SAWs in finite electrode structures developed by Temex Microsonics in collaboration with CMAP/Ecole Polytechnique) at the disposal of HUT for this study.

U5-D-2 512C-H 1:45 p.m.

CALCULATION OF THE SAW-INDUCED STRESS DISTRIBUTIONS IN AN ELECTRODE OF A SAW-DEVICE ON $LITAO_3$

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Acoustomigration is a well-known problem, which may occur in Surface Acoustic Wave (SAW)-devices operating at high driving levels. In order to improve the durability of the SAW-device against acoustomirgration the knowledge of the stress distribution is very important. Based on previously published reports about the calculation of the acoustic power, dynamic stresses and displacements in a homogenous isotropic Al-layer [1-3] for a given driving condition we expand this method for the calculation of the SAW-induced stress in a SAW-electrode of a SAW-device. Furthermore this method enables to determine the the stress distribution in a single electrode finger. The quantitative calculation of this stress is based on the combination of the widely used P-Matrix based model [2], which yields the potential power distribution and the resulting energy distribution in propagation direction for a given driving level and a FEM tool [4]. The latter yields the detailed stress distribution inside the electorde. The different stress distributions will be discussed. This approach provides the flexibility to determine the stress distribution for any input power, frequency, wavetype or metal layer in a SAW-device and its electrodes, too. Thereby we get information about the weakest point in the SAW device, which is very susceptible for acoustomigration and thus has to be systematically improved.

[1] U. Rösler, W. Ruile, K. Ch. Wagner, T.W. Johannes, G. Scholl, R. Weigel, "Energy Distribution in a Quartz Resonator", IEEE Ultrason. Symp. Proc., pp. 1-4, 1996 [2] F. Kubat, W. Ruile, L. Reindl, "P-Matrix based Calculations of the Potential and Kinetic Power in Resonating SAW-Structures", IEEE Ultrason. Symp. Proc., pp. 317-320, 2002 [3] F. Kubat, W. Ruile, T. Hesjedal, J. Stotz, U. Rösler, L. Reindl, "Distribution of the dynamic Strain and Stress components within a layered Film of a SAW device on LiTaO3", pp. 312-315, IEEE Ultrason. Symp. Proc.; 2003 [4] P. Smole, W. Ruile, P. Pongratz, "Characterization of Surface Acoustic Wave Propagation in a ZnO Layer on a Conducting Substrate," pp. 296-299 IEEE Proc. Ultrason. Symp., 2002
The authors would like to thank P. Smole for providing the FEM tools.

U5-D-3 512C-H 2:00 p.m.

A NOVEL PIEZOELECTRIC INTERDIGITED TRANSDUCER FOR THE EXCITATION OF HIGH FREQUENCY SURFACE ACOUSTIC WAVE

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The combination of boundary integral methods (BIM) and finite element analysis (FEA) has demonstrated its efficiency for modeling infinite periodic and finite non periodic surface acoustic wave transducers. Recently, we have shown that the use of a boundary element method (BEM) for the simulation of radiation conditions in periodic FEA offers more adaptability without any loss of precision for many kind of problems, such as inhomogeneous acoustic wave guides, passivated surface acoustic wave devices, piezocomposite transducers and even micro-machined ultrasonic transducers. In this work, we investigate the possibility to applied this approach to the simulation of finite non periodic devices with radiation boundary conditions. Actually, most of the vibrating devices implemented in acoustics are clamped to or built on a massive body in which electro-acoustic energy is radiated. The classical approach simply consisting in the simulation of isolated vibrators or rigidly clamped devices (for which displacements are set to zero in the embedment region) is revealed improper to rigorously predict their resonant behavior. We then propose to implement a computation code able to mix FEA and a BEM for the simulation of finite non-periodic structures with reasonable computation delays. In the case of radiation in semi-infinite fluids, the problem is simplified by the knowledge of the exact analytic form of the Green's function used to compute the boundary element contributions. However, this situation does not occur for semi-infinite solids which still requires some efforts in that pursuit. It is then necessary to compute the spatial Green's function relating the surface stresses to the displacements thanks to its spectral form (accessible analytically) by Fourier transform. In that matter, it is shown how to compute the Green's function asymptotic behavior along the wave number (or the slowness) for isotropic solid and to integrate the resulting contributions in the BEM. The contribution of the shear wave to the Green's function is also identified analytically. A generalization of these results to anisotropic solids is regarded. Finally, the boundary element computation consists in a combination of analytic and numerical integration. Fit procedures are finally developed to improve the convergence and to reduce the computation time of numerical integrations.

The authors thank Th. Pastureaud and R. Lardat for fruitfull discussions on the subject

U5-D-4 512C-H 2:15 p.m.

FAST FEM/BEM COMPUTATION OF SAW HARMONIC ADMITTANCE AND SLOWNESS CURVES

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The combination of the finite element method (FEM) and the boundary element method (BEM) for the simulation of surface acoustic wave (SAW) devices has been used by many authors. Although the FEM/BEM method only applies to the infinite periodic interdigital transducer (IDT), and is thus only an approximation of a real finite SAW device, its high degree of accuracy and reasonable computational burden have made it the basis of many advanced SAW parameter extraction codes. It has also been used as a mathematical tool for the analysis of surface waves propagating obliquely in an IDT and thus for obtaining slowness curves in a grating.

The FEM/BEM method relies on an integral representation of the substrate surface assuming a semi-infinite medium through spectral Green's functions, connected through a discrete formulation to the electrodes, which are treated acoustically by the FEM. The FEM part of the computation is numerically the heaviest. The FEM/BEM is a spectral method, and while the spectral Green's function of a semi-infinite substrate does not depend on frequency, the FEM problem for the electrodes has to be solved for every frequency point. When oblique propagation is moreover considered, the FEM problem again has to be solved for every transverse wavevector.

In this communication, we will summarize an approximation method that was introduced recently [1] and that requires the solution of the FEM problem only for the central frequency of the bandwidth of interest. The method will be extended to oblique propagation, in which case the solution of the FEM problem for only one transverse wavevector is required inside some angular range. SAW slowness curves inside and outside the stop-band of an infinite periodic IDT will be compared, with a particular view at the deformation of the slowness curve induced at resonance.

[1] V. Laude, A. Reinhardt, M. Wilm, A. Khelif, and S. Ballandras, "Fast FEM/BEM Simulation of SAW Devices Via Asymptotic Waveform Evaluation," IEEE Trans. Ultrason. Ferroelec. Freq. Control, to appear (2004).

U5-D-5 512C-H 2:30 p.m.

SAW DELAY LINES ON SINGLE CRYSTAL GAN FILMS ON SI AND SAPPHIRE : ACOUSTIC PARAMETER EXTRACTION

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Summary We present the measured data from the SAW delay line build on a single crystal blanket film of 2 and 4 micron thick GaN deposited on 4 inch Silicon and sapphire wafers. We found that the measured SAW velocity depends on film thickness and substrate (3800-5000 m/s). We extracted pure GaN SAW velocity (3700m/s), from the measured data is close to other published values for GaN. We also found that the higher conductivity of the Si wafer leads to a decrease of the center frequency of the delay line and provides less out of band attenuation i.e. less than 15 dB than the sapphire wafer i.e. 30 dB. We will report any correlation of the acoustic parameters like velocity, coupling coefficient and SAW performance with direction of propagation, surface morphology and X-ray characterization of the single crystal. Results Even though the single crystal GaN SAW devices have been already reported on Sapphire substrates 1 2 there has been no report of GaN SAW devices on Si substrates. Fabrication of the SAW devices on a large diameter Si wafers could open possibilities of integration with electronics, and using micromachining techniques for sampling and packaging structures. The crystalline structure of the GaN film grown on Si substrate is shown in Fig. 1, where XRD diffraction results are proving that good quality single crystal can be obtained on Si substrate. The layout of the SAW delay-line is shown in Figure 2. We measured (Fig 3) and calculated the SAW velocity with two different methods: delay time and center frequency. The velocity varied from 3800 to 5000 m/sec for different substrates, GaN thickness and propagation direction. We will present the detail data and fitting to the theoretical prediction in the full paper. It is clear from the Figure 3 that the Si substrate allows for a higher coupling between input and output, which can be explained by the conductivity of Si wafer of about 20 Ohm-cm. This results in the out of band rejection on Si being at least 15 dB lower than on isolating sapphire. As shown in Figure 3 the center frequency of the SAW devices on Si is about 20% lower than on sapphire. This again can be attributed to the conductive loading of SAW by the Si substrate. The conductive Si substrate also is the main reason for the input impedance at 1 MHz to be 17 pF in parallel with 2-3 kOhm versus purely capacitive input impedance on sapphire wafer of 1.7 pF. The surface of the GaN on Si has 14 times more roughness than surface of GaN on sapphire as shown in Figure 4. The high roughness may also contribute to more noise and high attenuation for SAW devices.

U5-D-6 512C-H 2:45 p.m.

RF-SAW FILTERS ON PYRO-SUPPRESSED WAFERS

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The increasing need for smaller, cost effective and better performing RF-SAW filters has placed a significant emphasis on production yields and new technologies. The majority of RF-SAW filters are fabricated on substrates such as leaky-SAW cuts of LiTaO3, which are pyro-electric. In addition, they are designed using coupled resonator techniques that result in very small metal geometries due to the high frequencies of operation (above 1GHz). It will be shown that these two factors, combined with the temperature cycles that the devices endure during the production process, often lead to significant pryo-electric related damage to the filters, thus resulting in poor electrical yield. Currently, fabrication and assembly processes for RF-SAW filters on pyro-electric substrates are modified to ensure that the pyro damage is reduced and/or eliminated. However, these processes are not entirely reliable, cost effective, or without second order effects on performance. Recently, several wafer manufacturers have introduced pyro-suppressed wafers as an alternative solution to this problem [1]. This paper compiles the results of several experiments realized on pyro-suppressed substrates using different design techniques, frequencies and materials. A comparison of the acoustic velocity and temperature dependence of the leaky-SAW parameters was done. The results presented show a negligible change in filter performance, and a dramatic improvement in electrical yield. Use of pyro-suppressed leaky-SAW LiTaO3 will allow the designer to take advantage of multiple design techniques and device layouts, as well as facilitate high volume production of high frequency devices.

[1] www.siliconlight.com

Session: FE3-D

PIEZOELECTRIC DEVICES

Chair: A. Akdogan
Rutgers University

FE3-D-1 512A-F 1:30 p.m. (Invited)

THEORETICAL STUDY OF THE INFLUENCE OF THE ELECTROMECHANICAL CONSTANTS AND NON LINEAR MECHANICAL LOSSES OF VARIOUS PIEZOELECTRIC MATERIALS ON THEIR PERFORMANCES IN POWER TRANSDUCERS

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A simple analytical model is developed in longitudinal resonance mode taking into account the piezoelectric and mechanical constants of the materials as well as a mechanical loss tangent depending on the relative mean strain S : tandm = tandmo + a S, where tandmo is the low power mechanical loss tangent and 'a' a coefficient characteristic of the non-linearity.

For a given acoustical load the power supplied to the load, the mechanical losses and the maximum internal stress are expressed as a function of the applied electric field at the series resonance frequency for various materials : Hard PZT, hard BaTiO3 and PMN-PT ceramics and a PMN-PT single crystal.

In steady state the limitation factor would be the loss power for PMN-PT ceramic and single crystal and the maximum stress for hard PZT and BaTiO3. In longitudinal mode the very high compliance of the single crystal goes against it, however its low acoustical impedance significantly reduces the internal stresses.

The hard lead-free barium titanate could be similar in radiated power to the hard PZT but it should be supplied with higher electric fields.

FE3-D-2 512A-F 2:00 p.m.

CHARACTERIZATION AND MODELING OF LOCAL DEFORMATION RESPONSE IN STRESS-BIASED PIEZOELECTRIC ACTUATORS

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Thunder actuators are stress-biased flextensional devices that demonstrate greater electromechanical displacement than unimorphs and bimorphs of similar dimensions. Numerous investigators have explored the factors that contribute to the performance of these actuators with particular attention being given to the importance of the extrinsic (domain wall translation) response mechanism. Based on the variation in lateral stress through the thickness of the piezoelectric layer within these devices, it has been suggested that the piezoelectric coefficient varies as a function of position within the layer, though no direct evidence has been presented. The highest d-coefficients are expected at the surface, because of greater non-180 domain wall motion than at other regions within the piezoelectric layer.

In this presentation, the results of Moire interferometry investigations of local strains within these devices will be reviewed. Samples were prepared by applying a diffraction grating to the cross-section of actuators with various piezoelectric:substrate thickness ratios. By using different thickness ratios, samples with different stress profiles (across the piezoelectric layer) were obtained. Interferograms were subsequently acquired using a four beam technique and the resulting local (depth-dependent) deformations under various applied electric fields were calculated from the changes in the spacing of the interference fringes. The technique permits effective depth-profiling of local deformations at reasonably high ($\sim$25 um) resolution.

The resulting local deformations were then analyzed using composite laminate theory. A least squares regression analysis approach was used to fit the data to depth-dependent piezoelectric response. As expected, higher d-coefficients were predicted for the free surface of the device compared to the interface with the substrate. The predicted values were in general agreement with expectation and are further considered from the perspective of recent reports in the literature regarding multi-axial loading effects on the electromechanical properties of lead zirconate titanate-based piezoelectric ceramics.

FE3-D-3 512A-F 2:15 p.m.

LIMITATION OF THE DEGRADATION EFFECT IN PIEZOELECTRIC MULTILAYER ACTUATORS WITH CERAMIC LAYER THICKNESS BELOW 50 μM

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Lead zirconate titanate multilayer actuators with varying ceramic layer thicknesses were characterized with the objective of better understanding the influence of the ceramic layer thickness on their piezoelectric properties. Bulk and multilayer samples of PNN-PZT ceramics with AgPd inner electrodes were prepared using multilayer technology and cofired at temperatures varying from 1050°C to 1130°C. Multilayer actuators with ceramic layer thicknesses of 17 μm to 280 μm were electrically characterized. With decreasing ceramic thickness, the dielectric constant ϵ and the large signal piezocoefficient d_{33} decreased in the case of multilayers in comparison to bulk samples. In particular, the degradation effect of the piezoelectric properties increased dramatically for the multilayers with a layer thickness below 70 μm. The possible origins of this degradation effect have been identified in the following interaction mechanisms that occur during cofiring of such ceramic/metal composites: Firstly, due to cofiring with AgPd electrodes, the sintering temperatures of multilayer samples were reduced. This causes a change in the microstructure and a shift from the morphotropic phase boundary. This consequently results in a decrease in the piezoelectric coefficients. Secondly, the incorporation of silver in the PZT lattice as an acceptor dopant influences the piezoelectric properties of the ceramics. As the ceramic thickness is decreased, a strong increase in the Curie temperature was measured. This indicates a change in the ceramic composition which is dependant on the layer thickness. Finally, it was shown that the thermal mismatch between the inner electrode and the ceramic contributes the most to the performance degradation of the actuators with respect to decreasing the layer thickness. Due to this, clamping forces are applied to the ceramics that cause the preferred orientation of the piezoelectric domains to be parallel to the poling direction. This results in the reduction of the piezoelectric induced strain and the large signal piezocoefficient. This effect is more noticeable with decreasing ceramic layer thickness, which was verified by measuring the remnant strain after the poling process. Two solutions have been studied to reduce the clamping forces applied to the ceramics: the incorporation of PZT powder into the electrode paste and the reduction of the electrode thickness. Due to the incorporation of PZT powder, two contradicting effects are observed. On one hand, the clamping forces are reduced due to the adjustment of the dilatation coefficient. Conversely however, the reduction of the piezoelectric active area results in a decrease of the actuator performance. An improvement was obtained by screen-printing thinner

electrodes, which causes a reduction of the compression strains applied to the ceramics. Consequently, an increase in the large signal piezocoefficient of 50 % could be achieved for samples with a 17 μm ceramic layer thickness.
This project is supported by the BMBF with contract number 03N1076A.

FE3-D-4 512A-F 2:30 p.m.

LOW-FREQUENCY, HIGHLY-SENSITIVE MAGNETO-ELECTRIC LAMINATE COMPOSITE FOR ANOMALY DETECTION

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A new generation of low-frequency magnetic field sensors, based on multilayer laminate composites of magnetostrictive Terfenol-D and piezoelectric Pb(Mg1/3 Nb2/3) O3-PbTiO3 (or PMN-PT), has been developed. When operated in an entirely passive mode at room temperature, this sensor has the potential for picoTesla resolution at milli-hertz frequencies, offering opportunity for small non-invasive sensors for magnetic anomaly and biological signal detection applications.
Office of Naval Research

FE3-D-5 512A-F 2:45 p.m.

TEMPERATURE DEPENDANCE OF A PIEZOELECTRIC SENSOR

E. P. GNANAMANICKAM*[1], J. P. SULLIVAN[1], and J. BROSCH[2], [1]School of Aeronautics and Astronautics, Purdue University, [2]Piezotechnologies.
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The material properties of PZT (Navy II) and Bismuth Titanate was studied at elevated temperatures using the resonance method. Specifically the behavior of the longitudinal charge coefficient and the dielectric constant were measured. Based on the longitudinal charge coefficient and the dielectric constant variation with temperature the piezoelectric voltage coefficient variation with temperature was obtained. Using ceramic from the same batch as the samples for the resonance method, two simple compression type accelerometers with central preload were built. One of the accelerometers had PZT(Navy II) as the sensing element and the other had Bismuth Titanate as the sensing element.

The behaviors of the accelerometers were compared at room temperature with an accelerometer build by PCB Piezotronics (PCB302A). Both the accelerometers were subject to a shock motion and the responses were studied to obtain a qualitative measure of the accelerometer design used. The response of the accelerometers under test showed good agreement with the PCB302A response at room temperature. The shock tests were then carried out at a range of temperatures starting from room temperature to about three quarters the Curie temperature of the sensing elements.

Based on the response of the accelerometers under test at room temperature a normalized voltage coefficient variation with temperature was obtained for the entire temperature range. This variation was then compared with the variation of the piezoelectric voltage coefficient measured using the resonance method. At temperatures less than half the Curie temperature there was good agreement between the voltage coefficient values obtained from the response of the accelerometer and the measured values. However at higher temperatures the voltage coefficient variation based on the accelerometer response was higher than the resonance method values

Dr. Keith Bowman, Purdue Univeristy

Session: FE1-D

SINGLE CRYSTALS
Chair: J. Yamashita
Toshiba Corporation

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

STRESS DEPENDENT ELECTROMECHANICAL PROPERTIES OF HIGH COUPLING CRYSTALS

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Strain levels about an order of magnitude larger than conventional lead zirconate titanate (PZT) piezoelectric ceramics were reported for <001>-oriented and poled multi-domain single crystals in the (1-x) $Pb(Zn_{1/3}Nb_{2/3})O_3$ - (x) $PbTiO_3$ system.[1] Approximately a 50% larger electromechanical k_{33} coupling was observed in this system compared to PZT.[2] These remarkable features have sparked significant development world-wide aimed at crystal growing, fundamental understanding, and applications in sonar and medical ultrasound. Novel sound projectors and receivers are now being realized as a result of the electromechanical and elastic properties discovered in the relaxor-ferroelectric (1-x) $Pb(B^{I}{}_{1/3}B^{II}{}_{2/3})O_3$ (x) $PbTiO_3$ single crystal system (where B^{I} = Mg or Zn and B^{II} = Nb.) Compared to standard PZT8 projector material, single crystals offer nearly triple the bandwidth due to their high coupling and an order of magnitude higher acoustic power due to their large piezoelectric coefficient. Their elastic compliance is approximately four times greater than PZT8. This allows for a compact acoustic source design for a given frequency. A vast improvement in axial resolution and contrast of medical ultrasound and sonar systems will occur as a result of the single crystal broadband capabilities. A major investigation of the electromechanical and mechanical properties of single crystals in the relaxor - ferroelectric (1-x) $Pb(B^{I}{}_{1/3}B^{II}{}_{2/3})O_3$ (x) $PbTiO_3$ system, where B^{I} = Mg or Zn and B^{II} = Nb, was conducted in our laboratory under DARPA and

ONR funding. Small signal (< 100 V/m) resonance-antiresonance, large signal (> 1 MV/m) electromechanical characterization, and mechanical strength under naval operating conditions were completed for crystals from world-wide sources. In sound projectors, the piezoelectric drivers are maintained under uniaxial compressive stresses (> 10 MPa) to prevent the drivers from going into tension where the piezoelectric elements are weak and fracture. In this work, we will show that the excellent small signal 33- mode electromechanical properties of single crystals are preserved under large signal drive and mechanical loading as required by sound projector applications. The effect of uniaxial compressive stresses ranging from 0 to 62 MPa on the electromechanical properties, such as length extensional coupling k_{33} , piezoelectric coefficient d33, and source level of oriented and poled single crystals driven by large fields (0.4 MV/m) under dc bias (0.8 MV/m) will be presented.

[1]S.- E. Park and T.R. Shrout, J. Appl. Phys., 82, 1804 (1997); IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 44, 1140 (1997).
[2]J. Kuwata, K. Uchino, and S. Nomura, Ferroelectrics, 37, 579 (1981); Jpn. J. Appl. Phys., 21, 1298 (1982).
The financial support of DARPA and ONR is gratefully acknowledged.

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

BROADBAND, HIGH POWER SONAR ARRAYS USING FERROELECTRIC SINGLE CRYSTALS

H. C. ROBINSON*[1], J. M. POWERS[2], and M. B. MOFFETT[3], [1]NUWC Division Newport, [2]EDO Corporation, [3]Anteon Corporation.
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Ferroelectric single crystal materials have been developed under the auspices of the Defense Advanced Research Projects Agency and the Office of Naval Research for use in sonar and ultrasonic arrays. The unique material properties of these crystals, particularly their low modulus, high piezoelectric constant and high material coupling factor, promise a revolutionary advance in sonar and ultrasonic technology. In particular, single crystal sonar projectors can be designed that offer over an octave of bandwidth from a single transducer design, substantially increased source level over current ceramic transducers, reduce size and reduce power amplifier requirements. Several prototype single crystal transducers and arrays have been developed for Naval applications whose performance demonstrated conclusively that the enormous potential of these materials can be realized in devices. The first demonstration was an array of sixteen longitudinal vibrators. Extensive testing of this array revealed that many properties of the arrays performance varied depending on how large the dc electrical bias and ac electrical drive was. However, it was also discovered that these performance variations correlated exactly with the variations in the measured material properties. This array showed a factor of three improvement in bandwidth over a comparable ceramic-based system, with as much as 15 dB higher source levels (or 30 times the acoustic power). All this improvement occurred with no increase in the drive amplifier size, indicating the tremendous performance improvements

possible when ferroelectric single crystal transducers are used in place of PZT ceramic ones. A second device demonstration was a compact, high power single crystal cylinder. This transducer showed very small impedance variations (3:1) over nearly a decade of frequency, while this projector is well matched to the power amplifier (i.e. 80% or more of the amplifier power is transferred to the transducer and not dissipated as heat) over 2.5 octaves of frequency. This implies that the amplifier that is needed to drive this transducer should be physically smaller in size, simpler to design and cheaper to build than an analogous ceramic based system designed to cover the same frequency band.
This work sponsored by DARPA and ONR

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

ROLE OF THE MN-DOPING ON STRUCTURAL AND ELECTROMECHANICAL PROPERTIES OF 0.93PZN-0.07PT SINGLE CRYSTALS

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Lead-based ferroelectric single crystals with (1-x)Pb(B1B2)O3-xPbTiO3 formula have emerged as a group of promising materials for various applications such as ultrasonic sonars and medical imaging transducers [1]. For example, (1-x)PZN-xPT near its MPB (x=0.09), for which the low phase transition temperature Trt is near 50°C and the Curie temperature Tc is at 175°C, exhibits along the [001] direction a longitudinal piezoelectric coefficients d33 of 2500 pC/N and a longitudinal coupling coefficient k33 of 93% [2,3]. Reducing the PT content x below 0.09 increases the Trt and therefore improves the temperature stability range of the electromechanical properties. Many researches are now focused on the doping of these complex perovskites with acceptors cations such as Mn2+ and Mn3+ to enhance the mechanical and electrical quality factors [4]. 0.93PZN-0.07PT single crystals with and without MnO2 addition have been grown by the method using the PbO flux [5]. The influence of the Mn-doping on the phase symmetry at room temperature and on the structural transitions temperatures Trt and Tc has been studied by X-ray diffraction. Piezoelectric constants of single domain and poly domain states with 0.5 wt.% MnO2 are reported to understand the role of the Mn-doping on extrinsic (domain wall motion) and intrinsic piezoelectricity. Finally, the temperature dependency of 0.93PZN-0.07PT-0.5 wt Mn% electromechanical properties such as k33, d33 and s33E will be reported.

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

APPLICATION OF PB[(ZN$_{1/3}$NB$_{2/3}$)$_{0.91}$TI$_{0.09}$]O$_3$ SINGLE CRYSTAL WITH GIANT K$_{31}$ MODE TO PIEZOELECTRIC BIMORPH

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The giant electromechanical coupling factor of k_{31} mode over 80% had been found by realizing the mono-domain in the case of Pb[(Zn$_{1/3}$Nb$_{2/3}$)$_{0.91}$Ti$_{0.09}$]O$_3$ (PZNT91/09) single crystal plates with the dimensions of 13^Lx4^Wx0.36^T mm[1,2). Investigating details in the process to obtain the giant k_{31} in PZNT91/09, it was clarified that the giant k_{31} and d_{31} could be obtained in the cases of; (1) the poled (100) crystal along [001] of the original cubic direction, (2) the poling temperature of 40°C in the rhombohedral phase of PZNT91/09, and (3) the controlling the process combination such as the DC poling and thermal treatment. When we poled three plate samples of Nos. 1–3 under a poling field of E=1.0 kV/mm, a poling temperature of 40°C and a poling time of 10 min, only the one sample of No. 3 had a giant k_{31} of 85.6%. The others were 42.2% (No. 1) and 40.4% (No. 2). Therefore, a thermal treatment over the Cure temperature (175°C) at 200°C for 30 min was carried out to depolarize the samples. On the following process, the poling field was increased until 2.0 kV/mm. As a result, the giant k_{31} was realized in the cases of No. 2 (k_{31}=86.2% at E=1.5 kV/mm) and No. 1 (k_{31}=79.5% at E=2.0 kV/mm) while the electromechanical coupling factors of the thickness mode (k_t) were almost the same of 54–60%. This means that the domain reorientation in thickness had been saturated; on the other hand, the one in the plate is changeable by the poling field. Furthermore, there was an optimum DC poling field for appearing the giant k_{31} on each individual plate sample. We prepared piezoelectric unimorphs and bimorphs to utilize the giant k_{31} in comparison with the ones fabricated by ordinary PZT ceramic plates with the same dimensions. Piezoelectric unimorphs were fabricated by sticking the piezoelectric plates together with center shim plates (15^Lx4^Wx0.10^T mm) composed of 42 nickel alloy. The coupling factors on the bending mode (k_b) using a PZNT91/09 single crystal plate with k_{31}=86.2% (d_{31}=-1890 pC/N) and a PZT ceramic plate with k_{31}=37.3% (d_{31}=-330 pC/N) were 64.7% and 20.6%, respectively. Furthermore, the series-type bimorphs were made from the unimorphs by sticking together with another PZNT91/09 single crystal plate (k_{31}=85.6%/d_{31}=-2100 pC/N) and PZT ceramic plate (k_{31}=37.0%/d_{31}=-325 pC/N). The k_b's were 69.8% (PZNT91/09 bimorph) and 31.2% (PZT bimorph). In addition, the PZNT91/09 single crystal bimorph showed the superior piezoelectric properties such as three orders of

magnitude larger than the PZT ceramic bimorph regarding the impedance ratio on the resonant and the anti-resonant frequencies.

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This work was partly supported by a Grant-in-Aid for Scientific Research (C) (No. 12650327) from the Ministry of Education, Culture, Sport, Science and Technology and the Murata Science Foundation. The authors would like to thank the Research Laboratory of Kawatetsu Mining Co., Ltd. and Fuji Ceramics Co. for supplying the PZNT91/09 single-crystal plate and PZT ceramic plate samples, respectively.

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

OBSERVATION OF HIERARCHIAL DOMAIN STRUCTURES IN PMN-X%PT CRYSTALS BY PIEZO-FORCE MICROSCOPY

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PMN-x%PT single crystals near morphotropic phase boundaries (MPBs) have excellent dielectric and piezoelectric properties, offering revolutionary advances in actuator, transducer, and acoustic sensor technologies. From their discovery, much effort has been devoted to the investigation of the origin of these excellent properties. In the current study, piezo-force imaging (PFM) and optical microscopy have been used to observe (i) the static domain structures; and (ii) the polarization switching process. Investigations have focused on (001) oriented PMN-x%PT (x=10, 20, 30, 35, and 40) crystals. Hierarchial domain organization has been found ranging in length scales from $\leq$100 nm to millimeters. The ultra-high strain and low-energy-loss of domain engineered PMN-30%PT is explained based on the observation of adaptive stress-accomodating hierarchial domains.

Office of Naval Research

Session: FC1-D
ENHANCING MICROWAVE STANDARD PERFORMANCE
Chair: E. Burt
JPL

FC1-D-1 511CF 1:30 p.m.

LARGE ENHANCEMENT OF CPT SIGNALS IN FREQUENCY STANDARDS

Y.-Y. JAU*[1], E. MIRON[2], A. POST[1], N. KUZMA[1], and W. HAPPER[1], [1]Princeton University, [2]NRCN.
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Coherent population trapping (CPT) spectroscopy has become a useful technique for probing atomic hyperfine resonances. The CPT signal is an on-resonance transmission peak observed when a modulated probing beam is passing through an alkali-metal vapor cell. The CPT - based frequency standards lock the local oscillators to the hyperfine frequency by tuning the oscillator frequency to the CPT resonance. The precision of atomic clocks is proportional to the linewidth divided by the signal-to-noise ratio (SNR). The conventional CPT clocks have low SNR especially for miniature vapor cells or for higher buffer gas pressure. We have developed a method to improve the CPT signal by 1 to 2 orders of magnitude at the same noise level. We believe that this new method will greatly enhance the implementation of CPT in frequency standards. The results of experimental measurements and theoretical calculations will be presented.
Prof. Michael Romalis

FC1-D-2 511CF 1:45 p.m.

HIGH PRESSURE CPT SIGNALS USING INTENSITY MODULATED LIGHT

A.B. POST*, Y.-Y. JAU, N.N. KUZMA, M.V. ROMALIS, and W. HAPPER, Princeton University.
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Coherent Population Trapping (CPT) is a promising technique for use in miniature atomic clocks, utilizing modulated light rather than microwaves to detect clock resonances. In this method, frequency-modulated light is typically used to probe cells containing sufficiently low buffer gas pressure such that the ground-state hyperfine structure remains clearly resolved. However, at the higher pressures needed to inhibit diffusion to the walls in miniature cells, conventional frequency-modulated CPT fails to detect the clock resonance. We present theory and validating experimental results of high-pressure CPT signals using intensity-modulated light. Circularly polarized light tuned to the Rb D1 line pumps most of the atoms to the F=2, m_F=2 sublevel, where the microwave "end resonance[1] is excited. We will show experimental data and briefly discuss linewidth broadening mechanisms.
[1] *Y.-Y. Jau, A. B. Post, N. N. Kuzma, et al., Phys. Rev. Lett. (in press, 2004).*

FC1-D-3 511CF 2:00 p.m.

BUFFER GAS EXPERIMENTS IN MERCURY (HG^+) ION CLOCKS

S. K. CHUNG*, J. D. PRESTAGE, R. L. TJOELKER, and L. MALEKI, Jet Propulsion Laboratory.
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We describe the results of the fractional frequency shifts measured from various buffer gases that might be used to increase the loading efficiency and cool ions

trapped in a small mercury ion clock, currently under development at JPL. The small mass, volume and power requirements of space clock limits the uses of turbo or ion pumps, and hence, hermetically sealed vacuum system, incorporating a suitable getter material with a fixed amount of inert buffer gas is a practical alternative to the ground-based system. The collision shifts of 40,507,348. 0157x Hz clock transition in the ambient earth magnetic field for helium, neon and argon buffer gases were measured. In addition to the above non-getterable inert gases we also measured the pressure shifts due to hydrogen and nitrogen gases which are getterable and may be used as slowly leaked buffer gases when incorporated with a small ion pump. We also measured the frequency shift due to the low methane gas partial pressure in a fixed, higher pressure neon buffer gas environment. Methane gas interacts with mercury ions in a peculiar way as to preserve the ion number but to relax the population difference in the two hyperfine clock states and thereby reduce the clock resonance signal.
This work was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contracts with the National Aeronautics and Space Administration.

FC1-D-4 511CF 2:15 p.m.

LASER-PUMPED, VAPOR-CELL ATOMIC CLOCK EMPLOYING A HIGH BUFFER-GAS PRESSURE RESONANCE CELL

J. CAMPARO*[1], J. COFFER[1], and J. TOWNSEND[1,2], [1]The Aerospace Corporation, [2]University of Southern California.
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In the laser-pumped gas-cell atomic clock, the short-term stability is significantly influenced by phase-noise to amplitude-noise conversion. Briefly, when resonant laser light passes through a vapor, the lasers intrinsic phase fluctuations induce random variations in the mediums absorption cross-section. As a consequence, laser phase-noise (PM) is converted to transmitted laser intensity-noise (AM), and this noise can exceed the shot-noise limited detection level of the gas-cell clock by orders of magnitude. The PM-to-AM conversion process is of particular concern for ultraminiature and chip-scale clocks, where broad linewidth VCSEL diode lasers are used to generate the clock signal (i.e., lasers with a significant amount of phase noise). Motivated by our previous studies examining the influence of pressure-broadening on the PM-to-AM conversion process, we have constructed a conventional laser-pumped, vapor-cell clock using a high buffer-gas pressure resonance cell. We use a cleaved-facet, TJS diode laser with a linewidth of 20 MHz (similar to VCSELs) and generate our clock signal in a Rb87 vapor confined with 100 torr of N2. This pressure of N2 is roughly ten times larger than that normally found in conventional gas-cell clocks. A single resonance cell is used to generate locking signals for both the laser wavelength and the clocks crystal oscillator, so that the device has real potential for miniaturization.

Without optimization of cell temperature or laser intensity/geometry, our present short-term Allan deviation is 1.8x10-12/$\sqrt{\tau}$, reaching 6.4x10-13 at 16 seconds. This is to be compared with previous results using TJS diode lasers (i.e., 6.4x10-11/$\sqrt{\tau}$), and the best result to date using a cleaved-facet diode laser (i.e., 1.4x10-11/$\sqrt{\tau}$). In the long-term, the stability is limited by temperature variations of the resonance cell. Our results bode well for achieving high-quality gas-cell clock performance from an ultraminiature device, and in the presentation we will discuss the clock in more detail. Additionally, we will present measurements of various clock sensitivities (i.e., the clock's light-shift coefficient, temperature coefficient, and microwave-power coefficient).

FC1-D-5 511CF 2:30 p.m.
(Invited)
METHODS FOR REDUCING MICROWAVE RESONANCE ASYMMETRY IN COHERENT-POPULATION-TRAPPING BASED FREQUENCY STANDARDS

L. S. CUTLER*, M. ZHU, and J. E. BERBERIAN, Agilent Laboratories.
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It is well known that the microwave resonance in CPT (Coherent Population Trapping) can be asymmetric if the Rabi frequencies due to the 2 CPT inducing radiations are not equal. The asymmetry leads to error in determining the resonance frequency. The problem has been treated theoretically for 3 and 4 level systems using the rotating wave approximation and neglecting off-resonance excitations. These results will be presented as well as techniques for reducing the asymmetry.
Work partially supported by DARPA

Session: FC2-D
APPLICATIONS, JITTER, AND MINIATURE OSCILLATORS
Chair: M. Frerking
Innovative Technology Products

FC2-D-1 511DE 1:30 p.m.

MECHANICALLY-COUPLED MICROMECHANICAL RESONATOR ARRAYS FOR IMPROVED PHASE NOISE

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Reductions in phase noise by more than 26 dB have been obtained over previous micromechanical resonator oscillators by replacing the single resonator normally used in such oscillators with a mechanically-coupled array of them [1] to effectively raise the power handling ability of the frequency selective tank by a factor equal to the number of resonators used in the array, and all with virtually no increase in volume or cost, given that all resonators are integrated onto a single die using batch processed MEMS technology. Specifically, a mechanically-coupled array of ten 15.4-MHz 40μmx10μmx2μm free-free beams embedded in a positive feedback loop with a single-ended to differential transimpedance sustaining amplifier achieves phase noises of -109 and -133 dBc/Hz at 1 kHz and far-from-carrier offset frequencies, respectively. When divided down to 10-MHz, these effectively correspond to -112 and -136 dBc/Hz, respectively, which represent more than 17 and 26 dB improvements over recently published work [2]. Unlike bulk quartz crystal oscillators, the phase noise performance of oscillators reference to micro-scale mechanical resonators at close-to-carrier offset frequencies is mainly limited by a combination of the electrical (i.e., capacitively-transduced) and mechanical (i.e., spring-softening [3]) nonlinearities of the micromechanical resonator, rather than by the sustaining electronic device. A direct consequence of this is a $1/f^3$ noise that depends greatly on the resonators deflection amplitude x, according to modeling of this phenomenon (to be detailed in the full paper), which predicts that phase noise can be reduced by minimizing the deflection amplitude while maximizing output power. The use of an array of resonators with combined outputs does just this by allowing each resonator to move a smaller amount while still sourcing a substantial combined output. Mechanical coupling of this array insures that all resonators vibrate at exactly the same frequency. The measured frequency spectra of fabricated one-, three-, ten- and hundred-free-free beam resonators show peak values that increase with the number of resonators, as expected, to the point of reducing the overall motional resistance by more than 14X. There is some reduction in Q, from 6,800 to 2,432, for the 100-resonator mechanically-coupled array, but this final Q is still enough for good close-to-carrier performance, and attaining higher power output with small amplitude is presently the more important goal. In particular, the ability of the 100-resonator array to avoid amplitudes past the critical Duffing [3] nonlinear amplitude allows it to attain much better close-to-carrier phase noise (by more than 10 dB) than its 10-resonator counterpart, whose resonators must vibrate at amplitudes larger than the critical point to attain the same far-from-carrier phase noise.

References: [1] K. Wang, *et al., Journal of MEMS*, vol. 9, No. 3, pp. 347-360, Sep. 2000. [2] Y. Lin, *et al., IEDM'03*, pp. 431-434 [3] H. Nayfeh and D. T. Mook, *Nonlinear Oscillations.* New York:Wiley, 1979.

This work was supported under DARPA Cooperative Agreement No. F30602-01-1-0573.

FC2-D-2 511DE 1:45 p.m.

THE CALCULATION OF FREQUENCY SOURCE REQUIREMENTS FOR DIGITAL COMMUNICATIONS SYSTEMS

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Digital communications systems utilize frequency sources, such as oscillators and synthesizers, in multiple locations as frequency and time references. This paper will discuss the methods used to derive frequency source performance requirements, such as phase and clock jitter, from top-level communications system requirements, such as bit error rate (BER) verses signal to noise ratio (SNR). A quadrature phase shift keyed (QPSK) system will be used to concretely illustrate the derivation process, but the methods outlined will be applicable to other types of digital communications waveforms with suitable modification.

Frequency sources are utilized in digital communications systems as local oscillators (LOs), and data clocks in both transmitters and receivers. LOs provide frequency sources with the necessary spectral purity and frequency stability to generate and remove the RF carrier that hosts the digital modulation. Data clocks provide the necessary timing purity and stability to generate the digitally modulated signal and recover the digital data from the modulated signal. Clock and carrier recovery loops are used to lock LOs and data clocks in receivers to those in the transmitter in coherent systems. It will be shown that the high pass properties of these loops have a fundamental impact on the definition of appropriate frequency source performance measures, both for transmit and receive frequency sources. It will also be shown that these loop high pass properties allow the use of the standard variance rather than the Allan variance to define statistical parameters, thus connecting the stationary statistics used in communications theory with the non-stationary statistics used in frequency source theory.

Critical top-level performance requirements for digital communications systems are bit error rate (BER) verses SNR or BER degradation (from an ideal system), time and probability of acquisition, and drop-out parameters such as probability of loss of acquisition. Environmental factors (temperature, vibration, etc.) also impact these performance measures.

This paper will discuss how BER degradation is effected by phase purity and stability parameters in LOs and timing purity and stability parameters in data clocks. In this discussion, appropriate measures of the phase performance of LOs and timing performance of data clocks will be defined and related to parameters effecting BER degradation. Results will be presented showing the levels of LO and clock white and flicker noise required as a function of data rate and recovery loop bandwidth for QPSK systems. Similar discussions will be presented on acquisition and dropout parameters and will be used to define and specify appropriate frequency source performance measures.

Finally, the impact of environmental factors on frequency source and communications performance parameters and will be discussed, formulas to specify appropriate frequency source environmental sensitivity parameters will be derived, and specific results will be presented using QPSK systems.

FC2-D-3 511DE 2:00 p.m.

THE PERFORMANCE OF THE ANTI-JITTER CIRCUIT WITH ENHANCED FEEDBACK ('EF-AJC')

M. J. UNDERHILL*[1,2] and J. BRODRICK[2], [1]University of Surrey, [2]Toric Limited.
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The Anti-Jitter Circuit (AJC) was announced at the EFTF in 1996 [1]. It is a fundamentally different approach to phase and time jitter suppression, reducing phase noise and time jitter on any input signal by a feed-forward cancellation process. The process is self-adjusting so that as the frequency is changed, even over a 10:1 range, the degree of cancellation and noise suppression is maintained.

The technology has undergone progressive improvements since 1996 (reported in EFTFs 1997, 1998, 1999 and 2000 and [2]). In the joint IFCS/EFTF 2003 conference in Tampa, a tool (A2S2) for AJC system design was presented, together with some examples of simple (DC-removal) feedback arrangements resulting from the use of this tool [3].

The paper describes a further substantial advance to AJC technology using a new technique, designated Enhanced Feedback (EF). This gives a significant improvement in phase noise suppression and ultimate (intrinsic) noise level after suppression in the 100Hz to 1MHz close-to-carrier region, typically by at least 20 to 40dB. For example, at 10kHz from carrier, the ultimate suppression limit is predicted to be better than -130bBc/Hz with the AJC operating up to 1GHz. This performance allows the AJC to clean-up a poor quality but low power VCO to give an adjacent channel noise performance for the combination that substantially exceeds the performance of a typical VCO, having a Q of around 100 or more. Also, the new technique reduces the AJC lowest suppression frequency typically 100-fold (to below 100Hz), without requiring the use of large value, on-chip capacitors. The core current of the AJC integrator discharge can thus be lowered substantially, which will enable efficient AJC operation at GHz frequencies.

In an EF-AJC, the intrinsic noise curve and the suppression curve can be arranged to fall at up to 18dB per octave away from the carrier. It can thus be used as an effective band-pass filter for FM demodulation. If better than 18dB per octave filtering is required, two or more EF-AJCs may be used in cascade. In addition, a further modification allows any AJC to be used as an FM demodulator.

Because the basic AJC process of noise suppression is self-referential, there is no AJC noise suppression at or below the lowest suppression cut-off frequency. The EF technique, lowers the cut-off frequency of a basic AJC, reduces the intrinsic noise and allows a ultimate noise (rejection) profile to fall more steeply than the 6db per octave noise profile of the typical VCO.

References [1] M. J. Underhill, M. J. Blewett, Spectral Improvement of Direct Digital Frequency Synthesisers and Other Frequency Sources, Proc. 10th EFTF, Brighton, pp. 452-460, 5-7 March 1996. [2] M.J. Underhill, The Adiabatic Anti-Jitter Circuit, IEEE Trans. UFFC, Vol. 48, No. 3, pp. 666-674, May 2001. [3] M.J.Underhill The Noise and Suppression Transfer Functions of the Anti-Jitter Circuit Joint IFCS and 17th EFTF, Tampa, USA, 5-8 May 2003.

FC2-D-4 511DE 2:15 p.m.

DIRECT MOUNTING OF QUARTZ CRYSTAL ON A CMOS PLL CHIP

H. KIM*[1], J. LIM[2], K. CHOI[2], D. KENNY[3], and T. JACKSON[1], [1]Department of Electrical Engineering, The Pennsylvania State University, [2]Department of Computer Science & Engineering, The Pennsylvania State University, [3]Saronix East Development Center.
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Motivated by the current demand for potable wireless devices, we are attempting to reduce the size of frequency reference source by directly mounting a quartz crystal on a CMOS PLL chip. This paper presents the experiment and its results.

The approach of direct mounting of quartz crystal on a CMOS PLL chip provides number of advantages and challenges. The advantages are:

1. Compact form factor, no separate crystal packaging needed 2. Less stray effects, less power, and less cost due to close mounting of crystal on chip

The challenges are:

1. Crystal mounting affects resonant frequency 2. On-chip digital noise affects resonant frequency 2. On-chip temperature affects resonant frequency 3. Capping of crystal on chip

We have fabricated two PLL prototype chips including the on-chip oscillator circuits and mounted the 155.52 MHz AT-cut mesa quartz crystals on them. The quartz crystals are mounted with conductive epoxy on the chip surface bonding-pad and epoxy is cured in a vacuum oven at 160 °C for 40 minutes. The chip sizes are designed slightly larger than quartz crystal resonator so that whole quartz crystal resonator is located within the perimeter of the chips. The largest chip size is 1.85 mm by 3.7 mm, however, the actual oscillator and PLL circuits occupy only about 10% of total chip area.

We achieved successful mounting and chip designs. The on-chip oscillator generates 155.52 MHz frequency signal without difficulty. We measured 2.98ps RMS jitter over 12 KHz to 20MHz bandwidth and 3.34ps RMS jitter over 10 Hz to 10MHz bandwidth. The SSB phase noise at 10Hz is 65 dBc/Hz, at 10 KHz is 123 dBc/Hz, and at 10MHz is 149 dBc/Hz.

The on-chip PLL uses 8KHz reference frequency to lock 19.44 MHz VCXO output. The PLL circuit consists of frequency divider, frequency comparator, and Opamp. Digital frequency divider and comparator generate on-chip noise that affects the oscillator noise characteristic. We measured 13 ps RMS jitter when the PLL circuit is in operation.

The measurements of various other aspects are currently being carried out and the design improvements are being developed.

This work was supported in part by Pittsburgh Dightal Greenhouse and Saronix

FC2-D-5 511DE 2:30 p.m.

JITTER ANALYSIS OF DIGITAL FREQUENCY DIVIDERS IN COMMUNICATION SYSTEMS

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Jitter reduction in clock networks and synthesizers is pivotal to the success of any digital system. Excessive jitter in communication systems can increase the bit-error-rate (BER) and violate timing paths, causing catastrophic failures. The performance of frequency dividers in clock generators and frequency synthesizers is often either ignored or underestimated. In this paper, a thorough analysis of jitter due to digital frequency dividers is given under various conditions.

A digital frequency divider is a sampled digital system. The sampling clock is usually derived from either a free running voltage-controlled oscillator (VCO), a phase-locked loop (PLL) closed loop system, or a crystal oscillator. There are two main types of digital frequency divider structures: asynchronous dividers and synchronous dividers. Both are considered in this work. Models for both are devised and the prediction of their performance under various conditions has been verified with experimental data with both ideal and jittery input clocks.

The most obvious method of jitter being introduced by frequency dividers is through supply noise. Supply voltage variation causes shifts in the threshold voltage of the individual gates in the frequency divider. This causes variation in both the zero crossings as well as duty cycle distortion in the output waveform of the frequency divider. If dividers are cascaded in an asynchronous fashion, a duty cycle to jitter translation mechanism causes an increase in spurious performance with division ratio. This has been verified experimentally. The severity of this translation depends on circuit topology and input clock noise. As an example of the frequency divider model, three different CMOS logic topologies are analyzed: Static CMOS, MOS Current Mode Logic (MCML), and dynamic logic.

In previous works, an ideal clock has been assumed to drive the digital frequency divider. In this study, both ideal and jitter input clocks are considered. A non-ideal input clock has been found to have a profound impact the frequency dividers performance. In the case of a fractional-N PLL, the frequency divider receives a jittery clock signal with correlated noise. Correlated noise in the frequency domain manifests itself as undesired spurious response. It shown that the translation of this correlated noise to the output depends on the relationship between the spur frequency locations and the frequency division ratio. This can result in situations where spurs actually increase with division ratio, contrary to the 6dB reduction in spur levels as predicted by conventional theory. The effect of jitter of an input clock signal with uncorrelated noise sources on digital frequency dividers has also been studied and modeled. The model results agree well with experimental data.

FC2-D-6 511DE 2:45 p.m.

2.4 AND 2.5 GHZ MINIATURE, LOW-NOISE OSCILLATORS BASED ON SURFACE TRANSVERSE WAVE RESONATORS AND A SIGE SUSTAINING AMPLIFIER

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Next generation analog-to-digital converters (ADCs) are challenged to achieve 100 MHz bandwidth with 100 dB signal-to-noise ratio (SNR) and 100 dB spurious free dynamic range (SFDR). For such ADCs, clock jitter can easily become the limiting factor on performance. This paper describes the development of 2.4 GHz and 2.5 GHz miniature, low noise oscillators intended to provide the low jitter clock source for high performance ADCs. The primary design goals for the oscillator are to achieve an integrated jitter of 10 30 fs and to fit within a volume of 0.33 cm^3 (0.02 in^3). To meet the low-jitter objective, the oscillator is designed for low close-in phase noise as well as for a low wideband phase noise floor. Low close-in phase noise and small size are achieved through the use of a surface transverse wave (STW) resonator as the stabilization element along with a SiGe sustaining amplifier. SiGe enables the sustaining amplifier to provide the excellent 1/f noise performance of silicon at GHz frequencies. A low wideband noise floor is achieved through the combination of high oscillator loop power and low noise figure, which are simultaneously attained through a two-stage sustaining amplifier design. Measurements performed on free-running prototype oscillators demonstrate a phase noise of 107 dBc/Hz at a 1 kHz offset from the carrier and a wideband noise floor of 175 dBc/Hz, with a resulting integrated jitter of 19 fs. The oscillators provide 5 dBm of RF output power and consume 0.37 W from a 3.3 V power supply. The prototype oscillator circuitry consumes a printed circuit board area of only 11 by 13 mm^2. Ongoing work is currently in progress to improve the sustaining amplifier close-in phase noise by 15 dB, further reduce the wideband noise floor, and make the oscillator voltage tunable. A package that minimizes the vibration sensitivity of the STW resonator is also in development.

This work was supported by John A. Kosinski, Ph.D., of U.S. Army CECOM and James D. Murphy, Ph.D., of DARPA under DAAH01-00-C-R197 and DAAB07-02-C-L433.