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POSTER SESSIONS: 5:00–6:30 p.m.

*** Author presenting Paper**

Session: P3FC-A
FREQUENCY STANDARDS
Chair: R. Wang
JPL

P3FC-A-1 S2

PERFORMANCE OF PARCS TESTBED CESIUM FOUNTAIN FREQUENCY STANDARD

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A laser-cooled Cesium fountain frequency standard has been developed to mirror the design of PARCS (Primary Atomic Reference Clock in Space) – an experiment intended to fly on the International Space Station. We report on its performance. In addition, we describe its use as a testbed for investigating implementations of the optical system and of atom cooling/preparation motivated by space applications, yet still relevant to ground systems.

P3FC-A-2 S3

ADIABATIC PASSAGE IN TWO-LEVEL CAESIUM ATOM: APPLICATION TO FREQUENCY CONTROL IN ATOMIC FOUNTAIN

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An application of cold atoms in atomic fountain produce sizable frequency shifts in this kind of frequency standards since atomic collisions are different at the low temperature achievable with laser cooling. This frequency shift results from unequal collision-induced energy shifts of the two hyperfine states of a "clock transition". In the recent work [1] a new method based on a transfer of population by adiabatic passage is used to perform a measurement of the cold collision frequency shift at the percent level. In the present paper this approach has been developed theoretically in several ways. First, the transition probability for the two-level atom to be excited by a pulsed radiation field is studied as a function of field strength for six different pulse shapes: Blackman, hyperbolic secant,

Lorentzian, hyperbolic secant squared, Lorentzian squared, and Gaussian. Spontaneous decay during the pulse duration is assumed to be negligible. It is also assumed that an atom-field frequency detuning has temporal dependence. With these assumptions, it was shown that the behavior of the transition probability differs qualitatively for these pulses. Second, the numerical solutions of Bloch equations are compared with asymptotic solutions in the limit of weak and very large field strengths. The numerical and analytical results in this paper could be tested using pulsed radiation fields interacting with hyperfine components of Cs atom [1]. We also discuss further developments and metrological applications.

References

1. F.Pereira Dos Santos, H. Marion, S. Bize, Y. Sortais, A. Clairon and C. Salomon, Phys.Rev.Lett. 89, 233004 (2002).

P3FC-A-3 S4

POWER DISSIPATION IN A VERTICALLY-INTEGRATED CHIP-SCALE ATOMIC CLOCK

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The vertically-integrated microfabricated atomic clock physics package recently developed at NIST [1] requires 75 mW of power to run, most of which is used to heat the Cs vapor cell to its operating temperature of 80 °C. We present here an analysis of the thermal transport in the structure and propose an improved design to reduce the power consumption to below 10 mW. An atomic clock operating on a comparable amount of power could be battery-operated, opening the door to the use of atomic frequency references in portable applications such as wireless communications and global positioning.

The cell is thermally isolated from the substrate on which it is mounted by two thin glass supports, each of cross-sectional area 0.25 mm^2 and height 0.5 mm. Six gold wire bonds of diameter 25 μm and length 4 mm connect the cell heaters and photodiode to the substrate. Thermal modeling of our structure indicates that 30 mW of power is dissipated by thermal conduction to the baseplate through the spacer and an additional 24 mW is dissipated by conduction though the wire bonds. The remaining 30 mW is presumably lost through conduction to the air surrounding the structure and radiation.

In order to make battery-operation of the device feasible, it is desirable to reduce the power dissipation of the physics package to below 10 mW, or by roughly one order of magnitude over the present operating power. This can be achieved through a combination of vacuum packaging and an advanced thermal isolation spacer. This new spacer design takes advantage of a low-conductivity, micromachinable material to reduce the heat conduction through the spacer. Thin gold traces printed on the spacer allow electrical conduction to the cell and photodiode, while maintaining a reasonable degree of thermal isolation. Specific designs and implementations will be presented, in addition to results from both analytical and finite-element thermal modeling.

[1] See, S. Knappe, et al., A microfabricated atomic frequency reference, these proceedings.

P3FC-A-4 S5

THE PHARAO TIME AND FREQUENCY PERFORMANCE VERIFICATION SYSTEM

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The PHARAO cold atoms clock, whose flight is scheduled in 2007 with the ESA ACES mission, will be assembled and tested at the CNES facilities in Toulouse. The assembly of the engineering model has already started with electrical integration of the on-board computer. Integration of the microwave source will start in February 2004 and final integration of the vacuum tube and optical bench is foreseen in next months. Checks of the metrological performances of both the engineering and flying models is one of the main challenges of integration activities. As an accuracy test at the 10E-16 level (mission goal) can not be obviously performed on Earth due to the gravitational field, a test at the 10E-15 level is needed to extrapolate the behaviour of the clock performances in space. This necessitates a complete time and frequency laboratory at the 10E-15 level at the CNES facilities with low phase noise sources and time transfer devices. The test system is comprised of : - A liquid helium cryogenic microwave oscillator from the University of Western Australia. This low noise oscillator (10E-14@1s) will drive the PHARAO clock to improve its short term frequency stability - The CNES hydrogen maser (EFOS B type "10E-14@10s and 10E-15@1000s", from Neuchatel Observatory), - A mobile cesium fountain (FOM) from the BNM-SYRTE for long term stability and accuracy - A dedicated GPS link to compare the mobile fountain to the BNM-SYRTE fountains and a phase stable optical link between the H-maser and the assembling room of PHARAO. This paper will present the detailed architecture and metrological features of this time and frequency test system. A preliminary evaluation of the metrological performances of the PHARAO microwave source will also be presented.

P3FC-A-5 S6

A FREQUENCY STANDARD BASED ON EXPANDING COLD ATOM CLOUD

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Here we present a proposal of a atomic frequency standard based on a Cs atomic cloud expansion, which was previously trapped and cooled by using the MOT technique. During the expansion process the atoms are submitted to a sequence of two microwave pulses, characterizing the well known two separated oscillating fields method. This type of clock shall have a short-term stability as good as $10^{-11}t^{-1/2}$.

Our system is composed of a Magneto Optical Trap (MOT) within the limits of a Pyrex cell, and a antenna to provide the microwave radiation. In a first stage, about 10^8 atoms are trapped for over 10s. After the trapping phase, atoms are pumped to the 6S1/2 (F=3) ground state, the magnetic field an light are turned off and the cloud will freely expand for about 4ms. During this interval, a sequence of two microwave pulses at 9.192GHz promotes the transition, which is the second definition. In the following, a flash of trapping light detects the 6S1/2 (F=4) atoms. The duration of the microwave pulses as well as the interval between the will be varied in order to find the better conditions, concerning the stability.

This work was supported by FAPESP.

P3FC-A-6 S7

THE 133CS FOUNTAIN FREQUENCY STANDARD IN BRAZIL

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Continuing the efforts towards the construction of a Cs-Fountain frequency standard in Brazil, a progress report of the Brazilian scientific time and frequency metrology program is presented. The Cs- fountain possesses a preparation region in the (1,1,1)-geometry, which is used for laser cooling and launching. This configuration allows efficient capture and launching. In one second about 10^8 cesium atoms are caught in the magneto-optical trap from a vapor cell at room temperature and pressure of 10^{-7}Pa (kept by a 60 l/s ion pump). The preparation chamber is made of stainless steel. The free flight cylinder is made of AU4G aluminium. We have introduced a titanium connector to join these two parts.

A 50mW external cavity laser diode (SDL 5402) is locked 160MHz to the red of the 62S1/2 F=4 $\rightarrow$ 62P3/2 F=5 transition. Light from this laser is used to inject into a 500mW amplifier (SDL TC30) to provide power for the six cooling beams. The repump beams are provided by a diode laser stabilized in an external cavity configuration tuned to the 62S1/2 F=3 $\rightarrow$ 62P3/2 F=4 transition. The detection laser is of the same configuration and is resonant with the cycling transition. The light is guided from the optical bench to the vacuum chamber by polarizing optical fibers and collimators mechanically aligned with a few mrad accuracy. Before being injected into the optical fibers the laser beams are separated into two parts the upper three beams and the lower three beams. Each group of beams passes through an acusto optical modulator (AOM), in

order to shift its frequency to about 10 MHz below the atomic resonance. For the launching process a frequency difference is introduced between the AOMs.

The interrogation cavity is made of copper and the quality factor is about 8000. This cavity is cylindrical and operates in the TE011 mode. The microwave frequency is generated by an ultra-stable BVA quartz oscillator. The microwave synthesizer was constructed in collaboration with the BNM-SYRTE time and frequency group.

We vary the frequency difference between the two AOMs and detected the atoms in a time-of-flight method. At the present we are working on launching the atoms into the cavity in order to produce the Ramsey fringes.

We express our most sincere gratitude to the BNM–SYRTE team for their precious collaboration. This work has been supported by FAPESP and CNPq.

P3FC-A-7 S1

AN EXAMINATION OF THE MÜSSBAUER EFFECT AS THE BASIS FOR A TIME/FREQUENCY STANDARD

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A variety of resonance phenomena are used as the basis for time and frequency standards. These include mechanical resonances in piezoelectric resonators, electromagnetic resonances in microwave cavities, and level transitions in atomic standards. Each type of resonance has its own set of advantages and disadvantages with respect to ultimate stability, sensitivity to environmental effects, and practical considerations in size, weight, power, cost, and complexity of the physical implementation. In this context, we are examining the potential for using the Mössbauer effect as the basis for a time and frequency standard. The Mössbauer effect, which is essentially the recoiless emission and absorption of gamma rays, was discovered in 1957 by then graduate student Rudolph Mössbauer. Whereas atomic standards are based upon transitions between atomic (electron orbital) levels, the Mssbauer effect arises from transitions between nuclear (atomic nucleus) energy levels. Our initial analysis of candidate resonances has identified four promising Mössbauer Isotopes with relative linewidths (for a Mossbauer Transition, this is the ratio of natural line width Γ to the transition's photon energy E_γ) on the order of 10^{-14} to 10^{-16}: ^{57}Fe, ^{73}Ge, ^{181}Ta, and ^{157}Gd. Other relevant characteristics including state lifetimes, natural abundance, and environmental sensitivities have also been determined. In this paper we will discuss the basic form of a proposed Mössbauer effect time and frequency standard, the resonance parameters being examined, and the results of our analysis of approximately 100 candidate nuclear systems.

Session: P3FC-B

SENSOR TECHNOLOGY
Chair: R. Lucklam
University of Magdeburg

P3FC-B-1 Q9

SINGLE BOARD IMPEDANCE ANALYZER AND TRANSIENT ANALYSIS OF QCR SENSOR RESPONSE

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Summary This contribution focuses on a single board data acquisition unit, which has been configured to act as impedance analyzer for Quartz Crystal Resonator (QCR) sensors. The digital concept together with fast circuitry and optimized controller software allows also a rapid data acquisition that transient phenomena in the range of seconds can be recorded. Motivation Acoustic-wave based sensors are highly sensitive to changes of the acoustic properties at their interface. Best known is the Quartz Crystal Microbalance (QCM), which can detect mass changes on a picogram. Those sensors are also known to respond to viscoelastic properties of the material(s) adjacent the device surface. Whereas the QCM only needs to be included in an oscillator, more complex applications of quartz crystals, e.g. as biosensor acting in a liquid environment, require at least the determination of the elements of the equivalent circuit, usually the modified Butterworth Van Dyke circuit of a quartz crystal. With a previous development [1] we could show the capability of a single board solution for sensor applications. The new fully digital concept should improve three features: frequency range, impedance range, cycle time. Results Heart of the new impedance analyzer concept is a fast analog-to-digital converter used for direct sampling, an adequate FPGA as well as an embedded microcontroller for real time data processing. The system allows high SNR data acquisition at frequencies up to 90 MHz. The signal reconstruction is performed by regression implemented as hardware sine regression in the FPGA to meet dynamic requirements We tested our impedance analyzer with chemical and biochemical systems, which are known to be subjected to changes in viscoelastic properties. Those changes are characterized by a distinct change in the acoustic properties, which finally result in a distinct change of the electrical impedance of the quartz crystal. Beside the changes in the characteristic values like the equivalent circuit parameters we first could determine also the transient behavior of these parameters. The data give access to molecular mechanisms on the time scale of $\tau \sim \omega^{-1}$. [1] J. Schröder, R. Borngrüber, R. Lucklum, P. Hauptmann, Rev. Sci. Instr. 72 (2001), pp. 2750-2753.
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P3FC-B-2 Q10

METHODOLOGY OF DESIGN OF ELECTRONIC CIRCUIT OSCILLATORS FOR QCM SENSORS IN LIQUID MEDIA

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This work deals with the development of a design methodology of electronic circuit oscillators for quartz crystal microbalance (QCM) applications in damping media. The developed methodology allows the design requirements of an oscillator topology to be obtained as a function of the resonator operating conditions (the characteristics of the working media and of the mass to sense). This methodology allows the study of the oscillation condition and the obtaining of the critical values of the components, the possible oscillation areas and the optimal expressions that allow to maximize the losses maintaining the oscillation. The methodology has been applied to the Miller topology. Using the developed approaches, four QCM Miller oscillators of high sensibility for their use in damping media were implemented and characterized experimentally.

P3FC-B-3 Q11

MILLER OSCILLATORS FOR HIGH SENSIBILITY QUARTZ CRYSTAL MICROBALANCE SENSORS IN DAMPING MEDIA

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In this paper, a new contribution to the design of quartz crystal oscillators for high sensibility microbalance sensors is presented. The oscillation condition for Miller configuration was studied in order to optimize the design components to obtain oscillators for use in extreme conditions of damping. Design equations relating the value of the active and passive components with the maximum supported damping and measured mass have been obtained. A CAD tool has been developed to help users in the design of microbalances adapted to the application requirements. To increase the mass sensitivity, four optimized microbalance circuits of augmenting frequencies have been developed. The components of the circuits have been optimized in order to maintain the oscillations in a wide dynamic range of resonator loss. A calibration of the sensors has been made, and

in order to determine the real sensibility of the mass sensors, the frequency noise has been studied.

P3FC-B-4 Q12

ELECTRONIC CIRCUIT SYSTEM OF HIGH SENSITIVITY MASS DETECTION FOR QCM-BIOSENSOR

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In this paper, the electronic circuit system with the high sensitivity mass measurement for biosensors the intended use as detection of dioxins, PCB, environmental-stressors, and marker proteins for infections is described. The design technology of the crystal resonator and electronic circuit system for telecommunication equipment is applied for design specification of quartz crystal microbalance (QCM)-biosensor. Oscillation frequency of crystal resonator is 8.93MHz with AT-cut fundamental vibration mode. For biosensor, crystal resonator immobilized antibody is used in solutions. The amount of oscillation frequency change and the amount of antigen-antibody reaction are related with an ultrasensitive microbalance. The antigen-antibody reaction is expected to measure in solution. Therefore the oscillation frequency stability of quartz resonator in solution serves as an important problem to improve the detection limit.

The outline of an electronic circuit system is described. The block diagram explains this electronic circuit composition. Then, in the experiment result, as for measurement technology, the frequency measurement technology of the crystal oscillator for telecommunication is utilized. The temperature in precision variable temperature oven is settled as $+25.00$ $+/-0.05$degrees C. Ultra pure water is used as a model solution. For measurement of oscillation frequency, heterodyne detection method is used. Filter is used in order to reduce signal noise. The 10th harmonics of crystal oscillator is used to increase the mass-sensitivity of QCM-biosensor. The detection result of frequency stability is expressed in the average value of the specified time. For 60 minutes, the frequency satiability of 510-9 is obtained; it means about 5 ppt of frequency satiability level. Realization of the QCM-biosensor with high frequency stability is expectable using the design technology and measurement technology of the crystal resonator for telecommunication.

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Session: P3U-C
MODERN SAW MATERIALS
Chair: K. Hashimoto
Chiba University

P3U-C-1 E1

SAW SUBSTRATE WITH EXCELLENT TEMPERATURE STABILITY SUITABLE FOR DUPLEXER OF US-PCS

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The pass-bands of a transmission (Tx) and a receiving (Rx) of the Personal Communication Services (PCS) handy phone in US are 1850-1910 MHz and 1930-1990 MHz, respectively. The transition bandwidth between the Tx and the Rx is very narrow as 20 MHz compared with other systems. A duplexer for the PCS using surface acoustic wave (SAW) requires a SAW substrate, which has both the good temperature stability and the optimum electromechanical coupling factor. Some of Rayleigh waves on various substrates have a good temperature characteristics, but almost all of their electromechanical coupling factor are too small for the US-PCS. Recently, it has been reported that a shear horizontal (SH) type of leaky SAW (LSAW) on Ta- or W-IDT/ST-90° X quartz, SiO2/ 10° Y-X LiNbO3, or SiO2/36° Y-X LiTaO3 has good temperature characteristics. But, the first one has too small coupling factor, the second one has too large for the US-PCS duplexer, and the third one shows insufficient resonator characteristics. In 2003, authors reported the US-PCS SAW duplexer having good temperature stability, a steep frequency characteristics in transition band, a low loss, and a large out-of band suppression[1]. This paper describes the detail for the new substrate having the good temperature stability, the optimum electromechanical coupling factor, and sufficient resonator characteristics.

(1) M. Kadota, T. Nakao, N. Taniguchi, E. Takata, M. Mimura, K. Nishiyama, T. Hada, and T. Komura : SAW Duplexer for PCS in US with Excellent Temperature Stability, Proc. IEEE Ultrason. Symp., p.2105, 2003.

P3U-C-2 E2

ALL-LANGASITE-PACKAGED SURFACE ACOUSTIC WAVE PRESSURE SENSORS

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We are developing a surface acoustic wave (SAW) pressure sensor based on all langasite (LGS) package, which consists of a diaphragm with Au electrodes and a cover, both made of YX-LGS. It is hermetically packaged by using flip-chip

bond technique. In order to reduce the temperature dependence of pressure sensitivity over a large temperature range, a way of minimizing the pressure induced shift in the turnover temperature by a proper selection of the crystalline orientation in conjunction with the location of the SAW resonator on the substrate is analyzed. Some cuts in the neighborhood of YX-LGS which are associated with high pressure sensitivity, high electro-mechanical coupling coefficient(k^2=0.415) and low value of temperature coefficient of SAW delay(TCD=0) simultaneously have been found in vicinity of 250 centigrade degrees. Experimental data are obtained from the sensor subjected to pressure range from 0Pa to 0.6MPa, and temperatures up to 300C. The pressure sensitivity is $14*10^{-10}$ fractional frequency change per unit Pa, and it is in good agreement with the theoretical result.

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P3U-C-3 E3

NSPUDT STRUCTURES WITH INCLINED REFLECTORS ON LANGASITE

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The concept of wave propagation direction reversal instead of IDT directivity reversal has been suggested in [1]. Presently the feasibility of concept has only been experimentally proven on quartz substrates. Langasite with orientation yxlt/48.5°/26.6° is one of the most attractive materials for NSPUDT principle application. However we have discovered certain restrictions to straightforward application of this concept to langasite substrates with aluminum metallization. As the 90 degrees reflection in inclined reflecting arrays with aluminum metallization is relatively low in comparison to 180 degrees reflection from ordinary gratings, low loss filters have to be narrow band due to increased number of reflecting strips. The low reflection is a characteristic feature that we often observe in inclined reflecting arrays made with speeding up coatings. The present contribution deals with experimental measurements of the reflection in inclined arrays of thin-film strips made with different metals on langasite yxlt/48.5°/26.6°. We study the reflection in inclined arrays with the angle of incidence 46.3° from ordinary aluminum coating with different thickness in comparison to slowing down coatings such as Au/Ti, W, Ni/Cu/Ti and to some others. We also present experimental data on the NSPUDT behavior of transducers with these coatings. Explanations of experimental results are given in terms of SAW propagation modeling in gratings with modified version of free software developed by K. Hashimoto. For one of the test structures with 100 reflectors in each array of a U-path arrangement we have got the following insertion loss in forward and in reverse directions without matching: for Au (h/lambda=0.5%) -27

dB and -32 dB, for Ni/Cu/Ti (h/lambda =1.5%) -29 dB and - 42 dB, for Al (h/lambda=2%) -26 dB and -36 dB and for thick Al (h/lambda=4%) -36 dB and -40 dB. Obtained results show that besides aluminum coatings, copper based multi-layer structures can provide useful features for reflection increase in inclined reflecting arrays on this cut of langasite with moderate change in central frequency. The NSPUDT behavior of Cu coatings is well pronounced and this feature is beneficial for filters with inclined reflectors. Gold coating has resulted in somewhat higher reflection and in comparative reduction of natural directivity. This feature may in its turn find application in different types of structures, such as ordinary resonators with 180 degrees reflection. The results of this contribution provide guidance to designers in the choice of film material. References 1. S. Dobershtein, A. Shvetsov, S. Zhgoon, Proc. IEEE Ultrason. Symp., 2003, pp. 2077-2080.
The use of free software developed by K. Hashimoto is gratefully acknowledged

P3U-C-4 E4

PROPAGATION CHARACTERISTICS OF SHEAR-HORIZONTAL-TYPE SURFACE ACOUSTIC WAVE ON LANGASITE WITH AU OR TA_2O_5 THIN FILM

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In a previous work, we reported the coupling factor and the temperature characteristic of a pure shear-horizontal (SH)-type surface acoustic wave (SAW) on langasite (LGS), at Euler angles of (0° , θ, 90°), with a high-density thin film, such as a gold (Au) film or a tantalum pentoxide (Ta_2O_5) dielectric film [1]. The measured values of the coupling factor for θ=20° were 0.80% and 0.61%, for the sample with a Au film and that with a Ta_2O_5 film, respectively. For both films, the measured frequency shifts in the temperature change for θ=20° showed that a temperature characteristic with a zero temperature coefficient of delay (TCD), which is the same as that of ST-90° X quartz with the free surface, can be obtained by choosing the film thickness. In this paper, the propagation characteristics, mainly the propagation loss and the bulk waves radiation loss of the SH-type SAW on (0° , θ, 90°)-cut LGS with these films are investigated experimentally. The cut angles θ of 0° and 20° were chosen because the coupling factor of 1.0% and zero TCD can both be expected between these cut angles. Two types of simple delay line samples were fabricated using a double-electrode interdigital transducer (IDT) pair with the wavelength (λ) of 20 μm, an overlap length of 100 λ and a 30-finger pair. One is the Au/LGS structure with an IDT pair and a metallized propagation path formed by a dc-sputtered Au film with a thickness of 0.015 λ. The other is the Ta_2O_5/Al/LGS structure in which an rf-sputtered Ta_2O_5 film was deposited on a conventional Al-IDT pair and a free propagation path. The propagation loss was obtained by subtracting the insertion loss of the transducer pair with the propagation path length L of 50 λ from that of the transducer pair with L=300 λ. The bulk waves radiation loss from the IDT was estimated by subtracting the propagation loss and the

conversion loss from the insertion loss. For the Au film, the estimated values of the bulk waves radiation loss for θ=0° and 20° were 5 dB and 4 dB, respectively. The propagation loss for θ=20° decreased to 0.005 dB/λ at the Ta_2O_5 film thickness of 0.012 λ, from 0.039 dB/λ in the sample with no film, and increased at film thicknesses greater than 0.021 λ. This minimum value was approximately one-third of that for the Au film. The bulk waves radiation loss for θ=20° also decreased to less than 1 dB at the Ta_2O_5 film thickness of 0.05 λ, from 11 dB in the sample with no film. On the other hand, for θ=0° , the values of the propagation loss for both films were less than 0.01 dB/λ, and the bulk waves radiation loss of 9 dB remained after loading with the Ta_2O_5 film. From the above results, it is clear that the energy trapping effects of loading with the Ta_2O_5 film depend on the cut angle. [1] S. Kakio, M. Nozawa, and Y. Nakagawa, Proc. 2003 IEEE Ultrasonics Symp., p.2122.

P3U-C-5 E5

TEMPERATURE COMPENSATED LANGASITE FAMILY COMPOUND $CA_3NBGA_3SI_2O_{14}$ CRYSTAL FOR SAW APPLICATIONS

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The langasite family structure is represented by general chemical formula A_3 BC_3 D_2 O_{14}. The $A_3BC_3D_2O_{14}$-type crystal belongs to the trigonal symmetry, the point group32 and space group P321. Among them, well-known La based langasite family compounds such as $La_3Ga_5SiO_{14}$ (LGS), $La_3Nb_{0.5}Ga_{5.5}O_{14}$ (LNG) and $La_3Ta_{0.5}Ga_{5.5}O_{14}$ (LTG) have attracted significant attention because of their zero-Temperature Coefficient of Delay (TCD), higher coupling coefficients and slower acoustic velocities than other SAW materials, and are also expected to be used for the IF filter of Wide Band Code Division Multiple Access (W-CDMA). However, their melting temperatures are very high as around 1500°C, The langasite structure is a very complex one with 4 distinct cation sites which allow large substitution. Therefore, one of main purpose of our work is to search for new SAW langasite family compounds with both more superior piezoelectric properties and lower melting temperatures compared with that of $La_3Ga_5SiO_{14}$. Growth of $Ca_3NbGa_3Si_2O_{14}$(CNGS) was attempted by the conventional RF-heating Czochralski technique with a platinum crucible (50mm in diameter and height). It has been experienced that while the rate of crystallization along the z-axis is much less than those along any other attempted directions, great difficulty is often encountered in obtaining large crystals in this pulling direction due to the unavoidable occurrence of opaque regions. Therefore the pulling axis was chosen in parallel to the x- or y-axis in order to minimize the cracking during the growth. The crystals obtained were generally prismatic with clearly defined face of (001). Transparent and colorless single crystals of CNGS up to about 30mm in diameter and 60mm in length were successfully grown from the melt of 1325oC under the optimum growth conditions of the pulling axis of y, a crystal

pulling rate of 1.0mm/h and rotation rate of 10rpm. The lattice constants a and c of the crystal determined by an X-ray diffraction measurement were 0.811 and 0.4979nm, respectively. The crystal density was measured as 4120kg/m^3 by the Archimedes method. All the elastic, piezoelectric and dielectric constants at 25oC were determined in this study. The dielectric constant $\epsilon_{11}{}^T$ and $\epsilon_{33}{}^T$ were 18 and 28, respectively. Elastic compliances $s_{11}{}^E$, $s_{33}{}^E$ and $s_{44}{}^E$ were 9.06, 12.5 and 21.87x$10^{-12}$$m^2N^{-1}$, respectively. The electromechanical coupling coefficients k_{12} and k_{25} were 0.11 and 0.18, respectively. The coupling coefficient k_{12} of 0.11 was somewhat smaller than that of LGS due to the crystal quality. The piezoelectric constants d11 and d14 were -4.13 and 10.2x$10^{-12}$$CN^{-1}$, respectively. The existence of orientations of CNGS with zero temperature coefficient has been predicted on the material constants determined by the present authors. The simulation was carried out so that the temperature-compensated Rayleigh SAWs were located around (15°, 60°, 17°) and (15°, 60°, 165°) substrates with v of 2730 and 2810 m/s, and k^2 of 0.48 and 0.57%, respectively.

P3U-C-6 E6

THEORETICAL CALCULATION OF SAW CHARACTERISTICS OF THE GDYCOB SINGLE CRYSTALS

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The various piezoelectric crystals such as $LiNbO_3$, $LiTaO_3$ and LiB_4O_7 have been grown, up to now, and their piezoelectric property has widely been investigated because of interest in SAW application of filter and resonator devices. In recent years, new material $RCa_4O(BO_3)_3$ (R=La, Nd, Sm, Gd, Er and Y) has been studied, and their growth were investigated. Since the crystal is non-hygroscopic and chemically stable with good mechanical properties, it is interested in application for nonlinear optical devices. Especially, $Gd_xY_{1-x}Ca_4O(BO_3)_3$ (GdYCOB) exhibits excellent optical (SHG) characteristics, and their single crystals can be grown with CZ technique at a low cost. However, few studies on their piezoelectricity and SAW properties have been reported. Thus, we fabricated IDTs on X, Y and Z cuts of GdYCOB crystal, and measurements of the SAW characteristics such as velocity, coupling factors and temperature coefficients were reported at past conference. It is expected that the SAW properties comparable to those of $LiTaO_3$ can be obtained in GdYCOB. In this study, we report theoretical analysis of the SAW characteristics, and investigate the properties in detail. The analysis was performed by the use of material constants obtained by resonant measurement, and SAW velocities and coupling constants were calculated at various crystalline cuts and propagation directions. Especially, the result calculated at Z-cut of GdCOB(x=0) accorded substantially with measured results. Two SAW propagation modes (lower and higher mode) existed on this cut. From the dependence on propagation direction, the highest velocities of

3200m/s and 3488m/s were obtained at X-axis propagation from measured and theoretical results, respectively, and it was also revealed that the higher mode cannot propagate in this direction from both results. In the case of the higher mode, the highest velocities and coupling factors k^2(measure: 0.9%, calculation: 0.8%) were obtained at Y-axis. From the theoretical analysis, it is revealed that the higher mode is leaky mode. The results at other cuts are also reported, and optimum crystalline cuts and propagation mode are discussed.

Session: P3U-D

SAW TRANSDUCERS
Chair: P. Smith
McMaster University

P3U-D-1 E7

NOVEL APPROACHES TO THE ELECTROMAGNETIC DESIGN OF CSP RF-FILTERS WITH IMPROVED SELECTIVITY

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The most important technologies for small size RF-filters for mobile phones are SAW and FBAR filters. While the pass band performance of these components is mainly determined by the acoustic parts of the device, the close-in and wide band selectivity is primarily determined by the electromagnetic behaviour of the on-chip structures and the package. Also the matching is influenced to some extent. To get a good filter performance up to 6 GHz or beyond, the electromagnetic design is crucial.

Some general considerations on the influence of electromagnetic parasitics on different filter types are given and possible compensations of different coupling mechanisms are discussed. For the actual electromagnetic design a precise simulation is necessary in most cases and has therefore been developed recently. The focus of this paper is on real live design examples, especially on a very demanding case, where one package for two different types of filters had to be designed: a two track DMS and a one track DMS with series resonator, each for $50\Omega/50\Omega$ single-ended/balanced operation. To achieve a high stop band attenuation the geometry of the device should be symmetric. The specific problem was that the component dimensions together with the fixed footprint forces a completely unsymmetric geometry of chip and package layout. This challenge was met by a new integral design approach. Another example shows for the first time the usage of an electromagnetic compensation mechanism for a single-ended/single-ended filter to achieve a high stop band attenuation.

P3U-D-2 E8

SCANNING WINDOW TECHNIQUE IN SPUDT OPTIMIZATION

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Here we suggest an original SPUDT synthesis algorithm that can keep control of filter parameters according to any desired priority scheme, i.e. provides a desired compromise between insertion loss, triple transit suppression, stopband rejection, in-band ripple, etc. For mounting of IDTs we use elementary cells of about ten types. Each cell is one wavelength long and includes 3-4 electrodes of different widths. Cells may be active or passive, they may include reflectors or not. Positions of SAW sources and reflectors are different in different cells. The essence of the suggested synthesis algorithm is analysis of all possible combinations of cells in a local region of the IDT, "window". The "window" scans step by step throughout both input and output IDTs. Criterion of the choice of the best "window" composition at each step is the closeness of the filter parameters to the desired specification according assigned priorities. Thus, optimization of SAW sources and reflectors distribution is performed simultaneously. Successful combination of neighbor cells provides not only good SAW source distribution but also resonant acoustic regions, which reduces IDT dimension. In some cases the algorithm provides a SPUDT dimension about twice shorter compared with bidirectional IDTs having similar frequency responses. Because of huge number of cell combinations under analysis, one of the most important problems is fast estimation of each IDT modification. Calculation of the filter response is based on the T-matrix description [1]. T-matrixes of individual cells of all types are calculated ones in the beginning of the process. T-matrixes of ITD parts outside the "window", are calculated only ones at each "window" position. So, only T-matrix of the "window" is calculated for each IDT modification. Knowing T-matrixes of IDTs one can calculate P- and S-matrixes, and all frequency characteristics. During the synthesis process 105-107 IDT modifications are analyzed. It usually takes 0.5-10 hours of CPU. This technique is applicable to different substrates with any piezoelectric coupling strength, to structures with any level of SAW reflectivity, to one-channel filters and multi-channel (quasi-slanted) IDTs. References: [1] D.P.Morgan. - 1995 IEEE Ultras. Symp. Proc., p.215.

P3U-D-3 E9

INVESTIGATION OF SINGLE-FINGER INTERDIGITAL TRANSDUCERS AS PROGRAMMABLE REFLECTORS

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In the last decade, the splitfinger interdigital transducer(IDT) was proposed to be used as programmable reflector because the P11sc of splitfinger IDT is very small. Thanks to this intriguing property, splitfinger IDTs were frequently used in wireless passive surface acoustic wave(SAW) identification systems and sensors. In this paper, the single-finger IDT used as programmable reflector was investigated. The periodic metal gratings deposited on 128°YX-$LiNbO_3$ substrates show an extraordinary character: In a certain ratio of electrode height and wavelength, the reflection of short gratings almost disappears. At the same time the reflection of open gratings is big. In this situation, the single-finger interdigital transducer can be used as programmable reflector. The amplitude modulation is great enough. The height/wavelength dependence of amplitude modulation was simulated in this paper. The results of practical devices were compared with those of the simulation. When one uses single-finger IDT instead of splitfinger IDT, the work frequency can be twice as before if one uses the technology with the same resolution to produce SAW devices.

P3U-D-4 E10

FEUDT PERIODIC CELL WITH DIFFERENT WIDTH ELECTRODES

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A periodic cell of the floating electrode unidirectional SAW transducer (FEUDT) in the general case of electrodes of finite thickness and of different width has been investigated. The simulation is based on the impedance method/natural boundary element method (IM/NBEM) which has been developed in [1], [2] for calculating of a periodic cell consisting of an arbitrary number of different elastic electrodes placed on a piezoelectric substrate. As an example, a modified six electrode FEUDT cell has been examined. Because of complexity, until now this cell has been considered for regular electrode grating only (all gaps and all electrode widths are equal). In this case mechanical reflections compensate each other and the problem of cell calculation, in part, can be considered in electrostatic approximation. However, there is no reason to consider this regular case as the optimal. In order to obtain more general results, the important parameter of unidirectionality as a phase shift between reflection and transduction centers in the case of electrodes of finite thickness and of different width has been calculated. In the regular case this phase shift is practically independent of the electrode thickness. For different width electrodes the behavior of phase shift is drastically changed, and strong dependence on the electrode thickness is found. In contrast to the regular case, one can see a lot of possibilities to reach the optimal phase shift equal to 45 degrees.

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electric admittance of a complex periodic electrode cell, in Proc. 2003 IEEE Ultrason. Symp., pp. 1676-1679.

P3U-D-5 E11

LOW LOSS SAW DOUBLE-MODE STRUCTURE SUPPRESSING SPURIOUS RADIATION

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SAW has been successfully employed in a number of signal-processing devices, such as RF filters, IF filters, duplexers and other SAW devices for recent digital mobile communications. It is expected to realize low loss performances for these devices according to the increase of the terminal sensitivity. The transverse-double-mode IDTs structures are generally used for low loss and high rejection filters. The double mode IDTs structure on 42deg.Y-X LiTaO3 is selected as our experiment for low loss EGSM filter. We have observed Leaky-SAW radiation pattern at first. SAW radiation patterns are obtained using a heterodyne interferometer-type laser probe method. Two spurious radiation modes are observed in the conventional double-mode structure. First mode wave is traveling toward the same direction of the main SAW response on bus-bar edge. Second mode wave is traveling toward the direction 42deg. angle rotated from the main SAW direction. We success to suppress the first sourious mode by using wave-guide structure which reduces the SAW velocity on edge of aperture. The first sourious mode wave is not observed and low loss frequency characteristics are measured in new IDT structure. The wave-guide structure is optimized by testing the various parameters of the structure. Consequently, loss of the filter is improved by the new wave-guide structure.

Session: P3U-E
SAW PROPAGATION THEORY
Chair: B. Potter
Vectron International

P3U-E-1 E12

THE BASIC SCATTERING THEOREM

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An important theorem, regarding the plane wave reflection from a period of a short-circuited infinite regular grating (IRG), is formulated and proved in general. Arbitrary strength of reflections, as well the propagation and scattering losses, are taken into account. Physically well founded arguments, based on the

system symmetry only, are applied to validate a vital assertion which may be unhesitatingly used now in both COM-analysis and P-matrix modeling approaches, suitable to create fast simulation tools for accelerated synthesis of different SAW systems with distributed feedback (DFB). The local reflection coefficient (r) per grating period is one of the key phenomenological parameters, required by these approaches. In case of the leaky surface acoustic wave (LSAW) devices the reflection coefficient magnitude |r| depends not only on the metallization ratio and normalized thickness of electrodes, but on the frequency also [1]. However, the phase reflection characteristic arg(r), calculated properly with respect to a center of symmetric discontinuity, must comply with the following non-dispersive condition: If the plane waves (or their subsystems), launched normally upon a period of infinite regular grating from opposite directions, are reflected perfectly equally in both directions with respect to the same cross-section, i.e., r(+) = r(-) = r, then the corresponding reflection coefficient (r) is necessarily a pure imaginary value, even in the presence of dissipation. Note that, previously, this statement was thought to be valid for the loss-less (non-leaky) waves because of the power conservation principle; then its validity was extended in the presence of dissipation by using the COM formalism [1]. However, since COM approach is suitable, strictly speaking, in case of rather small perturbations, the perfect generalization of the claimed affirmation under arbitrary perturbation strength looks to be a vital requirement. It is necessary for unambiguous analysis and synthesis of various LSAW devices, taking into account inevitable propagation losses. One has to emphasize here that the established statement is a characteristic feature of just symmetric DFB systems, which impose a certain restriction on the wave mode scattering within the periodically perturbed area. In practice, the assertion may be violated, probably, at the ends of finite length gratings, where a small fitting should be applied to specify the edge-effect corrections of the phase of the reflection coefficient in the vicinity of "$\pm\pi/2$"-values. Nevertheless, the cause of this possible disturbance is a system asymmetry, but not dissipation.

[1] B.V. Sveshnikov, A.P. Shitvov, and K.K. Bhattacharjee, "Evaluation of Dispersion in COM Parameters", IEEE Ultrasonics Symposium Proceedings, 2003, pp. 715-719

P3U-E-2 E13

UNIVERSAL FUNCTIONS FOR THE ANALYSIS OF ELECTROMAGNETIC INTERACTIONS IN SAW DEVICES

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In spite of the availability of a large number of commercial software packages for the analysis of electromagnetic fields, SAW devices defy a satisfying usage of these packages. This defiance is primarily due to the peculiarities of SAW devices which are not commonly shared by other RF signal processing devices for which the packages are designed; e.g. comparatively strong anisotropy and the presence of many geometrically complicated thin metallic structures positioned on

interfaces. The method of singular surface integrals (SSI) is particularly suitable for this class of problems. However, successful application of the SSI method is demanding and requires specialized expertise in mathematics. To combat these problems we have developed the method of Fast-MoM utilizing a number of Universal Functions, which we can pre-calculate and store for frequent future usage. The Fast-MoM has been conceived in order to separate the task of scientific computing from the task of engineering analysis. In this paper we detail the construction and processing of universal functions for the EM analysis in SAW devices, and discuss new strategies for accelerating the computations and enhancing the accuracy of the numerical results. In particular we discuss the involvement of the mutipole expansion technique, and introduce a novel technique for obtaining multipole expansions without utilizing the so-called Addition Theorem, the availability question of which is a sever bottleneck in many cases. Sampling the universal functions at typically 4, or 16 points, and simply adding and subtracting the sampled data, the engineers can ensemble a capacitance, an inductance, an impedance, or in general an interaction matrix, the straightforward solution of which leads to the desired physical quantities of interest. In terms of simple examples we will demonstrate the merit of this method for analyzing cross-talk, interference, and EM scattering in SAW devices.
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P3U-E-3 F13

SAW PROPAGATION IN COMPLEX PERIODIC SYSTEMS OF STRIPS

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Complex periodic structures including several strips per period with different width and spacing, some being connected to each other (within a period) or left isolated, are frequently applied in single-phase unidirectional transducers. Although a generalized BIS expansion method can be applied for their analysis, it is cumbersome and numerically inefficient.

A new method is proposed here, exploiting the recent theoretical results on electrostatics of multiperiodic systems of strips. Let certain strips (say A and B) in a period be either short-circuited or free (these are strips that would be connected to the IDT bus-bars), while the others are interconnected as mentioned above. Three cases have direct theoretical solutions in the frame of electrostatics [1], where: - certain voltage is applied between A and B, - an incident electric field excites currents in short-circuited A and B, - or excites voltage between A and B, when left free. These solutions help us to formulate the dispersive equation for the SAW propagating in the system of short-circuited A-B, corresponding the short-circuited complex, typically unidirectional IDT. The analysis is applicable for both the Rayleigh and transverse (or pseudosurface) waves supported by given piezoelectric substrate characterized by its planar harmonic Green function [2].

The above useful extension to the electrostatic spectral theory of multiperiodic strips [1] will be detaily presented and illustrated with numerical examples concerning typical SPUDT structures. The resulting simple spectral theory of SPUDT will be presented as well, for the thansducer modelling (evaluation of its frequency responce and P-matrix parameters over an entire passband) and optimization.

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P3U-E-4 F12

FAST METHOD OF SOLUTION FOR MIXED ELECTROSTATIC PROBLEM IN PERIODIC ARRAYS

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The present paper describes the algorithm of fast solution of mixed electrostatic problem (MEP) for periodic array of electrodes including electrode groups characterized by different electrical boundary conditions: open-circuited, short-circuited or isolated. Such systems are utilized in bi-directional or unidirectional transducers with withdrawal weighting, variable electrode polarities or capacitive weighting of filter sections, in multistrip couplers, reflectors etc. Usually the simulation of electric charge distribution in periodic array of electrodes is performed using the model of fixed potential (base-potential) and its Fourier-transform (element factor) [1,2]. In this model, the system of linear equations is obtained. The accurate solution of this system with multi-dimensional matrix is a complicated problem. A method suggested in the present paper is an iterative procedure, which utilizes two basic solutions (base-potential [1] and base-dipole [3]) without building linear system of equations. The elementary cycle of this procedure includes two stages. At the first stage, for n-th approximation of potential P(n) the charge distribution Q(n) is calculated using base-potential, which is corrected according to the initial boundary condition for fixed charges. At the second stage, for the found n-th charge distribution the distribution of electric potentials P(n+1) is determined, using base-dipole, which is corrected according to initial boundary condition for fixed potentials. Then the stages 1-2 are repeated, and the algorithm is characterized by fast convergence. This method was utilized for analysis of effect of charge distribution at the edges of the transducer on filter performance, for withdrawal-weighted and capacitive-weighted tapered transducers. As a result, the structures mentioned above were optimized to provide improved selectivity. The results of simulation are confirmed by experimental data for filter with frequency 60 MHz (bandwidth BW3=15 %, ultimate rejection UR=60 dB) and for filter with frequency 140 MHz (BW3=10%, UR=62 dB).

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Sonics and Ultrason., vol. SU-26, No.3, pp.235-242, (1979). [3] Y.Abramov, W.Dunzow, and V.S.Orlov, Electrostatic Field Model with the Given Charges on Electrodes of the Infinite Periodic Grating Proc. of the IV Seminar Acoustic Electronic Devices. Moscow, 1991, p.24-26.
Diplom Mathematic, SAW Disagner

P3U-E-5 F11

NUMERICAL MODELING OF ONE-PORT RESONATORS BASED ON HARMONIC ADMITTANCE

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This paper presents a FEM/BEM based approach for modeling synchronous one-port resonators. This method is an extension of the method based on harmonic admittance by P. Ventura et al. [1]. In this work the method is extended to account for the resistance of the electrodes and the dielectric loss. With these two significant sources of loss included, this approach is as accurate as the general FEM/BEM-based analysis for arbitrary structures, but is significantly faster than the latter. This approach makes an efficient tool for the simulation of ladder filters consisting of synchronous LSAW one-port resonators. The harmonic admittance is calculated numerically based on FEM/BEM, from which the mutual admittance between electrodes of the resonator and the admittance of the resonator are found. A non-iterative algorithm is developed for extracting poles of the harmonic admittance corresponding to SAW and LSAW propagation; the details are discussed in the paper. The resistance of the electrodes is commonly included as a lumped element added to the resonator admittance calculated under the assumption of zero resistivity of the electrodes. It is found that including the electrode resistance in this way results in distortions of the resonator response. It is shown that the resistance distributed along the length of the transducer is more accurate and gives results consistent with experimental data. The dielectric loss is accounted for in the calculations of the harmonic admittance by adding an imaginary part to the dielectric permittivity tensor. This is directly incorporated in matrix formalism used for analysis of partial waves, with generally complex coefficients of the acoustic tensor. Experimental and calculated responses of one-port resonators and ladder filters are presented to verify the approach. The devices are fabricated on lithium tantalate and lithium niobate, with various values of aluminum thickness and line/space ratio of electrodes.

P. Ventura et al., EFTF, pp. 200-204, 1995

P3U-E-6 F10

CONSIDERATIONS ON COUPLING-OF-MODES EQUATIONS FOR SHEAR HORIZONTAL TYPE SAW

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Since shear horizontal type Leaky SAW on an interdigital transducer has loss and dispersion according to scattering and radiation of bulk wave, it cannot be appropriately expressed by the conventional Coupling-of-modes(COM) equation.

Plessky successfully derived a simple COM equation for the dispersion characteristics of shear horizontal type SAW[1]. The COM equation had not include transduction terms and an equation of busbar current. Koskela et.al. derived an approximated expression for admittance of infinite IDT[2]. Hashimoto et.al. determined coupling coefficient from Koskela's admittance formula. But, it has frequency dispersion changed sharply around the upper stop band[3].

In this paper, a COM model which satisfies the Koskela's admittance formula and has coupling coefficient changed smoothly is examined.

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P3U-E-7 F9

THE IMPROVEMENT ON THE COM PARAMETERS EXTRACTION AND DEVICE SIMULATION FOR LEAKY SURFACE WAVE DEVICES

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Extraction of COM parameters and simulation of SAW device by P matrix calculation has been extensively used in SAW device design. The leaky surface wave device has strong propagation attenuation as frequency is within or above the stop band. The frequency-dependence attenuation has to be included in simulation. We proposed a way to extract COM parameters by directly using the harmonic admittance curve [1]. For the usual grating with two electrodes in a wavelength, the upper edge of stop band for shorted circuit grating f_u is overlapped with the lower edge f_l of stop band for open circuit grating, so in the harmonic admittance curve, the pole is canceled with the zero, there is no corresponding peak. We use the virtual phase shift excitation [2] to make the f_u shift from f_l, such that there appears again the pole and zero simultaneously in the harmonic admittance curve. From the peak value and half width of such pole and zero, it is easy to extract the mutual coupling coefficient and excitation coefficient. Different from [2], we use both real and imaginary phase shift

excitation with various magnitudes, so we can move the frequencies at pole and zero arbitrarily. So we can extract COM parameters including a propagation attenuation constant at various frequencies within certain frequency range. The attenuation is varying with the frequency. The knowledge on this attenuation-frequency curve is the key point to accurate simulation. By our approach, once the code is done, it is easy to obtain such curve. In device simulation, we use different parameters for different frequencies instead of unique parameter over whole frequency region. The simulation results of several device structures are compared with the results obtained by finite electrode Green's function method [3] as accurate reference. By the traditional simulation, the agreement in lower frequency part is good but the discrepancy is evident in the higher frequency part. After our new approach, the results are in good agreement with the finite electrode calculation in whole frequency band. This method has the advantage of short computation time over the finite electrode simulation. It is very important for device optimization. The same method is also successfully applied to SPUDT structure. By using this approach, the result of optimized design for dual mode structure filter is presented. [1] Y. Zhang, etc., IEEE Trans. UFFC-40, pp. 183-192, 1993 [2] Julius Koskela, etc., IEEE Trans. UFFC-46, pp.806-816, 1999 [3] P. Vantura, etc., 1995 IEEE Ultrasonics Symposium Proc. pp. 257-262

Session: P3FE-F
MATERIALS PROCESSING
Chair: D. P. Williams
Sandia National Laboratory

P3FE-F-1 W4

GRAIN ORIENTATION OF NEW LEAD-FREE PIEZOELECTRIC CERAMIC IN THE SYSTEM OF $(BI_{1/2}NA_{1/2})TIO3$-$(BI_{1/2}K_{1/2})TIO_3$-$BATIO_3$

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A new lead-free piezoelectric system of $(Bi_{1/2}Na_{1/2})TiO3$-$(Bi_{1/2}K_{1/2})TiO_3$-Ba TiO_3 (BiNT-BiKT-BT) has shown promising properties compared to other non-lead piezoelectric systems. Incorporation of BiKT to the binary system of BiNT-BT has improved the coupling coefficients (k_p & k_t) and piezoelectric coefficient (d_{33}). In this ternary system, a d_{33} of about 150 pC/N, coupling coefficient of k_t=45%, relative permittivity of 850, dielectric loss of 2.1%, and remnant polarization of $37\mu C/cm_2$ has been achieved in the bulk polycrystalline body. Texturing of this ternary system has been carried out by using the $SrTiO_3$ templates, which are fabricated via Molten Salt Synthesis (MSS). Texturing of up to 73% in the (00l) direction compare to the polycrystalline body has been shown when heat treatment carried out in 1170C-2h in oxygen atmosphere. The effect of

incorporation of a third component (BiKT) on the stability of the templates, degree of texturing, and the electromechanical properties of grain oriented samples are the issues which will be addressed.
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P3FE-F-2 W8

PZT THICK FILMS BY DIRECT-WRITE TECHNOLOGY

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Lead zirconate titanate (PZT) thick films have been prepared on alumina substrates using a Direct-Write technology, called Micropen. Pastes with solids loading of 30 to 50 vol.% PZT were prepared by thoroughly mixing the powder, a-terpineol (carrier) and ethyl cellulose (binder). Thick films of 50 to 200 mm were deposited, dried and then sintered at 1000° to 1200°C for 30 minutes in PbO atmosphere. Comparison of the thick film properties revealed that the dielectric constant and remnant polarization of the films sintered at 1000°C were higher, likely due to less severe lead loss. The effects of three sintering aids, i.e., PbO, Li2O-Bi2O3, and a borosilicate glass, have been investigated on the microstructure and electrical properties of the PZT thick films. It was observed that a 2 wt.% lithium bismuth oxide additive has a positive effect on the dielectric constant and remnant polarization of the PZT thick films sintered at 1100°C for 30 min. The microstructures of the films revealed that the additives beyond 1 wt% would result in excessive shrinkage and formation of large pores and cracks at sintering temperature of 1100°C and above. Using low viscosity pastes, films and lines with thickness as small as 5 mm can be written on the substrates, showing surface roughness of about 200 nm. The properties of the films including dielectric constants, loss, hysteresis loops, d33 coefficients, and impedance spectra of the PZT films are presented.
The authors would like to acknowledge the financial support of Office of Naval Research (ONR) and New Jersey Commission on Science and Technology (NJCST).

P3FE-F-3 W9

TEMPLATED GRAIN GROWTH OF $Bi_{0.5}NA_{0.5}TIO_3$ WITH SEEDS OF THE SAME MATERIAL

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With growing concern on health and safety worldwide, a requirement for environmentally-benign piezoelectrics are continually increasing. The $Bi_{0.5}Na_{0.5}TiO_3$ (BNT) ceramic is a promising piezoelectric material without the lethal element of Lead. Templated grain growth technique (TGG) is now employed widely

to utilize the better piezoelectric properties along certain crystallographic directions, enabling competition of non-lead piezoelectric materials. This study attempts to prepare the BNT-based ceramics using TGG with the BNT seeds itself, which is different from what have been attempted by other groups using different compounds as seeds in reactive templated grain growth technique (RTGG). Using seed and matrix of the same material help preserve the aligned orientation after sintering and reduce the composition variation locally. The BNT-based seeds were synthesized and sieved to required particle size. High fraction up to 100% of seeds was mixed with binder to create an extrudable paste. Green parts were extruded into cylindrical shape and dried in the oven. The dried parts were fired to eliminate binder and sintered to achieve the high density. These specimens were characterized in term of density, microstructure and piezoelectric properties.

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P3FE-F-4 W10

MOLDING OF HIGH ASPECT RATIO FERROELECTRIC MICROSTRUCTURES

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Fabrication of high aspect ratio structures of complex perovskite materials using photoresist templates is reported in this work. Water based (Pb,Ba)TiO3 (PBT) and 2-methoxyethanol based PbZr0.52Ti0.48O3 (PZT) sol-gel precursor solutions were used to infiltrate prefabricated photoresist templates on various substrates. The solutions were deposited by vacuum infiltration assisted dip coating. Pyrolysis and crystallization of the pillars were performed after removal of the gel layer formed on the surface of the mold. During crystallization process of nano structures photoresist was removed simultaneously. Nanostructures of PZT and PBT were obtained with various aspect ratios. Structural, dielectric and electromechanical properties of the resulting structures will be described.

P3FE-F-5 W11

ELECTROPHORETIC DEPOSITION OF BATIO3 FILMS FROM AQUEOUS SUSPENSIONS

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Electrophoretic deposition (EPD) is a colloidal process wherein ceramic materials are shaped directly from a stable colloid suspension by a dc electric field. High green densities can be achieved by EPD from suspensions with relatively

low solids content. EPD is applicable to the production of barium titanate films which is a well-known ferroelectric material. At present, most studies on the forming of BaTiO3 films using EPD process have been conducted in organic solvents, such as acetylacetone, diethylene glycol dimethyl ether, pyridine and ethanol etc. Organic liquids generally have a lower dielectric constant, limit the charge on the particles and need higher field strengths in EPD process. Electrophoretic deposition from aqueous suspension is gaining more and more attention because it is a low-cost, high-efficient and environmentally benign process for fabricating thin and thick ceramic films. Many ceramic films such as Al2O3, ZrO2, ZnO etc have been deposited from aqueous media. But electrophoretic deposition of BaTiO3 from aqueous suspension has seldom been reported. It is a meaningful work to study the possibility of depositing BaTiO3 from aqueous suspension by EPD process.In this paper, our work focused on the fabrication of barium titanate films from aqueous media. Nano-sized BaTiO3 was well dispersed in water using poly (acrylic acid co-maleic acid) as dispersant. The suspensions characteristics have been studied in terms of zeta potential and viscosity. Electrophoretic deposition was performed at electrochemical analyzer. Dense, uniform and bubble free BaTiO3 films have been formed from stable BaTiO3 suspension through EPD process under low applied dc voltage. Results showed that electrophoretic deposition from aqueous suspension was a feasible, low-cost and environmentally benign method to form BaTiO3 thin and thick films.

P3FE-F-6 W12

EFFECTS OF LI2CO3 AND BI2O3 ADDITIVES ON SINTERING TEMPERATURE AND PIEZOELECTRIC PROPERTIES OF PCW-PMN-PZT CERAMICS FOR MULTILAYER PIEZOELECTRIC TRANSFORMER

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In this study, in order to develop the low temperature sintering ceramics for multilayer piezoelectric transformer, PCW-PMN-PZT ceramics using Li2CO3, Bi2O3 and CuO as sintering aids were manufactured, and their microstructural, dielectric and piezoelectric properties were investigated. When the only CuO was added, specimens could not be sintered below 1000°. However, when Li2CO3 and Bi2O3 were added, specimens could be sintered below 1000°. Li2CO3 and Bi2O3 addition were proved to lower sintering temperature of piezoelectric ceramics due to the effect of Li2O-Bi2O3 liquid phase. Li2CO3 and Bi2O3 added specimens showed higher piezoelectric properties than those of the only CuO added specimens. At 0.2wt% Li2CO3 and 0.3wt% Bi2O3 added specimen sintered at 980°, the dielectric constant(ϵr) of 1610, electromechanical coupling

factor(kp) of 0.51 and mechanical quality factor(Qm) of 1367 were shown, respectively. These values are suitable for multilayer piezoelectric transformer application.
This work was supported by KEPRI

P3FE-F-7 W13

WITHDRAWN

P3FE-F-8 X11

INVESTIGATION OF THE FORMATION MECHANISM OF PEROVSKITE PHASE IN (1-X)PST-XPT CERAMICS PREPARED BY ONE-STEP-SINTERING-METHOD

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Compositions in the perovskite family, having the general formula Pb(BB)O3, are known as ferroelectric relaxors, which have excellent dielectric, piezoelectric and ferroelectric properties. However, such materials are difficult to fabrication reproducibly without the appearance of a pyrochlore phase that can be detrimental to the dielectric and ferroelectric properties. In this paper, the solid solutions of lead scandium tantalate-lead titanate, (1-x)Pb(Sc0.5Ta0.5)-xPbTiO3, PSTT(x) for short, were synthesized by a conventional mixed-oxide method (or named as one-step-sintering-method) using lower sintering temperature (1200°–1300°). The XRD patterns showed the percent of the perovskite phase of the PSTT(x) ceramics could be as high as 90 %, the highest was up to 100%. The thermodynamics of the perovskite phase of the PSTT(x) ceramics was investigated. The ionic radii and the ionic bonding are considered as the two key factors for forming perovskite phase in Pb(BB)O3 compositions. The perovskite forming impact factor T was defined as the times of tolerance factor and the percent of the ionic bonding in Pb(BB)O3 compositions. It was found that the calculated Ts values can interpret very well our experimental results and the relative ease sequence of fabrication of the lead-based perovskite.
This work was supported by Natural Science Foundation of China (NSFC) (10175045) and Specialized Research Fund for the Doctoral Program of High Education of China (SRFDP) (20020610014).

P3FE-F-9 X12

OPTICAL PROPERTIES OF SINGLE CRYSTAL SM2(MOO4)3

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The ferroelastic-ferroelectric single crystal were grown at 1185C by Czochralski method. In order to observe the optical properties of the sample, we got UV-VIS transmission, photoluminescence and Raman spectra. The transmission spectra of Sm2(MoO4)3 were measured in the range of 0.2 1.2μm by the spectrophotometer (Carry 5) and PL spectra were measured from 340 to 900nm. Raman spectra were observed at temperatures of 25C to 250C. The existence of a soft mode associated with the phase transition in the ferroelastic-ferroelectric crystal Sm2(MoO4)3 has been examined by the measurement of temperature dependent Raman spectra.

P3FE-F-10 W5

TEMPLATED GRAIN GROWTH (TGG) OF PMN-PT TEXTURED COMPONENTS BY LAYERED MANUFACTURING (LM)

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The net-shape capabilities of Layered Manufacturing (LM) and the cost-efficient growth technique of templated grain growth (TGG) have been combined to fabricate textured piezoelectric $Pb(Mg_{1/3}\ Nb_{2/3})O_3$ -$PbTiO_3$ (PMN-PT) components. A two-step molten salt synthesis (MSS) process of $Sr_3Ti_2O_7$ and $SrTiO_3$ was utilized for fabrication of high aspect ratio $SrTiO_3$ seed crystals by optimizing conditions including temperature, salt:oxide ratio, and salt type. The optimum conditions for (100)-oriented $SrTiO_3$ seed synthesis were found to be 1200°C heat treatment for 4 hours in 100% NaCl flux to produce a majority of high aspect ratio platelets and elongated platelets (up to 20:1) between 10-30 mm in length. Five to ten volume percent of the resulting $SrTiO_3$ seeds were dispersed in a PMN-PT (65/35) matrix and aligned during tape casting. Seed alignment is being further investigated in PMN-PT filament for extrusion and LM component deposition. The components were subject to heat treatments of 1250°C for 10 hours in order to texture the samples and enhance the (h00) peak intensities of PMN-PT. Lead-based additives such as lead oxide and lead carbonate were introduced to create a liquid phase during heat treatment of the samples, in order to enhance grain boundary migration through the PMN-PT matrix. Scanning electron microscopy (SEM) studies revealed that the grown PMN-PT regions from the $SrTiO_3$ seeds were approximately 40-60 mm in

length after proper heat treatment. X-ray diffraction (XRD) studies showed an enhancement in the (100) and (200) peak orientations of PMN-PT. From this data, the Lotgering factor (f) was calculated, indicating that the samples were textured up to 50%. The characteristics and properties of textured PMN-PT ceramics produced by tape casting and LM via TGG will be reviewed.
The author would like to acknowledge the Office of Naval Research (ONR) for their support.

P3FE-F-11 W6

INFLUENCE OF PROCESSING CONDITIONS ON THE MORPHOTROPIC PHASE BOUNDARY AND FERROELECTRIC PROPERTIES OF $PB(ZN_{1/3}NB_{2/3})O_3$-$PB(NI_{1/3}NB_{2/3})O_3$-$PB(ZR_{1/2}TI_{1/2})O_3$ SOLID SOLUTIONS

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Ceramics solid solutions within the ternary system of $Pb(Zn_{1/3}Nb_{2/3})O_3$-$Pb(Ni_{1/3}Nb_{2/3})O_3$-$Pb(Zr_{1/2}Ti_{1/2})O_3$ were synthesized via two methods: the mixed oxide method and the columbite method. Phase development of the calcined powders and the crystal structure of sintered ceramics were analyzed by x-ray diffraction and Raman spectroscopy. The ferroelectric properties of the ceramics were characterized by a combination of dielectric, hysteresis, and high temperature x-ray diffraction measurements. It was observed that for the binary systems PZN- PZT and PNN-PZT, the change in the transition temperature (T_m) is nearly linear with respect to the PZT content. Ferroelectric properties were analyzed to elucidate the nature of the phase transformation and identify the impact of the processing conditions. With these data, ferroelectric phase diagrams were derived showing the transition between the pseudo-cubic relaxor behavior of PZN and PNN to the tetragonal normal ferroelectric behavior of PZT. This transition was also correlated to changes in the diffuseness parameter δ. When comparing ceramics prepared by the columbite method and the mixed oxide route, ceramics prepared by the mixed oxide method showed a lower remanent polarization P_γ and a higher coercive field Ec. Additionally, ceramics prepared by the columbite method displayed sharp transitions in ferroelectric properties across the MPB composition, whereas these transitions were obscured in ceramics prepared by the mixed oxide method. It is proposed that the different reaction paths influenced the degree of compositional heterogeneity in these complex perovskite solid solutions, which was clearly reflected in the nature of the phase transition.

P3FE-F-12 W7

REDUCED TEMPERATURE SYNTHESIS OF $PB_3MGNB_2O_9$

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$Pb_3MgNb_2O_9$, often expressed as $Pb(Mg_{1/3}Nb_{2/3})O_3$ or PMN, is a useful relaxor material for high dielectric constant applications and electrostrictive and piezoelectric transducers. Data are reported for the formation of PMN powders by the columbite ($MgNb_2O_6$) route, with emphasis on the stability of the final perovskite phase. A variety of starting materials and processing methods were used to investigate the formation of the $MgNb_2O_6$ precursor as well as its conversion to the final $Pb_3MgNb_2O_9$ reaction product (i.e. perovskite). Characterization data are reported for each step in the processing cycle. Specifically, MgO and Nb_2O_5 were examined by electron microscopy and X-ray diffraction (XRD), before and after mixing, as well as after repeated calcinations and milling to characterize the size, shape and purity of the starting materials and the reaction product. A pure columbite phase was formed after calcining at 1200°C for 12 hours. Similarly, PbO was characterized before and after mixing with the $MgNb_2O_6$ precursor by electron microscopy and XRD. PbO and $MgNb_2O_6$ were mixed in stoichiometric proportions and reacted under various thermal-processing conditions. The perovskite phase of PMN formed after 12 hours at 650°C. Data are reported for the reaction pathway, phase stability and morphology of the required perovskite powder. Powder characteristics are related to the electrical properties of ceramics formed from PMN.

Session: P3FE-G

TUNABLE/RF
Chair: R. R. Neurgaonkar
Rockwell Scientific Co.

P3FE-G-1 S8

OPTIMIZATION OF HIGH TUNABILITY BARIUM STRONTIUM TITANATE THIN FILMS GROWN BY RF MAGNETRON SPUTTERING

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Barium strontium titanate ($Ba_{0.5}Sr_{0.5}TiO_3$) is a solid solution perovskite with a field-dependent permittivity. At microwave frequencies, its tunable dielectric

constant and low loss make it a competitive choice for varactors and other tunable circuit elements. Much attention has been focused on the production of low-loss films for such applications, with little emphasis on how the film properties contribute to the circuit loss. When tunable elements are implemented in circuits, electrode loss dominates over film loss. In applications such as phase shifters, where cascaded tuning elements provide a predetermined amount of tuning, circuit designs using high tunability films minimize the number of tuning elements required, resulting in an overall reduction in circuit loss.

When growth conditions are optimized for superior electrical properties, tunability and film loss are the two quantities of interest. By changing the oxygen partial pressure during growth, the amount of excess Ti incorporated into the film is changed. Films with higher excess Ti contents exhibit lower losses, higher breakdown voltages, and lower permittivities than more stoichiometric films. While all of the films approach the same high-field capacitance limit, the total tunability is determined not only by the zero-field permittivity but also by the breakdown voltage; a device must be able to tolerate sufficient applied bias to reach its high-field capacitance limit. By balancing these factors, we have produced capacitors with an unprecedented 13.71:1 (92.7%) tuning ratio at an applied field of 4.7 MV/cm.

P3FE-G-2 S9

REVERSIBLE DIELECTRIC NONLINEARITY AND MECHANISM OF TUNABILITY FOR

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In this paper, a brief review was presented on the reversible dielectric nonlinearity and the mechanism of tunability for ferroelectric ceramics. First, a classification criterion of dielectric nonlinearity was proposed. Second, several kinds of mechanism of reversible dielectric nonlinearity were discussed in view of the macroscopic phenomenological thermodynamic theory, the ferroelectric domain, the polar nano-region, the field induced phase transition and the grain boundary layer, respectively. Next, alternating current dielectric nonlinearity was simply introduced. Finally, the authors suggest that reversible dielectric nonlinearity should be discussed in the following aspects: scale, temperature and frequency. The most important factor among all kinds of possible physical mechanism should be aimed at under a certain circumstance. The authors also suggest to built up a set of general approach for quantitating of reversible dielectric nonlinearity.

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P3FE-G-3 S10

AN INVESTIGATION OF BST:$MGTIO_3$ AND X7R:$MGTIO_3$ BASED CERAMICS FOR MICROWAVE APPLICATIONS

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There is a growing demand for dielectrics with field-tuneable permittivity for use in frequency agile filters and phase shifters at microwave frequencies. Paraelectric phase composition of BST is a popular choice because of its non-linear properties demonstrated by the field dependence of the permittivity. However, the dielectric properties of BST compositions are temperature dependent, and thereby compromise the tuneability. In this paper the dielectric properties of temperature stable X7R dielectrics ($\Delta C \leq 15\%$ for $55^\circ C \leq T \leq 125^\circ C$), barium strontium titanate (BST) and their composites with magnesium titanate (MT) have been investigated to determine their field tuneability as a function of temperature. Magnesium titanate a low permittivity material has been used to attenuate the relative permittivity and lower the dielectric loss of BST and X7R for microwave applications. A series of (1-x)BST : (x)MT and (1-x)X7R : (x)MT composites have been synthesised ($x = 0.0$ to 0.5), at sintering temperature ranging from $1200^\circ C$ to $1400^\circ C$. Structural characterisation of these composites have been carried out and their dielectric permittivity was measured as a function of temperature and DC bias. The results are compared to those of BST and assessed for their use in device applications. The effect of $MgTiO_3$ incorporation and sintering temperature is also discussed.
Engineering and Physical Research Council (EPSRC) of the UK for sponsoring this research project.

P3FE-G-4 S11

DIELECTRIC BEHAVIOUR OF COMPOSITE FILMS OF NICKEL-ZINC FERRITE AND BARIUM TITANATE IN LOW FREQUENCY AND MICROWAVE FREQUENCY RANGE

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Abstract

Ferrite/ferroelectric thick composite films of nickel zinc ferrite and barium titanate have been fabricated. Samples were made of powders of nickel zinc ferrite with general composition Ni1-xZnxFe2O4 where x = 0.0, 0.1, 0.2, 0.3 and 0.4 processed by citrate-route. Barium titanate in different proportions is

mixed with sintered powders of nickel zinc ferrite. Dielectric properties such as dielectric constant (ϵ') and dielectric loss tangent (tanδ) were measured as a function of sample and experimental parameters in the low frequency region (100 Hz-1MHz) and in microwave frequency region (8-13 GHz). ϵ' and tanδ were found to vary linearly with frequency and composition of ferrite loading in ferrite/ferroelectric thick composite films. The dielectric loss tangent increases with ferrite loading. Ferrite/ferroelectric composite materials with reduced dielectric losses can be used for microwave applications.

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P3FE-G-5 S12

DESIGN OF A SI MMIC COMPATIBLE FERROELECTRIC VARACTOR SHUNT SWITCH FOR MICROWAVE SWITCHING APPLICATIONS

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We have designed a capacitive shunt switch, based on ferroelectric varactors as a potential replacement for RF MEMS switches for microwave applications. Our implementation is based on a coplanar waveguide (CPW) transmission line shunted by a ferroelectric varactor. The novelty in the implementation comes from the elimination of any moving parts (as in MEMS switches) for switching. The concept of switching ON and OFF is based on the dielectric tunability of the ferroelectric thin-films. From our current collaborative research with the Air Force Research Laboratory (AFRL), the relative dielectric constant of a nanostructured BST thin-film can be tunable from as high as 1200 at zero bias to 300 at a voltage bias related to a biasing field of $\sim$80 kV/cm. At zero bias, the capacitance of the varactor will be very high resulting in the signal shunted to ground, isolating the output from the input (OFF-state). When the dc bias voltage is increased, the capacitance will be reduced, allowing the signal to be output (ON-state). Thus the large dielectric tunability of a ferroelectric thin-film is used for microwave switching.

We have designed and simulated the ferroelectric varactor shunt switch of 5 μm x 5 μm area. From electromagnetic simulations performed, the isolation of the switch between 20 and 40 GHz (OFF state S21) is better than 20 dB. The insertion loss of the switch is below 2 dB up to 40 GHz. The performance of the switch is comparable to RF MEMS switches realized to date. The ferroelectric varactor shunt switch proposed is in the normally OFF state compared to RF MEMS capacitive shunt switches, which are in the normally "ON" state. The varactor shunt switches are capable of switching at $\sim$30 ns switching speeds,

where as the RF MEMS switches are slower ($\sim$10μs) because of the mechanical movement involved. A lower bias voltage ($\sim$10V) can be used for the ferroelectric varactor compared to RF MEMS switches (40-50V) for switching. Also, integration with RF/mixed signal electronics is highly feasible using the proposed varactor switch. This paper addresses the design, optimization, electromagnetic simulations, electrical modeling, and experimental integration of the ferroelectric varactor shunt switch with Si MMIC compatible process.

Authors acknowledge Ms. Bonnie Riehl, a Ph.D. student in our group, Dr. Rand Biggers and Dr. Angela Campbell, Air Force Research Laboratory, WPAFB, for the development of nanostructured BST thin-films used in our work. Authors also acknowledge collaboration with Prof. Spartak Gevorgian at Chalmers University of Technology, Sweden.

P3FE-G-6 S13

INFLUENCE OF STACKING PERIODICITY ON THE DIELECTRIC TUNABILITY PROPERTIES OF (BA1-XSRX)TIO3 MULTIALAYERS FILMS

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A strong DC electric field dependence of dielectric constant makes Ba1-xSrxTiO3 ferroelectric thin film to be promising materials for tunable microwave devices. For application in severe rugged environment, the films were requested to have larger tunability, lower dissipation factor and lower temperature dependency of dielectric constant. In this paper, the effects of multialayers structure on the dielectric tunability properties were investigated as a function of the stacking periodicity of BST films. Ba0.3Sr0.7TiO3/Ba0.7Sr0.3TiO3 multilayers films fabricated on LaAlO3 (100) and Pt/Ti/SiO2/Si (100) substrates were fabricated by sol-gel techniques layer-by-layer. The different thicknesses of the stacking periodicity were obtained from a several highly dilute solutions and different velocities of spin-coating, and the total thickness of films were 400 nm. Films were characterized by XRD, FE-SEM, HREM and dielectric measurements. As the thickness of the stacking periodicity decreased, the diffraction peaks of Ba0.3Sr0.7TiO3 and Ba0.7Sr0.3TiO3 overlapped, and the films have larger tunability. When the thickness in the stacking periodicity is 80 nm, the films have lower dielectric loss. It was found that all films had small temperature dependency compared to the signal composition Ba0.3Sr0.7TiO3 or Ba0.7Sr0.3TiO3 films. A model of larger volume of the interfaces in the two adjacent layers was proposed to understand the effects of the dielectric properties.

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Session: P3FE-H
MATERIALS CHARACTERIZATION
Chair: V. H. Schmidt
Montana State University

P3FE-H-1 X5

ABOUT THE DETERMINATION OF THE ELECTROMECHANICAL COUPLING FACTOR OF THE FERROELECTRIC PLATE VIBRATING IN THICKNESS-SHEAR MODE

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The paper deals with the determination of the electromechanical coupling factor k26 of the selected rotated Y-cut GaPO4 resonators, and k15 of polarized ferroelectric PZT plate, vibrating in the thickness-shear mode. The IEEE Standard on Piezoelectricity [1] recommends to apply the dielectric method, and determine the thickness-shear coupling factor from the measurement of the free and clamped permitivities of the sample. In this case, it is not so easy to define the frequency at which the clamped permitivity have to be measured. It is known that electromechanical coupling factor is also useful to the expression of the influence of piezoelectric properties on the resonance frequency of the thickness shear vibrations of the plate [2], [3]. We use this knowledge for the proposal of the resonant method for the determination of the electromechanical coupling factor k26 of the rotated Y-cut GaPO4 resonators, and k15 of polarized ferroelectric PZT plate. The derived method is described in the contribution. The results of the measurements of k26 and k15 with the derived resonance method are compared and discussed with the results obtained by using of the dielectric method and method mentioned in our work [4].

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DIRECT STRAIN-FIELD HYSTERESIS MEASUREMENTS IN PZT FILMS VIA SCANNING FORCE MICROSCOPY

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Recent progress in the deposition of ferroelectric thin films via various techniques has prompted enormous interest in their applications in microelectronic devices including ferroelectric memory cells, pyroelectric arrays, micromachined transducers, etc. The size of these devices is now approaching to the micron dimensions where the properties of ferroelectric elements might be different from their bulk (macroscopic) behavior. The investigation of the domain structure at the submicron scale is extremely important for predicting the properties of microdevices and nanoscale switching characteristics. Ferroelectric domain imaging is currently performed by scanning force microscopy (SFM) technique, which is becoming a standard procedure for the investigation of ferroelectrics and related materials. SFM is typically used in a piezoelectric mode where the amplitude and phase of the local piezoelectric deformation are measured via a conventional lock-in technique. Polarization switching is performed by slowly varying dc bias field applied between the tip and the counter electrode, while the polarization state is monitored by measuring weak-field piezoelectric response. Recently, a new procedure has been proposed [1], where an instantaneous strain is measured as a function of the instantaneous voltage applied to the tip (local strain-field or butterfly hysteresis loops). In this work, we present the results of local electromechanical strain measurements in PZT thin films of several compositions and orientations. The influence of the Maxwell stress, inhomogeneous electric field distribution and surface layer with low dielectric constant will be addressed along with the nanoscale switching effects that could arise at the nanoscale. The frequency, ac-field amplitude, and dc bias field dependences of the measured signal will be reported. It will be shown that in PZT the frequency-dependent strain can be associated with the domain wall dynamics near the ferroelectric surface. It will be also demonstrated that the local strain-field hysteresis is always asymmetric due to the pronounced effect of the built-in electric field at the ferroelectric surface. The results are complemented with the macroscopic strain-field hysteresis measurements performed by conventional techniques. 1. S. Dunn, J. Appl. Phys. 94, 5964 (2003)

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P3FE-H-3 X7

NONLINEAR PIEZORESPONSE IN FERROELECTRIC THIN FILMS STUDIED BY SCANNING FORCE MICROSCOPY

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The development of microelectromechanical systems (MEMS) combining micro sensors and micro actuators with Si-based circuitry in small-size devices has recently become an important area in microelectronics. Incorporating piezoelectric thin films into the MEMS design provides several advantages including large electric field-induced deformation, rapid response, good linearity, and high stress sensitivity. More importantly, piezoelectric actuation is favorable for the downscaling of micro devices. Due to their small thickness, ferroelectric films typically operate under the high electric field even at a small driving voltage. Therefore, the nonlinearity of the piezoelectric properties of ferroelectric films may become essential and piezoelectric deformation may not be predicted based on simple thermodynamic equations. The goal of this work was to study nonlinear piezoelectric properties of $Pb(Zr,Ti)O_3$ (PZT) and $(Pb,La)TiO_3$ (PLT) thin films at the macroscopic (by laser interferometry) and nanoscale (by scanning force microscopy - SFM) levels. The comparison of the macroscopic and local measurements is done in order to understand the nature of the piezoelectric response by SFM. It is found that the local piezoresponse of PLT films measured in the interior of uniformly polarized areas (domains) is almost linear with increasing driving voltage until it approaches to the coercive one. On the contrary, the corresponding macroscopic response is essentially nonlinear suggesting significant contribution from the motion of 90 domain walls. In PZT films the local piezoelectric behavior is shown to be strongly nonlinear as compared to almost field-independent macroscopic piezocoefficient. In particular, the local piezoelectric deformation of PZT films may display both sublinear and superlinear features depending on the polarity of as-grown domains. Some domains are unstable with respect to the driving field and switch into the opposite polarization state under an ac-voltage several times smaller than that required for global polarization reversal. This phenomenon is explained by the presence of charged domain boundaries below the surface and by their local electric-field-induced depinning. It is shown that SFM can be, in principle, used not only for polarization mapping of ferroelectric surfaces but also as a probe for studying local polarization profiles beneath the SFM tip.

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P3FE-H-4 X8

THICKNESS DEPENDENCE OF THE MICROSCOPIC AND MACROSCOPIC PIEZOELECTRIC PROPERTIES OF LEAD ZIRCONATE TITANATE THIN FILMS

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The thickness dependence of the piezoelectric properties of sol-gel derived $PbZr_{0.52}Ti_{0.48}O_3$ (PZT) thin films was investigated using scanning force microscopy (SFM) and double-beam laser interferometer techniques. Microscopic measurements were performed on different locations of the films in order to determine the influence of the microstructure and domain assemblages on the local switching by SFM. The effective longitudinal piezoelectric coefficients (d_{33}) were determined after poling the films to the saturation. The d_{33} thickness dependence was then measured using local (SFM) and average macroscopic (interferometer) techniques. The local piezoelectric coefficients were roughly independent on the film thickness and depended strongly on the morphology of the grains and initial domain structure. On the other hand, the macroscopic d_{33} gradually increased with increasing thickness reaching saturation at d_{33} =55 pm/V. The difference in the local and macroscopic piezoelectric effects in PZT films will be analyzed and related to both instrumentation and nanoscale switching effects.
The work is performed within the project POCTI/CTM/44732/2002 from the Portuguese Foundation for Science and Technology (FCT). A. L. Kholkin is grateful to the Spanish Ministry of Education, Culture and Sport for a grant SAB2001-0160. J. M. Herrero and C. Zaldo thank CAM 07N/0077/2002 and MCyT MAT2002-04603-C05-05 projects.

P3FE-H-5 X9

ANALYTICAL MODELING OF APPARENT D33 PIEZOELECTRIC COEFFICIENT MEASURED BY THE DIRECT QUASISTATIC METHOD FOR DIFFERENT BOUNDARY CONDITIONS

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The most commonly used technique for measurement of direct piezoelectric d33 coefficient in ferroelectric ceramics is the simple sub-resonance dynamic (or quasistatic) method. This technique is widely used in research laboratories and in industries for quality control of piezoelectric products, because of its simplicity, low cost, good accuracy, and possibility to carry out measurements over a relatively wide range of dimensions, geometries, frequencies, temperatures and driving pressure amplitudes. One difficulty with this technique is that the

measured d33 values depend strongly of the mechanical boundary conditions of setup and the sample. For example, these values are strongly dependent on the sample aspect ratio (thickness /lateral dimension) and the type of contacts used to collect the charge and apply the pressure on the sample. In this study we present an analytical model in which apparent (measured) d33 is a function of the aspect ratio, the mechanical properties of the contacts and the properties of piezoelectric ceramics. Using derived relations it is possible to obtain the true value of d33 in the wide range of boundary conditions. The analytical results are compared with simulations using Finite Element Modeling (FEM) and with experimental data, and good correlation is found among them. Effect of the geometry of the contacts used to apply the force and collect the piezoelectric charge from the sample on apparent d33 value is specifically addressed. The results of this study should be helpful in designing instruments for measuring direct piezoelectric properties (also know as Berlincourt-type instruments), interpreting differences in the values of coefficients obtained from various sources and in helping to obtain the true d33 of piezoelectric materials for all dimensions of samples.

P3FE-H-6 X10

COMPLEX RARE-EARTH SUBSTITUTED LEAD TITANATE PIEZOCERAMICS

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A rare earth element or pairs of rare earth elements have been often used in the last decades in the preparation of various materials for solid oxide fuel cell (SOFC), oxygen storage, supraconductors, microwave applications and ferroelectric random acces memories (FRAM). Rare-earth substituted piezoelectric ceramics with composition $Pb_{1-3x/2}$ $Ln_x Ti_{1-y}$ $Mn_y O_3$ (with Ln = La, Ce, Pr, Nd, Sm, Eu, Gd) have been investigated due to their high Curie temperature, high anisotropy in electromechanical properties (large k_t/k_p ratio) and good surface acoustic wave (SAW) properties. These materials can be employed in high frequency applications like linear array transducers, SAW filters etc. In this work we have investigated the properties of new compositions of Gd, Nd and a mixture of Gd+Nd -added Pb(Ti,Mn)O3 ceramics, containing a few percent of Bi, to partially substitute lead. The samples have been prepared starting from high purity oxides by solid-state reaction of oxide powders, within the sintering range 1100-1220°C. Structural and morphological investigations were performed on poled samples. The use of X-ray diffraction together with microstructural examination by transmission electron microscopy has shown evidence for the formation of tetragonal perovskite phase. The domain structure and the lattice

imperfection of the PT-type samples have been investigated by a high resolution transmission electron microscope (HRTEM). Samples with diameter 10mm and thickness 1mm have been employed for electrical characterization. Material coefficients have been investigated as a function of temperature. Dielectric permittivity and resistivity were measured with a four-wire probe also on unpoled samples in a wide temperature and frequency range. Surface acoustic wave properties have been also investigated.

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Session: P3FE-I

DOMAINS SWITCHING
Chair: D. Viehland
Virginia Tech

P3FE-I-1 T11

PULSE ELECTRIC FIELD INDUCED PHASE TRANSITION BEHAVIORS OF LA-DOPED PB(ZR,SN,TI)O3 ANTIFERROELECTRIC CERAMICS

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High power pulse electric field could induce antiferroelectric(AFE)- ferroelectric (FE)- antiferroelectric phase transitions for La-doped Pb(Zr,Sn,Ti)O3 ceramics. The strength of applied pulse electric field was 5kV/mm, the width of the pulse electric field were 200ns and 400ns respectively. After the pulse electric field applied the ceramic samples, the ceramics experienced and completed a AFE-FE-AFE phase transitions procedures, the specimens produced a pulse polarization in the time domain, The strength of the pulse polarization was about 25-30 μC/cm2, the width of the pulse polarization were about 400ns and 800ns respectively. both the pulse electric field and the pulse polarization composed a pulse hysteresis loop (P-E curve). Comparing with the quasi-static process hysteresis loop (P-E curve), the pulse hysteresis loop could provide more information about the phase transition of La-doped Pb(Zr,Sn,Ti)O3 ceramics dynamically.
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P3FE-I-2 T12

COOLING-RATE-DEPENDENT DOMAIN STRUCTURES OF PMN-PT SINGLE CRYSTALS OBSERVED BY CONTACT-RESONANCE PIEZORESPONSE FORCE MICROSCOPY

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Domain structures of PMN-PT ($Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$) single crystals have been observed by Piezoresponse Force Microscopy (PFM). Recently, Yan *et al*[1] have found that dielectric properties of PMN-PT single crystals in the ferroelectric phase strongly depended on cooling rate across relaxor-ferroelectric phase transition temperature ($T_{R\text{-}F}$). They expected that if cooling rate across $T_{R\text{-}F}$ changed, the average domain size in ferroelectric phase would change. In order to examine their prospects, we observed domain structures of PMN-PT single crystal using contact-resonance PFM (CR-PFM) in the air at room temperature after thermal treatments with various cooling rates. CR-PFM is a suitable tool for observing delicate domain structures such as microdomains due to its low modulation voltage (typically $0.1V_{p\text{-}p}$).

PMN-PT single crystals with practically morphotropic phase boundary composition were grown by the Bridgman method. The Curie temperature of the specimens was approximately 175 °C, which was estimated from the permittivity measurements. The thermal treatment process is as follows:(1) The sample was heated from room-temperature to 220 °C. The heating rate is 60 °C/h. (2) kept at 220 °C for six hours. (3) cooled down from 220 °C to room-temperature with various cooling rate ranging from 15 °C/h to 60 °C/h. We found that shapes and average sizes of domains depended on the cooling rate. Before thermal treatment, finger-print-patterned domain structures 500 $\sim$ 1000 nm in width were observed. After thermal treatment under the cooling rate 15 °C/h, finger-print-patterned domains were also observed. On the other hand, after thermal treatment under the cooling rate 30 °C/h, circular domains 50 $\sim$ 300 nm in diameter were observed. Furthermore, after thermal treatment under the cooling rate 60°C/h, finer circular domains were observed. Their diameter was 20 $\sim$ 100 nm. Our results corresponded with Yan/s prospects qualitatively.

[1] F. Yan, P. Bao, Y. Wang, H. L. W. Chan, and C. L. Choy, Appl. Phys. Lett. 81, 4580 (2002).

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P3FE-I-3 T13

LOCAL SWITCHING PROPERTIES OF DENSE NANOCRYSTALLINE $BATIO_3$ CERAMICS BY AFM PIEZORESPONSE INVESTIGATIONS

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Barium Titanate $BaTiO_3$ has extensive use in electronics as material for multilayer capacitors, embedded capacitance in printed circuit boards, thermal imaging and actuators. The present endeavour in the microelectronics is the miniaturisation of the ferroelectric elements which imposes the corresponding reduction of their grain sizes. The study of size-dependent properties in the nanometric range, in connection with the microstructural characteristics is of main importance for improving the technical performances of the ferroelectric components. Preparation of dense, bulk nanocrystalline ceramics requires ultra-fine, non-agglomerated powders with a narrow particle size distribution and a suitable densification technique to minimise grain growth. Ultrafine BT powders (30-40nm; $35m^2/g$) were prepared by precipitation from an aqueous solution of $TiCl_4$ and $BaCl_2$ at 90°C at pH$\sim$ #14. Dense sintered samples (relative density: 97%; 100 and 50 nm grain size) were obtained by Spark Plasma Sintering at 800-930°C for 2 min. The phase transitions were studied by Raman spectroscopy and differential scanning calorimetry. The AFM study indicates that the material remains intrinsically ferroelectric at the smallest size of 50nm, as proved by the local hysteresis measured in some regions. The permittivity measurements performed in the range (150, 180)°C at frequencies of (1Hz, 1 MHz) showed a diffuse ferro-para phase transition. The geometric grain limitation at nanometric scale leads to a superparaelectric state with mixed intragranullar (nanometric short range order) and transgranullar (ferroelectric long range order) dipole interactions.

P3FE-I-4 T14

IN-SITU DOMAIN OBSERVATION OF $PB(MG_{1/3}NB_{2/3})O_3$-$PBTIO_3$ SINGLE CRYSTALS NEAR THE CURIE TEMPERATURE USING CONTACT-RESONANCE PIEZORESPONSE FORCE MICROSCOPE

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The domain-structure images of (001) plates of $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PMN-PT) single crystals were successfully obtained near the Curie temperature using a contact-resonance piezoresponse force microscope (CR-PFM). Relaxor characteristics have been discussed and have mostly been understood in terms of microdomains (polarized microclusters), although a unified model which can consistently explain everything about relaxor characteristics has not been provided yet. The microdomains are the evidence of the lack of long-range order and originate from non-uniform crystalline fields. This lack of long-range order has been believed to be due to local fluctuations in the distribution of *B*-site cation composition. This microdomains have been investigated mainly by diffraction methods such as the neutron-diffraction method, the extended-X-ray-absorption fine-structure method and the X-ray diffuse-scattering method. Thus, we tried to obtain real-space images of the microdomains using CR-PFM.

During conventional PFM observations at sufficiently higher temperatures, the modulation voltages applied between the tip and the counter electrode induced polarization reversals and destroyed local domain structures under the tip. In order to resolve this difficulty, contact-resonance mode, which is a mechanical vibration mode of a cantilever with two nodes at the tip and the root of a cantilever, was adopted. For the contact-resonance-mode operation, the frequency of the modulation signal was maintained near the resonance frequency of the cantilever deflection when in contact with the sample surface. Utilizing contact-resonance mode, we were able to operate PFM imaging with a reduced amplitude of the modulation signal (typically 4.0 $V_{p\text{-}p}$ to 0.1 $V_{p\text{-}p}$).

PMN-PT single crystals with practically morphotropic phase boundary composition were grown by the Bridgman method. The Curie temperature of the specimens was approximately 175 °C, which was estimated from the permittivity measurements. The domain-structure images of PMN-PT single crystals were successfully obtained at various sample temperatures up to 205 °C. Below the Curie temperature, finger-print patterned domain structures 500–1000 nm in width were observed. After the sample was heated up above the Curie temperature, circular domains 30–100 nm in diameter were emerged.

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Session: P3FE-J
MODELING AND THEORY
Chair: D. Viehland
Virginia Tech

P3FE-J-1 U1

NUMERICAL MODEL OF INFLUENCE OF EXTERNAL ELECTRIC LOADING ON ELECTRO-ELASTIC FIELD IN FERROELECTRICS

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A mathematical modeling of behavior of possible proposed ferroelectric structures exposed various external loading can usefully support the design of real ferroelectric devices. This paper presents our numerical model of ferroelectric crystal specimen. The proposed model considers a ferroelectric crystal with an internal domain structure. The model is based on physical description that includes linear electro-elastic state equations, Newtons law and Gauss law, which are completed by the possible boundary conditions reflective the concrete external loading. The numerical method used for the formulation and approximation of the model keeps mixed-hybrid finite element method approach. The used method leads to a large system of algebraic equation, much larger in comparison to other numerical method, but it has some other advantageous properties. Besides, the development of our own software tool enables determination of special needs and could allow in the future modeling of sophisticated feroelectric crystal structures including for example possible local inhomogenities. The paper includes general description of sample geometry and physical model including possible restriction. Further the weak formulation, approximation and some results acquired as outputs of implemented model are presented. The electric part of the model was implemented in advance, so it was already described in [1].

[1] J. Královcová, J. Maryka. Model of Influence of External Electric Field on Domain Wall in Ferroelectrics. Proceedings of SIMONA 2003, Liberec, Czech Republic.

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P3FE-J-2 U2

A FATIGUE MODEL FOR PZT THIN FILMS

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In Dawber-Scott fatigue model, the polarization of ferroelectrics was derived to be the liner function of N and f (N is the switching cycle and f is the test frequency) on the hypothesis that the fatigue arises from the oxygen vacancies. Based on the consideration that both oxygen vacancies and injection electronics might be responsible for the fatigue, the polarization should be the power function of N and f. Our simulation results agreed with the experiment perfectly.

P3FE-J-3 U3

THERMAL FIELDS AND THERMAL STRESSES IN SEMICONDUCTING BARIUM TITANATE

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Semiconducting barium titanate ceramics exhibit an anomalous electrical resistivity increase above the Curie temperature. This phenomenon is well known as the positive temperature coefficient of resistivity (PTCR). A lot of applications have been made by using this unique property. All of applications involve repeated cycles of heating and cooling. Rapid temperature changes, which may be induced in protection devices and heating elements under current surges, cause thermal stresses which may initiate and propagate cracks due to thermal shock and fatigue. Mechanical failure may result in loss of electrical function. In addition, thermal gradients result in a non-uniform distribution of intensity of electric field in samples. Therefore, researches of thermal fields and thermal stresses in materials with PTCR are important. The present work is devoted to investigation of distribution of temperature and electric field and also calculation of thermal stresses in PTC-thermistors. The investigations of spatially-time distribution of temperature and electric field in PTC-thermistors based on semiconducting barium titanate under current loading was carried out. The analysis was made on the basis of the numerical decision of the non-linear thermal conductivity equation. It has been shown, that at conditions of intensive heat exchange of element with environment (large magnitudes of the heat transfer coefficient) the large thermal gradient takes place. The difference in temperature between the centre and the surface of the samples may reach several tens degrees. The maximum of temperature difference between centre and outer faces of an element takes place when the material temperature immediately exceeds the Curie point. This fact is explained by extreme behavior of the thermal capacity at phase transition. Later, a reduction of the thermal gradient takes place and the device passes into a steady state. The electric field is sharply non-uniform and basically is concentrated in the central area of PTC-thermistor. The data about temperature distribution were used for calculation of thermal stresses. In short time range (when ferroelectric phase transition takes place) the stresses change sign in center of the samples. It is explained by behavior of thermal expansion coefficient of barium titanate, which exhibits a negative value in transition region. Numerical experiment and the analysis of the obtained results have shown that the magnitude of tensile stresses can achieve 30 MPa directly after phase transition.

P3FE-J-4 W1

CALCULATION OF ELECTRONIC STRUCTURE OF FERROELECTRIC $CATIO_3$ IN CUBIC AND ORTHORHOMBIC PHASES

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The electronic structure, energy gap, total and partial density of states of crystal $CaTiO_3$, in cubic and orthorhombic phases, are studied using full potential linearized augmented plane wave method (FP-LAPW) by means of the first principles. The calculations have been made in the framework of density functional theory (DFT). The results show an indirect band gap of 2 eV at Γ-R points in

the Brilluin zone for the cubic phase and a direct band gap of 1 eV at point Γ for the orthorhombic phase. The calculated band structure and density of states, in comparison with the previous theoretical results, show better agreement with the experimental results.

P3FE-J-5 W2

RESIDUAL STRAIN AND FERROELECTRIC BEHAVIOURS OF $PB_{0.7}LA_{0.2}TIO_3$-BASED PEROVSKITE

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Complex perovskite structures with the general formula of $AA(BB)O_3$ exhibit many unique ferroelectric and piezoelectric behaviours, in association with the order-disorder transition and lattice strains. While several existing physical models have been proposed to explain some of these behaviours, we report the effects brought about by partial substitution of Pb^{2+} (1.19) in pseudocubic $Pb_{0.7}La_{0.2}TiO_3$ (PLT-A) by three divalent cations, namely Ca^{2+} (0.99), Sr^{2+} (1.12) and Ba^{2+} (1.34). Mechanical activation at room temperature can trigger the formation of nanocrystallites for these pseudocubic perovskites. An increasing level of A-site substitution in $Pb_{0.7}La_{0.2}TiO_3$ led to the ferroelectric to relaxor transition and quantum paraelectric-like behaviour, depending on the difference in ionic radius of the A-site substitution. There occurs a level of residual lattice strains, the sign and magnitude of which are dependent on the size mismatch between $Ba^{2+}/Ca^{2+}/Sr^{2+}$ and Pb^{2+}. The residual strains strongly affect the long range polar order in $Pb_{0.7}La_{0.2}TiO_3$, leading to the normal ferroelectric to relaxor and/or quantum paraelectric-like behaviour. In association with the breakdown in polar long range order arising from the residual strains, a large enough shrinkage in the perovskite lattice can effectively freeze Ti^{4+}. Having systematically investigated the observed ferroelectric to relaxor transition and quantum paraelectric-like behaviours observed in $Pb_{0.7}La_{0.2}TiO_3$ doped with varying levels of Ca^{2+}, Sr^{2+} and Ba^{2+}, a new phenomenological model is presented for the correlation between residual strains and the ferroelectric behaviours.

P3FE-J-6 W3

ELECTRONIC STRUCTURE OF PIEZOELECTRIC $PBTIO_3$ IN CUBIC AND TETRAGONAL PHASES

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The electronic structure of piezoelectric $PbTiO_3$, in cubic and tetragonal phases, are studied using full potential linearized augmented plane wave method (FP-LAPW) by means of the first principles. The calculations have been made in the framework of density functional theory (DFT). The calculated results show a direct band gap of 1.6eV at the X point in the Brillouin zone for cubic phase and an indirect band gap 1.8eV at Γ point for tetragonal phase. It is also better agreement in comparison with the previous theoretical and the experimental results.

Session: P3FE-K
CAPACITORS AND DIELECTRICS
Chair: D. McCauley
Ferreoelectric Material Systems

P3FE-K-1 U4

DIELECTRIC BEHAVIOR OF CALCIUM COPPER TITANIUM OXIDE UNDER HIGH ELECTRIC FIELD

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In 2001, the pseudo-perovskite calcium copper titanate ($CaCu_3Ti_4O_{12}$, or CCTO) was reported to exhibit abnormally high dielectric constant. That the dielectric constant (K) of CCTO ceramic can be up to 12,000 and that of single crystal CCTO is close to 100,000, while maintaining stable dielectric constant for an extended temperature range. The literature to date has focused on the mechanism responsible for the anomalous dielectric behavior but CCTOs potential as a high energy density dielectric material has never been investigated. In this paper, we examined CCTOs dielectric properties under high electric field conditions. The CCTO powder was prepared by the conventional solid state reaction, attrition milling, and subsequent sintering. Our preliminary results confirmed the high dielectric constant reported in the literature. Further results of dielectric measurement under DC bias and polarization behavior will be discussed.

P3FE-K-2 U5

SIZE EFFECT OF BARIUM TITANATE BASED CERAMICS SINTERED IN REDUCING ATMOSPHERES

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With further developments in electronics, the miniaturization of electronic parts has proceeded quickly and the desire to increase the capacity of base metal electrode (BME) multilayer ceramic capacitors (MLCC) has also become more and more remarkable. Therefore, how to control the grain size and improve dielectric properties in order to cope with thinning the layer thickness is still a

challenge. In this paper, high purity Barium Titanate (BT) nano powders were used to fabricate temperature-stable BT-based ceramic materials for application in BME-MLCC. The effects of the initial grain sizes of BT powders on the phase structures, microstructures and dielectric properties of the ceramics were investigated. The pure BT nano-powders prepared by chemical method with the average grain sizes of 30, 85, 100, 150, 250 and 350nm, were mixed with appropriate amount of additives of MgO, MnO2 and Ho2O3. The mixtures were milled, dried, pressed into disc-shaped form, and then sintered at 1200 1300°C for 2h in reducing atmospheres (97%N2/3%H2) followed by annealing in a weak oxidizing atmosphere at 1000 oC for 3h. BME-MLCC sample were prepared by roll-to-roll method using the BT powder of 250nm with Ni electrode paste. The microstructures of the ceramics were observed by SEM. The dielectric properties were measured using HP 4194A LF impedance analyzer over a temperature range from 60oC to 150oC at 1 kHz and 1 Vrms. The inhomogeneous core-shell microstructure was also investigated by TEM and EDS analysis. Non-reducible BT-beases X7R type ceramic materials with grain size form 100nm to 400nm were prepared systematically with high performance. The initial grain size of BT powders affects significantly the microstructure and dielectric properties. The dielectric constant could be enhanced by increasing the initial particle size. Using BT powder with size of 250nm, high density BME-MLCC samples (ceramic grain size of 300nm) were obtained sintered at 1217oC, exhibiting high dielectric constant above 3000, and TCC less than $\pm$ 11.5%, with good reliablility, meeting the requirement of X7R specification. The inhomogeneous core-shell microstructure was found to form in the X7R samples. The core is composed of Pure BT, and the shell is composed of nonferroelectric solid solution of BT and additives.

P3FE-K-3 U6

SODIUM BISMUTH TITANATE MODIFICATIONS FOR HIGH TEMPERATURE CAPACITOR APPLICATIONS

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The Sodium Bismuth Titanate family is a promising material for lead free, high temperature ceramic capacitor materials. This study investigates how modifications to the base composition modify the dielectric and crystallographic behavior. The goal is to modify this structure to create a material that has X7R-like dielectric behavior, while maintaining its inherently good high temperature dielectric properties. Achieving this goal will produce a material with a wide working temperature range to replace the current industry standard, barium titanate. Widening the range that the dielectric material is useful will alleviate design problems and create a component that is less susceptible to drastic environmental changes. This material research is at the forefront of high temperature lead free capacitor materials. Areas of interest at this point are aeronautical and space applications, however, many other avenues would benefit from a material such as this. Compositional modifications have been performed and compared

to theoretical modeling to determine if the properties can be predicted by the model.

P3FE-K-4 U7

$PB_{0.5}CA_{0.5}TIO_3$ THIN FILMS AS AN ALTERNATIVE MATERIAL FOR VARACTORS AND DRAMS

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In the search of materials with high dielectric constants, $Pb_{0.5}Ca_{0.5}TiO_3$ thin films are here proposed as alternative materials for memory applications and HF devices. Films were spin-coated onto $Pt/TiO_2/SiO_2$-/(100)Si substrates from precursor solutions synthesised by a sol-gel method reported elsewhere [1]. Crystallisation of the films was carried out by Rapid Thermal Processing (RTP). Unique pseudocubic phase is observed by glazing incident x-ray diffraction (GIXRD) in 420 nm thick films. Dot Pt electrodes were provided on the film surface by a shadow mask to get an array of capacitors that permits to perform dielectric measurements. Dielectric constant (K) as a function of temperature (150-400K), frequency (500 Hz-1MHz) and applied voltage between -15 V and +15V were carried out. Broad maximums of K versus T are obtained close to room temperature, which shift to higher values at higher frequencies and fulfil the Vogel-Fulcher law (relaxor-like behaviour [2]). Values, as expected for thin films, are reduced as compared with bulk ceramics, but are close to 300. This means that K is quite stable with temperature in a width range (about 100 K). Deduced voltage tunabilities (the degree of variation in the dielectric constant as a function of the applied electric field, Tun $=(C_{max}\ C_{min}\ )/C_{max}$ for this broad range are >50% and, since dielectric losses are low (tgd$<$ 0.015), the figure of merit of the films, FOM=Tun/tgd , results very attractive for their potential use in circuits for HF devices (i.e.,varactors). Providing good electrode contacts (reduced resistivity), the films can be integrated with Si by the integrated circuit technology. This allows fabricate devices above the 7 GHz range, due to the low K frequency dispersion. The moderated high K values mean a capacitance density close to 30 fF/square micron and 2 nm of equivalent SiO_2 thickness; furthermore, the leakages density current for applied voltages up to 5V are $<$ 10^{-8} A/cm^2. These properties seem quite useful for dynamic random access memories, DRAM, since a large charge is available for moderated write voltages with low leakages. That is confirmed by the pulse behaviour of one microcapacitor which shows a voltage drop below 5% of the total voltage for 200 ms, the usual refresh time in a DRAM. Both, memory and HF applications are discussed on the base of size effects, that say, geometrical reductions.

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P3FE-K-5 U8

SOL-GEL DERIVED LA-MODIFIED PZT THIN FILMS ON NI/CU FOILS FOR PCB EMBEDDED CAPACITORS

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For the application of embedding passive devices into printed circuit boards (PCBs), a low-cost and low-temperature chemical solution deposition process has been developed to mass-produce perovskite Pb(Zr,Ti)O3 thin-film capacitors on base-metal foil. La-modified PZT(PLZT) has been widely considered as the first candidate material for PCB embedded capacitive applications. By taking advantage of sol-gel spin-on-coating technology, Energenius recently developed a new sol-gel technology for coating PLZT thin films on Ni-plated Cu foils, which are designated as a standard base metal material for future PCB embedded applications. Without observed significant ageing effect in precursor solution within a period of R&D cycle over 6 months, PLZT (15/52/48) thin films with excellent dielectric properties have been obtained using a relatively low annealing temperature of 550oC in air. Dielectric property characterizations reveal the feasibility for PLZT thin films to achieve the designated performance of capacitance density 200nF/cm2, dielectric loss 1%, and DC breakdown voltage 25V. Repeated coating tests proved good uniformity and high reproducibility. Therefore, this pseudo-ferroelectric PLZT thin film technology would open the market to test embedded passives in high-density and high-speed circuit applications.

P3FE-K-6 U9

EVALUATION OF SOL-GEL DERIVED BST THIN FILMS FOR EMBEDDED CAPACITOR APPLICATION

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High-k embedded capacitor, as a promising candidate to minimize the cost of printed wire boards (PWBs), attracts many researchers to develop high- k materials on metal foils [1-3]. The barium strontium titanate (Ba1-xSrxTiO3) has been considered to be the most promising material due to its high dielectric constant, low dissipation factor and low leakage current density. In addition, BST meets the current requirement of environment protection in electronic industry in that it is lead free. However, there is an obstacle for using BST thin

films as a suitable high- k dielectric material, i.e. its high crystallization temperature, 700oC on traditional Pt/Ti/SiO2/Si substrate. And in competitive PWB region, the use of noble-metal electrode must be minimized to reduce the cost. In this study, B0.5S0.5TiO3 precursors were prepared by a modified sol-gel processing. Thin films of 500nm thick were spin-coated onto nickel-coated copper foils, and annealed at different temperature under ambient atmosphere. Microstructure characterization showed that the films are pervoskite random orientation crystalline, grain size of 40nm. And the films are smooth, crack-free and good adhesion with the foil substrates. No diffusion of copper ions into BST films was observed. The effect of nickel layer on BST crystallization is discussed. The excellent dielectric properties, such as high dielectric constants, low dissipation factors and low leakage current density suggest that the sol-gel derived BST thin film on nickel-coated copper foil is suitable for embedded capacitor application.

P3FE-K-7 T10

SPATIAL RESITIVITY PROFILING OF MULTILAYER CAPACITORS AS A FUNCTION OF FURNACE CONDITIONS

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Commercial X7R $BaTiO_3$ multilayer ceramic capacitors (MLCCs) were examined to better understand the failure mechanisms involved under typical HALT conditions. These samples were initially examined in their as received state using a semiconductor probing station adapted for use as a DC high resistivity profiling device. The samples were then annealed in various partial pressures of oxygen (PO_2) in an effort to alter oxygen vacancy concentration and change the density of electronic carriers in the samples. Using both DC and AC profiling it was found that there was a decrease in the insulation resistance of the dielectric material as samples were reduced in low PO_2 atmospheres. This was thought to be a possible source of life test failure for $BaTiO_3$. Insulation resistance was also shown to decrease as a function of increasing temperature. HALT testing (small numbers) of reduced MLCCs suggested a threshold level of PO_2 before the onset of degradation.

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Session: P3U-L
MEDICAL SIGNAL PROCESSING II
Chair: C. Hall
Philips Research

P3U-L-1 F1

FILTERING OF CHIRPED ULTRASOUND ECHO SIGNALS WITH THE FRACTIONAL FOURIER TRANSFORM

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The fractional Fourier transform represents a generalisation of the conventional Fourier transform which allows signals to be transformed into domains which are between the time and frequency domains defined by conventional Fourier analysis. The technique was properly formalised by A.C.McBride and F.H.Kerr [3], although it was original specified sometime before that.

Previous work [1] has shown that the application of the fractional Fourier transform to conventional, un-coded ultrasound signals has little advantage over conventional filtering techniques such as band-pass filtering. However, the fractional Fourier transform can be 'tuned' to be sensitive to signals of a particular chirp rate [2] and can, in theory, achieve levels of pulse compression similar to those obtained using a matched filter.

To this end a system was developed which could generate and transmit linear chirp coded ultrasound signals. This system was then used with a simple phantom arrangement with signals of varying chirp rates. The fractional Fourier transform was then used to process the resulting signals.

In the full paper submission the results obtained will demonstrate how the fractional Fourier transform is sensitive to signals of a specified chirp rate and how the technique may be used to determine the chirp rate of the transmitted signal from the received echo signal, without a-priori knowledge. When the transform was used with the 'optimum' transform order corresponding to the chirp rate of the signals, the resultant signals in the transform domain demonstrated a degree of pulse compression similar to that which could be obtained through the use of matched filters. These results will also be used to demonstrate that once a chirp signal was identified by a peak in the fractional Fourier domain, the original chirp signal which caused the peak could be isolated from the rest of the signal by windowing the transform domain signal and performing the inverse transform.

The results from matched filtering and from the fractional Fourier transform will then be compared and the matched filter results will demonstrate a greater degree of pulse compression and more significant signal identification. However, the fractional Fourier technique could be used without any knowledge to the transmitted signal, whereas the matched filter requires knowledge of both the

transmitted signal and the transfer function of the transducer. Further work will be carried it to determine the best way of extracting useful information from the fractional domain signals.

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P3U-L-2 F2

THE USE OF CHIRP OVERLAPPING PROPERTIES FOR IMPROVED TARGET RESOLUTION IN ULTRASONIC RANGING SYSTEMS

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The ability of many bat families to navigate, identify and capture prey species has interested scientists for many years. It is known that bats possess extremely sophisticated echo location capability utilising chirp sequencing allied with an adaptive antenna system that enables extremely high resolution in 3-D space. One particularly interesting aspect is that bats appear to resolve and locate targets with scattering dimensions less than the emitted signals wavelength. They identify their targets shape by resolving multiple and closely reflecting points along the axis of distance. Such techniques could possess significant potential for ultrasonic imaging. In this paper we investigate the feasibility of applying one aspect of bat behaviour namely, the use of overlapping frequency modulated signals (LFM chirp), to achieve improved ultrasonic image resolution. The fundamental theory is based on the use of temporal and frequency information where fine resolution is obtained by resolving interference patterns in the frequency domain. When multiple chirp echoes overlap, the spectrum of the resulting combined echo contains peaks and notches at particular frequencies (interference patterns) determined by the time separation of the individual reflections. Those peaks and notches can be used to determine the fine delay between the individual reflections by applying an inverse frequency transformation to the temporal domain. Therefore position of reflecting point closer than the limit imposed by the bandwidth can be resolved. The paper is organised as follows. Section 1 reviews the fundamental theory of the bat echolocation system. A straightforward simulation environment that incorporates a 1-D representation of the transducer system, propagation medium loss and multiple target characteristics is developed in section 2. These are then used to analyse the influence of different coded sequences, target position, strength and number,

on the resultant processed data. The system comprises a filterbank to extract the time of occurrence of a group of echoes and a frequency analysis tool extracts the fine delay of multiple echoes in the group. In section 3 the feasibility of such a technique is investigated with real data and the bandwidth limitation constraint involved in the Ultrasonics domain. In section 4 various means of overcoming the limitations of the bat inspired ultrasonic imaging method are investigated. Section 5 concludes the paper.

P3U-L-3 F3

ULTRASOUND IMAGING SYSTEM USING COMBINATIONAL CODING OF EXCITATION

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Increasing penetration to a deep body is one of the most important targets for clinical image quality. To this end, Coded excitation is a fundamental solution means improving signal to noise ratio (SNR) without degradation of resolution. In order to improve the SNR, the coded excitation requires longer pulse containing many wavelengths. However, a nonlinear characteristic of signal processing such as dynamic beam forming degrades the resolution. Decoding error tends to appear at different distances where focusing parameters vary at the long pulse decoded. In order to achieve a high lateral resolution, the beam forming is normally performed based on a low f-number and real-time dynamic focusing, which limits the maximum length of coded waves. Although multi-channel individual decoding before beam forming can solve the problem, it demands an enormous size of hardware. In this study, we propose a technique of combination codes for excitation to overcome the problem. The technique consists of the following two steps: (1) Transmitting Combinational Code. Combinational Code means compounding of two codes of comparatively short pulse length and dividing decoding process into two procedures. (2) In decoding process, The first process decodes signal of sub-aperture sum of beam-former. [1] And the second process decodes signal of full aperture of beam-former. Using these two steps, equivalently long pulse coding and decoding process is achieved and so this technique can acquire high SNR without degrading lateral resolution. In the case of 3 x 5 codes, the combinational coding technique improves SNR 11.4dB calculated in simulation. Moreover, we present the analytical results of estimating lateral resolution of the technique in detail. This study is comprised of simulation and preliminary experimental results.

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P3U-L-4 F4

A NEW FLEXIBLE DIGITAL RESEARCH PLATFORM BASED ON A STANDARD US SCANNER: RESULTS AND APPLICATIVE PERSPECTIVES

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In spite of its diffusion in medical diagnostics, Ultrasound Imaging (UI) is considered non reliable in some applications where classical radiological methodics (i.e., CT and NMR) still remain the gold standard. Three main reasons concur to determine this performance gap: high operator-dependent accuracy, possible failure with difficult patients, and low specificity in some applications (i.e., mammography). Nevertheless, the employment of UI in medicine is ever increasing thanks to its intrinsic and unique peculiarities, like low costs, non-invasivity and good comfort for patients. The present scenario could be changed in the near future by adopting more sophisticated processing and scanning techniques presently used in other fields (i.e., underwater sonography). A strong limitation to this knowledge transfer is given by the difficulty in making practical experiments without designing expensive ad-hoc hardware solutions. This paper presents a high flexible and fully reconfigurable hardware suitable to accomplish this task. It is noteworthy that the result has been achieved just by making few modifications on a commercial Technos scanner by Esaote. A new front-end has been designed allowing for the transmission of arbitrary waveforms different channel by channel and loaded in local memories by the unit control PC. Seemingly, the PC is used to load the active transmit/receiving apertures, the focalization laws and the pulsing control timings. To ensure the highest flexibility in the receiving processing two alternatives have been developed to process received data. The first one is based on a grabber unit designed to capture up to 30 sec of real-time radio-frequency echoes. These can be transferred to an external PC by means of a SCSI link for a successive off-line processing using common software tools (i.e., Matlab). The second one, set up to allow a real-time processing, is based on a fast optical Gigabyte ethernet link between the ultrasound scanner front-end and an external processing PC with a dedicated optical-to-PCI bridge toward the computer memory. The availability of real-time processing facilities is not a simple add-on to the system but a real must for specific applications where to have a direct feedback of the dynamic of the phenomena under study (i.e., contrast media) is mandatory to drive the experiments. This special hardware allows to test almost all beamforming and processing techniques (i.e., synthetic aperture beamforming, coded transmission, contrast media specific processing, harmonic beamforming, etc.). Interesting results concerning techniques which are at present out of the processing capabilities of present ultrasound scanners are presented.

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P3U-L-5 F5

AN OPTIMIZED ECHO-PROCESSING ALGORITHM USING TMS320C6202DSP PROCESSOR FOR SMALL SCALE ULTRASOUND SYSTEMS

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Although the development of the ultrasound imaging systems based on the DSP processor has been attempted because of its easy reconfiguration, its high data rate still remains the limitation. In this paper, we have developed the echo processor that can process at least 1024samples/scanline for the duration of 5khz PRF using TMS320C6202-250Mhz DSP. The realized functional blocks in the echo processor is composed of magnitude calculation, log compressor, edge enhancement FIR filter, zone blending, Black hole/noise spike filter, lateral filter. In order to develop the optimized echo processor algorithm for the DSP architecture, we programmed each functional block suitable for the internal DSP architecture in assembly language and estimated the processing speed of each block. From the result, we demonstrated that the maximum PRF was 4.4khz and the magnitude calculation block took 17934 cycles/scanline ,on the other hand the other blocks were processed within 10000 cycles/scanline. Therefore, in order to increase the processing speed of echo processor block, we need to increase the processing speed of magnitude calculation block. This was solved by utilizing the next functional block, log compressor because the magnitude calculation block given by "m=root(i^2+q^2)" ,(i=inphase componenets, q=quadrature components) can be combined with the log compressor block given by "y=log(m)" ,and the combined block can be shown as y=log(root(i^2+q^2))=(1/2)log(i^2+q^2) :(we call it UPMALO ,the United Processing of MAgnitude calculation and LOg compression) This equation shows that the above two blocks can be processed by LUT reference without the square root operation that requires many iteration and the echo processor can be processed faster. However, since the 16bit i ,q data cause i^2+q^2 to be 31bit and the LUT has 16bit data, 4Gbyte memory space is required for LUT, which is not suitable for the small scale ultrasound system. Therefore UPMALO algorithm should be modified to meet this criteria. For this, we first modified UPMALO algorithm to "log(i)+(1/2)log1+$(q/i)^2$,(i>q)" and then we replaced (1/i) with ln(i)-ln(i-1) by using 1/i =d(ln(i))/d(i) =[ln(i)-ln(i-1)]/[i-(i-1)]=ln(i)-ln(i-1) to remove the division operation (q/i). Finally, we got the modified UPMALO. Modified UPMALO: logroot(i^2+q^2)=log(i)+(1/2)log(1+[qln(i)-ln(i-1)]^2) When combining magnitude calculation and log compressor blocks using Modified UPMALO algorithm, they can be processed within the internal DSP processor memory because it requires only 64kbyte LUT space, and the processing speed became faster as much as 8000 cycles/scanline than the case of conventional algorithm. Under this condition, the maximum PRF was 5.5khz and there was no degradation of the image quality compared to the conventional echo processor algorithm. If the modified UPMALO is optimized in assembly language level, the maximum PRF can be over 5.5khz.

P3U-L-6 F6

A REAL-TIME CLINICAL ULTRASOUND CONTRAST DOSIMETER WITH ADAPTIVE ALGORITHMS

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Recent advances in ultrasound technology and contrast agents allow the detection of flow at the level of the microcirculation. However, information on the concentration of bubbles present in systemic blood is rarely available in clinical studies. Quantitative information on the rate at which bubbles are disappearing from the vascular system is important, especially for modelling required for measurements of blood flow and volume. We describe a stand-alone system, which provides real time, quantitative measurement of contrast agent dose in arterial blood and which is suitable for clinical use.

We used a modified Interspec XL (Vingmed) pulse Doppler system operating at 5 Mhz with a probe situated over the femoral or brachial artery. The transmitter of the scanner was modified so that the Mechanical Index is less than 0.01, to avoid disruption of the microbubbles. The quadrature output components of the demodulated Doppler signal are acquired and digitised in real time using a PC. The entire process of data acquisition, analysis and real-time display is implemented in Matlab (Mathworks Inc). Adaptive algorithms were developed to improve performance in the repsence of clutter and poor signal-to-noise.

The adaptive algorithms developed can extract the Doppler signals even when the signal-to-noise ratio (SNR) is low. The algorithms perform postfiltering, noise power determination, power compensation, self-soft thresholding and wave smoothing. These algorithms adaptively reduce noise and enhance the Doppler signal, allowing reliable measurement of Doppler signal power, mean frequency and mean intensity in real time. The algorithms have been successfully tested with both simulated noise real-time Doppler signals and in in-vivo measurements using animal models.

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This work was supported by the Canadian Institutes of Health Research and the National Cancer Institute of Canada.

P3U-L-7 F7

AUTOMATED DETECTION OF THE AORTIC VALVE CLOSURE EVENT IN TISSUE VELOCITY IMAGES

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Background and purpose: Ultrasound doppler based Tissue Velocity Imaging (TVI) curves from the anterioseptal basal region of the apical long axis (APLAX)

view of the left ventricle are known to contain peaks caused by aortic valve movement. Using these peaks the timing of aortic valve opening (AVO) and closure (AVC) may be found. In this work we have focused on AVC, which divides the heart cycle into systole and diastole and is useful for automated analysis of cardiac events.

Methods: The tool used for analysis of the ultrasound recordings was a customized ultrasound analysis toolbox (GcMat, GE Vingmed Ultrasound) for Matlab with capabilities for automatic mitral ring detection and extraction of velocities from TVI images at any time and location in the images. Using an automatic mitral ring detector (AutoDEQ, GcMat) in the APLAX view, the point of the mitral ring closest to the aortic valve could be located. Based on this point a region of interest (ROI) was defined to cover the aortic valve. Using an empirical formula based on heart rate a time interval expected to include AVC was set. Velocities for all cells within the ROI were then extracted for all frames in the time interval of interest of the TVI image, and differentiated to obtain acceleration. For each cell the largest acceleration value was found. Finally the cell among all cells in the ROI having the largest acceleration value was found, and thereby the point in the time and space having largest acceleration. By doing this procedure, the time event corresponding to a peak representing AVC was found. For validation of this method, the time events suggested by the described algorithm using the APLAX view were compared to a reference method for 11 patients at rest. In the reference method AVC time events were set manually by a clinician from parasternal M-mode recordings of the aortic valve. All timing values were calculated as the time difference from the previous triggering point of the ECG. The TVI recordings had a mean frame rate of 160 frames/sec.

Results: The error between manual M-mode AVC timing and the timing by the above automated algorithm was less then 20 msec for nine of the 11 patients (82%). The mean error for these nine patients was 8.9 msec. In two cases (18%) the error exceeded 20 msec. In case A the error was 20.3 msec and in case B 83.9 msec. In case B the automated algorithm detected velocities originating from mitral leaflet movements, and therefore missed AVC. We conclude that automated detection of the aortic valve closure event from TVI images of the APLAX view is feasible with small errors and has potential for usage in systems for automated analysis of cardiac events.

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P3U-L-8 F8

IMPLEMENTATION OF DIGITAL SYNTHETIC APERTURE TECHNIQUE FOR A HIGH FREQUENCY ANNULAR ARRAY

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A digital synthetic aperture technique was used to improve the depth of field of a focused, high frequency, 5-ring annular array transducer. The transducer was fabricated in-house using a 9-μm polyvinylidene difluoride (PVDF) membrane with a single ground plane and a copper clad Kapton film with the array pattern etched into the copper. The transducer consists of five, equal area rings, with 100-μm spacing between each ring. The transducer has an aperture of 9 mm, a geometric focus of 9 mm, a center frequency of 40 MHz, and a fractional 15-dB bandwidth of 75%. Insertion loss at the center frequency is 37 dB or lower and cross talk between rings is better than 20 dB. Synthetic aperture methods were applied in the post-processing stage to digitized echo data. The algorithms were initially tested on single lines of simulated data with delays inserted to represent the echoes received at the various annuli from reflectors at different depths. Next, pulse/echo data from a wire phantom were captured using each individual ring in the transmit/receive mode. The wire phantom consisted of a 75-μm diameter chromium wire spaced at 1 mm by 1 mm distances over an 8 mm depth. Data were also collected for all transmit/receive ring pairs using a Panametrics 5900 pulser/receiver as the driving source, and the signals were digitized at a sampling rate of 1 GS/s. The digitized wire phantom echo data were processed to simulate focusing the array at different focal depths. This was achieved by calculating appropriate time delays for various foci which, when applied to the received echoes, effectively focused the array over a range of depths. The digitized A-lines were then windowed using a gating function to only include the focused portion of the signal in the final image. A full A-line was constructed from a collection of windowed foci at a range of equally spaced depths. Using this method, an image can be produced in which the depth of field has been improved from $\sim$270 μm for a 40-MHz single element transducer to $\sim$3 mm for the 40-MHz annular array transducer. Other methods for enhancing image quality involved utilizing frequency equalization. Lateral beamwidth (LBW) is dependent on the f-number as well as the wavelength of the transducer. Since different combinations of the annular rings can be excited, the effective diameter of the transducer may be changed, and by including only low or high frequency information from the received signal the LBW may be kept constant, thus ensuring that the echoes from an object in the focal plane are independent of its lateral position.

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Session: P3U-M
TISSUE CHARACTERIZATION
Chair: J. Greenleaf
Mayo Clinic

P3U-M-1 G1

CAUSAL TRANSIENT PROPAGATION IN MEDIA WITH CLASSICAL OR POWER-LAW LOSS

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The manner in which transient waves propagate in a medium with classical viscous losses is generally addressed by determining solutions of the wave equation that was originally derived by Stokes in 1845. Exact solutions are difficult to obtain and, as a result, approximations are sometimes made to reduce the equation order to one of second order. For propagation in a classical viscous medium, this results in an attenuation that depends on frequency with a power law exponent of exactly 2, and zero dispersion. A related problem, and one of particular interest in relation to ultrasound propagation in tissue, concerns propagation in media with an absorption coefficient that depends on frequency with a power law from 1 to <2. In fact, in the diagnostic frequency range (1 to 20 MHz), many types of soft tissue have such a dependence and exhibit significant dispersion that should be in accord with the Kramers-Kronig relations. Based on the fundamental properties of soft tissue, no differential equation has yet been derived that properly describes wave propagation in such media. However, based on a frequency-domain wave equation using previously derived causal dispersion relations, a causal solution has been recently obtained [1]. Using this solution it is shown that transient propagation problems can be solved either analytically or numerically depending on weather or not simplifying assumptions are used. Examples are used to illustrate this approach for power-law exponents in the range from 1 to 2. The question as to the conditions under which the effects of dispersion can be neglected, especially for wideband B-mode ultrasound tissue imaging, will be addressed.

[1] N.V. Sushilov, and R.S.C. Cobbold, Frequency-domain wave equation and its time-domain solutions in attenuating media J. Acoust. Soc. Am., vol. 115, (April) 2004.

P3U-M-2 G2

THE ULTRASONIC ATTENUATION COEFFICIENT FOR HUMAN BLOOD PLASMA IN THE FREQUENCY RANGE OF 7 - 90 MHZ

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Measurement of the ultrasonic attenuation coefficient of biological tissue has been a subject of great interest, since this coefficient is important in the design of ultrasound medical instrumentation and maybe used as a tissue characterization parameter. Particularly, in terms of blood, the attenuation coefficient has been measured for animal blood and plasma, but the results are limited to 10 MHz. Nowadays, the use of ultrasound in medicine with frequencies beyond 10 MHz is a reality, such as ultrasound biomicroscopy where the frequency can approach 100 MHz. Therefore, it becomes relevant to measure, at higher frequencies, the parameters related to the wave interaction with biological tissue. The objective of this work is to present experimental results of the ultrasound attenuation coefficient of human blood plasma in the frequency range of 7 - 90 MHz. The method employed a pulse-echo substitution technique for frequencies up to 20 MHz and a transmission substitution one for frequencies beyond 20 MHz. A sample of about 0.4 mL of plasma was placed inside of a polystyrene cuvet and immersed, with the transducers, in a water bath with the temperature controlled at 36.5 degrees Celsius. The results indicate the attenuation coefficient following the power law frequency dependence with an exponent of 1.43, which is compatible with the results for low frequency. At the same time, the results also point to a relaxation mechanism present in the vicinity of 10 MHz.
To CNPq, CAPES and FAPERJ

P3U-M-3 G3

RESOLUTION IMPROVED ULTRASOUND ATTENUATION ESTIMATION BASED ON RF-DATA OF SPATIAL COMPOUND SCANS

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Different methods for determination of quantitative acoustical tissue parameters based on the analysis of raw or rf data are well established, where ultrasound rf data contain most information, including the frequency content of the back scattered echoes. With a minimum size of 1 cm in axial direction, usual procedures for parameter estimation require large regions of interest to obtain reliable results. On the other hand parameter imaging applications in ultrasound tissue characterization require both: smaller resolution cells and reliable parameter estimates. The hypothesis is that ultrasound attenuation estimates based on multidirectional scans in combination with tomographic procedures have the potential to decrease the size of the resolution cell. Assuming a non-attenuating medium with homogenous scatterer distribution the rf data for spatial compound scans in five directions (form -17° to +17° in steps of 8.5°, one transmission focus, three receiving foci) were simulated using the Field II package [1]. From these data the sound field correction functions were extracted. After including frequency independent attenuation of 5 dB/cm and adding different sized inclusions (1..10 mm in diameter) with lower attenuation of 2 dB/cm, the estimates were compared to conventional parameter estimation. By a resolution cell in

the same dimension as the inclusion the difference between simulated and estimated values was reduced about five times. In measurements the rf-data of complete spatial compound imaging scans of tissue mimicking phantoms with a clinical ultrasound device (HDI 5000 in SonoCT® mode, Philips medical, Bothell) are used for attenuation estimation. From the rf data sets of all scanned angles the attenuation values were determined in uniform, overlapping ROI of 10 mm length and 3 mm width. Assuming these attenuation data as projections of the local attenuation distribution obtained from different directions, the local values are found by application of the inverse Radon transformation. In any case, routines for correction of time gain compensation and sound field characteristic were applied. The analysis of 64 single estimates in a 8 by 8 matrix results in a mean attenuation coefficient of α=4.22 $\pm$ 0.79 dB/cm (at 6.5 MHz), which is in good agreement with the value of the phantom obtained in transmission mode. This analysis of rf data from spatial compound imaging procedures provides local attenuation coefficients leading to parameter images. In comparison to conventional scans the ROI size could reduced down to 3 mm. In first clinical tests parameter images from homogenous tissues like testis and parotid gland, based on raw data were obtained. In combination with conventional b-mode imaging the diagnosis of pathological changes in these tissues could be improved by additional parameter imaging. [1] J. A. Jensen - http://www.es.oersted.dtu.dk/staff/jaj/field

P3U-M-4 G4

DEPENDENCE OF TISSUE CHARACTERIZATION FEATURES ON REGION OF INTEREST SIZE: STUDIES ON PHANTOMS AND IN VITRO PROSTATE TISSUES

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In our previous work on prostate tissue, we noted an apparent dependence of the computed tissue characterization features and the size of the ROI chosen. We are studying this effect in a systematic fashion by computing feature values for ROI's of different size and shape in both phantoms and in excised prostatic tissue. Data were acquired using a Diasonics Spectra scanner and a linear array transducer with a center frequency of 5 MHz, digitized at 48 MHz and processed off line. Phantom data were acquired from a graphite-gel phantom having a known attenuation and Rayleigh scattering characteristics. Calibration was accomplished by acquiring from a second similar phantom with known backscatter and attenuation. Features computed include SNR, four features from the co-occurence matrix (entropy, angular second moment, contrast, and correlation), two phase features (normalized phase profile maximum, phase profile variation

coefficient), three cepstral features (weighted average of peak locations, normalized average peak amplitude, energy in the lower portion of the cepstrum as a fraction of the total) and three backscatter features (slope, intercept, and midband value).

As expected, the features all exhibited larger variance when small ROI's were used. Most features exhibited a dependence on ROI size although some features were strongly dependent on ROI size only for small ROI sizes. The nature of the size dependence varied widely for different features.

Conclusions: ROI size has a significant effect on the computed value of most tissue characterization features. Since benign or normal tissue regions are usually larger than cancerous ones, there is a tendency to choose larger ROI's in benign tissues and this will lead to falsely optimistic classification of normal vs. abnormal tissue. To avoid this problem, careful control of ROI size must be exercised during acquisition and processing.

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P3U-M-5 G5

VISCOELASTIC CHARACTERIZATION OF IN-VITRO CANINE AND PORCINE TISSUES

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Mechanical properties of biological tissues are of interest for assessing the performance of elastographic methods that evaluate the stiffness characteristics of tissue. The mechanical properties of interest include the frequency dependent complex moduli, storage and loss moduli of tissues. Determination of the mechanical properties of biological tissues is often limited by proper geometry of the sample, as well as uniformity of the stress-strain relationship. Dynamic load testing measurements were performed on canine and porcine liver tissue frequency range from 0.1 to 100 Hz. Tests were conducted using an EnduraTEC ELF 3200, a dynamic testing system for determining the mechanical properties of materials. Tissues were cut to cylindrical shapes with a thickness less than one-third the diameter (20 mm), and were oriented in the system longitudinally. Experiments were conducted by uniaxially compressing tissue samples using plexiglass platens larger than the specimens and measuring the load response. Also evaluated were the stiffness changes of tissues subjected to either radio-frequency thermal ablation, or uniform tissue temperature elevation. The resulting moduli spectra were then fit to a generalized Kelvin-Voigt fractional derivative model. The data agree well with the model and in comparing the results from the normal tissue with that of the thermal lesions and boiled tissue, the concept of a complex modulus contrast is introduced and its applications to elastography are discussed. Also presented is the dependence of the modulus to the ablation temperature for minimally ablative thermal therapies.

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P3U-M-6 G6

MEAN SCATTERER SPACING ESTIMATION USING WAVELET SPECTRUM

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Mean scatterer spacing (MSS) has been proven as an effective method for characterizing biological tissue structures, especially for liver tissue. Periodogram, cepstrum and spectral autocorrelation are the major techniques proposed for MSS estimation. However, due to the interference of diffusive scattering echo, it is difficult to estimate the MSS of the regular (quasi-periodic) scatterers. Robust techniques, such as the spectral autocorrelation method, which can tolerate the diffusive speckle interference are preferred. A newly developed spectral analysis technique known as Periodic Wavelet Transform (PWT) is proposed for MSS estimation in this study. The PWT works in the same way as Fourier transform, their differences are: the transformation kernel is a concatenation of wavelet basis instead of sinusoidal basis, and the spectrum is calculated in scale space instead of in frequency space. PWT uses an optimal generalized Harr wavelet for transformation, which must be constructed from the signal to be transformed by an algorithm devised by Benedetto et al. recently. Since the basis is constructed under the hypothesis that the signal is periodic and contaminated by noise, it will neglect the non-periodic components as much as possible. Thus PWT is an adaptive and robust generalized spectral analysis technique. Performances of PWT are evaluated based on simulation and In Vitro experimental datum. In Vitro RF pulse echo of porcine liver interrogated by a broadband 5MHz transducer is sampled by an 8-bit, 20MHz A/D converter for MSS estimation. The MSS is estimated to be 0.85 mm. The peak in the wavelet spectrum can be detected at a high confidence with 7dB peak to sidelobe ratio. Since the detected periodic signal is found explicitly in PWT, the SNR (or regular to diffusive ratio) can be computed. For the liver signal its SNR is estimated to be -2dB, if its regular scatters are assumed to be positioned periodically perfectly. Comparing to other techniques, since PWT provides an MAP estimate of SNR, therefore PWT can provide different SNR estimates, if different regularity conditions are hypothesized. For example, if the variation of the regular scatter spacing is assumed to be 3%, then the SNR is estimated to be 3dB instead. Thus PWT provides a vector of features for better characterization the embedded tissue structure. Theoretical, simulation, and experimental results will be presented.

Session: P3U-N

BLOOD FLOW
Chair: T. Thomas
Siemens

P3U-N-1 G8

TEST PHANTOMS FOR COLOR FLOW IMAGING SYSTEMS

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In view of the current state that test phantoms for estimating the performances of a B mode ultrasound scanner have been widely used. We have developed test phantoms for estimating the performance parameters for color flow imaging systems. This is needed for maintaining the performance of the color flow imaging systems in hospitals and for testing in manufacturing works. At first, we discussed primary quantities that must be maintained and tested for clinical use. The following parameters are essential for clinical diagnosis using by color flow imaging systems. 1) dead zone boundary; 2) penetration depth; 3) spatial resolution; 4) image uniformity; 5) tissue color suppression performance; 6) lowest detectable observed velocity; 7) highest detectable observed velocity; 8) temporal resolution. Second, we present configurations of our color flow phantom. The phantoms consist of a block of material and a straight channel flow. The former mimics the ultrasonic properties (sound velocity, attenuation and scattering) of tissues. The latter represents a blood mimicking fluid, representing flowing blood. It is essential that the block and the channel are identical with a human tissue or vein in their acoustic properties. We have proposed new type of tissue mimicking material made of polymer alloy. Polymer alloys consist of two or more polymers with different acoustic properties, and so acoustic impedance and velocity can be adjustable by modifying type and content of each individual polymer. In this time we employed the combination of silicon rubber, polyurethane and poly methyl methacrylate. Acoustic impedance and acoustic velocity of this alloy show 1.5 MRails and 1540 m/s. Moreover, this phantom has a benefit of stability compared to a tissue mimicking material made with agar, which has been used widely in phantoms of a B mode ultrasound scanner. We will report structures and performances of our newly developed color flow Doppler phantom in detail.

P3U-N-2 G9

EFFECT OF BEAM SHAPE ON TECHNIQUES THAT USE DOPPLER SIGNAL POWER FOR MONITORING VESSEL SIZE CHANGE

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The power of a Doppler signal depends, amongst other factors, on the volume of blood in the sample volume. If all other factors remain constant, changes in the power of the signal could be used to determine changes in the diameter of a vessel. This is the basis of several studies purporting to measure flow changes in cerebral arteries. However, exact proportionality between power and area relies on uniform insonation across the width of the vessel. Uniform insonation of the arteries is not usually achievable in transcranial studies because the ultrasonic field of the transducer is distorted by the passage of the sound through the temporal bone. A computer model was developed to study the effect of vessel diameter changes on the power of the Doppler signal in a non-uniform field. Beam shape and vessel position were combined to create a 3-D representation of the system. The ultrasound fields were measured in a water tank through samples of temporal bone. MRI was used to collect anatomical information on the middle cerebral artery. This information was used to identify the locus of the centre line of the vessel in a volume of interest at 5-6 cm from the skull. A volume with a circular cross-section of a selected diameter (2, 3 or 4 mm) was created along the centre line. This model vessel could then be translated or rotated with respect to the ultrasound field. The model was used to make a comparison of the effects of diameter changes at various locations within the ultrasound field, corresponding to a range of configurations of vessel and beam. An array of power values was calculated by moving the model vessel relative to the beam, over a grid of points covering the whole of the measured ultrasound field, and calculating the returned power at each point. A subset of positions was selected that included only those points where the power was at least 50% of the maximum for that field in keeping with the clinical situation where the operator would attempt to maximise the Doppler signal. The power calculations were then repeated for this subset of positions using vessel diameters that had been increased and decreased from the initial value by 10%. The changes in power were compared with the changes in area for each of the three model vessels. It was found that, for most combinations of beam and vessel position, the change in power did not match the change in vessel cross-section. Near the point of maximum sensitivity in the ultrasound field the modelled value of the change in signal power was always less than the change in area, with discrepancies of up to 35% in the case of the 4 mm vessel. At larger distances from the centre of the field, this difference became smaller until the calculated power change exceeded the area change. The discrepancies were larger for vessels with larger initial diameters. The differences in power due to non-uniform insonation mean that techniques that rely on the change in the power of the Doppler signal to predict a change in the diameter of a vessel must allow for the effect of non-uniform insonation.

VOLUME FLOW MEASUREMENTS WITH A NOVEL SEMI-AUTOMATED 4D DOPPLER ULTRASOUND SCANNER

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The Encore PV (Vuesonix Sensors, Wayne, PA) is a novel, real time three-dimensional (i.e., 4D) ultrasound scanner that detects all the absolute blood flow velocity vectors within a volume using a 2D array transducer and calculates blood flow. An initial validation study was conducted comparing volume flow measurements obtained from the Encore (in vitro and in vivo) to those from an invasive transit-time flowmeter.

In vitro, a pulsatile flow pump (model PFS-A-3-1-G, Shelley Medical Imaging Technologies, London, Canada) was used to simulate carotid type waveforms with pulsatile flow rates from 60 to 600 ml/min. Encore volume flow measurements were compared to an invasive technique for volumetric blood flow measurement utilizing a calibrated flowprobe placed tightly around the vessel under examination and connected to a TS420 flowmeter (Transonic Systems Inc., Ithaca, NY). In vivo, 10 second data sets of the volume flow in the distal aorta of six rabbits were obtained simultaneously with the Encore PV and the flowmeter. The Encore PV automatically calculated the center line of the aorta and used the velocities and the functional area to determine the vessels instantaneous volume flow. Mean and maximum volume flows were recorded with both units. Data was compared using linear regression and Bland-Altman analysis (due to the lack of independence).

Encore and Transonic measurements both matched the pump settings well ($r^2 > 0.99$; $p < 0.0001$) with mean errors of -11.8
respectively. In vivo, aortic volume flows between 10 and 200 ml/min were measured. Both mean and maximum volume flows obtained with the two scanners correlated significantly ($p < 0.0001$) with r^2 values of 0.86 and 0.62, respectively. The corresponding root-mean-square-errors were 6.9
mean flow and 61.2
Bland-Altman analysis showed less variation for mean than for maximum flow measurements (2 standard deviations were 15.6 ml/min versus 56.1 ml/min for mean and maximum flows, respectively).

In conclusion, a new semi-automated 4D Doppler device (the Encore PV) has been tested in vitro and in vivo. Volume flow measurements with this unit are comparable to those of an invasive flowmeter.

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P3U-N-4 G11

APPLICATION OF DOPPLER MEASUREMENT USING MULTIPLEXED DUAL-CHIRP SIGNALS TO MULTIPLE REFLECTORS

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In this paper, we propose a method to measure a flow speed of multiple reflectors based on the Doppler shift using multiplexed dual-chirp signals. An up-chirp signal and a down-chirp signal are multiplexed for individual bandwidths. As the measured frequency shift corresponds to the time average of the velocity over the period for the pulse width, we cant set the pulse width of the chirp signal so long. In our previous study, it was shown that, by dividing the bandwidth of the chirp signal and multiplexing, we can detect lower speed without expanding the pulse width. However, it was examined only to the single reflector. In the actual application, the reflector consists of many weak scattering objects like erythrocytes. Therefore, in this paper, we propose the improvement method for multiple reflectors. At first, the case of two reflectors moving same velocity is examined. In this case, though the compressed waveform of the received up-chirp signal and that of the received down-chirp signal are same shape, the both signals are separated temporally. Similarly, in the case of many reflectors moving same velocity, it would appear that the compressed up and down-chirp signals of the each reflector are also separated. In the experiment, two slugs 2[mm] in diameter was placed on a belt separately for moving targets, and they were moved by 14[cm/s] in velocity. The center frequency of transmitted signal is 1[MHz], bandwidth is 1[MHz], number of multiplex is two, up-chirp signal has bandwidth of 0.5-1.0[MHz] and 1.0-1.5[MHz], respectively. The experimental results show that those time intervals between the position of the compressed up-chirp and that of the compressed down-chirp related to the velocity of the moving targets.

P3U-N-5 G12

INTER-FRAME CLUTTER FILTERING FOR HIGH FREQUENCY FLOW IMAGING

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Current high frequency (HF) flow imaging systems ($>$ 20 MHz) employ mechanically scanned single element transducers. With this approach, successive traces are modulated by the transducer beam function, and the received tissue and blood signals undergo spectral broadening of the Doppler frequency

spectrum in proportion to the transducer speed. Conventional high pass clutter filters that operate within a single frame of acquisition will attempt to remove this clutter signal and in doing so will also remove slow blood flow information. Consequently, HF microvascular flow imaging has generally been limited to scan speeds of 1-2 mm/s, which severely constrains frames rates (0.25-0.5 Hz for 4 mm scans). In this study, we investigate inter-frame clutter filtering in a HF flow imaging system with the objective of improving the performance of HF microvascular imaging at high frame rates. The approach is to apply the clutter filter on pulse ensembles (corresponding to a specific beam location) acquired in successive frames rather than on ensembles within a single frame. An inter-frame filter exploits the correlation of tissue signals on a time scale of the frame rate, is therefore insensitive to tissue spectral broadening, and thereby can achieve improved sensitivity to low blood velocities. A stationary echo cancellation filter was used, averaging over 2 to 4 frames. After filtering, the data underwent velocity and power Doppler processing on ensembles within each image frame. Experiments were conducted at a center frequency of 40 MHz (7 cycles; 10 kHz PRF) using a previously reported HF color flow system in combination with a recently described high frame rate 'wobble' 40 MHz PVDF transducer (F# 2). In vitro experiments were conducted using a 1 mm wall-less vessel flow phantom at frame rates of 10 and 20 fps (4 mm scans). For frame rates of 10 and 20 fps, the average tissue velocity broadening (-20 dB) within each frame was measured to be 14 mm/s and 31 mm/s respectively. For flow velocities as low as 1 mm/s, Doppler power in the vessel was retained after inter-frame filtering at both 10 and 20 fps. For these low velocities, lying well within the tissue velocity broadening, power Doppler imaging would not be possible with conventional clutter filtering. Velocity estimates compared well (+/- 1 mm/s) with known velocities down to 7 mm/s, below which a degradation of estimation statistics was evident. This pilot study, therefore, suggests the potential for performing inter-frame clutter filtering to improve frame rates for HF flow imaging of the microvasculature.

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P3U-N-6 G7

VELOCITY AND ACCELERATION ESTIMATION EMPLOYING NONUNIFORM SAMPLING

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Conventional PW Doppler systems acquire an ensemble of N echoes per beam at a constant repetition interval $T_{\mathrm{pri}}=1/f_{\mathrm{prf}}$. Nonuniform sampling uses variable intervals lengths. The shortest interval defines the velocity range and longer intervals increase the total time span and, therefore, the velocity resolution without

increasing N (With interleaving, the frames rate is approximately reciprocal to N.). Relative velocity resolution for low velocities is gained at the expense of relative velocity resolution at high velocities and SNR. This concept has previously been adapted from RADAR to medical ultrasound by our group, where cross correlation techniques are applied to all pairs of echoes (not only to consecutive echoes) in the ensemble to determine scatterer displacement. Two problems still had to be tackled: (1) With increasing time span, acceleration has to be considered to avoid ambiguity and incorrect velocity estimates. (2) To measure slow axial flow velocities, it is important not to consider pairs of echoes that are decorrelated due to high lateral or elevational flow. (1) Due to acceleration (a), velocities (v) are a function of macro time. For a given macro time t_m, several cross correlation functions C representing different interval lengths (kT_{pri}) may exist (E.g. the echo pairs [$e(1T_{pri})$, $e(7T_{pri})$] and [$e(3T_{pri})$, $e(5T_{pri})$] are both centered around $4T_{pri}$.). To combine the multiple C, they are rescaled as functions of v considering the fact that the displacement of scatterers due to a given velocity v is proportional to the (macro) time interval. Averaging $C(kT_{pri},t_m,v)$ reduces the width of the global maximum (v-resolution) and suppresses the local maxima (aliasing, ambiguity). The arrangement of combined $C(t_m,v)$ in macro time-order forms a velocity-time-diagram (v-t-D), in which the trajectories describe $v(t_m)=v_0+at_m$. To determine the likeliest trajectory, an initial estimate for $v0$ and a is based on the unambiguous $C(1T_{pri},t_m,v)$. Next, only the maxima of the C are mapped into the v-t-D as Booleans. In an iterative process, the maxima for larger intervals kT_{pri} are added to the v-t-D, considering only an unambiguous range with respect to the previous estimates. The optimal trajectory is found in each step by linear regression. An alternative approach is to fill the v-t-D with normalized correlation values, averaging all C representing the same t_m. The sum of correlation values along a trajectory is taken as the optimization criterion. Instead of the sum, the symmetry of the C with respect to the trajectory may be used. (2) To detect decorrelation, the following criteria were confirmed to be effective: Normalized correlation coefficient. Similar signal energy in both echoes. Slope of correlation coefficient as a function of k. Simulation showed relative tolerance of 1.5% for velocity estimates and of 5.0% for acceleration estimates (N=9 pulses in $17T_{pri}$). In vitro and in vivo experiments confirm improved robustness of nonuniform sampling and the feasibility to show e.g. changes of a over time in arteries.

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P3U-N-7 G13

TRANSIT TIME BROADENING: A PULSED-WAVE DOPPLER ULTRASOUND PERSPECTIVE

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Many studies on transit time broadening have been performed over the years to characterize the effect of this spectral broadening phenomenon on the Doppler spectrum. However, the dependence of transit time broadening on the range gate, which is an important parameter in the pulsed-wave (PW) operating mode, has not been carefully addressed. To this end, we have provided a concise analysis of how the range gate may contribute to transit time broadening in the PW Doppler spectrum. The analysis is performed by examining the extent of transit time broadening for different single-scatterer flow paths through the sample volume. From both physical and mathematical perspectives, we have shown that different parameters govern transit time broadening at different beam-to-flow angles. In particular, at higher beam-to-flow angles, the sample volume boundaries that scatterers traverse through are mainly defined by the ultrasound beam width, and thus the spectral broadening bandwidth is influenced by ultrasound beam parameters such as focal length and aperture size. This finding is consistent with the previous studies on transit time broadening. On the other hand, at lower beam-to-flow angles, the sample volume boundaries that scatterers traverse through are primarily defined by the axial limits of the range gate, and thus the spectral broadening bandwidth is dependent on range gate parameters such as the axial length and the transmitted pulse length. It follows that there exists a specific beam-to-flow angle at which a change in the governing parameters of transit time broadening occurs. We have referred to this angle as the transition beam-to-flow angle. An in-house PW Doppler ultrasound simulation model has been used to verify the derivations made in our study. From this model, the effects of different physical parameters on the transit time broadening bandwidth have been examined. Doppler spectra have been obtained at various beam-to-flow angles for different single-scatterer simulation settings. These results, which demonstrate close agreement with our derived theory, will be presented.
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Session: P3U-O
IMAGING TECHNIQUES AND MODELING
Chair: P. Li
National Taiwan University

P3U-O-1 H13

EDGE SHADOWS AROUND RIGID, ABSORBING, AND NON-ABSORBING CYLINDERS

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Edge shadows are often observed on images of rounded cavities, such as cysts, as narrow dark lines, aligned with the ultrasound beam, and extending distally from the cavity edges. We hypothesised that the acoustic properties of the

cavity material are 'encoded' in the appearance of the shadows, and so could be revealed by an increased understanding of their physical origins. As a step toward this, we aimed in this study to investigate the relative importance, in edge shadow generation, of the beam refracted through the rounded cavity to that reflected from it.

We developed a pulsed, finite beam wave equation solution to simulate images of liquid cylindrical cavities embedded in tissue-mimicking material (TMM). Using this, we investigated the relative importance of reflection and refraction to the production of edge shadows around cylinders with $\pm$10% speed of sound (SOS) relative to the TMM, when insonated with a strongly focussed beam. The main criterion used to assess the significance of refraction was the proportion of the pulse-echo sensitivity within the cylinder, relative to that outside. The effect on the images of the presence or absence of absorption, and of scattering centres, within the cylinder was also studied. The images of these penetrable cylinders were then compared to those of rigid and evacuated cylinders, for neither of which could refraction be occurring. Edge shadows in the +10% SOS case have two parts, and are qualitatively different to those in the -10% case. On the +10% SOS cylinder, the beam corresponding to the part of the shadow immediately beneath the edge of the cylinder was almost totally reflected with at most 8% of the pulse-echo sensitivity inside the cylinder. In contrast, refraction was much more important for the beam producing that part of the shadow lying beneath the critical angle, with up to 70% of the sensitivity lying within the cylinder. For the -10% SOS case, with no critical angle, only the shadow beneath the cylinder edge was present. Again, significant refraction was occurring, but less than at the critical angle, with up to 36% of the sensitivity within the cylinder. Inclusion of attenuation of 0.5dB/cm/MHz within the cylinder appeared simply to darken only those parts of the images which had, according to the sensitivity criterion, involved significant refraction. Inclusion of scatterers within the cylinder had negligible effect on the image intensity distal to the cylinders, indicating that little energy was 'trapped' within the cylinder. The images of the rigid and evacuated cylinders were very similar to each other. However, despite the fact that refraction was not occurring in these cases, the edge shadow was significantly darker than for the edge shadow on either of the penetrable cylinders.

These initial results have shown that edge shadows around positive and negative SOS cylinders are qualitatively different from each other, with both refraction and reflection contributing significantly in different regions of the shadows. Ongoing simulations, together with in vitro data, will provide a full explanation of the edge shadowing phenomenon.

KNOWLEDGE BASED EXTRACTION OF LEFT VENTRICULAR ENDOCARDIAL BORDER FROM 2D ECHOCARDIOGRAMS

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Background: Extraction of the endocardial border of the left ventricle is a key challenge in cardiac ultrasound imaging. The cardiac anatomy may be difficult to determine automatically without incorporating knowledge of both wall shape and intensity signature into the detection algorithm. The aim of this study is to establish a knowledge based framework for automated extraction of the left ventricular endocardial border. The method permits use of manually diagnosed reference data in an edge detection algorithm, and is based on comparing the similarities between the test case and the training sets of a validated case database.

Methods: Three landmarks, including two end points of the atrioventricular plane, and the apex, were manually established in both training and test sets which consisted of intensity normalized cardiac ultrasound images. In the training sets, the endocardial border was also outlined. A region of interest (ROI) for possible edge locations was established in both test and training sets based on a spline through the three landmarks.

A number of candidate lines were laid out relative to the ROI, spanning from the interior of the ventricle, into the myocardium. The pixel intensity profiles along the lines were organized into a feature vector, which can be interpreted as a geometrically normalized candidate image.

Similarities between test sets and training sets were evaluated using several distance measures applied to corresponding candidate lines, including sliding sum of absolute differences (SAD), and cross correlation. The test set was classified based on a nearest neighbor classifier.

Optimum candidate line displacements for the test set were found using a dynamic programming approach on data obtained when calculating the distance measure. Based on these displacements, the contour of the test set was generated from the manually outlined contour of the matching training set.

Results: The proposed method forms a basis for utilization of manually segmented reference data in a mathematical framework. We have shown that this framework can be used for robust extraction of the left ventricular endocardial border.

Conclusion: The strength of the proposed method is its ability to utilize expert knowledge directly for extraction of clinically relevant parameters from ultrasound data. The framework can be widely extended, and further work will include functionality that allows the user to suggest a diagnosis, causing the matching algorithm to rely more on plausible cases than irrelevant diagnoses. The method can also be extended to constitute a basis for decision support,

where one or several diagnoses are suggested based on similarities between a new case and the contents of a reference base.

P3U-O-3 H11

EVALUATION OF 2-D SPECKLE TRACKING BASED STRAIN RATE IMAGING USING A 3-D HEART SIMULATION MODEL

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We have presented an alternative 2-D correlation-based speckle tracking method for strain rate imaging (SRI) using a longer firing interval (about 10 ms), which produces higher average frame-to-frame strain than traditional Doppler-based SRI, and also allows global tracking of the underlying tissue. To characterize local deformation with Lagrangian strain estimates, we compute frame-to-frame displacements using 2-D phase sensitive speckle tracking algorithms, and then perform spatial registration by accumulating displacements in the initial geometry. Since every point on the myocardial wall must return to its initial position after exactly one cardiac cycle, residual accumulation error (i.e., error in accumulated displacement after exactly one cycle) can be used as a robustness measure of tracking algorithms. Preliminary results from an image sequence, captured from a porcine inter-ventricular septum at a relative frame rate (RFR) of 50 frames/cycle (frame rate/heart rate), showed the average residual accumulation error can be as high as 15% of mean peak displacement. To understand the performance of this 2-D SRI method, a controlled 3-D heart kinematic simulation model with physiological deformation was developed. Peak strain rates at fast contraction and relaxation periods are about 2 Hz. Torsion, peaked at the end of systole, is added to this model, causing portions of the wall to move in and out of the image plane. A phased-array imaging system with a 3-D point spread function was employed to generate an initial 2-D ultrasound image sequence at a RFR of 450 frames/cycle. The imaging plane is chosen at a 20 degree angle with respect to the long axis of the heart, mimicking a typical long-axis view in echocardiography. Slower frame rates were obtained by simply decimating the initial image sequence by proper factors. Results show that the average residual accumulation error in the radial direction reaches a minimum (about 1% of mean peak displacement) at a RFR of 76 frames/cycle. In addition, the measured accumulated displacement profile at this RFR exhibits the best match to the theoretical prediction. At this RFR, peak strain between two adjacent frames is 2-3%, and peak out-of-plane motion is about 10% of the elevational speckle size. However, unlike pure in-plane strain cases, the average discrepancy between measured and theoretical accumulated displacements monotonically increases to about 2.5% of mean peak displacement at the end of systole. The accumulation error map also shows good spatial correlation

with out-of-plane motion and cross-correlation coefficient maps. These results suggest that out-of-plane motion plays a significant role in the residual accumulation error (baseline-drifting phenomenon) widely observed in cardiac SRI. Finally, displacement maps depend on scan angle, which can be eliminated by transforming the coordinates in the scan plane back to the heart coordinate system.
This work is supported by NIH grant HL-67647.

P3U-O-4 H10

EVALUATION OF THIN COMPRESSION PLATES FOR MAMMOGRAPHICALLY COMPATIBLE BREAST ULTRASOUND

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We are developing a combined digital mammography/3D ultrasound system for use in breast cancer imaging to better detect and/or characterize breast lesions. Scanning a GE Logiq 9 M12 transducer array over a mammographic plate introduces an attenuating layer with sound speed and impedance different from that of tissue, reducing signal level and affecting beam focusing. Thus, choice of a suitable plate is essential for accurate sonographic detection of lesions. Similar work has been reported, but in this study a more complete and definitive characterization of image quality through mammographic plates of varying materials, (e.g., Lexan, polyurethane, mylar) and thicknesses is presented. Quantitative measures such as spatial and contrast resolution, signal strength, and reverberation levels were compared to images without a plate. In vivo patient studies comparing images obtained with standard hand held scans versus 1.0mm thick plates examined restricted access concerns, coupling issues, and overall lesion clarity. Filters were added to account for differences from the standard Lexan plate in x-ray transmission properties. When lateral beamforming corrections were implemented to partially account for the speed of sound through the plates, experiments conducted on 25 μm line targets with several plastic plates between 0.25-2.5 mm thick demonstrated image quality measures close to those with no plate present. In some plates $\leq$1.0 mm thick, a worst-case 5% reduction in linear spatial resolution and a maximum 4 dB signal loss averaged over 4 cm were observed. In those better plates up to 2.5 mm thick, reverberation levels were consistently 40dB down from the signal maximum. Restricted access to areas of interest, such as lesions near the chest wall, was compensated for by imaging in trapezoidal (virtual convex) format. Thinner plates that are more flexible than thicker plates of the same material allowed for closer contouring to and more complete coverage of the breast margins at the expense of violating possibly irrelevant rules for maximum bowing of mammographic plates. After accounting

for signal loss through the plate, cyst and lesion images were generally as clear as those obtained with hand held, direct contact sweeps.
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P3U-O-5 H9

A FEASIBILITY STUDY ON THE DEVELOPMENT OF ULTRASONIC PARAMETRIC IMAGING BASED ON NAKAGAMI STATISTICAL MODEL

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Nakagami parameter calculated from those received echoes in tissues was demonstrated to be able to encompass various scattering conditions. To extensively investigate the feasibility of applying Nakagami statistical model to form an ultrasonic parametric image, 2-D computer simulations from media of different scatterer concentrations and measurements of a tissue-mimicking phantom that contained a strong point reflector of an inserted needle were carried out in this study. Each simulated image composed of 256 A-lines was acquired from random scatterer media using a 5 MHz ultrasound. Consequently, Nakagami parameter image was calculated from a 2-D window, size equal to a resolution cell, sliding throughout the whole acquired data. Due to finite number of data in each window, the calculated parameter tends to vary greatly associated with variation of strong echoes. Thus, a modified algorithm was studied and applied to filter the variation. The simulated results showed that the average of local Nakagami parameters were increased from $0.50\pm$ 0.0026 to $0.68\pm$ 0.0204 corresponding to the increase of scatterer concentrations ranged from 2 to 32 scatterers/mm2. Furthermore, in addition to capability of differentiating various scatterer concentrations distributed in the phantom, the parametric image obtained from measurements is able to localize clearly the fine needle better than that of B-mode image. Although the resolution of the parametric image generally is not as good as B-mode, its capabilities of detecting variation of scatterer concentration and strong scatterer make the Nakagami parametric image able to characterize tissues more quantitative than conventional B-mode imaging.
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P3U-O-6 H8

ANALYSIS AND MEASUREMENT OF SPECTRAL CHARACTERISTICS AND SPATIAL RESOLUTION OF HIGH FREQUENCY ULTRASOUND IMAGING SYSTEMS

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High frequency ultrasound (HFUS) in the range above 20 MHz can be utilized for high resolution and non invasive skin and eye imaging. Due to the lack of HFUS arrays, imaging systems for these applications are usually based on mechanically scanned single element transducers. With increasing frequencies, the attenuation of water, which is used as propagation medium between the transducer and the tissue, becomes more and more dominant. Its low pass characteristics result in a significant reduction of the systems center frequency and bandwidth, and thus in a loss of spatial resolution. In this work, the spectral characteristics and the spatial resolution of HFUS imaging systems are analyzed. A Gaussian model of the systems transfer function was developed, taking the frequency dependent attenuation of the water path into account. Predictions, which are derived from this model, are compared with measurement results. We have developed a HFUS skin imaging system with a spherically focused PVDF-transducer (Panametrics, Waltham, USA) with 2 mm aperture diameter and 4.3 mm focus length. This transducer is designated for electro-acoustical conversion in a broad frequency band around a nominal 100 MHz center frequency. For the validation of this specification, measurements on a steel ball as equal phase reflector were performed. To assess the influence of the water path, rf echo signals were acquired from a glass plate, which was located at the transducer focus. Under both conditions, the spectral characteristics and spatial resolution were analyzed. The frequency dependent attenuation of the water path was calculated as the difference between the two spectra from the steel ball and the glass plate. Based on these measurements a model for the degradation of the spectral characteristics depending on the water path length was developed. Using this model, an optimal set of transducer parameters for desired spectral characteristics of the system can be predicted. Furthermore, the potential and limits of inverse filters for the optimization of the systems response were analyzed. Echoes were acquired with a 0.23 mm long water path between the transducer and the steel ball. As a result, a 102 MHz center frequency and a 120 MHz bandwidth (-6 dB) were measured. Analyses of the echoes from the glass plate resulted in a 58 MHz center frequency and a 71 MHz bandwidth (-6 dB). This significant difference between the two spectra is a result of the frequency dependent attenuation of the water path. The measured results are in a very good agreement with theoretical considerations. Spectral analyses, performed on phantom and in vivo measurements over depth, as well as B-mode images are presented. It is shown that the implemented system enables high resolution imaging with a minimum axial resolution of 9.2 μm.

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P3U-O-7 H7

USE OF A COMPOSITE NON-LINEAR MODEL INCLUDING MICROBUBBLES AND TISSUE TO EXAMINE HARMONIC EFFECTS FOR ULTRASONIC PROPAGATION AND BACKSCATTER IN COMPLEX TISSUES

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Several numerical modeling studies have examined non-linear propagation of ultrasound in tissue (KZK equation). Similarly, other investigations have studied non-linear backscatter characteristics from ultrasound contrast microbubbles (RP equation). However, very few reports on combined tissue-bubble models are available, especially in the area of non-linear contribution of microbubbles to ultrasonic propagation and backscatter in complex tissue where both blood vessels and surrounding soft tissue are incorporated. Results from such studies should contribute further to the continuing optimization of harmonic imaging techniques.

In this study, the well-known KZK equation is adapted to include tissue and blood vessels with microbubbles. A composite approach utilizing the equivalent non-linearity and attenuation parameters for the blood vessel with varying amount of contrast (volume fraction of bubbles to blood: 10^{-8} to 10^{-5}) provides the resultant equation which is then solved using a time-domain finite difference technique. Harmonic analysis of tissue propagation shows that the microbubbles induce significant nonlinearity in the propagating wave, which influences both harmonic generation and waveform distortion by causing spatial shifts of the harmonic focal points (2^{nd} and 3^{rd} harmonics) and production of higher amplitude harmonic wave components. For example, a microbubble volume fraction of 10^{-7} resulted in $> 400\%$ increase in the 2^{nd} harmonic wave component over the tissue-only model. Wave-diffraction patterns of the multi-harmonic components varied mainly as a function of bubble concentration within the local blood vessel. Use of the conventional tissue-only model did not reveal these focal points or the significant higher harmonic generation.

These results provide a means for understanding harmonic effects in a realistic composite tissue-blood vessel model and should provide pathways to improve signal-to-noise ratio in harmonic imaging. Experimental studies to further refine these models are currently underway.

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IMPROVING RELIABILITY IN MEASUREMENT OF MINUTE CHANGE IN WALL THICKNESS USING TEMPLATE MATCHING

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Background: For assessment of elasticity of the arterial wall, the change of dozens of microns in wall thickness due to heartbeat is measured by the phased tracking method [H. Kanai, et. al, IEEE Trans. UFFC, 44, 1996; H. Kanai, et. al, Circulation, 107, 2003] with transcutaneous ultrasound. In worst cases, however, there are some regions where echo from the luminal interface cannot be recognized at all in B-mode images and changes in thickness cannot be accurately measured. In such regions, the ultrasonic beam is not perpendicular to the luminal surface when the vessel is not straight or the luminal surface is not smooth in the case of atherosclerosis. To exclude such regions, in this paper, a matching processing was introduced to evaluate the waveform of the minute change in thickness. **Method:** An ultrasonic beam was sequentially scanned at 60 positions in the carotid artery with a linear-type probe of 7.5 MHz. Along each beam, multiple points are set in the arterial wall and layers with thickness of 375 μm are defined between each successive two points. The change in thickness of each layer is obtained by measuring displacements at these two points using the phased tracking method. The lowest value of the change in thickness was validated as being 0.5 μm [H. Kanai, Electron. Lett. 35, 1999]. In our matching process, a few template waveforms were prepared as the model waveforms of the change in wall thickness. Each template was expanded or compressed to the same length as the measured waveform in the time axis using a linear interpolation. Then, by multiplying a normalized constant, A, the modified template is expanded or compressed on the amplitude axis to minimize the error between the template and the measured waveform. The residual error is employed for evaluation of the measured waveform. **Experimental results:** For four subjects, whose luminal interfaces were recognized at all in their B-mode images, the residual errors in changes in thickness were evaluated at multiple points set from luminal surface to the adventitia side along the ultrasonic beam. We divided the wall into 3 layers with same thickness along the ultrasonic beam. The average of the residual error (the constant A) in these 3 layers were calculated to be 19.8% (0.29), 13.2% (1.23), and 19.5% (0.47), respectively. The central layer had the lowest error and the normalized constant A was closest to 1. The artery diameter increases in cardiac systole and the wall thickness became thin. In the luminal region when its interface was recognized, however, the layer thickness became thick. In this case, the normalized constant A had negative value. From these results, the proposed method shows whether the measured waveform of the change in thickness is correct or not. **Conclusions:** In this paper, a method was proposed to evaluate the reliability by calculating the error between the measured and template waveforms. It is possible that the

reliability of the elasticity image will be improved by excluding waveforms with high error values.

Session: P3U-P
CLINICAL TISSUE CHARACTERIZATION
Chair: J. Miller
Washington University

P3U-P-1 H5

ULTRASONIC IMAGING OF BIOCHEMICAL CHANGES IN TISSUES

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Ultrasonic Mechanical Relaxation (UMR) imaging was developed to visualize elastic and time-varying viscous properties of soft tissues. Viscoelastic properties change depending on the biochemical environment of tissues. For example, regions of high cell metabolism within breast cancers are acidic. Stromal tissues in the reduced pH media have fewer hydrogen crosslinks between collagen fibers because of changes in surface charge density. This effect softens the affected tissues within otherwise stiff tumors. In addition, hydrogel data predicts that relaxation times for viscous creep in acidic polymers should shorten. Thus UMR methods have the potential to identify metabolically active regions in heterogeneous tumors that offer the greatest resistance to conventional therapies. UMR may also find uses in following the actions of matrix metalloproteinases and their inhibitors as they break down and solidify the extracellular matrix in soft tissues to facilitate neovascularization during tumor growth and wound healing. This paper extends the experimental study reported last year using hydrated gelatin and ex-vivo tissues.

Two gelatin samples (pH 6.5) were constructed, one using a buffer and the other with saline. NaOH was injected into both samples and subsequent changes were imaged using UMR after 5, 20 and 50mins. UMR techniques produce images of elastic strain and viscous creep relaxation time constants resulting from step-stress stimuli applied during RF echo frames acquisition at a high rate. Relaxation time constants (T_1 and T_2) are estimated for each pixel from the time series of strain images. Experiments included acidic and neutral pH injections on gelatin samples and ex-vivo bovine liver samples. Imaging results were interpreted by comparisons with equivalent sample measurements obtained using a cone-plate viscometer. We developed an analytical framework to relate imaging and viscometer estimates via principal strains derived from the constitutive equations of linear elasticity theory.

Injections of acidic and basic solutions produced elastic contrast in regions that grew in size and intensified over time. Strain contrast was maintained in the unbuffered gels for days but faded completely in the buffered gels after

several hours. Neutral pH injections produced no strain contrast. Although stiffness increased if the pH either increased or decreased about 7, time constant T_2 increased linearly with pH (64s/pH unit). Acidic regions in liver samples produced similar trends with greater contrast intensity compared to gelatin because of gelatins greater buffering capacity. We also found that relaxation times decrease with the applied stress rate. A clear advantage of T_2 imaging over elastic imaging is a much weaker dependence on boundary effects. We also found that trained operators tended to naturally apply constant stress rather than constant strain in hand-held situations, and thus clinical applications of UMR imaging are expected to be straightforward. Above results suggest that pulse-echo ultrasound without contrast enhancement has the potential to image alterations in stromal tissue structures caused by biochemical changes.

P3U-P-2 H4

LOCAL INVERSION OF TRANSIENT SHEAR-WAVE PROPAGATION FOR ELASTICITY AND VISCOSITY MAPPING IN SOFT TISSUES: THEORETICAL AND EXPERIMENTAL ANALYSIS

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Observation of transient shear-wave propagation in soft tissue is of great interest for the study of tissue viscoelastic properties. In previous work, we introduced a technique, called Supersonic Shear Imaging (SSI), able to generate transient shear waves using the acoustic radiation force and image their propagation in real time in soft tissues. Inversion methods were used to recover elasticity from the shear-wave propagation. In this work we present a precise and robust inversion algorithm taking into account not only elastic but also viscous properties of soft tissues. Based on a Voigt model, this algorithm is designed to provided quantitative and local estimation of soft tissue elasticity and viscosity. In a first part, the influence of viscosity on transient shear waves is modeled and analyzed using a 3D analytical formulation of the mechanical Greens function in a viscoelastic medium. It is shown that the spatial and temporal shape of experimental shear waves induced in soft tissues using SSI can only be accurately modeled by taking into account tissue shear viscosity. The respective influences of viscosity, elasticity or diffraction on the shear wave shape are carefully studied and discriminated. In a second part, taking advantage of the previous modeling, a local inverse problem permitting the recovery of shear elasticity and viscosity is presented and validated using the Greens function based simulation tool. The role of viscosity on the accuracy of the elasticity estimation is studied. The influence of out of plane shear propagation on the inversion algorithm is discussed. Finally, in media presenting shear viscoelasticity heterogeneities, finite difference simulations are used to study the spatial resolution of the algorithm

and its sensitivity to the signal-to-noise ratio. Experiments on calibrated tissue-mimicking phantoms presenting different viscoelastic properties are presented validating the simulation results. First in vivo results on breast women are presented.

P3U-P-3 H3

DIAGNOSTICS OF PROSTATE CANCER BASED ON ULTRASONIC MULTIFEATURE TISSUE CHARACTERIZATION

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Diagnostics of prostate carcinoma using ultrasonic multifeature tissue characterization allows the detection of tumors at an early stage. Malignant areas within the prostate can be located with a high degree of accuracy while keeping the system independent of the diagnostic skills of the operator. Radio-frequency ultrasonic echo data of the prostate is captured during the usual examination of the patient with standard ultrasound equipment. Several features describing the histological characteristics of the underlying tissue are calculated after dividing each data frame in up to 1000 regions of interest and compensating the echo data for diffraction and system dependent effects. Spectral features, textural features of first and second order and morphological descriptors are applied. In comparison to former work of the same group, additional spectral features that contain phase information were calculated using the generalized spectrum (spectral autocorrelation) approach. In addition, spectral features based on autoregressive (AR) models were evaluated for comparative reasons. Two network-based fuzzy inference systems working in parallel classify and separate the regions of interest. Following morphological analysis combines clusters within the malignancy maps, which consist of conventional B-mode images with areas of a high cancer probability marked in red. During a clinical study, radio-frequency ultrasonic echo data of 100 patients has been recorded. Prostate slices with histological diagnosis following radical prostatectomies act as the gold standard. The ROC curve area is between A=0.84 and A=0.86 for isoechoic tumors and for hypo- and hyperechoic tumors, respectively. Standard deviations are as low as 0.02 for the first system and 0.01 for the second system. All three spectral approaches evaluated in this work, conventional Fourier spectrum parameters, generalized spectrum parameters and AR parameters, yield comparable classification rates for the underlying prostate data sets.

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P3U-P-4 H2

ULTRASONIC TISSUE CHARACTERIZATION AS A PREDICTOR OF WHITE MATTER DAMAGE: RESULTS OF A PRELIMINARY STUDY

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Premature infants are prone to white matter damage (WMD), which is associated with cerebral palsy (CP) and cognitive impairment. Ultrasound (US) is the preferred imaging modality to detect WMD. To improve on existing diagnostic rates, quantitative measures incorporating new information are needed. We are investigating US texture measures as new indicators of white matter health.

This work outlines a novel filtering scheme for neonatal cranial ultrasound scans that exploits a variable orientation Gabor filter. A texture measure is obtained from the output of the filter, which is novel for the discrimination of WMD. Experiments using these measures suggest that US texture measures can be predictors of patient outcome.

The experimental image data consists of a set of ultrasound B-mode images from 18 patients (12 with normal outcome, 6 who developed CP). Retrospective film images were digitized with a 3200 dpi scanner. Film images were used because they have greater spatial resolution than digital images. Modern digital US equipment has bandwidth restrictions and may reduce texture information. The images were used without correcting for machine settings and without removing speckle. A radiologist isolated choroid plexus and white matter tissue samples from the images.

The experimental results are a continuation of reported work [1]. Previously, to each image we applied two non-linear processing techniques. The non-linear processing consisted of the difference between mode and median filters (DMM) and enhancement through grey-level morphology (GM). For each output, the texture within each tissue sample was described by a statisical measure (STAT). From STAT values, ratios and differences for the two tissue types were calculated. These measures formed separate populations based on patient outcome.

In the new, extended approach, we apply a variable Gabor filter directed along the theoretical axis of insonation within the US image. We calculate a second texture measure by obtaining the normalized surface area (NSA) for each tissue sample. From the Gabor-filtered images, both the ratio and difference values are calculated from both texture measures (STAT and NSA). Both measures from the Gabor-filtered images form populations that correspond to patient outcomes. Two tailed Student t-tests were performed on the data. P values in the range of 0.0001 to 0.017 were calculated for the data processed with the Gabor filter.

The NSA values were obtained after processing with the non-linear techniques. These ratios and differences also formed two populations. P values in the range of 0.0007 to 0.0024 were obtained for NSA values after processing with DMM and GM. While the data set used to date is small, the initial results indicate that further study of this method is warranted. 1 "Texture-based Tissue Char-

acterization: A Novel Predictor for Brain Injury?" 2nd IASTED International Conference on Biomedical Engineering, Feb. 2004.
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P3U-P-5 H1

CONSTRUCTION OF REFERENCE DATA FOR CLASSIFICATION OF ELASTICITY IMAGES OF ARTERIAL WALL

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Background: For the evaluation of dynamic mechanics, there are some methods to determine the elasticity of the arterial wall by measuring the pulse wave velocity and rough change in the diameter. However, a method for accurate tissue characterization to diagnose the vulnerability of atherosclerotic plaque with sufficient accuracy has not yet been reported. We have developed the phased tracking method [H. Kanai: IEEE Trans. UFFC, 43, 1996] for imaging the cross-sectional elasticity. For classification of elasticity images, it is necessary to determine the elastic modulus of each tissue component such as lipid, blood clot, fibrous tissue, and calcified tissue. In our previous study, elastic moduli of lipid and fibrous tissue were determined by *in vitro* experiments [H. Kanai, Circulation, 107, 2003]. However, elastic moduli of calcified tissue and blood clot are not yet determined. This presentation shows the reference data for these two tissue components. **Method:** In *in vitro* experiments, 8 extracted human femoral arteries were placed in a water tank. The change in internal pressure was generated by using an artificial heart. An ultrasonic beam was sequentially scanned at 60 positions with a linear-type probe of 7 MHz, and multiple layers were preset from the luminal surface to the adventitia along each ultrasonic beam with constant intervals of 375 μm just before the ejection period. Displacements of two points at near and far surfaces of each layer were simultaneously tracked by applying the phased tracking method to the received echo. The minute change in thickness of each layer due to heartbeat was determined by subtracting these two displacements. The elasticity image was obtained from the change in thickness of each layer along each beam and the internal pressure measured by a pressure sensor. The spatial resolution of elasticity images is 150 μm and 75 μm in the axial and radial directions of the artery. A needle is fixed on the external surface of the posterior wall to identify the plane scanned by ultrasound. After ultrasonic measurement, elasticity images were compared with pathological images. **Experimental Results:** We have already measured elasticity distributions of fibrous tissue and lipid as 1.0$\pm$0.63 MPa and 81$\pm$40

kPa, respectively [H. Kanai: Circulation, 107, 2003]. Moreover, in these *in vitro* experiments, elasticity distributions for calcified tissue and blood clot were determined to be 1.4±0.76 MPa from 674 pixels in elasticity images and 101±68 kPa from 1009 pixels, respectively. **Discussion and Conclusion:** Unfortunately, elasticity distributions of blood clot and lipid were similar. Distributions of calcified tissue and fibrous tissue were partly overlapped each other. Considering from these elasticity distributions, it is still difficult to distinguish blood clot from lipid. However, using the reference data obtained in this paper, it is supposed that the elasticity images are classified into the following categories: fibrous tissue, calcified tissue, and lipid/blood clot.

P3U-P-6 I1

PARAMETRIC IMAGING ON A CLINICAL SCANNER

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Ultrasonic scatterer size estimation and imaging has proven to be both feasible and useful for monitoring, diagnosis, and study of disease. We are implementing scatterer size imaging and attenuation coefficient imaging on a clinical scanner equipped with a research interface. The interface provides radio frequency echo data over the image of a sample, which are then analyzed offline. Echo data from a reference phantom, acquired using the same transducer and scanner settings used in acquisition from the sample, accounts for system dependencies on the data. Backscatter coefficient and attenuation coefficients are estimated for small regions. Scatterer size images are generated by performing a modified least squares fit of the backscatter estimate to a theoretical model, which relates backscatter to scatterer size. Extensive tests in well-characterized hantoms have demonstrated the accuracy of the method as well as revealed limitations.

Ultrasonic scatterer size estimates generally have large variances due to the inherent noise of the spectral estimates used to calculate size. Compounding partially correlated size estimates associated with the same tissue, but produced with data acquired from different angles of incidence, is an effective way to reduce the variance without making dramatic sacrifices in spatial resolution. Theoretical expressions have been derived for the decorrelation of echo data when the aperture is rotated about a point in the scanned field. The expressions, verified using data from uniform phantoms, enable optimized spatial compounding routines to be designed. Initial compound acquisitions on the clinical system have been done using manually generated scripts supported by the research interface. Results confirm theoretical expectations of the improvement in signal to noise ratio of scatterer size estimations with selected compounding parameters.
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LIVER FATTY CHANGE CLASSIFICATION USING 25MHZ HIGH FREQUENCY ULTRASOUND

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Fatty change (steatosis) of liver is frequently seen in patients with chronic hepatitis C, alcoholic liver disease and non-alcoholic fatty liver disease (non-alcoholic steatohepatits). Severe steatosis may cause liver cirrhosis. In this study, B-mode images of 15 fresh human liver samples obtained during operations were acquired to evaluate ultrasounds ability in determining the grade of liver fatty change. B-mode images were acquired at 25 MHz, 7 MHz and 3.5 MHz. Image features derived from gray level concurrence and non-separable wavelet transform were extracted to classify the grade of fatty change using a classifier known as the support vector machine. After image acquisition, each liver sample subsequently underwent histological examinations and liver fatty change was graded from 0 to 3 (0: no fatty change; 1: less than 33% of hepatocytes affected; 2: 33% to 66% of hepatocytes affected; and 3: more than 66% of hepatocytes affected). The 4 grades were then combined into 2 classes (non-stetosis (grade 0) and stetosis (grade 1-3), 3 classes (non-steatosis, mild steatosis (grade 1), and prominent steatosis (grade 2-3)) and 4 classes (all different grades). Classifications using the extracted image features by the support vector machine were tested with the leave-one-out method and correlated with histology. For the 25 MHz B-mode images acquired by a single crystal transducer with mechanical scanning, the results showed that the best classification accuracy of 2, 3 and 4 classes were 91.3 %, 84.0 % and 82.0%, respectively. Compared with the results acquired from a clinical scanner at 3.5 MHz and 7 MHz, the classification accuracy was significantly better with 25 MHz high frequency ultrasound. The best classification accuracy of 2, 3 and 4 classes were 75.2 %, 75.2 % and 72.4 %, respectively with a 3.5 MHz convex probe and 75.3 %, 72.7 % and 67.3 %, respectively with a 7 MHz linear probe. Thus, it is concluded that liver fatty change can be accurately characterized using 25 MHz high frequency B-mode ultrasound even though the performance declines as the number of classes increases. The classification results at lower frequencies, on the other hand, are noticeably lower than those at 25MHz. Details of the data acquisition protocols and classification procedures will be presented. Limitations of 25 MHz ultrasound in clinical settings, including interference of the abdominal wall and insufficient penetration depth, will also be discussed. A potential remedy is to use a high frequency needle-type micro-machined transducer for minimally invasive examinations.

CLINICAL TEST OF RULES (RADIOFREQUENCY ULTRASONIC LOCAL ESTIMATORS)

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An echographic method for investigating biological tissue internal structure in order to differentiate pathological regions was proposed one year ago [1]. The method, named RULES [2,3], is based on radiofrequency (RF) echographic signal processing. It permits to extract spectral parameters related to the organization and mechanical properties of investigated tissue. Spectral images are produced through a processing procedure, based on a statistical analysis of Local Estimators (LE). They are calculated from the spectral coefficients of Discrete Wavelet Packet Transform. The tissue portions, which exhibit the same LE homogeneous distribution, were put in correspondence with condition and type of tissue identified by histological studies. In order to guarantee the diagnostic applicability of the method it is necessary to sustain a high image production rate by means of a real time acquisition and processing system. A hardware-software platform, FEMMINA, Fast Echographic Multiparameter Multi Image Novel Apparatus, [4], dedicated to real-time signal and image processing of continuous sequences of RF frames was employed. By exploiting FEMMINA capability to extract a multitude of parameters and their simultaneous visualization, various RULES versions characterized by specific LE were proposed for three different medical application fields: prostate pathology detection, carotid artery plaque differentiation and breast tissue characterization [1]. The obtained encouraging results have led us to initiate the clinical validation of method for breast tissue differentiation in order to identify cysts, fibroadenoma and to detect tumors. These results will be presented in this work together with the results coming from the clinical experimentation on prostate where the RULES features are employed for localizing pathological zones in order to guide the bioptical sampling.

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Session: P3U-Q

3D
Chair: O. Basset
CREATIS

P3U-Q-1 I4

A NEW 3D ULTRASONIC MODEL OF PATHOLOGIC CAROTID VESSELS BASED ON GENERALIZED CYLINDERS

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The aim of this work is to elaborate a 3D biological model able to reproduce the acoustic behavior of human vessels. The model enables the representation of various anatomic structures including bifurcations and the associated pathologies like local arterial wall thickening, aneurysms, stenosis and atherosclerotic plaques. Such a tool can be of interest for the development and validation of various ultrasonic signal and image processing applications such as data segmentation, tissue characterization, elastography or Doppler techniques. The topology of the vascular structure is generated starting from a complex-shaped object within the family of right generalized cylinder RGC [Azencot, Graphical Models, 2003]. A continuous deformation of a planar curve (contour) along the objects axis describes its 3D surface. The contour locally orthogonal to the axis is modeled by a finite Fourier series. The object is divided into sections of variable length where the shape variation rule remains unchanged. A very concise description of a RGC family having the same statistical properties is obtained by applying an auto-regressive stochastic model to state variables. This object gives access to morphological parameters such as curvature and torsion of the axis area of cross-sections, and volume of a cylinder segment. The whole phantom is built with the superposition of different concentric objects of the same type, which respectively compose blood, vessel wall and surrounding tissues. The model considers also fluid-dynamic displacements of the scatterers (erythrocytes), based on the Navier-Stokes equation, to simulate the blood flow circulation through the vessel. A cyclic pulsating blood velocity profile is integrated in the model to simulate a realistic heart pulsation. The acoustic characterization of each region in terms of number, density and distribution of scatterers, reflection amplitude, is performed using FIELD (program developed by J. A. Jensen, Orsted-DTU, Tech University Denmark). Ultrasound radiofrequency echo-signals are obtained for a virtual ultrasound probe that can be arbitrarily located with respect to the phantom. As examples of application, three physiological acoustic phantoms of a carotid artery will be presented. The first corresponds to a healthy vessel with 6 mm lumen diameter and 0.2 mm intima-media thickness. The second one includes a plaque involving a 60%

stenosis degree. The last phantom represents a vessel branching between the common, internal and external carotid arteries. A linear scan of the phantoms was simulated with a 7.5 MHz 192-element linear array transducer. Numerous Color Doppler images obtained in all cases through a standard autocorrelation estimator are compared to the reference velocity distribution. Limitations of the adopted Doppler frequency estimator are thus clearly evidenced.

P3U-Q-2 I5

3-D ULTRASOUND CALIBRATION USING A PHANTOM WITH REDUCED COMPLEXITY

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Accurate registration of ultrasound images in 3-D space could be useful in a variety of medical applications. The geometric transformation from the image plane of an ultrasound transducer to a 3-D position sensor is vital in order to register the locations of ultrasound images in 3-D space. A widely used framework for 3-D ultrasound calibration is the use of Levenberg-Marquardt optimization on data collected from a phantom with known geometry.

A simple to construct phantom that has been used before for the 3-D calibration task is a cross wire phantom. Although simple to construct, there are well cited problems in precisely locating the position of the wire intersection in the cross wire phantom due to beam width issues. In several papers, viable alternatives that improve the precision of locating calibration points compared to the cross wire phantom are presented, but with an associated increase in phantom complexity and necessary precision of phantom construction.

This paper presents the design of a novel phantom for 3-D calibration that both avoids the problems of the cross wire phantom while not adding significant complexity or required precision to the phantom construction task. Data from the phantom is processed utilizing the commonly used Levenberg-Marquardt optimization as formulated and discussed in [1] in relation to its application to 3-D ultrasound calibration.

The phantom consists of, at minimum, one wire target submerged in a water bath and oriented parallel to the flat bottom of the water tank at some fixed height, or two coplanar wires parallel to the bottom of the water tank if it is desired to obtain two calibration equations per image.

The phantom was translated and rotated along the bottom of the water tank so that it always remained parallel to the bottom of the water tank and at the same height above the bottom of the water tank. The wire target or targets therefore remained in a single plane that could be used as an easily identifiable geometric feature for calibration . Since the phantom could be placed with a variety of orientations within the plane parallel to the tank bottom, clear, easy to identify images through the circular wire cross section could be obtained from a variety of interrogation angles. Points on the wire that defined a plane of fixed

height parallel to the bottom of the tank were used as inputs to the optimization. The transformation between the ultrasound image plane and the tip of a 3-D position-sensing articulated arm was determined in this manner.

Results of the calibration procedure and tests quantifying reconstruction accuracy conducted by scanning a simple wire phantom with known geometry are presented.

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P3U-Q-3 I6

VARIABILITY OF THREE-DIMENSIONAL HIGH-FREQUENCY ULTRASOUND MEASUREMENTS OF SMALL TUMOR VOLUMES

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The intra-observer variability in volume measurements of small (less than 2 mm^3) lesions using three-dimensional (3-D) high-frequency ultrasound imaging has been assessed in tissue-mimicking phantoms and a murine liver metastasis model. The capability to noninvasively monitor progression of small tumors maximizes the time over which lesion growth and responses to treatment can be studied. All images were acquired using a VisualSonics Vevo 660 micro-imaging system with a 40 MHz transducer. The resolution of the single-element transducer was 40×70 μm^2 at the 6 mm focal depth. The transducer was translated in the elevation dimension and 3-D images of $8\times8\times6$ mm^3 volumes were reconstructed from parallel B-mode planes separated by 30 μm. Volumetric images were produced in approximately 20 s. Tissue-mimicking phantoms containing simulated lesions were constructed from 15% by weight gelatin with 0.5% by weight silicon dioxide scatterers in the lesions and 2% by weight silicon dioxide in the background. Murine liver metastases were produced by injecting B16F1 melanoma cells into the mesenteric vein of C57Bl/6 mice. Detectable metastases developed within three weeks. Images were acquired from the phantoms and in a sagittal orientation from anesthetized animals with the region of interest centered at the depth of focus. Phantom lesions and mouse tumors were manually outlined in parallel planes separated by 50 μm. Volumes were calculated by summing the outlined areas and multiplying by the inter-slice distance. Four phantom lesions and five liver tumors were analyzed to determine the intra-observer variability of volume measurement by manual segmentation. Measurements were repeated five times by the same operator under the same conditions to obtain means and standard deviations of each volume. Small liver metastases were hypoechoic, approximately spherical, and comparable in shape

and contrast to the emulated lesions. The mean volumes of the liver tumors ranged from 0.45 mm^3 to 1.31 mm^3, whereas the mean phantom lesion volumes varied from 1.45 mm^3 to 1.93 mm^3. The size discrepancy reflects the technical difficulty of manufacturing small lesions. The standard deviations of the volume estimates from the phantom images ranged from 0.015 to 0.050 mm^3 and the coefficients of variation ranged from 1.00 to 3.23%. Standard deviations ranged from 0.018 to 0.10 mm^3 and coefficients of variation from 3.78 to 10.7% for the liver metastases. No consistent relationship was observed between the means and standard deviations of the volume estimates. Larger variability was obtained with the murine tumors because more uncontrolled parameters affect the appearance of *in vivo* tumors, including contrast, shape, surrounding anatomy, and respiratory motion. However, the coefficients of variation of the murine tumor volumes were small compared to the growth observed when the same tumors were imaged two days later, in which time the volumes had at least doubled.

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P3U-Q-4 I7

ULTRASOUND SPATIAL COMPOUNDING VIA REGISTRATION OF 2D SLICES INTO 3D VOLUME

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3D spatial compounding involves imaging the same region of interest, from different insonation windows and angles and then combining the values from the intersecting B-scans to construct the final 3D data set. The key to effective spatial compounding is accurate registration between the compounded data. However, designing accurate and fast registration methods is always challenging.

In this paper, a new non-linear deformable registration method for ultrasound spatial compounding is proposed. Unlike traditional 3D-to-3D registration, the acquired scattered 2D slices are registered directly into the 3D volume to perform only one 3D reconstruction which saves computation time. This novel method includes two steps. First, multi-resolution cubic B-spline registration (MRBR) is used to determine global and local nonlinear deformations following rigid registrations. The registration of 2D to 3D is achieved by allowing the amoeba optimizer to iteratively move control points in the homologous 3D space to positions that minimize the correlation ratio (CR) cost function calculated from the intensity values of the image pairs. Global and local deformations are estimated step by step through a sequence of coarse-to-fine control lattices. Then 2D slice images are divided into partly overlapped sub-images to estimate the residual local deformations far away from the control points. The correlation coefficient (CC) after MRBR is used as a threshold (CC_ave). Subimages with CC less than CC_ave are further aligned using B-spline registration.

An in-vitro phantom study was performed on a tissue-mimicking abdominal phantom (CIRS, Inc.), using a 3.5-MHz phased-array transducer. We first acquired a 3D ultrasound data set of the phantom by tracking the transducer using the magnetic position sensor. A forward mapping trilinear reconstruction algorithm was then adopted to reconstruct the 3D volume. We then performed a second freehand scan to collect a number of scattered 2D ultrasound slices using different insonation angles. Between acquisitions, the phantom was moved to simulate patient motion between two 3D ultrasound scans. CC between the two image data sets before registration was 0.735. After MRBR, CC increased to 0.952. CC further improved to 0.987 after the sub-image technique. The Sub-image technique can be 20 times faster than the approach of putting more control points to correct residual local deformations. In an in-vivo study, we imaged the leg muscle of a healthy subject using a 7.5-MHz linear-array transducer. CC increased from 0.754 to 0.963.

The results of in-vitro and in vivo trials demonstrated that we can get accurate registration using the new technique, which shows great promise for reducing tissue motion and local deformation in spatial compounding.

This work was done while Jie Liu and Niko Pagoulatos were at the University of Washington.

P3U-Q-5 I8

THEORETICAL AND EXPERIMENTAL HIGH-FREQUENCY NONLINEAR ULTRASOUND PROPAGATION THROUGH MULTILAYERED MEDIA

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There is an increasing interest in high-frequency ultrasound biomicroscopy (UBM) for small animal and superficial tissue imaging. A significant degree of nonlinearity is generated in the beams transmitted by UBM systems. Since accurate measurement of such ultrasound fields in tissue is not a trivial task, more accurate and efficient simulation tools would be beneficial. High-frequency nonlinear ultrasound propagation through multilayered liquid and tissue media is studied theoretically and experimentally. The field from a 20 MHz circular focused transducer with 3 mm aperture radius, F# $= 1.6$, was simulated using a multilayer propagation model and compared with experimental measurements performed in water on a tissue-mimicking phantom. The propagation model includes the effects of diffraction, attenuation, dispersion, nonlinearity, and refraction and energy conservation at layer boundaries. It is based on the work of Zemp et al. [J. Acoust. Soc. Am., 113, 139-152, 2003], and is capable of simulating pulsed- and continuous-wave propagation from sources of arbitrary geometry and arbitrary excitation. A non-uniform grid spacing scheme is used to achieve enhanced computational efficiency. The model employs a second-order operator-splitting

fractional-step algorithm, which propagates each effect over incremental steps [Tavakkoli et al., J. Acoust. Soc. Am., 104, 2061-2072, 1998]. An angular spectrum approach is used to model diffraction, thus providing efficient and accurate solutions in both the near-field and off-axis. The multilayer transmission algorithm, which includes the effects of refraction and energy conservation, is based on the method of Christopher and Parker [J. Acoust. Soc. Am., 90, 507-521, 1991], and is applied in the spatial frequency domain at layer boundaries. Hydrophone measurements were performed at the focal region in water using a three-layer media configuration consisting of 3 mm of water, a 3 mm thick cylindrical tissue-mimicking phantom, and 4 mm of water. Simulations were performed taking into account the acoustic properties of the media and the experimentally determined transducer source excitation. Agreement within 5% was achieved between measured and simulated amplitude spectra, compared for the first four harmonics, for a range of 50% bandwidth pulsed-wave source pressures ranging from 5-100 KPa. This model is capable of simulating realistic finite-amplitude propagation from high-frequency transducers through multilayered biological media, and is useful for the study of nonlinear ultrasonic fields in layered tissue, as well as for transducer design optimization.
CIHR, NCIC, ORDCF

P3U-Q-6 I9

ULTRASOUND HIGH FREQUENCY IMAGE OF HUMAN ESOPHAGUS IN VITRO

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Ultrasound has been widely used in clinical gastroenterology to obtain in vivo images of the digestive tract. However, the images are related to ultrasound commercial systems operating at frequencies between 7.5 and 12 MHz. In order to detect minimal changes in the esophagus wall, like cancer or displasia, the ultrasonic system must operate at higher frequencies to improve the image resolution. This work has the objective to present images of the esophagus wall in vitro. Basically, the ultrasound pulse echo system setup consists of a monocycle pulse generator exciting a PVDF transducer (center frequency at 31 MHz) and a high frequency pre-amplifier. The rf backscattered signal was sampled (sample frequency of 500 MHz) by a digital oscilloscope and transmitted, using the GPIB interface, to a microcomputer to process the image. The tissue sample was immersed in a saline bath at room temperature. The image, 5 mm wide and 35 mm deep, was formed by a linear scan of the sample at steps of 10 micrometers. The sample was obtained during the autopsy of a female with 44 years old died from lung cancer with liver metastasis. Visual analysis revealed a normal esophagus. The image shows six layers of the wall corresponding to squamous epithelium and lamina propria, muscularis mucosae, submucosa, circular smooth muscle, intermuscular connective tissue and longitudinal smooth muscle. The results demonstrate the potential use of high frequency ultrasound

to image the esophagus wall, with enough resolution to distinguish the several layers. Future work must consider diseased esophagus.
To CNPq, CAPES and FAPERJ

Session: P3U-R
TRANSDUCER TECHNOLOGY
Chair: V. Varadan
The Pennsylvania State University

P3U-R-1 I10

QUANTITATIVE ESTIMATION OF ACOUSTIC STREAMING EFFECTS ON ULTRASONIC POWER MEASUREMENT

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OBJECTIVE: At National Metrology Institute of Japan (NMIJ), we are developing an ultrasonic power measurement system by using a radiation force balance method for ultrasonic power standard in Japan. Our initial target frequency range is between 0.5 MHz and 20 MHz, and the power range in is between 1 mW and 500 mW. We have almost finished constructing the radiation force balance system and are now evaluating the measurement uncertainty of the system. It is important for accurate measurements to estimate the influence of the acoustic streaming accompanying the ultrasonic power measurement on radiation force method. In this paper, we will show the experimental results of quantitative estimation of the acoustic streaming on the ultrasonic power measurements by using two types of targets. The effects of the acoustic streaming on the radiation force balance method were measured quantitatively. **METHOD**: In order to estimate the magnitude of acoustic streaming in the radiation force balance method quantitatively, we measured the radiation force by using both an absorbing target and a thin PET film with a thickness of 5 μm and a diameter of 40 mm, which is identical to the size of the absorbing target. The total force applied to these targets can be calculated by the sum of the true radiation force and the force generated by the acoustic streaming. The PET film target is almost transparent, so generated radiation force is considerably weaker than the force generated by the streaming. If the propagation loss in the PET film is negligible, the ratio of true ultrasonic power measured by the absorbing target and by the PET film can be expressed as $2(1\text{-}T^2)$, where T is the measured ultrasonic transmission coefficient of the PET film as a function of frequency. By using these relationships, we can determine the ratio of the streaming component in the "ultrasonic power" in the case of using absorbing target **EXPERIMENTAL RESULT**: The ultrasonic powers obtained before and after removing the acoustic streaming were measured. The result shows that the measured ultrasonic power values are 10 to 20% larger than the values

where it is assumed that the acoustic streaming does not exist. **SUMMARY**: In this paper, we have estimated the effects of acoustic streaming on the ultrasonic power measurements quantitatively. It is important for estimating the total measurement uncertainties of this system.

P3U-R-2 I11

DEVELOPMENT OF MINIATURE HYDROPHONE WITH PZT FLIM DEPOSITED BY HYDROTHERMAL METHOD

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Recently, the PZT piezoelectric film deposited by hydrothermal method has been studied actively in our laboratory. This PZT film has piezoelectricity without polling process and it is easy to form the piezoelectric film on the substrate with complex shape by hydrothermal method. We reported about a water immerse type ultrasound sensor with an acoustic radiation area of 10mm x 10mm and resonance frequency of 3MHz in 2003 IEEE International Ultrasonics Symposium in Honolulu. A needle type ultra miniature hydrophone was developed by depositing PZT piezoelectric film with thickness of 20 μm on an end of a titanium wire with diameter of 0.3mm, length of about 150mm by the hydrothermal method in this time. It is desirable that hydrophone should have as small shape as possible in order to avoid from disturbance in ultrasound acoustic field to be measured by itself. Recently, needle type hydrophones using a tiny piezoelectric element with diameter of about 40μm. However regretfully, their body have similar sizes as conventional hydrophones with maximum diameter of a few mm and length of about 50mm in spite of tiny size piezoelectric element. Therefore, it was difficult to reduce disturbance by the hydrophones in acoustic field measurements. On the contrary, since the body of hydrophone developed in this study is the titanium wire with diameter of 0.3mm, the disturbance by our hydrophone in acoustic field measurement can be reduced remarkably. It was confirmed that receiving sensitivity of our hydrophone was about -270 dB (0dB=1V/μPa) in frequency range from 1 MHz to 20 MHz. We will report about the structure, frequency characteristics of receiving sensitivity, directivity etc. of our hydrophone developed using hydrothermal method.

P3U-R-3 I12

ENERGY AND PULSE CONTROL POSSIBILITIES USING ULTRA-TIGHT INTEGRATION OF ELECTRONICS AND PIEZOELECTRIC CERAMICS

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A high degree of integration between an ultrasound sensor and its associated electronics makes it possible to design ultra-tight systems with low power consumption. In this process, the simulation of a complete system including both mechanical and electronic parts enables effective optimizations on a system level. One effective tool to achieve this is the use of SPICE models for the piezoelectric devices and the ultrasonic transmission media together with models for the electronics.

This paper reports on the investigations of the energy consumption to generate ultrasound pulses with piezoelectric crystals, and compares measurements with system simulations where SPICE models are used.

An optimized ASIC driver stage in bare die format is mounted directly onto a 4 MHz PZ27 piezoelectric crystal which has a static capacitance of 5 nF. The setup enables precise measurements of the energy needed to excite of the crystal, and minimizes the influence of parasitic components. Measurement results show that a maximum energy consumption of 85 nJ is reached when an excitation pulse width of 120 ns is used. Further, the consumption is lowered when shorter and longer pulse widths are used, and reaches 70 nJ for excitation pulse lengths of 70 ns and 240 ns.

The total energy required to drive an ultrasound crystal consists of the energy to charge the static capacitance, the internal losses, and the energy transferred as sound. Further loss is introduced for nonadiabatic charging. This occurs when a fixed voltage source, e.g. a battery, is used to supply the circuit. The crystal is then charged and discharged regularly with a certain pulse width. The energy consumed to charge a crystal with a static capacitance of 5 nF to 5 V should then be 125 nJ, not considering internal losses and energy transferred as ultrasound. The same estimate is predicted by system simulations based on previously published SPICE models for the piezoelectric devices.

This estimate differs significantly from the measured results presented. To verify the procedure used, comparative measurements were made on a standard capacitor of 5 nF. This gave energy consumption very close to that predicted by the estimates.

As one step to investigate these differences, comparisons are presented in the frequency domain. The behaviour of the piezoelectric device has been measured with a network analyzer and is compared to simulated results. Further it is shown that the absence of wiring and interconnections between the electronics and the driven crystal in the setup used give excellent pulse control possibilities, and reduces the need for broadband electrical matching networks.

P3U-R-4 I13

TECHNIQUE FOR REDUCING VARIANCE IN TRANSDUCER ARRAY PULSE-ECHO RESPONSE

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Ultrasound imaging system performance is determined in large part by the weakest link in the processing chain. As digital technology evolves and costs less,

and as greater use is made of high bandwidth imaging modes (e.g. harmonic imaging) it becomes significantly more important to ensure that each transducer array is operating close to that of the original optimized design. Unfortunately, it is costly and sometimes impractical (in the case of very high frequency transducers) to control the critical dimensions and material properties of all transducer components. Consequently, there is interest in finding low cost approaches for circumventing the problems caused by variations in transducer performance. It is also observed that most modern high end systems have programmable waveform generators in the transmit signal path and / or a versatile digital filter in the receive signal path. While it is possible to measure pulse-echo responses of individual elements or form a composite pulse echo response of an array and store that in a system for the purposes of deriving an optimal compensation filter, this is somewhat cumbersome. In the approach used here, power absorbed (Re(VI*)) is measured and used as a surrogate for a measure of pulse-echo response. The advantage of using this measure is that the system can self-measure this parameter by tracking both applied voltage and current during a transmit firing. Thereafter, the electrical stimulation to the transducer was scaled by the ratio of absorbed power (versus frequency) in an ideal reference transducer to the measured absorbed power in the transducer in question. (The electrical stimulation approach used here can be replaced by using a similarly modified receive filter.) This procedure was investigated using a 1D thickness mode transducer model that included two matching layers that were allowed to vary randomly over a range +/- 15% (equivalent to approximately +/- 2 microns or 0.1 mils). In a simulation run involving 100 random designs, the spectral performance of the corrected transducer was observed to be much closer to desired spectral performance than for the original uncorrected case. The mean deviation of the pulse-echo response measured over the 20 dB bandwidth was reduced to approximately one third of the value obtained without using the compensation approach. Conclusion: A relatively simple and effective approach is described for compensating for manufacturing variations in transducer pulse-echo spectral performance.

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P3U-R-5 J13

HIGH DENSITY INTERCONNECTIONS FOR POLYMER ULTRASOUND TRANSDUCERS

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Polymer ultrasound materials such as polyvinylidene fluoride (PVdF) provide a cheap, mass producible means of manufacture for fine pitch array type ultrasonic transducers. Using modified semiconductor fabrication techniques it is possible to fabricate electrode structures from thin film metals, directly on the surface of the piezopolymer. Photolithographic techniques are used to define the pattern. A sawn kerf is not used as the acoustic cross talk coefficient is thought to be sufficiently low. The fine pitch of the elements needed for high frequency

array transducer applications presents a challenge when making the electrical interconnect to each electrode element. This issue is not exclusive to polymer based transducers and is seen when connecting to any fine pitch transducer. A solution presented in the literature is the use of Z-axis conducting polymer matrices such as those produced commercially, which are commonly used to make connections to LCD displays in watches, phones etc. The disadvantage of this method is that a certain amount of pressure needs to be applied to the connection and if this pressure is relaxed, the connection is discontinued. A development of the Z-axis polymer is that of the Z-axis adhesive. This takes the form of a photo initiated epoxy matrix with a dispersion of gold-coated hollow polymer spheres. The intended use of this product is to connect Ball Grid Array (BGA) type chip packages. This product has the advantage of being self-supporting in that pressure need only be applied during the cure process. Once cured, the two conductor faces are held in place by the epoxy and the coated polymer spheres maintain the connection. A method that utilises such a Z-axis adhesive to achieve high density interconnects between PVdF and the tracks on a PCB is presented. This process uses a 'hot bar' cure process to apply the heat and pressure to the appropriate area that forms the interconnect. In addition to the hot bar, there is a water-cooled block separated from the heated section by an insulator; this is necessary to avoid long range de-polarisation. The process is performed above the softening point of the PVdF film (130°C). The pressure applied to the 'hot bar' holds the film in place and the area in close proximity does suffer some distortion. This distortion is minimised by the water-cooling and using the current apparatus does not extend more than 1.5 mm from the connection area. To date the maximum pitch that has been attempted has been 250 μm. The elements are 220 μm wide on a 250 μm pitch. The PCB tracks are gold plated, 125 μm wide track with an equal gap. This allows for a large alignment tolerance. The method presented is a simple and cost effective means of making multiple high-density connections in parallel. Its use for other materials such as piezocomposites etc. is under investigation. This method is an effective alternative to the previously published use of Z-axis polymer films.

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Session: P3U-S

CMUT TECHNOLOGY
Chair: S. Smith
GE Global Research

P3U-S-1 J9

A LOW-NOISE, WIDEBAND ELECTRONIC SYSTEM FOR PULSE-ECHO ULTRASOUND IMAGING WITH CMUT ARRAYS

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The design of a front-end electronics for ultrasound imaging systems using CMUT arrays in pulse-echo operation needs several requirements. The electronic system must provide the transducer with a relatively high bias voltage for linear operation and high sensitivity; it must handle tone-bursts with amplitudes of tens of volts with low distortion, to drive the transducer elements in transmission; it must amplify the received echoes by adding low noise to achieve the large dynamic ranges required in pulse-echo imaging equipments; further, these functions must be carried out preserving the broad immersion bandwidth of CMUTs, which is desirable to obtain high image resolution, as well as to allow other operation modes like harmonic imaging. In this work, design criteria of a low-noise, wideband front-end electronics suitable for CMUTs are given. One important question to answer is which configuration of the receiving amplifier assures the best performance. The basic configurations of non-inverting and trans-impedance amplifier are both analysed, optimised and compared through PSpice simulations, by using a modern commercial op-amp as an amplifier, and representing the transducer with a model previously developed. Simulation results show that the main contribution to the system noise does not come from the input noise voltage and current of the amplifier, as expected, but from the external resistors. In addition, the trans-impedance configuration yields a signal-to-noise-ratio at least 10 dB higher than that of the equivalent non-inverting amplifier. A custom electronics is also implemented, having approximately 40 dB gain in a bandwidth extending from 1 MHz to 15 MHz, and the performances are evaluated using a fabricated 64-element CMUT array.

P3U-S-2 J10

A FRONT-END INTEGRATED CIRCUIT FOR 3D ACOUSTIC IMAGING USING 2D CMUT ARRAYS

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Integration of front-end circuits with 2D capacitive micromachined ultrasonic transducer (CMUT) arrays has been a challenging issue due to the small element size and large channel count. We present a front-end drive-readout integrated circuit suitable for 2D CMUT arrays used in 3D ultrasonic imaging. The circuit consists of a pulser for driving the CMUT array element by a high voltage pulse, a metal pad for connection to the CMUTelement, a low noise readout amplifier for buffering the received echo signal, and a switch for protecting the inputs of the readout amplifier not only from the DC bias of the CMUT but also from the high voltage pulser in transmit mode. We developed an equivalent electrical model for simulating the CMUT, where the model parameters were obtained through a finite element analysis using ANSYS. Based on this model we performed the pre-layout simulations for each sub-circuit using the Cadence Analog Artist, where a 10p̃F load capacitance was assumed to model the routing and off-chip parasitic capacitances. The layout of the circuit fits into 200×200 μm^2 area that satisfies the Nyquist spatial sampling requirement for a 2D transducer aperture operating at 3.5M̃Hz. We also performed post-layout simulations using the extracted circuit by Cadence Analog Artist and compared the results with the pre-layout simulation results to examine the possible effects of the parasitic components on circuit performance. We observed that the pre- and post-layout simulations were in agreement, proving the validity of our electrical model. The noise power at the output of the readout amplifier was measured as 6.45ñV/$\sqrt{Hz}$. An experimental chip consisting of 4×4 array of circuit cells was formed for the initial test studies and scheduled for fabrication in AMS 0.8 μm, 50Ṽ CMOS technology. The designed circuit is suitable for integration with CMUT arrays through flip-chip bonding or CMUT-on-CMOS process.
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P3U-S-3 J11

CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS (CMUT) WITH ISOLATION POSTS

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We report on a CMUT featuring isolation posts (PostCMUT) to solve a device reliability problem caused by charging during fabrication and operation. The PostCMUTs were fabricated using a newly developed process based on the wafer-bonding technique. Paired tests showed the superior reliability characteristics, obtained without ultrasonic performance degradation, of the PostCMUT design compared to those of earlier CMUT designs. PostCMUTs, the first design reported so far that solves the reliability problem, constitutes a key milestone in CMUT commercialization.

Even though single crystal silicon membrane CMUTs show improved mechanical reliability and yield compared to surface micromachined CMUTs they still suffer from charging problems. This is caused by trapped charges in the thin

dielectric layer used to insulate the electrodes. At least two sources of charges generated within this layer exist. One is the fabrication process and the other is the strong electrical field within the transducer cavities during operation. Charges can be trapped as well in surface/interface states as in sites within the dielectric layer, thus causing several deleterious effects as shown in this paper.

The PostCMUTs had one or a few oxide posts of desired height and pattern that replaced the oxide isolation layer between their electrodes. The area of the oxide posts was designed small enough so that charges trapped in them had a negligible effect on device operation.

The PostCMUTs were fabricated by a newly adapted wafer-bonding technique since they are difficult to fabricate using surface micromachining techniques. The PostCMUTs were fabricated as described earlier with one additional lithography step to pattern the silicon oxide layer. PostCMUTs with single crystal silicon 82 μm square membranes, 1 μm thick, were fabricated. The oxide post height was 0.3 μm. Conventional CMUTs with identical dimensions and a fully covered oxide layer (0.3 μm) were fabricated for comparison. The total oxide post area of the PostCMUTs was 45μm^2, i.e. 0.7% of the oxide area of the conventional CMUTs.

Our experiments showed that with conventional CMUTs the CV (capacitance-bias voltage) curve shape changed during a few initial tests due to a redistribution of trapped charges caused by the fabrication process. A subsequent 80 hour 30 VDC and 140 VAC, 2 kHz spiking paired test, caused all conventional CMUTs to show either a shift ($>$20V) in their operation point or permanent stiction of their membrane to the bottom electrode due to the field from induced charges trapped in the oxide layer. In contrast to this, charging was never observed with the PostCMUTs. With these devices the CV curve looked almost identical in the initial test and after the pulse test. No hysteresis, neither in the ultrasonic transmission nor in the reception tests was observed after the membrane had been in contact with the posts. This indicated that the PostCMUT design remedied another serious problem with conventional CMUTs operating in the collapsed region, namely hysteresis.

P3U-S-4 J12

COMPARISON OF MEASUREMENTS AND SIMULATIONS OF CMUT CELLS AND ARRAYS

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In recent years, much work has been done on the examination of capacitive micromachined ultrasound transducers (CMUTs). Compared to standard piezoelectric transducers, they have superior properties: they are fabricated with well established semiconductor processes which achieve very small fabrication tolerances and a high reproducibility. Further on, compared to piezoelectric transducers, CMUTs show higher bandwidths and, therefore, allow higher resolutions in ultrasound imaging equipments.

The modeling and simulation of CMUTs is still quite a challenging task. Modeling of CMUTs with lumped components is fast and allows a basic prediction of the behavior of the devices. But these models are subject to many simplifications and restrictions. In order to improve the evaluation of the parameters required for the simpler models, and to achieve better insight to the physics of CMUTs, analysis tools solving the constitutive equations are needed. Based on the finite element (FE) method, we are able to 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. This allows a more accurate rediction of the behavior of CMUTs.

Starting with the observation of a single cell, we compare measured and simulated data of the collapse voltage, the membrane displacement, the pressure pulse in the fluid for a given electrical excitation and the sensitivity of a receiving element. The mechanical and acoustic crosstalk and the shape of the pressure pulse are examined on CMUT-arrays. Again, we show comparisons of simulation and measurement results.

P3U-S-5 J6

THEORETICAL ANALYSIS OF MUT USING A SIMPLE 1D MODEL

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The new concept of Micro-machined Ultrasound Transducer (MUT) gives rise to new opportunities in the development of high density integrated imaging devices. The possibility to manufacture ultrasound transducers based on electrostatic forces (as first introduced by Khuri-Yakub et al.) has recently received a particular interest, from both theoretical and experimental points of view. Many analytical approaches have been proposed to develop efficient tools providing the most important characteristics (coupling, radiation pressure, acoustic impedance, etc.) of simple MUTs architectures (circular shapes of the membrane). The simulation of electrostatic excitation and fluid/structure interaction can be accurately performed using commercial finite element analysis (FEA) package (for instance ANSYS). However, most of these developments does not rigorously account for the periodicity of the corresponding structures, which is a typical feature of actually implemented MUTs. The present work proposes a very simple theoretical analysis based on the material resistance theory to describe the flexural motion of the MUT, associated with periodic Green's functions development to take into account radiation in water.

The proposed approach consists in using a 1D 2-node finite element of the Hermite's kind, which means that its elastic properties are described using 3rd degree polynomials for which the nodal unknowns are the displacements as well as the displacement gradients. It is then shown that only 2 elements are required to accurately describe the fundamental symmetric and anti-symmetric flexural vibrations, yielding an extremely simple but efficient model based on the

combination of only 2 algebraic equations. Radiation boundary conditions are taken into account by using a Bloch-Floquet development of the 2D Green's function formulation inserted in boundary elements at the solid/fluid interface. The corresponding equations are detailed and first results are reported, confirming previous conclusions obtained using other periodic FEA approaches but also enabling a simple and efficient analysis of actual MUTs working. The computation results particularly are used to derive mutual parameters (admittance, displacement, front velocity) providing an estimation of cross-talk phenomena. It is also shown how these results can be used to estimate the directivity of a probe based on MUT arrays.

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Session: P3U-T
SURGICAL TRANSDUCERS
Chair: S. Smith
GE Global Research

P3U-T-1 J7

FOCUSED ULTRASOUND THERMAL SURGERY, IMAGING, AND ELASTOMETRY USING THE SAME PHASED ARRAY: FEASIBILITY STUDY

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The goal of this study is to develop a multifunctional phased array which will perform the following tasks: Acquire B-scan images for therapy positioning, sonicate at high intensity for tissue ablation, and make tissue elastometry measurements for monitoring temperature elevations and tissue coagulation. In a feasibility study, we used a 24-element cylindrically curved 1.1 MHz linear array (curvature radius = 40 mm, element length = 30 mm, and l/2 element center-to-center spacing). The final version will be designed based on these results and will consist of 128 elements. The 24-element array was able to output enough power for tissue ablation and displacement and allowed for electronic beam steering of up-to 7cm off center without significantly disturbing the beam profile. B-mode imaging was acquired with five or six neighboring elements driven together in burst mode at the higher harmonic frequency of the array. Image scan sequences were controlled by a specially designed switchboard that designated the arrays elements for either imaging or high power mode. Elements assigned to high power channels can be used either for ablation or tissue displacement.

The resulting beam showed that in the diagnostic mode a good degree of collimation could be achieved with a beam width of about 4 mm at a distance of 35-45 mm from the transducer. The spatial resolution was between 3 and 4 mm. The axial resolution was between 1.0 and 1.5 mm. This is sufficient resolution

for targeting in therapeutic applications. The collimated beam from 5 elements was also used for tissue displacement estimation. In this case, displacement was created by short bursts (5-20ms) from the elements that surround the imaging elements. Imaging elements acquired A-mode signals. Displacement is estimated in the area of interest using a cross correlation technique. In order to show the feasibility of the method, we measured displacement for a silicone tissue phantom and registered changes in phantom displacement with a rise in temperature after high intensity sonication. The ultimate goal for elastometry estimation using 64-128 element arrays is to measure harmonic tissue displacement caused either by amplitude modulation of displacing HIFU signals or by local harmonic motion caused by sonication of the tissue with two focused ultrasound beams driven at slightly different frequencies.

The clinical goal is to develop a transrectal phased array applicator that can be used to ablate prostate tumors. The combination of the imaging, monitoring, and treatment in a single phased array will reduce the cost of the combined method and make treatment outcomes better by providing feedback for exposure control.

P3U-T-2 J8

DESIGN, FINITE ELEMENT ANALYSIS AND EXPERIMENTS STUDY ON ULTRASONIC TORSIONAL SURGERY TOOL

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Ultrasonic torsional transducers have been introduced in ultrasonic welding, ultrasonic motor etc. recently. The chief aim of this paper is to study the performance of torsional transducer used in ultrasonic surgery tools. Torsional vibration is more efficient than longitudinal vibration since maximum coupling can be achieved by transmission into tissue in a direction normal to the axis of the tool, which is very useful in cutting tissues like tendon, cartilage and bone etc. We designed torsional transducer with two longitudinal piezoelectric stacks normally placed to the direction of the tools axis, which convert the longitudinal vibration into torsional vibration. Design method is based on analytical method and FEA piezoelectric couple model, which could determine parameters such as the resonant frequency, dimension, torsional vibration angle, impedance, stress etc.We construct torsional surgery tools with different size and horn shape. Experiments are made to test performance of these tools and compare the cutting efficiency with longitudinal tools. Results show that torsional surgery tools have advantages in cutting bone and fibrous tissue.

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A MECHANICAL TRANSFORMER AND A FOCUSING APPLICATOR FOR THE TRANSMISSION OF ULTRASONIC WAVE THROUGH THIN ULTRASONIC TRANSMISSION LINE

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We have developed a method of transmitting ultrasonic wave through a thin sapphire fiber for interstitial ultrasound applicator. As we have reported previously, a sapphire fiber with a diameter of 100-200 microns can be used as a flexible transmission line well above few tens of MHz range [1]. In order to transmit ultrasonic wave through a thin transmission line (we use sapphire fibers with a diameter of 200 microns), developments of an efficient transformer from a transducer to the transmission line, and an emitter from the transmission line to tissues are required. Mechanical Transformer: We designed two types of mechanical transformers, one is a conical cone transformer and the other is a tapered rod. Using PZFLEX, conversion efficiencies for both transformers were obtained for the propagation of ultrasonic wave at 2.25 MHz. The diameter of the transducer was supposed to be 3 mm. According to the analysis, a mechanical transformer in a shape of a tapered rod was constructed using Alumina ceramics. The sapphire fiber was inserted in the hole of the rod and bonded, and the transducer with the diameter of 3mm was bonded at the base of the rod. The conversion efficiency with the transformer was enhanced 14 dB at 2.5 MHz, as compared to the one without the transformer. Focusing Applicator: Ultrasonic wave radiated from the surface of the rod is directed. Therefore by using an elliptical mirror, the ultrasonic wave can be focused. We manufactured a semi-elliptical mirror and tested at 2.25 MHz. The ultrasonic wave was radiated from a fused quartz rod with a diameter of 2 mm. The rod was placed in the mirror and the ultrasonic field was measured using Acoustic-Intensity-Measuring System, NTR Systems, Inc. The ultrasonic field radiated from a mirror with the diameter of 11.5 mm was focused in a region of approximately 2 mm dia. $\times$ 6 mm. [1] T. Moriya, et al, 2003 IEEE Ultrasonic Symposium, P1N-4

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Session: P3U-U
ULTRASONIC MOTORS AND ACTUATORS
Chair: Y. Yong
Rutgers University

P3U-U-1 J4

LOCALIZED HEATING EFFECTS OF LIQUID BASED ON SAW STREAMING

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When a liquid droplet is placed on a surface acoustic wave (SAW) propagating surface, a longitudinal wave is radiated into the liquid. The droplet dynamics depends on the SAW amplitude. With increasing the SAW amplitude, liquid droplet becomes stream, jet and atomization. This phenomenon is known as SAW streaming. We pay attention to the droplet temperature during SAW streaming phenomenon, because it is well known that the temperature of a piezoelectric crystal surface increases with increasing SAW amplitude. A 128YX-LiNbO3 single crystal was utilized as the SAW substrate. The SAW delay line with two interdigital transducers (IDTs) was fabricated on it. The liquid thin film, which was supported by a filter paper, and liquid droplet were placed in the center of the IDTs. A pulse modulated RF frequency signal was fed to the IDT. In the measurement, the pulse width is fixed at 1 ms. We measured the liquid temperature by changing duty cycle, and applied voltage. The temperature was measured by a thermoelectric thermometer. First, we measured the temperature of the water thin film. The SAW was generated from one IDT. The experimental results show that the saturated temperature of liquid was the function of applied voltage and duty cycle. The maximum temperature was 90 °C at 35 Vpp and 75% of duty cycle. The time constants for rise and fall due to switch off were below 20 seconds. This means that the rapid heating and cooling are possible by the SAW. The temperature distributions on the crystal surface were measured. The results show that the only edges and inside the acoustic path of the filter paper with water were heated. Therefore, we concluded that localized heating is possible by SAW streaming. Second, the temperature of the water droplet of 10 μl was measured. Due to avoid moving of the droplet, the SAW was generated from the two IDTs. As the water droplet became jet or atomization at high-applied voltage, the measurements were carried out below 25Vpp. The maximum temperature was 50 °C at 25Vpp and 50% of duty cycle. The time constants for rise and fall were also about 20 seconds. We also measured the temperature of glycerol/water mixture droplet. When concentrations of those were higher than 40 wt.%, the maximum temperature is higher than water droplet at the same condition. This is due to the viscous damping of the longitudinal wave. Therefore, the temperature is depended on

the liquid viscosity. For the high viscous solution, the liquid stream, jet and atomization prevent. High voltage signal can be applied to the IDTs. Moreover, we succeeded to continuous temperature control, such as 23 °C-50 °C-30 0°-45 °C, by changing applied voltage. The obtained results indicate that a novel micro-liquid heating system is realized by the SAW device.

P3U-U-2 K1

DEVELOPMENT OF A MULTILAYER ACTUATOR WITH PMN-PT SINGLE CRYSTALS FOR AN IMPLANTABLE HEARING AID

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Conventional hearing aids employ either electromagnetic transducers or piezoelectric bimorphs. The electromagnetic devices do not have wide enough bandwidth and thus suffer from sound distortion and acoustic feedback. The piezoelectric bimorphs are fragile and do not provide big enough force to compensate for deep hearing loss. We developed a multilayer actuator with piezoelectric single crystals, PMN-PT, for a new implantable hearing aid. The actuator is used as an ossicular vibrator coupled to the stapes of human cochlear linkage to efficiently transmit high frequency vibration signals to the inner ear. The vibration signal is coming from a miniature microphone and hearing aid electronic circuits implanted behind the auricle. The actuator in this work has a multilayer structure to overcome the shortcomings of the conventional devices, and can afford big enough force and vibration displacement to the stapes of cochlea while maintaining structural robustness. The actuator was made of PMN-PT single crystals for good electromechanical energy coupling efficiency while preserving small dimensions. Layers of biocompatible materials coat the actuator for implantation in human middle ears. The PMN-PT crystal was grown by the Bridgman method. Detailed structure of the actuator was designed through finite element analysis and its performance was measured through experiments. Miniature actuators were fabricated to have fifteen layers of PMN-PT crystals and have the dimension less than 1 mm. The actuators were measured to provide up to 1 micro-meter displacement with 5 V driving voltage, which is large enough for practical application to hearing aids. Through experimental impedance analysis and numerical finite element analysis, detailed performance of the actuator is compared with that of electromagnetic transducers.

A NOVEL ULTRASONIC MOTOR WITH A BUILT-IN CLUTCH MECHANISM FOR A FORCE-FEED-BACK ACTUATOR

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This paper presents a novel ultrasonic motor devised for application to a force-feed-back device used for a haptic virtual reality system. A rapid reactive force generation enables to present the realistic touch of a surface roughness and hardness on a virtual object. Ordinary ultrasonic motors (USMs) have a quick response compared with electromagnetic motors (EMMs) that are normally used for a force-feed-back device. EMMs can generate a torque free condition and counterforce. However, a torque free condition doesnt exist on USMs. The existing position can be maintained because of the frictional force between the contact surfaces. Hence, it will be hard to control a rotor by external force even though a good drive control technique would be developed. From above reasons, to have a clutch mechanism within a USM is devised and produced in this study. A stator consists of two multilayer piezoelectric actuators (MPAs) in a line, a metal case for holding MPAs, and a L-shaped thin plate, which forms a triangle with the metal case. The plate functions as a displacement magnifier and the control of a frictional force between the stator and rotor. Key points of this USM are the driving technique of MPAs. For a USM operation, MPAs are driven by two-phase ac voltage. A rotor rotates by an elliptic motion formed at the corner of the plate. For a clutch-off operation, MPAs extracted by dc voltage make the corner of the plate move toward the metal case of the stator and the plate separates from the rotor. By some experiments, it is confirmed that a contacting force between the rotor and plate decreased with MPAs extraction by an applied dc voltage. The plate had a displacement over 30 μm and the response time of approximately 0.3ms. The rotor rotated by the driving signal of an ac voltage of 50 Vpp. When superimposing the clutch-off signal of 50V dc voltage to the driving ac signal, the rotor separated from the stator and the rotor revolution speed decreased up to zero. It means the clutch-off operation was just working. Removing the clutch-off signal, the rotor rotated again rapidly. From those results, the operation of the novel ultrasonic motor with a built-in clutch was confirmed.

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PREDICTION METHOD FOR THE FUNDAMENTAL RADIAL MODE OF MULTI-MODE ULTRASONIC MOTORS

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Previous developments in micromotors suggest that piezoelectric ultrasonic motors possess significant advantages over electromagnetic and electrostatic devices with regard to torque and power output. With regard to microfabrication, the design originally reported by Koc et al., is particularly attractive due to its minimal number of components, simple configuration and single-phase drive system. The stator of this ultrasonic motor is composed of a piezoelectric ceramic annulus bonded to a thin metal annulus with four inward pointing arms at its inner circumference. These arms are in permanent contact with the rotor, positioned along the axis of the motor system. Motor efficiency is maximised when the radial mode of the piezoelectric ceramic annulus is matched to the bending mode of the metal arms, creating tangential forces on the rotor. However, design optimisation is not straightforward, as multiple mode coupling can lead to catastrophic failure of the intended mechanism. Although finite element modelling can be employed to evaluate different motor assemblies, a first cut analytical approach for approximation of the arm bending modes and ring radial modes is required. This can be particularly problematic for low values of the ring G-ratio, the ratio of the inner to outer diameter.

In order to overcome the limitations of the existing analytical equations for radial mode approximation, a finite element modelling method was used. The PZFlex software was employed extensively to compute resonance frequency spectra and electrical impedance graphs for annuli fabricated from a range of ceramic materials and G-ratios ranging from 0 to 1. Five different piezoelectric ceramic materials were investigated: Ferroperms PZ21, PZ27, PZ29, and TRSs PZN 4.5% PT and PZN 8% PT. An impedance analyser was used to measure the fundamental radial mode of a PZ21 annulus with a thickness of 5 mm. Very good agreement was seen between the results obtained by the finite element modelling and the impedance analyser (7.7% error), providing practical validation of the modelling method. Using existing analytical theory, the percentage errors increased to 67.9% and 201.1%. Best-fit line equations were calculated for the frequency vs G-ratio plots derived by the finite element modelling. For all of the cases tested, the mean absolute error between the modelled and the best-fit data ranged from 1.6% to 7.2%, with the standard deviation varying from 0.9% to 4%.

This approach was then used, in conjunction with a previously reported analytical solution for extraction of the arm bending modes, to design suitable multi-mode motor assemblies. These were then evaluated using finite element models of the complete motor assembly and good results were obtained.

P3U-U-5 K4

CHARACTERISTICS, MODELING AND SIMULATION OF A TRAVELLING WAVE ULTRASONIC LINEAR MOTOR

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Within the framework of a comparative study on two types of linear ultrasonic motors, the first one using the standing wave method and the second one the traveling wave approach, a prototype of a standing wave ultrasonic linear motor has been realized and studied. In this paper, the attention is related to the characteristics of a traveling wave ultrasonic linear motor. After a brief state of the art of that type of motor, the working principle is presented. It is based on piezoelectric actuators that convert electric energy to mechanical energy in the form of vibrations of an elastic body. The points at the surface of the vibrating stator perform an elliptic motion with a frequency in the ultrasonic range. The slider, which is pressed against the vibrating body by a prestressing force, can move linearly thanks to the friction forces presented at the interface between the stator and the slider. To describe this phenomenon, an analytical model is built using wave theory and contact mechanism laws.

Analytical modeling is then validated by FEM simulations. Transient and steady-state responses of the system are obtained. As a function of the voltage applied to the piezoelectric ceramics, the deformation amplitude of the stator is achieved. Harmonic analysis is also performed to find out the resonance frequency of the system and thus achieve a maximal amplitude response. Different geometries and materials are simulated with the aim of obtaining the greatest deformation amplitude. The comparison between the results will be helpful to choose the best solution for the construction of a prototype and a test bench.

The different results will then make it possible to validate the analytical model and show if the hypotheses made at the beginning match with the reality. These results will then help us to optimize the motor performances, specially to improve the slider driving force and velocity by varying parameters like material properties, geometrical dimensions or prestressing force. Furthermore, the comparison between the two types of ultrasonic linear motors, the standing wave type and the traveling wave type, will allow a case study depending on the application, which appears to be of great help, especially in the pre-study process, where one of these two different motor types is to be chosen.

AN EFFECTIVE FREQUENCY TRACKING CONTROL AND BALANCING COMPENSATION BETWEEN CW AND CCW ROTATION SPEED TECHNIQUES FOR ULTRASONIC MOTOR

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The relationship between the rotation speed of an ultrasonic motor (USM) and its driving frequency behaves nonlinear with time-variability. The rotation speed of the USM is progressively reduced as its temperature rised with material and frictional losses. Furthermore the performances of the USM when rotating clock-wise (CW) and counter-clock-wise (CCW) are inconsistent. As a result, the practical applications of USM are limited. In this paper, we show the research on the speed control techniques of a traveling- wave type ultrasonic motor. At first, we take an effective way to adjust the speed of the USM by changing the driving frequency. As it is known, the speed frequency characteristic of the USM looks like a mountain-shaped curve having a peek at the resonant frequency of the stator, and this curve keeps shifting with the rise of the temperature. To detcect the speed, a sensor, which is a segment (isolated electrode) of the piezoelectric ceramic element bonded on the stator of the USM, is used. The sensor's output voltage is linear with the rotation speed. Based on this fact, a USM speed controller, which consists of a PI (Proportional-Integral) circuit, VCO (Voltage Controlled Oscillator) and sensor signal processing circuit, is designed to eliminate the nonlinearity and time-variability. In order to ensure the stability of the controller, some measurements are taken in order to let the driver always operate at the right hand of the peek of the mountain-shaped curve, and at the same time it can approach the peek. Second, aiming at losing balance between the CW and CCW rotation speed, a balancing compensation algorithm is put forward, and which is implemented with hardware. The experimental results show that after putting the speed controller and balancing compensation controller together into the driver, the speed of the USM possesses of linearity and time-invariability with a command voltage, and the CW rotation speed of the USM have a better accordance with the CCW. The good performance and the small size of the driver make the USMs that we have developed to be put into practical use.

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P3U-U-7 K6

EXPERIMENTAL STUDY OF HEAT RADIATING SYSTEM IN ELECTRONIC APPARATUS USING ELECTRO-MECHANICAL VIBRATOR PUMP

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We propose a new type water pump equipped in electronic apparatuses, because such electronic apparatuses as a personal computer and so on are faced with severe heat storage in themselves. Therefore, we have studied water-cooling systems to radiate the heat stored in such apparatuses. This paper deals with experimental considerations of a heat radiation system using an electro-magnetic drive-type vibrator. The heat radiating system proposed here is composed of a flat type tuning fork driven by electro magnetic elements and a water course formed on an acrylic plate surface. The vibrator is 35l x 24w x 0.4t [mm^3] and a thin plastic plate is attached at the every top of the arm of tuning fork. The tuning fork vibrator is placed in the water course and driven by electro magnetic elements placed out of the water course. The vibrator is excited in its asymmetric vibration mode and the driving frequency is about 200[Hz]. The vibration displacement of the vibrator in water and the water streaming were considered experimentally changing the input voltage and the driving frequency. As a result, the strong water streaming through the course was observed when the input voltage is from 1 to 2[V] and the driving frequency is from 190 to 210[Hz], and then the velocity of the streaming was from 1.5 to 7.8[cm/s]. At last, water cooling effects of the trial system were also measured. It was confirmed from these fundamental experiments that the system presented here operates effectively for a water cooling system to radiate the heat stored in electronic parts.

P3U-U-8 K7

OPTIMAL DESIGN ON STATOR OF A 3-DOF ULTRASONIC MOTOR

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We have developed a 3-DOF ultrasonic motor with a cylinder-shaped stator and a spherical rotor. The ultrasonic motor provides 3-DOF rotations around x, y, and z-axes, which is implemented by two second-order bending modes with orthogonality and first-order longitudinal mode of the stator. The three modes must satisfy following conditions: (1) the differences between the three modal frequencies are as small as possible; (2) a piezoelectric ceramic group for exciting

longitudinal mode is located on the modal node plane; (3) two piezoelectric ceramic groups for exciting bending modes with the same shape are located on the modal wave peak or valley. In our previous research, in order to satisfy these conditions, a parameter fitting design method is used. However, it is an experiential design method with low efficiency and time consuming , sometimes we could not obtain a desired solution. This paper puts forward an optimal design method on the stator. First, some design variables, such as characteristic lengths L1, L2, L3 and L4 of stator, are defined by dynamic sensitivity analysis. Second, a mathematical model for the stator is established by combining FEM and analysis methods. Based on the model and mentioned above conditions, an objective function used in the optimal design is established selecting L1, L2, L3 and L4 as the optimal parameters. Finally, the Constrain Variable Metric (CVM) method is adopted for searching optimal parameters, and an optimal design program of the stator is developed in the MATLAB environment. Authors designed and implemented a prototype 3-DOF ultrasonic motor and a stator with diameter 20 mm, height 67 mm, and mass 157 g from the optimal design program. The paper also gives the optimal design process for the stator in detail. The modes of the stator have been measured using Polytec Company PSV-300F-B type Laser Doppler Vibrometer. The experimental results show that the stator's modes and modal frequencies measured are consistent with the results obtained by the optimal design program that saves a lot of time.
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P3U-U-9 K8

NOVEL HORN DESIGNS FOR POWER ULTRASONICS

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A variety of Industrial applications exist where power ultrasonic elements such as the ultrasonic horn are used. These included the Automotive, Food Preparation, Medical, Textile and Material Joining and Fabrication Industries. In many of these devices the ultrasonic horn is a key component. The standard transducer used in these devices consists of three main parts, the backing, the piezoelectric elements and the horn. Standard horn designs have changed very little since their inception. There are four common types of horns. They are; constant, linear, exponential and stepped, which refer to the way in which the area changes from the base to the tip. A magnification in the strain occurs in the horn that in general is a function of the ratio of diameters. In addition the device is generally driven at resonance to further amplify the strain. The resonance amplification is determined by the mechanical Q, which is dependant on the attenuation of the horn material and radiation damping. The horn length primarily determines the resonance frequency. At JPL a rock-sampling tool based on an ultrasonic horn was developed to drill, abrade and core rock samples including hard basalts. This device is an ultrasonically fed impact device, which uses the ultrasonic vibrations of the horn tip to feed a sonic resonance of a loosely connected mass.

Although these standard horns are found in many current industrial designs they suffer from a few key limitations when used for USDC applications. In addition, manufacturing a horn requires the turning down of the stock material (e.g. Titanium) from the larger outer diameter to the horn tip diameter, which is both time consuming and wasteful. In this paper we will present novel horn designs, which overcome the length limitation discussed above and also describe horns that are specifically designed for impact work. A particular design that has been found to overcome the length limitation is the folded horn. In this design the horn elements are folded which reduce the overall length of the resonator (physical length) but maintain or increase the acoustic length. In addition initial experiments indicate that the tip displacement can be further adjusted by phasing the bending displacements and the extensional displacements. A further modification is the dog bone horn, which uses an end mass on the horn tip to increase the impact efficiency of the horn. The experimental results for these and other novel horn designs will be presented and compared to the results predicted by theory.

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P3U-U-10 J3

CONFIGURATIONS OF ULTRASONIC MOTORS USING MULTIPLE LONGITUDINAL TRANSDUCERS

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Vibration and load characteristics of 65 kHz and 30 kHz ultrasonic motors with multiple bolt-clamped Langevin type PZT longitudinal transducers (BLT) of 20 mm diameter are studied. To obtain the motor with strong structure, two types of ultrasonic motors, which are driven by longitudinal vibration systems, are proposed and studied. One is a 65 kHz ultrasonic motor using a complex transverse vibration rod and a longitudinal vibration circular disk with three longitudinal transducers. Three longitudinal transducers are installed normally along the circumference of the circular disk and transverse vibration rods are installed normally in the center of the circular disk. Three longitudinal transducers are driven simultaneously with phase difference of 120 degrees using three 500 W static induction transistor power amplifiers and an arbitrary waveform generator with three output voltages of phase difference 120°. The complex transverse vibration rod is driven in a circular vibration locus. The other type is a 30 kHz ultrasonic motor using a torsional vibration cylinder with three BLT longitudinal transducers of 15 mm diameter and a BLT longitudinal transducer of 30 mm diameter for driving the cylinder longitudinally to inducing vibration to the driving surface. Three longitudinal transducers are installed spirally along the circumference of the cylinder. Three longitudinal transducers are connected in parallel and are driven simultaneously with in phase using one power amplifier. A rotor is pressed statically to a driving surface using a nonlinear static

pressure source for inducing static pressure that is consists of metal spring and nano-carbon plastic rubber spring. The nonlinear characteristics of static pressure source for inducing static pressure to the driving surface and the rotor was studied for improving the load characteristics of the motor. Maximum revolution 200 rpm and maximum torque more than several Nm were obtained in this stage and there are possibility to increase the torque by improving the static pressure source and adjusting resonance frequencies of the consisting elements of the system.

P3U-U-11 J2

A SIMPLE MODEL OF A MULTI-LAYER PIEZOELECTRIC LONGITUDINAL ACTUATOR

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A simple approximate model of a multi-layer piezoelectric longitudinal (PZT stack) actuator has been developed. The commonly used PZT stack actuator is composed of numerous very thin layers of lead zirconate titanate (PZT) which are spatially laminated in series, but electrically connected in parallel. Each layer may be treated as a separate domain mechanically and electrically, but the degree of complexity inherent in such a model is prohibitive, and fortunately, unnecessary when only the gross dynamics of the structure, the motion, the stresses and force potential, are needed. The model treats the entire PZT stack as a single domain, and can account for various boundary conditions and the presence of stress bias. Predicted and measured impedance magnitudes compare favorably.

P3U-U-12 J1

TORQUE CONTROL OF A ROTARY TRAVELING WAVE TYPE ULTRASONIC MOTOR IMPRESSED HIGH LOAD TORQUE IN LOW SPEED RANGE

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A rotary traveling wave type ultrasonic motor (USM) impressed high load torque in low speed range is modeled using an equivalent circuit and a new torque control method without an external torque sensor is proposed to apply to a robot manipulator. Torque control experiments are conducted using this proposed control method to verify the equivalent circuit model. As an alternative to an electromagnetic motor, the USM has been attracted considerable attention. The rotary traveling wave type is more commonly used on industrial applications. In the traveling wave type USM, two orthogonal vibration modes are excited to resonance by piezoelectric ceramics. The stator that vibrates at resonance frequency synthesizes a traveling wave and the rotor that contacts the stator on

the crest of the traveling wave under pressure is driven by frictional force. Some studies about the USM are reported in past years. J. Maas and P. Ide et al reported the traveling wave type USM modeled using a basic equivalent circuit. Y. Kyodo reported torque control analysis based on the concept of equivalent circuit and mechanical internal resistance. However, conventional approaches are lack of adequate consideration of characteristic fluctuations caused by piezoelectric effect or load torque, so torque control of the USM without the external torque sensor still is not realized with high load torque in low speed range. A new model and control method are required to control torque of the USM. Firstly, the USM is modeled using the new equivalent circuit based on piezoelectric equations and a mechanical model. In mechanical approach, the ratio of the vibration speed of the stator to rotational speed of the rotor is assumed as 1: n, where n is a smaller variable than 1. According to this proposed equivalent circuit, if vibration amplitude of the stator stays constant, output torque of the USM is proportional to voltage magnitude applied to piezoelectric ceramics. Secondly, torque control method is proposed. Three parameters of two sinusoidal voltages: frequency, magnitude and phase difference are determined. Phase difference is 90 deg to keep driving efficient. Frequency is appropriately modulated to keep vibration amplitude constant. Vibration amplitude is measured from a sensor attached on piezoelectric ceramics and fed back to oscillation controller. Magnitude is controlled in accord with a value calculated from rotational speed and desired output torque. Next, controlling system is setup using field programmable gate array (FPGA) and digital signal processing (DSP) which rapidly process complex tasks in real time. Then torque control experiments are conducted. According to experimental results, torque control of the USM is realized by means of this proposed method. Validity of the model and the proposed control method is shown. Finally, this proposed method is applied to a robot manipulator.

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Session: P3U-V
ACOUSTIC AND OPTICAL SCATTERING
Chair: D. Hecht
DLH Laboratories

P3U-V-1 K9

AN OPTICAL TUNABLE NOTCH FILTER USING AN ULTRASONICALLY INDUCED LONG PERIOD FIBER GRATING

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This report presents experimental investigations of an ultrasonically generated optical fiber grating with a tunable center wavelength, a variable attenuation

and an arbitrary rejection band profile. A piezoelectric transducer is attached to a standard single mode fiber to excite a flexual ultrasonic vibration along the fiber. A periodic modulation of refractive index is induced by the ultrasonic vibration, and results in optical transmission loss at a specific wavelength decided by the modulation spatial period. The period is much greater than the optical wavelength, and a part of the propagation optical power is transferred to cladding modes. This is known as a long period optical fiber grating: a key device for wavelength division multiplexing communication. A dynamic tuning capability of center wavelength and rejection band profile is highly required. In the first part of this report, the authors pointed out the effects of polymer coating of the fiber on the acoustic absorption, and succeeded in exciting flexual traveling vibrations along the fiber at the frequency range from 200 kHz to 500 kHz. The ultrasonic wavelength was a few mili-meters at these frequencies. The stable optical notch filter characteristics were obtained using the traveling vibration with a good standing wave ration, while the optical attenuation level was modulated at the double of the ultrasonic frequency if the standing wave vibration was stimulated. A wide tunable range of 160 nm (from 1490 to 1650 nm) in optical wavelength was available for ultrasonic frequency range of 300 kHz, which covers the commercial optical communication band. Our experiment showed that the optical rejection band-width became smaller as the fiber length, and the band width was 2 nm for the optical fiber of 400 mm long. The rejection ratio was increased monotonically as the vibration amplitude of the fiber. A large rejection ration of 17 dB was achieved for the vibration velocity of 0.25 m/s. Being based on these results, we propose a novel method to change the rejection band profile. A twin-notch profile was successfully synthesized by frequency shift keying of the ultrasonic driving signal. This report studied the relationships between the keying frequency and duty ratio and the resultant attenuation band profile.

P3U-V-2 K10

WAVEGUIDE-TYPE ACOUSTOOPTIC FREQUENCY SHIFTER WITH HIGH DIFFRACTION EFFICIENCY DRIVEN BY SURFACE ACOUSTIC WAVE

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A new type of laser, called the frequency shifted-feedback (FSF) laser, with unique spectral properties has been developed and is noted for its potential applications in the measurements of hydraulic pressure, atmospheric temperature, and fiber dispersion. The FSF laser operation is achieved by feedback of the first-order diffracted light of an intracavity acoustooptic frequency shifter (AOFS). To realize the integration and stabilization of the AOFS, we have previously proposed the waveguide-type AOFS driven by a surface acoustic wave

(SAW) in a tapered crossed-channel proton-exchanged (PE) optical waveguide on a 128° -rotated Y-cut $LiNbO_3$ substrate for an optical wavelength of 1.55 μm [1]. A 35% diffraction efficiency was obtained for the length of the AO interaction region of 2 mm and the driving frequency of 200 MHz. In this paper, to clarify the condition for driving the AOFS with higher diffraction efficiency, the SAW power required for 100% diffraction (P_{100}) dependences of the length of the AO interaction region and the driving frequency are investigated. First, the AOFS with the length of the AO interaction region of 3 mm and an interdigital transducer (IDT) with a period length of 20 μm was fabricated. The fabrication conditions of the waveguide were the same as those given in the previous paper [1]. The diffraction property was measured at the driving frequency of 200 MHz. The peak of diffraction efficiency of 65% was obtained at the input voltage of 14 V_{rms}. The reduction of the undiffracted light power reached 90% at 17 V_{rms}. Theoretically, there should be no difference between the two voltages, however, a difference of 3 V_{rms} developed. At the voltage of more than 10 V_{rms}, the reduction of the undiffracted light power did not agree with the increment of the diffracted light power. This means that 25% of the input light power was lost or scattered. An optimization of the waveguide shape is needed to solve these problems. Next, a similar AOFS with an IDT with a 32 μm period length corresponding to the driving frequency of 125 MHz was fabricated. The SAW power at the reduction peak of the undiffracted light power was defined as the measured P_{100}, and was determined from the measured vertical particle displacement by means of an optical probe method. The measured P_{100} was 0.59 W, and was smaller than that at the driving frequency of 200 MHz by 30%. These measured values were in agreement with P_{100} calculated using a coupled mode theory which showed that there is an optimum driving frequency for each PE depth. Furthermore, FSF laser oscillation and an optical distance measurement with this AOFS were demonstrated. [1] S. Kakio, et al., Proc. 2003 IEEE Ultrasonics Symp., p.1808.
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P3U-V-3 K11

DEPENDENCE OF POISSON'S RATIO ON POROSITY IN NANOPOROUS FILMS USING BRILLOUIN LIGHT SCATTERING

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The mechanical properties of porous materials are known to depend strongly on porosity. Recently, nanoporous polymer and silica films have gained prominence for their use in low-dielectric-constant (low-k) applications in microelectronics. Use of low-k insulators promises to continue the trend of microelectronics miniaturization by reducing interconnection delay, crosstalk and power loss. The most

promising way to achieve low-k materials is by introducing porosity into materials that already possess a low dielectric constant. However, there is a lack of useful techniques to characterize their mechanical properties, especially the dependence of mechanical properties on porosity. This information is vital for accurate finite element modeling and for calculation and measurement of thermal expansion coefficients. Although Poissons ratio is one of a materials most important mechanical properties, theoretical predictions of the dependence of Poissons ratio on porosity are confusing. Depending on the author, Poissons ratio has been predicted to increase, decrease or stay constant as porosity varies. Thus there is a pressing need for accurate experimental measurements to prove or disprove different theoretical models.

To meet this need, we have applied Brillouin light scattering (BLS) for the first time to measurement of Poissons ratio in nanoporous methylsilsesquioxane polymer films. We studied five samples, all approximately 1 μm thick, with porosity in the range 14 to 40
show that BLS allows one to measure several different phonon modes in the same sample. Poissons ratio can be extracted by combining velocity information from the different modes. In these samples, the measured Poissons ratio decreased from 0.32 to 0.22 as the porosity increased over the measured range. This is a much more rapid decrease than is expected based on available models. We compare our results to predictions from several different authors. The observed behavior is qualitatively compatible with recent finite-element work and indicates problems with some of the theoretical predictions available. Thus, we demonstrate that BLS can provide quantitative values for Poissons ratio in nanoporous thin films that not only enable theoretical predictions to be tested, but also provide useful, previously unavailable, data for Poissons ratio of commercially important low-dielectric-constant films.

P3U-V-4 K12

DESIGN OF FUNCTIONAL DEVICES WITH RESONANT FILTER WITH A SIMPLE SONIC CRYSTAL STRUCTURES

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With the analogous to the photonic crystal device, the sonic crystal device has a possibility to perform various kinds of functional operations such as filters and wave-guide circuit component, with extremely smaller size. In case of the scale of structural size with matching acoustic wavelength and light wavelength, novel acousto-optic devices would be expected. In this paper, we study on a sonic crystal device, which would be applicable for functional devices used for sensing systems and communication systems. As the fundamental approach, we have fabricated a relatively large size test devices using diamond drill art works.

The device consists of array of hales with the size of around 100 μm on flat piezoelectric substrates. The size and the arrangement of dots are changing in order to investigate wave propagation properties such as a resonant and a scattering. We have measured the basic characteristics, such stop band characteristics and wave propagation in the sonic crystal. We estimated effects of the discontinuity, such as size and position of holes in the array. The results showed the possibility for realizing functional devices. We present the experimental results and indicate the possibility for realizing integrated functional devices with sonic crystals in a chip. We are now fabricating smaller size devices with the structure size of around several μm, one is MEMS technology using silicon substrate, the other is focus ion beam etching process using piezoelectric substrate.

Session: P3U-W

NDE IMAGING
Chair: N. Bilgutay
Drexel University

P3U-W-1 L13

SURFACE-BREAKING FLAW EVALUATION USING AN ADAPTIVE LASER ULTRASOUND SYSTEM WITH A PHOTO-REFRACTIVE QUANTUM-WELLS

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An optical two-wave mixing system with a photo-refractive quantum-wells is developed for characterizing cracks in noisy environment. An AlGaAs / GaAs multiple quantum-wells photo-refractive device features a quick response time of 10μs, thus enabling the system to cancel the disturbances caused by rough surfaces or mechanical vibrations of samples. Surface acoustic waves generated by a line-focused Q-switched Nd:YAG laser are used for flaw characterization. The incident laser energy was kept low enough to avoid damaging the sample surfaces. The Surface-breaking slots (distance: 5 15mm, depth: 1-9 mm, Angle: 30 150 deg and width: 0.2mm) were evaluated with a precision of 0.2mm using the system. Distances between the receiving point and a fatigue crack (distance: 5 15mm, depth: 5.5mm and) were also successfully measured.
This study was supported by the Budget for Nuclear Research of the MEXT, Japan

P3U-W-2 L12

QNDT OF SURFACE TILT DEFECTS BY PHOTOACOUSTIC MICROSCOPIC IMAGING

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In this study, basic experiments on quantitative nondestructive testing (QNDT) of simulated surface tilt defects using photoacoustic microscope (PAM) have been demonstrated. The specimens used in the experiments were pure aluminum plates. Surface tilt defects were fabricated in a specimen. The surface tilt defect was the slit-type simulated defect, whose length was fixed to be about 4.0 mm. The surface tilt defect with a width of 0.3 mm was introduced into the specimen by mechanical processing. The depth and angle values of the surface defects were 0.3 mm and 60, 70, 80 and 90 degrees in nominal value, respectively. The photoacoustic (PA) measurements were carried out with changing the modulation frequencies. The PA amplitude and phase images were obtained for the specimen with each tilt defect. Phase signal distribution obtained from phase image showed double peaks located at sidewalls of the surface defect. These peaks showed asymmetry except the case of the tilt angle of 90 degrees (vertical case). By defining the degree of asymmetry as the ratio of the difference between two peaks of phase signal distribution to the height of their mean value from the background, the correlation coefficient between tilt angle and the degree of asymmetry showed the value of 0.997. In conclusion, we were quantitatively able to evaluate the tilt angle value of surface defect with high precision. In addition, it seems to be useful for the evaluation of the progress direction of the important surface defect and the lifetime evaluation of various materials in the fracture mechanics.

P3U-W-3 L11

NONDESTRUCTIVE EVALUATION OF ADHESIVE JOINTS IN LAYERED STRUCTURES USING NONLINEAR MEASUREMENTS OF SECOND HARMONICS OF ULTRASONIC LAMB WAVES

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The increasing use of layered structures in manufacturing requires effective methods for nondestructive evaluation (NDE) of adhesive joints. In general, the performance of the layered structures is greatly determined by the quality of adhesive joints. As an effective NDE means, the ultrasonic Lamb wave method has been already used in evaluating the quality of adhesive joints. If the change in the dispersion relations of ultrasonic Lamb waves caused by the change of properties of adhesive joints is not obvious, then the use of the Lamb wave method cannot fully characterize the small change of properties of adhesive joints. It is gradually recognized that the nonlinear ultrasonic measurements can provide more sensitive data of material/structure properties. Because of the high sensitivities of nonlinear ultrasonic measurements for material/structure properties, we can take into account the use of nonlinear effects of ultrasonic Lamb waves for evaluating the quality of adhesive joints. The second-harmonic

signals of the primary Lamb wave propagation may provide more sensitive data of the properties of adhesive joints. It has been found that under certain conditions the second harmonics of the primary Lamb wave propagation may have a cumulative growth effect with the propagation distance. In other words, the second-harmonic signals may be effectively measured. The present work describes a method based on the nonlinear measurement of second harmonics of ultrasonic Lamb waves for NDE of adhesive joints. It is experimentally shown that under certain conditions the second harmonics of ultrasonic Lamb waves do have a cumulative growth effect along propagation direction. When ultrasonic Lamb waves have strong nonlinearity, the measurements of amplitude-frequency curves for second harmonics of ultrasonic Lamb waves at the surface of a layered structure (aluminum-epoxy-aluminum) have been performed for different cases, where the adhesive joints between the two aluminum sheets are, respectively, in perfect contact, in the state of disbonding, and including inclusions. The difference of amplitude-frequency curves of second harmonics of ultrasonic Lamb waves for these different cases of adhesive joints is obvious as compared to that of primary Lamb waves. A stress wave factor of second harmonics of ultrasonic Lamb waves can be introduced to effectively describe the properties of adhesive joints. This work presents a promising method for NDE of adhesive joints.
This work was supported by the National Natural Science Foundation of China under Grant No. 10004016.

P3U-W-4 L10

ULTRASONIC TESTING OF STEEL TUBES BY SUPERCRITICAL PARAMETRIC WAVE PHASE CONJUGATION

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Wave Phase Conjugation (WPC) or time reversal transformation of acoustic waves in presence of scattering objects open various possibilities in nondestructive testing of industrial production. Multiple scattering of incident wave is able to increase essentially the effective aperture of a phase conjugator that can be used as a principle of detection of scattering defects. In a simplest geometrical condition conjugator receives only some part of the scattered acoustic field produced by the incident beam. Due to this reason variations of volume density or sizes of defects within the propagation medium can cause changes of the acoustic energy of the incident wave at the conjugators aperture, and one can expect correlated variations of the Phase Conjugate Wave (PCW) retropropagated to the primary source.

This paper presents experimental results of application of this principle to quick control of metallic cyllindrical tubes including various volume densities and sizes of scattering defects. The magnetoacoustic phase conjugator under

supercritical electromagnetic pumping was used for real time WPC with giant amplification of weak acoustic signals. Several positions of the source and the conjugator in contact with the lateral side of the tube were tested. The tubes were displaced along their axis while the incident wave source and the conjugator were fixed. The amplitude of PCW signal received by the transducer was recorded as a function of the tube position. It is demonstrated that PCW amplitude is correlated to the volume density and size of the defects and that this procedure is usable for a quick sort of tubes after manufacturing.

The research described in this publication was made within the CNRS-RAS PICS program n° 5008, Interreg IIIa n° 56, and in part by support of the french embassy in Moscow (MAE), Award No. RP-2367-MO-02 of the U.S. Civilian Research & Development Foundation for the Independent States of the Former Soviet Union (CRDF), grant 02-02-16916 from RFBR, and grant 1553.2003.2 of the president of RF. The authors whish to thank B. Bisiaux and F. Lesage from CEV Vallourec for the loan of some industrial tubes.

P3U-W-5 L9

ULTRASONIC AIR-COUPLED METROLOGY OF MATERIAL SURFACES

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Air-coupled ultrasonic transducers for imaging purposes have been used since the 60's. Different kind of transducers flexural plates, capacitive transducers, piezoelectric and piezocomposite based transducers, cMUT- have been developed ranging the working frequencies from kilohertzs up to a few megahertzs.

The developed applications have intended to mimic the standard ones made with transducers coupled to the materials to be inspected through fluids. Very interesting applications have been reported from proximity sensors, flowmeters, plate wave generation up to real imaging of human skin. An interesting topic that takes advantage of the comparative small wavelength of ultrasound in air is the surface metrology. Recent papers by Hutching's group have shown the ability to detect vertical surface features as small as 5 mm with a 500 kHz wide band cMUT transducer.

The paper presented shows a new design of air-coupled transducer based on a 1-3 piezocomposite that can be shaped in different focal geometries. Single or "double crystal" transducers up to 4 MHz have been made and characterized. Surface and sub-surface information of soft materials have been obtained showing the big potential of air coupled ultrasound for materials where traditional optical and contact profilometry is difficult.

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P3U-W-6 K13

IN VITRO ULTRASONIC FORCE MICROSCOPY

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Ultrasonic Force Microscopy (UFM) was originally developed to investigate the mechanical compliance of materials with nanometer scale spatial resolution. Based on an atomic force microscope (AFM) but coupled with the concepts of ultrasound, UFM has been used to detect strain in quantum dots, sub-surface flaws in food packaging applications, and mechanical heterogeneities in semiconductor multilayers. Here, UFM is demonstrated to also be capable of mapping the compliance of various materials in vitro. Images of air membranes, polymer systems, and biological cells in aqueous solutions are included. Experimental capabilities, limitations, and artifacts are also analyzed. Ultimately, UFM is shown to be a promising technique for studying the compliance of structures in vitro with nanometer scale resolution.
NRC

Session: P3U-X

SIGNAL PROCESSING
Chair: E. Furgason
Purdue University

P3U-X-1 L4

MULTIPLEXED DUAL-CHIRP PULSE COMPRESSION METHOD FOR ULTRASONOGRAPHY

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Much research on pulse compression techniques has been carried out in the field of ultrasonic imaging. The frequency modulation (FM) chirp technique in particular has proved popular among researchers, and can be readily analyzed theoretically. However, by the naive FM chirp method, spurious scatter positions are apt to be imaged for the moving scatters because of their Doppler effect. Additionally, as the essential obstacle in implementing pulse compression method, a large separation region is required to receive echo signals after complete transmission of a very long pulse. Although shortening the transmitted pulse by applying multiplexing technique can reduce the separation region, the intelligible multiplexing method processed in the time domain results in the emergence of many unwanted signals after compression. That is, the spectrum amplitude of this shortened pulse differs from that of the original long pulse.

In order to solve the former problem, we adopt the dual-chirp pulse, which means the sum of an FM up-chirp and an FM down-chirp, as a transmitted pulse, and apply the separation-compression filter proposed in [1] to an echo signal. By this invention, we can obtain proper images scatter position without spurious image, and can simultaneously measure Doppler velocity. To solve the latter problem, multiplexing technique achieved in the frequency domain is proposed. The proposed multiplexing is based on division of the original long pulse in the frequency domain and preserves the spectrum amplitude. To explain this multiplexing procedure, we take two short pulses corresponding to the left and right half of the frequency spectrum of the long pulse. The phase of one of the two short pulses is then processed such that the two short pulses are superimposed in the time domain. Although the length of the multiplexed pulse must be the same as that of the original in order to preserve the spectrum amplitude properly, the energy of the pulse is concentrated in the center region of the pulse, meaning that the pulse can be cropped with little distortion of the compressed waveform. Preliminary experimental results using a phantom show the essential effectiveness of the proposed technique especially with larger numbers of multiplex parts.

[1] K. IWASHITA, T. MORIYA, N. TAGAWA and M. YOSHIZAWA, 2003 IEEE Ultrasonic Symp., pp.1219-1222 (Oct. 2003)

P3U-X-2 L5

DENOISING AND COMPRESSION OF ULTRASONIC SIGNALS USING MODEL-BASED ESTIMATION TECHNIQUES

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Two model-based decomposition methods useful for denoising and compression of ultrasonic RF signals are examined in this paper. Both methods yield decompositions that are sparse, data adaptive, and non-orthogonal. Sparse decompositions provide efficient denoising (i.e., noise reduction) by representing the signal in terms of a limited number of functions adapted to the signal. Consequently, they offer a high rate compression by representing the signal with the parameter vectors of composing functions. In addition, the estimated parameters can be used for flaw detection, deconvolution, object classification, velocity measurement, and ranging system. The first method utilizes the maximum likelihood estimation (MLE) principle to decompose the ultrasonic signal in terms of a finite number of Gabor functions. The parameter vectors of Gabor functions are optimized to achieve a minimum residual error between the observed and decomposed signal. The number of functions (model order) has been determined using the minimum description length (MDL) principle. For a given signal, MDL provides a measure to determine the optimal number of functions. Hence, the model order is adaptively increased with signal complexity. This property offers an effective means to optimally distribute the compression

budget (number of bits) across the signal. The second method also decomposes the ultrasonic signal into a limited number of elementary functions but by utilizing the matching pursuit (MP) decomposition strategy. Unlike MLE decomposition, MP decomposition is energy preserving, i.e., coherently distributes signal energy into composing functions. MP iteratively decomposes a signal into elementary functions that best represent signal structures. The order of decomposition is determined according to the desired noise level. Due to its energy preserving property, MP provides a time-frequency (TF) distribution of the signal by enabling linear addition of the TF distributions of composing functions. Furthermore, the parameters of this decomposition have a direct interpretation for the TF energy distribution of the signal, and can then be used for feature extraction. We have examined the MLE and MP decompositions for data compression and denoising of ultrasonic signals in terms of preserving the signal integrity, compression rate, and computational complexity. Compared to transform coding techniques based on orthogonal decompositions, the MLE decomposition method offers unparalleled compression rates (typically in orders of 25:1 for 10 dB level signal-to-noise ratio) while maintaining the integrity of the signal. However, because of the iterative optimization involved in estimation, the MLE method is computationally intensive. The MP decomposition also provides good signal integrity at high compression rates, although not as good as the MLE method. The MP method is fast enough to be implemented in a real-time data compression system. The performance of both algorithms will be presented using simulated and experimental ultrasonic NDE data.

P3U-X-3 L6

WAVEGUIDE DAMAGE DETECTION BY THE MATCHING PURSUIT USING THE GAUSSIAN CHIRP PULSES

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Guided-waves have been widely used for long-range nondestructive health inspection of various waveguides. Though non-dispersive waves are best for damage detection, it is often difficult to transmit purely non-dispersive waves. For instance, longitudinal waves centered at certain frequencies are used in waveguides damage inspection, but their shapes change as they propagate. Thus, accurate damage detection becomes very difficult especially when the pulse travels a long distance and it is very noisy. To expand the current non-destructive, elastic wave-based technique for longer-range inspection, the proper signal processing technique of the measured wave signal must be employed. The objective of this investigation is to develop an advanced signal processing technique for the guided dispersive wave signals measured during the non-destructive evaluation in waveguides. The key idea in this study is to take into account the distortion of the wave pulse by dispersion in the signal analysis. The amount of the dispersion is estimated during the analysis. In the present development, it is assumed that

a modulated-Gaussian pulse centered at a certain frequency is generated from the transducer. To extract meaningful pulses from the distorted, noisy signal, a matching pursuit method based on the Gaussian chirp dictionary is proposed. The Gaussian chirp dictionary plays a key role in simulating the distorted signal by dispersion. Unless the distortion is extremely severe, the proposed method can extract correctly and accurately the wave pulse reflected from damage. The matching pursuit algorithm estimates the parameters of the Gaussian chirp pulse that matches best the waveform of the reflected signal. Then, these parameters are used to determine the damage location. When the dispersion in a given waveguide is known, the size of a crack can be also evaluated. The proposed matching pursuit method based on the modulated Gaussian chirp is applied for damage detection in a cracked solid cylinder. For the crack size estimation, Love's theory was employed for the dispersion characterization

P3U-X-4 L7

PERFORMANCE EVALUATION OF DWT, DCT, AND WHT FOR COMPRESSION OF ULTRASONIC NDE DATA

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Ultrasonic imaging systems often require a large amount of data collection. Consequently, it is desirable to use data compression techniques to reduce data while maintaining the signal integrity to facilitate the analysis and remote access of ultrasonic information. Hence, the locally obtained ultrasonic images can be transferred efficiently through wireless or wired communication channels or computer networks to the remotely located experts for nondestructive evaluation. In this study the data compression performance of the discrete wavelet transform (DWT) using the Daubechies-20 kernel, the discrete cosine transform (DCT), and the Walsh-Hadamard transform (WHT) are examined using simulated and experimental ultrasonic data. Discrete transformations produce a different signal representation in the transform domain. For data compression and denoising purposes, the energy of the signal in the transform domain must be concentrated in fewer coefficients than in the time domain. If this concentration is achieved, data compression is realized by utilizing only the most dominant coefficients for data analysis, signal and image reconstruction, and data storage or transmission.

The correct ultrasonic data representation is paramount to the accurate analysis of the geometric shape, size, and orientation of the ultrasonic reflector, as well as to the determination of the properties of the propagation path. In ultrasonic imaging applications the parameters (e.g., arrival time, center frequency, and amplitude) governing the characteristics of the backscattered echoes are used for target detection, deconvolution, object classification, velocity measurement, and the ranging system. For this reason the compression of ultrasonic signals must be able to achieve data reduction while keeping good signal integrity. In this study the integrity of the ultrasonic signal parameters is evaluated as a function of the compression ratio, hence, the best transform to represent ultrasonic data can be determined. For a compression ratio of 95%, the DCT can represent

narrowband and broadband signals such that the center frequency can be estimated from the compressed signals with an error smaller than 2%. In the DWT and WHT cases, this error is smaller than 1% and 10%, respectively. Similar observations have been made about the accuracy of estimating the arrival time and amplitude from the compressed signal.

In this study we also present analytical results that show the relationship between the bandwidth of the ultrasonic echo and the data compression performance. For a narrowband ultrasonic signal the 5 most energetic coefficients of the DCT accumulate 63% of the total signal energy, while the DWT and the WHT accumulate 50% and 30% of the total signal energy respectively. In contrary, for a broadband ultrasonic signal the 5 most dominant DCT coefficients accumulate 30% of the total signal energy, while the DWT and the WHT accumulate 80% and 15% of the total signal energy respectively. Hence, the DCT is best for compressing narrowband echoes while the DWT is best for compressing broadband echoes.

P3U-X-5 L8

FLAW LOCATION FROM PERPENDICULAR NDE ULTRASONIC TRANSDUCERS USING THE WAVELET PACKET TRANSFORM

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Ultrasonic NDE systems using several transducers located at different planes is an option that permits to obtain complementary information during the inspection of a piece. Some combination techniques of the ultrasonic information coming from different sensors in perpendicular planes have been treated in recent papers [1-3]. Digital signal processing methods, using perpendicular-apertures information based on time envelope [2] and Wigner-Ville transform [3], have been utilised to obtain an accurate 2-D representation of isolated flaws contained into the inspected pieces. This paper presents the results of combining NDE ultrasonic traces by using the undecimated wavelet packet transform (UWPT). This method splits the traces into different frequency bands and selects the bands that exceed an energy threshold. To avoid synchronization problems, the combination is done with the time envelopes, resulting in a 2-D representation of the inspected piece for each frequency band. A final 2-D version with improved signal to noise ratio (SNR) is obtained fussing the different 2-D representations. A theoretical expression for SNR of the final 2-D representation is deduced. Two sets of experiments applying the proposed method are also presented. The first is performed over simulated registers with controlled SNR, and the second with real echo-graphic traces obtained from a specially-developed ultrasonic prototype, which integrates 2 linear arrays of 4 broadband transducers with apertures

located at perpendicular planes. Table 1 presents some results of a first experiment in which a rectangular piece with an ideal reflector is simulated. Eight transducers (4 horizontal and 4 vertical) have been considered for inspection in near field conditions. Because a sequential scanning was used, the echoes only affect the two transducers in front of the reflector (1 horizontal and 1 vertical). The traces coming from these transducers contain 1 echo pulse and coherent noise, while the other 6 transducers only generate coherent noise. This UWPT method uses Daubechies 4, 3 levels (8 bands) of decomposition and only the two bands with maximum energy (4 and 5 in this case) were selected. Results presented in Table 1 are the mean average of 1000 experiments for each SNR. Column 1 represents the initial SNR in dB. Columns 2-3 show the SNR of bands 4-5 (similar to initial SNR). Columns 4-5 are the SNR of the 2-D representations of bands 4-5 (double than columns 2-3, because combination uses the product operator [2]). Column 6 presents the SNR of the final 2-D representation. 1. A.W. Meyer and J.V. Candy. Iterative Processing of Ultrasonic Measurements to Characterize Flaws in Critical Optical Components, IEEE Trans. on UFFC, 2002 (8):1124-1138. 2. M.A. Rodríguez, A. Ramos, J.L. San Emeterio. Localization of isolate flaws by combination of noised signals detected from perpendicular transducers, NDT&E International, 2004 (in press). 3. M.A. Rodríguez. Ultrasonic Non-Destructive Evaluation with Spatial Combination of Wigner-Ville Transforms, NDT&E International, 2003 (6):441-445.

Table 1. SNR at different stages of the process

Initial SNR (dB)	Band4 SNR	Band5 SNR	2DBand4 SNR	2DBand5 SNR	Final 2D SNR
0	0.2036	0.2241	0.3060	0.3332	0
1	1.1702	1.1853	2.2532	2.2733	2.5857
2	2.1373	2.1560	4.1620	4.1888	6.5038
3	3.1152	3.1315	6.1264	6.1430	10.4900
4	4.0945	4.1101	8.0723	8.0983	14.4691
5	5.0789	5.0874	10.0710	10.0840	18.5474
6	6.0654	6.0869	12.0363	12.0539	22.4567
7	7.0542	7.0706	13.9782	14.0124	26.4253
8	8.0563	8.0644	16.0326	16.0330	30.4994
9	9.0505	9.0551	17.9990	18.0070	34.4687
10	10.0330	10.0511	19.9638	19.9913	38.3932

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Session: P3U-Y

NDE METHODS
Chair: D. Yuhas
Industrial Measurement Systems

P3U-Y-1 L1

CONCENTRATION CONTROL IN LACTIC FERMENTATION PROCESS FROM ULTRASONIC VELOCITY MEASUREMENTS

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In this paper, a study of the lactic fermentation using an ultrasonic velocity measurement technique is presented. Lactose has been proved to be an important environmental polluting agent. The lactic fermentation could be used to produce lactic acid, eliminating the undesirable lactose residuals. Moreover, the production of lactic acid using renewable resources is becoming more important as new applications arise: it is used as a raw material for biodegradable polymers and novel medical applications. The lactic fermentation includes several chemical reactions in association with the organism growth. In this bioprocess, the milk sugar (lactose) is transformed into lactic acid by the action of the acid lactic cultures. It is shown that the changes occurring during the course of the process can be on-line monitored by measuring the changes experienced by ultrasonic waves propagating through the fermenting media. Measurements of the ultrasonic velocity and density in the ternary mixtures (water-lactose-lactic acid) and during the fermentation of a lactose solution, by the action of lactic ferments, were carried out. Relations between the propagation wave parameters and the mass concentration of the fermenting medium components were obtained. These relations may be used to achieve an on-line control and optimisation of the lactic fermentation process.

P3U-Y-2 L2

CONFIGURATION OF A 20-MM-DIAMETER 150 KHZ ULTRASONIC LONGITUDINAL VIBRATION SYSTEM FOR PLASTIC WELDING

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Vibration and welding characteristics of a 20-mm-diameter 150 kHz ultrasonic vibration system for plastic welding are studied. The 150 kHz ultrasonic plastic welding system consists of a 20 mm-diameter bolt-clamped Langevin type

piezo-ceramic (PZT) longitudinal transducer, a stepped horn (vibration transform ratio N=3.0) with a supporting flange at a nodal position and a catenoidal horn (N=2.6) with a 4-mm-diameter welding tip. Total vibration transform ratio is 7.8. The vibration rod diameter of 20 mm is corresponding to 0.60 wavelength of longitudinal velocity that is larger than the conventional design criteria length that is under 1/4 wavelength to avoid radial resonance vibration. The 20-mm-diameter of PZT ring is corresponding to 0.95 wavelength that is less than 1 wavelength. Radial vibration amplitude measured using a laser Doppler vibrometer around the welding tip is less than 1/10 of longitudinal vibration amplitude of the welding tip surface. Maximum vibration velocity of the welding tip is 3.1 m/s (peak-to-zero value) and quality factor is about 900. The 150 kHz longitudinal vibration system is very simple compared with that was made previously using six 15-mm-diameter bolt-clamped Langevin type (PZT) longitudinal transducers installed in a radial to longitudinal vibration direction converter. Welding characteristics of 1.0-mm-thick polyurethane sheet specimens using 150 kHz, 94 kHz, 67 kHz, 40 kHz and 27 kHz welding systems with an 4-mm- to 8-mm-diameter welding tip are compared. Required vibration velocity decreases as vibration frequency increases. Using the 150 kHz welding system, weld strength per welded area over 20 MPa was obtained using welding tip vibration velocity of 1.0 m/s that is very small compared with that of 2.5 m/s of the 94 kHz welding system. Maximum weld strength per weld area obtained using the 150 kHz system is also larger than that of lower frequency systems.

P3U-Y-3 L3

LINEAR AND NONLINEAR ACOUSTIC PARAMETERS MEASUREMENTS IN PLATES WITH VARIOUS MOISTURE CONTENTS

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Variation of the moisture content is known to modify many of the mechanical properties of polymer materials. For this reason, the estimation of the absorbed quantity of water is a subject of growing interest in characterization of materials placed under variable relative humidity conditions. Different techniques can be used to tackle this problem: Nuclear Magnetic Resonance Spectroscopy, Karl Fisher titration, comparative mass measurements, ultrasonic measurements... In the present study, the later approach is used. Most often, papers devoted to the investigation of water absorption in solids with ultrasonic techniques, present linear properties (dispersion and attenuation) of bulk and Lamb waves. But up to now, only rare works using nonlinear acoustic measurements have been published. In this work, the moisture content in phenolic resin plates is investigated through linear and nonlinear acoustic parameter measurements. Linear measurements use insertion/substitution technique. This method is based on the

comparison of two broadband signals transmitted between two similar transducers immersed in water. The reference signal propagates through the fluid media, and the second signal crosses the plate inserted normally to the incident wave vector. Kinetic of water absorption in resins allows brief immersion of the sample without affecting the moisture content. This protocol leads to the determination of the phase velocity and attenuation evolution as a function of frequency, in the range 5-15MHz. Nonlinear measurements consist in evaluating the β parameter with a contact phase modulation method (Bou Matar et. al., Acoustic nonlinear parameter measurement in solid with a contact phase modulation method, in: IEEE-UFFC Symposium, october 8-11 2002, Munich, Germany). A high frequency tone burst signal and a low frequency pulse are inserted in the material by a contact transducer. The interaction between the waves creates a high frequency tone burst phase modulation which allows the determination of the nonlinear parameter. Dimensional characteristics of the resin plates are the side length L = 40mm and the thickness d = 3mm. They have been conditioned in order to ensure seven various controlled moisture contents with zero water gradient within. Evolution of linear and nonlinear properties obtained experimentally are discussed as a function of the effective moisture content within the samples. It shows a good sensitivity of the nonlinear parameter to the moisture content compared to the linear parameter.