1980 IEEE Ultrasonics Symposium Abstracts

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PLENARY

Opening Remarks: R. C. Williamson, *General Chairperson*

Opening Remarks: H. van de Vaart, *Chairperson*, Technical Program Committee

†**Sonar in Air—The Electronic Yardstick,** CONRAD H. BIBER, Polaroid Corporation, Cambridge, MA 02139.

In principle, a rangefinder system using sound is simple enough. Like light, a beam of sound will bounce off an object and return an echo to its source. By measuring the time interval between sending the pulse and receiving its echo, the distance from source to object can be calculated with great precision. Practically, however, we faced two technical challenges in bringing an effective focusing device to fruition. First, the system had to operate over the entire focusing range of the SX-70: 10.4 in to 30 ft. Second, the "beam" of sound had to be shaped in a way to best fit the needs of the photographer at the various distances within that range. Too narrow a beam, particularly in close-up shots, might miss the subject entirely; too broad a "flood" of sound might pick up echos from the wrong object, focusing the camera, say, on a doorway rather than the person standing within and beyond it. Often in engineering design, competing goals such as these work against each other, but in this project we found that as we homed in on one condition, we were also optimizing another—an example of outstanding fortune, rare in today's complicated world.

SIGNAL PROCESSING DEVICES

Chairperson: P. TOURNOIS

†**B-1 [Invited] The Impact of Convolver Characteristics on System Performance,**[1] ERNEST STERN, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.

The signal-to-noise ratio at the output of a matched-filter receiver is proportional to the time-bandwidth product (T · B) of the signal and to the power-aperature product (P · A) of a communication or radar system. Fixed analog matched filters allow efficient processing of large T · B product waveforms and hence allow a substantial savings in power, cost, and size due to reduction in P · A product. However, such systems are vulnerable to interference waveforms that are made similar to the signal. This vulnerability can be virtually eliminated with convolvers which permit the continuous changing of the waveform. The performance of practical convolvers is limited by finite dynamic range, amplitude and phase errors, and by internally generated spurious signals. This has the effect of reducing the signal processing gain below T · B and incurring a costly increase of P · A in compensation. Convolver performance criteria will be given in terms of typical system requirements. Measurement procedures used to determine dynamic range, spatial and spectral amplitude and phase errors, and internally generated spurious signals will be described.

[1]This work was supported by the Defense Advanced Research Projects Agency and the Department of the Air Force.

B-2 The Effect of Acoustic Dispersion and Attenuation on SAW Convolver Performance,[1] E. L. ADLER[2] and J. H. CAFARELLA, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.

Implementation loss, or degradation in signal-to-noise ratio relative to an ideal matched filter, must be minimized for system applications. The effect of acoustic dispersion and attenuation on the performance of surface-acoustic-wave (SAW) convolvers is shown to be equivalent to an ideal convolver in cascade with a linear time-invariant filter. Using this result the implementation loss due to dispersion and attenuation, transducer response, and various matching networks can be calculated using well-known circuit relations. The results of such calculations are given for two important signal waveforms: phase-shift keying (PSK) and minimum-shift keying (MSK). Design criteria are presented in graphical form contrasting the performance achievable with PSK and MSK modulation schemes for representative convolver amplitude and phase responses. This information provides useful guidelines with respect to acceptable tolerances on convolver phase, bandshape and bandwidth.

[1]This work was supported by the Defense Advanced Research Projects Agency.

[2]Visiting scientist, permanent address: McGill University, Montreal, PQ, Canada, H3A-2A7.

B-3 Hybrid Convolver/Binary Signal Processor Achieves High Processing Gain,[1] R. P. BAKER and J. H. CAFARELLA, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.

A hybrid analog/binary signal-processing technique has been developed which offers processing gains of 50–60 dB for spread-spectrum communication systems by cross correlating a signal with a number of time-shifted replicas of a reference waveform. This hybrid concept employs convolvers followed by binary integration circuits. The convolvers precondition any interference presented to the binary integrator so as to avoid serious degradation which would otherwise occur with binary quantization for some types of interference. In turn, the binary integrators overcome the dynamic-range limitation of the convolver. The convolver output is converted to I-and-Q video, quantized via analog comparators, and then fed to binary integrators for further time integration. Because the integration is done in programmable counters, the processing gain can be dynamically adjusted depending on signal-to-jammer ratios.

A prototype signal processor using these concepts has been developed, using a 10-μs acoustoelectric convolver operated at a signal bandwidth of 50 MHz to provide a processing gain of 27 dB. An 8-bit binary integrator array provided an additional 22 dB, for a total processing gain of 49 dB. Experimental results will be presented for both continuous wave (CW) and white noise interference.

[1]This work was supported by the Defense Advanced Research Projects Agency.

B-4 Doppler Insensitive Time Integrating Correlator Using SAW Convolver and CCD,[1] D. SHKLARASKY and P. DAS, Electrical and Systems Engineering Department, Rensselaer Polytechnic Institute, Troy, NY 12181 and L. B. MILSTEIN, UC, University of California, San Diego, CA 92037.

A silicon on $LiNbO_3$ SAW convolver is used as a distributed parallel analog multiplier to generate N delayed arbitrarily long time integrating correlations (TIC) (N being determined by the time bandwidth product of the SAW convolver). Before they are applied to the convolver inputs, the two signals to be correlated are each multiplied by slow rate "chirped" local oscillators (LO) of identical chirp-rate but opposite slope. Due to the delay-frequency ambiguity of the chirped inputs the convolver output signal can be interpreted as N frequency multiplexed correlations. These can be recovered by an appropriate spectrum analyzer (SA) which will display a one-to-one correspondence between range delay and frequency. By changing the SA bandwidth together with the slope of the chirped LO, an arbitrarily long integration time can be achieved. The range-frequency ambiguity of the inputs makes the system insensitive to doppler shifts of the input signals. So if a real time SA is used to analyze the convolver output, the number of points (in the range doppler plane) that can be displayed simultaneously is N^2. The paper discussed the design equations relating the convolver, the LO and the SA parameters, together with an evaluation of the system for various random and pseudo random signals, and a comparison of the system performance to other TIC systems. In the experimental part, the correlation capability of the system and its Doppler insensitivity are demonstrated using a chirped-z charge coupled device (CCD) real time SA. This SA has the added advantage of easily variable integration time.

[1]This work was supported in part by ARO Contract DAAG-29-79-C-0192.

B-5 An Improved SAW Time-Integrating Correlator with CCD Readout,[1] D. L. SMYTHE and R. W. RALSTON, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.

An improved version of the gap-coupled SAW/CCD accumulating correlator is described which exhibits a bandwidth of 40 MHz, a dynamic range of 40 dB, and an integration time of 10 ms. Rather than using counterpropagating SAW inputs, the new device applies the input to an electrode which is capacitively coupled to the CCD sampling fingers. This input technique enables the signal bandwidth to be doubled and provides more efficient coupling to the integrated varactor mixers. An improved understanding of the physical mechanisms of the integration process has made it possible to increase the integration time of this device at the expense of increased fixed-pattern noise, which in turn limits its dynamic range. Two schemes for cancelling this fixed-pattern noise have been implemented. One of these schemes uses a computer to store and subtract the noise. The other uses a CCD to delay the pattern noise, which is then subtracted from the output in a difference amplifier. A useful signal-processing gain of 30 dB with a 3.5-μs time window has been demonstrated using a wide-band signal dominated by Gaussian noise. Both the amplitude and the phase of the correlation between the signal and the reference are provided.

[1]This work was sponsored by the Air Force Office of Scientific Research and the Defense Advanced Research Projects Agency.

NOVEL LENSES AND TRANSDUCERS

Chairperson: B. R. THOMPSON

C-1 Electrostatic-Acoustic Transducers for Horizontal Polarized Shear Waves,[1] KAZUHIKO YAMANOUCHI and WOLFGANG SACHSE, Cornell University, Ithaca, NY 14853.

A new design is described for an electrostatic transducer (ESAT) which can be used in broad-band, noncontact acoustic emission measurements to detect only horizontally polarized shear waves. In the design, the static bias electrodes and the detecting electrodes are separate and are so arranged as to detect only SH-waves. Analysis of the new ESAT was made with a finite element method, obtaining a sensitivity of about 1 mV for shear displacements of 1 Å. Experimental results obtained with such a transducer will be presented.

[1] This work was supported by the National Science Foundation through a grant to the Materials Science Center at Cornell.

C-2 Composite Piezoelectric Transducers, R. E. NEWNHAM, K. A. KLICKER, S. Y. LYNN, W. A. SCHULZE, T. R. GURURAJA, T. R. SHROUT, and L. J. BOWEN, Materials Research Laboratory, The Pennsylvania State University, University Park, PA 16802.

Consideration of the influence of crystal symmetry, macrosymmetry, and interphase connectivity has been used to explore possible macrostructures of interest as piezoelectric composites. Based on these design considerations, ceramic-plastic composites have been fabricated with 3-3 phase connectivity by the replication of natural template structures such as coral. Composites prepared of natural template structures such as coral. Composites prepared in this way have piezoelectric g_{33} and g_h coefficients more than an order of magnitude higher than the coefficients of the homogeneously poled ferroelectric ceramic. A simplified fabrication technique has been developed by mixing volatilizable plastic spheres and PZT powder. When sintered and back-filled with epoxy, and poled, these composites give excellent piezoelectric voltage coefficients. Large voltage coefficients were also obtained from 3-1 piezoelectric composites made by embedding PZT fiber arrays in various polymers. For some of these composites the hydrophone figure of merit ($d_h g_h$) is 1000 times larger than solid PZT and 100 times that of PVF_2. Additional advantages include flexibility, mechanical strength, and low density. At high frequencies 3-1 connected composites show good potential for broad-band transducer applications, e.g., in ultrasonic imaging. The passband can be tailored as required by altering the geometry of the device and, in principle, bandwidths of about 100 percent are possible.

C-3 Properties of a PVDF Hydrophone with 100 MHz Bandwidth for Studying Medical, Nonlinear and Other Fields, D. R. BACON, Division of Radiation Science and Acoustics, National Physical Laboratory, Teddington, Middlesex, UK.

A broad-band hydrophone made from a PVDF membrane is described. It has a smooth frequency response, flat to ±3 dB up to 100 MHz, and gives accurate waveform reproduction. The hydrophone's performance characteristics have been studied to allow confident interpretation of the signals obtained under appropriate experimental conditions and to provide a clear understanding of the physical basis of its behavior. The frequency response, inferred from direct calibrations and measurements of nonlinear fields, agrees excellently with the predictions of a theoretical model, clarifying the piezoelectric behavior of the PVDF film used. Its directionality, which shows limited agreement with that of a stiff disk receiver, can be better understood by considering the three-dimensional piezoelectric properties of the PVDF film. Measurements of these characteristics, the hydrophone's electrical properties, and the performance of the cable and detection circuitry give the information necessary for its reliable practical use. The hydrophone is shown to be ideally suited for many practical applications, including the measurement of medical and nonlinear acoustic fields containing high frequency components. The use of nonlinear acoustic fields in conjunction with this hydrophone for the convenient calibration of other hydrophones is also illustrated.

C-4 A New Sound Focussing Lens—A Quasi-Parallel-Sided Lens, ZHAO HENGYUAN, ZHANG FUCHENG, and GUO XIAOWU, Applied Acoustics Institute, Shaanxi Teacher's University, Xian, China.

A new type of lens concentrating ultrasonic energy—a quasi-parallel-sided lens—is presented. The design of the lens is based on the law of refraction of sound and the condition under which the sound beams from the lens must be in phase at the focus. The lenses can also be used in acoustic imaging. Because the lens is thin, its most important feature, the attenuation losses of the lens material are smaller, and the lens is very easy to design. The computative formulas of lenses in which a bevel-shaped one and an arc-shaped one are included are given. These two kinds of lenses were respectively designed under the conditions that the frequency is 1.1 MC and the *F* number[1] is equal to 1, based upon the formulas mentioned above. The pictures of shape of these two lenses and their focussing properties are also given.

[1] The *F* number is focal length-to-diameter ratio of the lens.

C-5 Acoustic Lens with Electrically Controlled Refractive Index, M. PAPPALARDO, CNR Institute of Acoustics, Rome, Italy.

A new kine of cylindrical acoustic lens is described whose refractive index can be controlled electrically, thus permitting dynamic focusing. In principle the device is based on the stiffening of a piezoelectric material caused by its associated electric field. A first-order symmetric Lamb wave is generated in a piezoelectric ceramic strip poled along thickness. The perpendicular electric field associated with the wave will cause an increase of the elastic constant proportional to the square of the effective electromechanical coupling factor. If one of the two major surfaces of the strip is metallized and on the other is deposited an electrode of lateral dimensions = $\lambda/2$, it is possible to short circuit the electric field partially or completely in the region under the electrode by means of a variable resistance R. Giving to the electrode a well suited shape, the substrate under it can act very much like a planar cylindrical lens with a variable refractive index. Compared with the nonmetallized piezoelectric substrate, the refractive index can reach a maximum value of about 1.04. To the propagating Lamb wave a quadratic phase shift of the type exp $[-jx(R)x^2]$ is then applied. Making a contact between the boundary surface of the strip perpendicular to the wave direction and a fluid, the longitudinal transmitted wave will show a Fourier transform pattern at a variable distance $f = k/2\gamma[R]$ and so the system will reach the desired diffracted limited resolution. Since the refractive index range is small, a combination of lenses is used in order to obtain a significant variation of the focal distance. The thickness of the strip is less than the wavelength in the fluid, and therefore an array of the described devices must be used in order also to obtain a spatial diffraction limited resolution.

C-6 High Resolution Acoustic Probe,[1] W. DÜRR, D. A. SINCLAIR and E. A. ASH, University College, London, UK.

The design of ultrasonic equipment for medical diagnosis or for nondestructive testing frequently demands an accurate knowledge of the beams radiated by transducers or transducer arrays. It is customary to probe the radiated fields using a small transducer as a probe. In order to record the highest spatial frequencies, the effective aperture of the transducer should not exceed a half-wavelength; to have a little in reserve, it would be desirable to reduce the aperture to one quarter wavelength. We have devised a probe which satisfies this requirement at frequencies at least up to 10 MHz. The difficulty in conventional probes arises from the need to reduce the aperture of a chip transducer to such small dimensions. Instead, we use a metal cone, the tip of which forms the antenna aperture. The detected waves are then guided and, by means of a suitable acoustic lens, coupled to a transducer, which can be many wavelengths in diameter. A pair of probes working at 4 MHz have been constructed; we have been able to show that the resolution does indeed go down to a quarter of a wavelength–i.e., it is capable of recording evanescent waves near a diffracting obstacle. The probe is regarded as suitable for very precise measurements on acoustic radiating structures.

[1] This work was supported by the Science Research Council and by the Medical Research Council.

PHOTOACOUSTIC SPECTROSCOPY AND IMAGING

Chairperson: R. L. MELCHER

D-1 [Invited] Thermal-Wave Imaging and Microscopy,[1] ALLAN ROSENCWAIG, Lawrence Livermore Laboratory, University of California, Livermore, CA 94550.

Thermal-wave imaging and microscopy are important new developments in photoacoustics. Thermal-wave imaging results from the scattering and reflection of thermal waves by sample features having different thermal characteristics. These thermal waves can be generated either with intensity-modulated optical (e.g., laser) beams, or with intensity-modulated electron beams. This novel technique has several important capabilities, including three-dimensional imaging of subsurface features at resolutions that can be better than one micron. The potentials of this new concept are illustrated with examples of examination of solid-state electronic devices.

[1] This work was performed privately, and the opinions and conclusions are those of the author, and not of Lawrence Livermore Laboratory.

D-2 [Invited] Thermal-Wave Microscopy: A New Application of the Scanning Electron Microscope, E. K. BRANDIS, IBM, Hopewell Junction, NY 12533.

Although the main application of the scanning electron microscope (SEM) is to characterize surfaces and to determine the elemental composition of the sample, it is also possible to extract additional information about the sample by measuring thermal wave or acoustic signals. Initial photoacoustic or thermal wave experiments incorporated the use of intensity modulated optical illumination. The same experiments can be performed in an SEM by intensity modulation of the electron beam incident on the sample surface. Energy levels excited by the incident electrons de-excite mainly by the emission of electrons, X-rays, and generation of heat. The heat energy is transferred in a thermal wave mode at low modulation frequencies and can be detected for the generation of thermal wave images in an SEM.

D-3 [Invited] Condensed Matter Photoacoustic Spectroscopy and Detection Using GAS Phase Signal Generation and Detection, J. F. MCCLELLAND, Ames Laboratory[1] USDOE, Iowa State University, Ames, IA 50011.

This conference, which commemorates the centennial anniversary of the discovery of piezoelectricity, also coincides with the 100th anniversary of Alexander Graham Bell's discovery of the photoacoustic effect. Bell reported observations in 1880 of sound produced by a light beam chopped at an audio frequency and incident on absorbing matter. Recently this early discovery has served as the basis for a number of photoacoustic spectroscopy and detection studies. Three topics are briefly covered: 1) signal generation theory, 2) instrumentation, and 3) applications. In the signal theory section assumptions are outlined by which the one-dimensional heat equation is used to calculate signal dependences on optical and thermal sample properties. Instrumentation is discussed in terms of 1) spectrometers based on xenon lamp-monochromator, laser, and Fourier transform optical systems, 2) photoacoustic sample cells, and 3) signal processing. Applications include spectroscopy of opaque materials and preliminary studies using photoacoustic detection with semiconductor samples to characterize 1) CW laser heating and damage, 2) ion implantation and recrystallization, and 3) compositional variations in variable bandgap materials.

[1] Operated for the U.S. Department of Energy by Iowa State University under Contract W-7405-Eng-82. This research was supported by the Assistant Secretary for Basic Energy Sciences, Chemical Sciences Subactivity.

D-4 [Invited] Optoacoustic Spectroscopy of Condensed Matter, C.K.N. PATEL, Bell Laboratories, Murray Hill, NJ 07974.

The recent advances will be reviewed (achieved in collaborations with Drs. Tam and Nelson) in the pulsed laser, immersed or attached transducer optoacoustic spectroscopy of liquids and solids where we have obtained[1] spectra of condensed materials having absorption coefficients as small as 10^{-6} cm^{-1}. Using tunable dye laser pulse energy of ~1 mJ we have carried out both linear as well as nonlinear optoacoustic spectroscopy of organic liquids, water and heavy water, thin liquid films, powders and liquids at cryogenic temperatures.[2] The principles, applications, new scientific findings, and future directions will also be reviewed.

[1] C.K.N. Patel and A. C. Tam, *Rev. Mod. Phys.* (to be published).
[2] C.K.N. Patel and E. T. Nelson, *Nature* (to be published); E. T. Nelson and C.K.N. Patel (in preparation).

E-3 MSW Time Delays,[1] J. C. SETHARES, Rome Air Development Center, Hanscom AFB, MA 01731 and C. V. SMITH and J. M. OWENS, University of Texas at Arlington, Arlington, TX 76019.

A potentially important area for MSW time delays is in phased array antennas. We describe MSW characteristics required for phased array technology and the progress made towards achieving tunable time delay units required for this application. A 3-GHz MSW nondispersive electronically tunable time delay over a 6 percent bandwidth is described. The tunable time delay is implemented by cascading magnetostatic surface wave and magnetostatic backward volume wave delay lines. The two lines are designed and biased with different dc magnetics fields so that the dispersion slopes are opposite over a common operating bandwidth. This produces a unit with constant time delay, over this bandwidth, which is adjusted by a suitable bias field variation of 25 G.

[1] This work supported by RADC and AFOSR under a Summer Faculty Research Program.

E-4 Magnetostatic Wave Delay Line with Four Biphase Switchable Taps Operating at X-Band,[1] T. W. O'KEEFFE, J. D. ADAM, and MICHAEL R. DANIEL, Westinghouse Research and Development Center, Pittsburgh, PA 15235.

A magnetostatic wave delay line was constructed incorporating four single finger transducer taps and a 7-μm thick, 1-mm wide YIG film. The transducers and switching circuitry were defined on a 250-μm thick, 2.5-cm square alumina substrate via standard photolithography and ion milling techniques. The switchable phase shifters, one for each tap, each incorporated four p-i-n diodes and the necessary decoupled bias circuits. The four tap outputs were combined via two levels of microstrip power combiners to a single output lead. The MSW path length difference between taps was 1 mm providing a delay per tap of 20 nS at the design frequency of 9 GHz. A separate electronic exerciser circuit allowed four-bit correlations of various transmit and receive codes to be processed by the same device using a separate simple MSW delay line to simulate a radar transmit/receive delay time.

The device showed good correlation to various sequences of codes including the four-bit Barker code with an insertion loss of 20 dB. Correlation was also observed between two separate four-tap delay line devices, i.e., one as the transmitter and one as the receiver. The required permanent magnet measured approximately 2.5 cm cubed and provided a field of 4.6 kG.

[1]This work was supported by the Air Force Avionics Laboratory under Contract F33615-77-C-1068.

E-5 Dispersion Control in Magnetostatic Delay Lines by Means of Multiple Magnetic Layer Structures,[1] L. R. ADKINS and H. L. GLASS, Rockwell International, ERC, Anaheim, CA 92803.

The dispersive characteristics of magnetostatic surface waves (MSSW's) and magnetostatic forward volume waves (MFVW's) propagating in structures consisting of as many as four ferrite film layers of arbitrary magnetization have been investigated theoretically and experimentally. By proper selection of film thickness, magnetization and interfilm separation, the constant delay versus frequency region can be extended for MSSW propagation, while linearly dispersive characteristics can be obtained in the MSFVW mode. For example, at ~9 GHz, it is possible to achieve a linear dispersion over approximately 1 GHz bandwidth. Multiple layer structures of YIG and La, Ga YIG films on GGG were prepared using LPE growth techniques and evaluated as MSSW and MSFVW delay lines. The $4\pi M_s$ values of these films, controlled by the La, Ga doping, varied from 1750 G for pure YIG to ~1300 G, while the film thicknesses ranged from 5 μm to 25 μm. Good agreement was found between theory and experiment over a frequency range of 2–10 GHz.

[1]This work was supported by the Air Force Office of Scientific Research (AFSC), United States Air Force under Contract F49620-80-C-0045.

E-6 Synthesis of Magnetostatic Waves and Modes using Nonuniform Bias Fields,[1] F. R. MORGENTHALER, Department of Electrical Engineering and Computer Science and the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139.

How nonuniformly magnetic bias fields can control magnetostatic waves and modes in ferrite thin films is reviewed. In particular, we discuss how gradients in either the field magnitude, direction or both can be employed to synthesize wave or mode spectra to prespecified characteristics. Parameters affected include frequency, RF energy distribution, impedance, velocity of energy circulation, and the threshold governing the onset of nonlinear effects due to parametrically-unstable spin waves. The important case of a thin film disk that is surrounded by free space and magnetized to saturation along the normal to its plane is reviewed for the conditions of weak to moderate radial gradients or arbitrary form. It is shown that field profile required to control the frequency dispersion of a finite set of modes is not unique. Therefore independent control of other mode characteristics can be accomplished simultaneously.

[1]This work was supported by the U.S. Air Force, Contract No. F19628-79-C-0047.

ELASTIC CONVOLVERS I

Chairperson: T. A. MARTIN

F-1 [Invited] Wide-Band Elastic Convolvers,[1] H. GAUTIER and C. MAERFELD, Thomson-CSF, DASM, BP 53-06902 Cagnes/Mer, France.

Convolvers capable of processing wide-band (⩾100 MHz) or large time bandwidth product (⩾1000) signals are being actively researched for their many applications in spread spectrum telecommunications and fast signal processors. The planar elastic waveguide convolver still appears as a most attractive solution. Its simple geometry loads to an easy industrialisation, and its has proved feasible up to 300 MHz input frequency. Although its bilinearity factor is some 5-10 dB lower than of corresponding acoustoelectric devices, its input saturation level is at least 10 dB higher and the overall dynamic range is larger. When developing such convolvers, particular attention must be paid to beamwidth compression, material nonlinear efficiency, acoustic guiding, EM effect and port matching. The presentation will be based on theoretical and experimental grounds. Among the examples, there will be out production 40 MHz × 11.5 μs unit and our laboratory 100 MHz × 10 and 20 μs prototypes. All show better than 1-dB uniformity and -70 to -80 dBm^{-1} efficiency and allow for more than 30 dBm inputs. When it is possible comparison with other technologies will be made and foreseeable performance bounds will be discussed.

[1]This work has been sponsored by DRET.

F-2 High-Performance Elastic Convolver with Parabolic Horns,[1] I. YAO, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.

It has been demonstrated that wide-band convolvers can efficiently provide the important function of programmable matched filtering for continually changing codes in spread-spectrum communication systems. Because of the potentially low manufacturing costs, the development of truly high-performance elastic convolvers is very desirable. An improved elastic convolver based on the parabolic-horn beam-compression technique will be reported. This convolver uses short (1-μs) horns, accommodates waveforms with time-bandwidth products of 1000 and provides an F-factor of -70 dBm with less than 0.5-dB ripple in output frequency response. The features to be described include 1) a parabolic horn design procedure which takes into account SAW anisotropy, 2) a scheme for self-convolution suppression based on a dual-track geometry which suppresses this spurious output to more than 40 dB below the main convolution signal over the full device bandwidth, and 3) a simple output-circuit concept for minimizing the electromagnetic long-line effect.

[1]This work was supported by the Department of the Air Force.

F-3 Low Cost SAW Convolver with High Spurious Suppression,[1] PIERRE DUFILIE, Andersen Laboratories, Inc., Bloomfield, CT 06002.

Techniques have been developed for producing low cost monolithic SAW convolvers with excellent spurious suppression characteristics. Devices have been fabricated with 30 MHz bandwidth and processing times of 4 μs and 15.8 μs which have exhibited 40 dB suppression of unwanted spurious responses. These convolvers have been incorporated in electrical circuits to produce correlators for p-n coded waveforms with intended application in low cost spread spectrum communication systems.[2] Performance data will be presented along with the potential range of performance for this class of SAW Convolver.

[1]This work was supported in part by RADC under Air Force Contract F19628-79-R-0150.

[2]Haggarty *et al.*, "SAW processors versus competing technologies for spread spectrum data link applications," 78CH 1344-1 SW, pp. 567–572.

F-4 Dispersion and Multimoding in Monolithic Elastic Convolvers,[1] R. S. WAGERS, Texas Instruments Incorporated, Dallas, TX 75265.

Experimental and theoretical results are presented for dispersion and multimoding in monolithic convolver structures employing narrow acoustic waveguides. For metallic overlay waveguides, dispersion results are shown as a function of metal thickness and width. Theoretical explanations are provided for the small dispersion observed. A paired echo theory for the time domain sidelobes of the dispersive system is presented. The impact of waveguide distortion on convolver performance is discussed.

[1]This work was supported by CORADCOM and DARPA.

F-5 The Design and Performance of a Small Efficient SAW Convolver, B. DARBY, D. GUNTON, and M. F. LEWIS, Royal Signals and Radar Establishment, Malvern, Worcestershire, UK.

The efficiency of SAW convolvers can be enhanced by reducing the aperture of the interaction region, as this increases the power densities of the interacting acoustic waves. Various approaches to this problem have been described in the past, and last year's symposium saw a revival of the horn compressor with encouraging results.[1] We describe the development of a SAW convolver which also used horn compressors but which otherwise differs markedly from the device of Becker and Hurlburt. The devices we shall describe have similar bandwidth and interaction time, but greater efficiency, much greater simplicity, and very much reduced size, the overall convolver being housed in a brass box 80 × 14 × 5 mm.

[1]R. A. Becker and D. H. Hurlburt, in *Proc. 1979 IEEE Ultrasonics Symp.*, p. 729.

SAW RESONATOR FILTERS

Chairperson: W. R. SHREVE

G-1 Satellite Application of a SAW Resonator Filter, WILLIAM J. TANSKI, Sperry Research Center, Sudbury, MA 01776 and MARTIN BLOCK, Frequency Electronics Inc., New Hyde Park, NY 11042.

A 500-MHz two-port SAW resonator has been developed for use as an earth satellite frequency source noise suppression filter. The resonator, which utilizes a new reflector weighting scheme consisting of segmented and withdrawn lines to suppress sidelobes, will be described including design, packaging and electrical performance. This device must meet stringent environmental performance specifications under conditions of vibration, radiation, and pyrotechnic shock. The results of thorough testing to assess the suitability of SAW resonators for spaceflight will be presented. With this design, we have achieved the electrical performance goals with unloaded Q's of 22 050 (1.06 times the published material Q), out-of-band rejection of 23 dB, matched loss of 1.7 dB, and peak-to-peak out-of-band ripple of ±1 dB. The resonator will be operated with ±15 dBm input power and we shall discuss experimental results of the frequency variation with input power level. Preliminary tests show the vibration sensitivity is less than one part in 10^{10} per g, and the filter characteristics are insensitive to gamma radiation of up to 1 MRAD. The advantages we demonstrate of small size, low loss, relatively high power capacity, and insensitivity to adverse environmental conditions make resonators excellent candidates for spacecraft applications.

G-2 Nonlinear Characteristics of SAW Grooved Resonators, M. PLANAT, J. J. GAGNEPAIN, LPMO-CNRS-Besançon 25000, C. LARDAT, and L. PENAVAIRE, Thomson-CSF, DASM, Cagnes-sur-Mer 06802, France.

The nonlinear behavior of elastic waves propagating at a finite amplitude in a solid is at the origin of harmonic generation, amplitude-frequency effect and intermodulation. These phenomena prevent the operation of SAW devices like oscillators and filters at high powers. Both A-F effect and intermodulation are measured on SAW grooved resonators in the 100–500 MHz frequency range, by using a new experimental method which avoids spurious influence of temperature. Quantitative results are presented for quartz SAW resonators and comparisons are made with regular bulk wave resonators. The lower nonlinearities of SAW are pointed out. The second and third harmonic levels are calculated as a function of the nonlinear elastic constants of third and fourth orders. A general expression of the velocity-amplitude effect of traveling surface waves is deduced. This model confirms the experimental results and offers the possibility of determinating configurations with minimized nonlinearities for high power SAW devices.

G-3 Suppression of Reflective Coefficient Sidelobes of SAW Reflective Arrays by Means of Withdrawal Weighting, SHUI YONG-AN, JIANG WEN-HWA, ZHANG DE, and WU WEN-QIU, Acoustic Institute, Nanjing University, Nanjing, China.

The method of suppressing the frequency sidelobes of surface acoustic wave resonators by withdrawing the SAW reflective arrays which compose the resonators is the simplest one. It is an ideal form for designers, but the relations between the weighting and the frequency responses are not as simple as that of withdrawal interdigital transducers, so that it is difficult to find out the best weighting function from a desired response. We introduce an idea of complex impedance in case of interelectrode multireflection. As a result, we get an analytical expression for the reflective coefficients of the withdrawal arrays. It indicates a way to find out the desirable weighting so that the calculation process is simplified. The withdrawal reflective arrays with reduced sidelobes are obtained and their reflectivities are measured.

G-4 Microwave SAW Resonators Fabricated with Direct-Writing Electron Beam Lithography, P. CROSS, P. RISSMAN and W. SHREVE, Hewlett-Packard Laboratories, Palo Alto, CA 94304.

Lithographic resolution limitations present an upper bound on the center frequencies obtainable with SAW resonators. For example, with standard photolithography, linewidths smaller than 0.8 μm are difficult to achieve, restricting SAWR's on quartz to frequencies less than 1 GHz. Higher frequency devices require more sophisticated lithographic approaches. In this paper, we describe SAWR's with linewidths of 0.5 μm and below, fabricated with direct-writing electron beam lithography. The patterns are written using a two-level resist technique, PMMA on top of P(MMA/MAA), that minimizes the deleterious effects of electron backscatter and results in an undercut resist profile that facilitates subsequent aluminum liftoff. We have demonstrated SAW resonators at 1.57 GHz (0.5 μm linewidths) with insertion loss as low as 14 dB and unloaded Q up to 4000 (although not in the same device). Aluminum SAWR patterns have been produced with lines as narrow as 0.3 μm that should yield fundamental mode SAWR's up to 2.6 GHz when they are fully tested.

G-5 Broader-Band SAW Resonator Filters with a Single Critical Masking Step, R. L. ROSENBERG and L. A. COLDREN, Bell Laboratories, Holmdel, NJ 07733.

Monolithic two-section SAW resonator filters with Q-values $\lesssim$5000, low insertion loss, good sideband rejection, and first-order temperature stability have previously been demonstrated only in a crossed-resonator configuration with transducers deposited on top of the reflection gratings. This transducer placement requires accurate registration of a transducer mask over the grooves formed with the grating mask. For applications in the range of hundreds of MHz, where registration becomes difficult, we have investigated designs that require only a single critical masking step. Design relations and experimental results will be presented for optimized two-section filters fabricated with one critical mask and exhibiting Q's in a range below 5000. In particular, transducer-coupled designs are found to allow Q's substantially lower than expected from a naive approach based on directional coupling. Crossed-resonator designs (without overlapping components) still offer the lowest monolithically attainable Q's.

G-6 A SAW Ring Filter with a Phase Matching Electrode, N. FURUYA, H. MIYAMA, Y. NAKAYAMA, and Y. KINO, Matsushita Research Institute Tokyo, Ikuta, Kawasaki 214, Japan.

A low loss SAW ring filter containing a phase matching electrode has been constructed by the conventional photolithographic technique on a Y-cut $LiNbO_3$ substrate and successfully operated at 282 MHz. The filter has an insertion loss of 5 dB, passband ripples of less than 1 dB, stopband levels of 75 dB, and a 3-dB bandwidth of 3 MHz. The phase matching electrode is made of an electrically shunting thin film metal strip on a propagation path of the surface waves and changes the velocity of the surface wave. In the SAW ring filter, two surface waves are launched from an input IDT in the opposite directions and reflected twice by the sets of grating reflectors before they are superimposed at an output IDT. A phase difference between two waves at the output IDT increases ripples and loss of the passband frequency response. In 90° out-of-phase condition, which corresponds to a relative displacement of 1.5 μm of the grating reflectors at the frequency of 282 MHz, the ripples increase of 3 dB and the insertion loss also increases of 3 dB. The advantage of using the phase matching electrode is that the conventional photolithographic technique can be used to the similar ring filters operating even above 500 MHz.

PHOTOACOUSTIC SPECTROSCOPY

Chairperson: A. C. TAM

H-1 Fourier Transformed Infrared Photoacoustic Spectroscopy, The Technique and Its Application,[1] M. G. ROCKLEY, H. H. RICHARDSON, and D. M. DAVIS, Oklahoma State University, Stillwater, OK 74078.

An FTIR spectrometer head has been used to provide broad-band modulated light which is used to excite a sample in a photoacoustic cell. The photoacoustic interferogram can be Fourier-transformed to provide a photoacoustic infrared absorbance spectrum of the sample. This technique provides a very useful complement to diffuse reflectance and attenuated total reflectance techniques for studying surfaces and surface adsorbed species. This newly developed method is subject to a number of interesting effects such as particle size, the thermal diffusivity of the sample, and the reflectivity of the sample. These effects are discussed. Data describing the use of FTIR-PAS as a quantitative analysis technique down to the one-part-per-thousand level are presented. Several example spectra are presented including those of coal samples, asbestos, biological materials and different polymeric and carbon-filled polymeric materials.

[1]This work was supported by the National Institutes of Health under Grant 5R01GM 25353-02.

H-2 Fourier Transform Infrared Photoacoustic Spectroscopy of Solids,[1] B.S.H. ROYCE, Y. C. TENG, and J. ENNS, Princeton University, Princeton, NJ 08544.

The newly developed technique of Fourier transform infra red photoacoustic spectroscopy will be discussed. In this approach the normal detector of Fourier transform spectrometer is replaced by a photoacoustic cell, and the spectrometer's computer is used to process the interferogram so obtained. This interferogram has the form normally associated with an emission spectrum because of the selective absorption characteristics of the sample in the PAS cell. The method has been applied to obtain spectra of solids over the range between 4000 cm^{-1} and 400 cm^{-1} at a resolution of 4 cm^{-1}. Sample spectra will be presented and compared to transmission FTIR measurements. It will be shown that, under circumstances where the Christiensen effect interferes with transmission measurements, the PAS spectrum provides a well resolved absorption band in the same location as that indicated by Raman measurements.

[1]This work was supported in part by ARO-DAAG29-80-C-0053.

H-3 Photoacoustic Measurements of Nonradiative States and Defects in Semiconductors with ZnO Transducer, N. MIKOSHIBA, K. WASA, and K. TSUBOUCHI, Research Institute of Electrical Communication, Tohoku Univ., Katahira 2-1-1, Sendai 980, Japan.

Nonradiative states and defects in semiconductors were studied by means of a new photoacoustic (PA) technique at room temperature. Signal detection was carried out by a ZnO transducer which operates in a wide-band and high frequency range. In CdS, the fine structures due to A, B, C excitons and due to seven impurity states were observed as the maxima or minima in the PA spectra. It was also found that the spatial distribution of mechanical damage and defects in CdS, Si, and GaAs can be observed in the PA signals by scanning the laser beam spot across the sample. In GaAs, the PA signal gradually increases when the dark-line defects were generated under Kr^+ laser irradiation during several hours. In Si, the contour map of PA signal was obtained together with the transparent X-ray topograph of the sample. The distributions of defects in X-ray topograph and in PA signal have a relatively good correlation except for some parts of inhomogeneities of the sample, which are observed in the PA signal, but not observed in the X-ray topograph.

†H-4 Thermoacoustic Detection of EPR, R. L. MELCHER, IBM Thomas J. Watson Research Center, Yorktown Heights, NY 10598.

The techniques of photoacoustic spectroscopy have been successfully applied to the detection of electron paramagnetic resonance absorption in diphenyl picryl hydrazyl (DPPH). Small amounts (<1 mg) of DPPH were placed in a sealed acoustic cell containing a miniature microphone. The cell was placed in a microwave cavity (on waveguide) which was part of a conventional C or X band EPR spectrometer. As the resonance condition is satisfied the unpaired electron spins in the sample absorb microwave energy and transfer it via spin-lattice relaxation to the lattice causing an increase in temperature. This excess heat is then transferred to the gas in the cell causing a pressure rise which is detected by the microphone. The signal-to-noise ratio is enhanced through the use of amplitude modulation of the microwave energy or modulation of the applied magnetic field. Signal-to-noise ratios in excess of 100:1 at room temperature are readily achieved with this technique. The energy absorbed by the spin system can be calculated using standard results from EPR. The temperature rise of the sample and the increased pressure in the cell can be computed using the thermal piston model of Rosencwaig and Gersho with appropriate modifications. From the known cell geometry and microphone sensitivity the expected signal amplitude can be computed as well as the dependence on modulation frequency. In all cases the experimental and theoretical results are in excellent agreement.

H-5 Chemical Effects in Optoacoustic Spectroscopy, G. DIEBOLD and J. HAYDEN, Brown University, Providence, RI 02912.

The optoacoustic effect can be produced when radicals are introduced into an acoustic cell. Energy is deposited into the translational degrees of freedom of the gas by thermalization of the recoil energy of the photofragments and by radical recombination followed by vibrational relaxation. Furthermore, the photofragments can undergo various kinds of exothermic chemical reactions giving an amplification of the signal. Reactions include substitution, abstraction, and chain reactions. We have carried out a mathematical analysis of several chemical reaction schemes and have found nonlinear effects. In the case of atomic recombination a solution to the kinetic equations shows that the phase shift in the optoacoustic signal depends upon the intensity of the radiation, whereas the magnitude of the signal is independent of the steady component of the radiation. If two center chain reactions are present, the phase shift exhibits the same behavior but the amplitude can take an inverse square root dependence on the steady component of the incident light intensity. The amplitude of the signal is shown to be directly proportional to the photochemical chain length.

H-6 Photoacoustic Detection of a Chain Reaction, M. L. SHAND and R. R. CHANCE, Corporate Research Center, Allied Chemical Corporation, Morristown, NJ 07960.

The time evolution of the heat evolved in a photochemical reaction is measured with photoacoustic detection. Chopped CW light from 200 nm to 300 nm is employed as well as repetitively pulsed light at 260 nm. This photocalorimetric technique is applied to the solid-state photopolymerization of diacetylene crystals. The thermal energy evolved is as much as four times greater than the total light energy deposited in the sample when light is first incident on the sample and polymerization begins. This result required an average of approximately eight polymerized diacetylene units to be produced per absorbed photon. This experiment is the first definitive demonstration of the exothermic, chain-reaction nature of the photopolymerization process in these materials. Variation of the chopping frequency demonstrates that at the frequency used in these experiments all the photo-generated heat is within thermal length of the surface. Several different polymerizing materials are investigated. For samples with low yields, effects of the near coincidence of thermal length and absorption lengths dominate the time dependent signal.

BULK WAVES MAGNETOSTATIC WAVES ACOUSTOOPTIC DEVICES

Chairperson: B. R. MCAVOY

P-2 Observation of Piezoelectricity in Thin Films Formed by Anodization,[1] J. J. BERNSTEIN and R. M. WHITE, Department of Electrical Engineering and Computer Sciences, and Electronics Research Laboratory, University of California, Berkeley, CA 94720.

Piezoelectric response has been observed in thin films of ZnO, ZnS, Cu_xS, Cu_xZn_yS, and Cu_xZn_yO formed chemically and electro-chemically (by anodization) on metallic substrates. These films have been used to detect 10-MHz compressional ultrasonic waves as well as low frequency signals produced by tapping the substrates. The anodization process used is inexpensive and fast (for example, a 5-μ thick ZnO film was formed in ten minutes on a Zn substrate). The process could be used to deposit *in situ* piezoelectric sensors on almost any conducting solid. Possible film formation mechanisms will be discussed along with measured film properties such as strength of piezoelectric coupling, growth rate, surface morphology, and current-voltage characteristics.

[1]This work was supported by the National Science Foundation Grant ENG78-22193.

†P-3 Growth and Characterization of ZnO Epitaxial Films,[1] K. M. LAKIN, C. K. LAU, and S. TIKU, University of Southern California, Los Angeles, CA 90007.

Zinc oxide is an electronic material of increasing interest to acoustic signal processing applications employing surface and bulk acoustic waves. Of particular interest is the case of ZnO as grown on *R*-plane sapphire because of the wide range of other materials that can also grow on that substrate. The substrate orientation of *R*-plane sapphire favors the growth morphology $(11\bar{2}0)ZnO//(01\bar{1}2)Al_2O_3$ just as in the case of AlN. This orientation has the ZnO *c*-axis in the plane of the film and therefore is suitable for bulk shear wave generation as well as surface wave propagation. Three techniques that have proven most successful in the CVD of ZnO, the characterization of the material, and the results will be reported. In general, the films are grown in the temperature range of 400°-750°C, exhibit a high degree of crystal perfection, are optically transparent, and have near theoretical coupling coefficients.

[1]This work was supported by the Air Force Office of Scientific Research.

P-4 The Effects of Nonuniform In-Plane Fields on the Propagation Characteristics of Magnetostatic Surface Waves,[1] D. D. STANCIL and F. R. MORGENTHALER, Department of Electrical Engineering and Computer Science and the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139.

We have recently reported the observation of magnetostatic surface waves (MSSW's) in a rectangular YIG film placed between strips of Permalloy and in the plane of the strips. In such a configuration, the dc magnetic field between the Permalloy strips is primarily in-plane with a minimum halfwave between the strips. In the presence of such a gradient, a series of discrete modes appear below the low frequency end of the continuous MSSW band. Although we estimated the group velocities of these modes based on the slope of the phase vs. frequency data, the validity of the estimates rested on the assumption that primarily propagating modes (as opposed to standing wave resonances) were being observed. The results of pulse time delay measurements which agree with our previous estimates of group velocity and confirm the observation of propagating modes are reported.

[1]This work was supported by the U.S. Air Force, Contract F19628-79-C-0047.

P-5 Dispersion Relations for Magnetostatic Waves,[1] I. J. WEINBERG, University of Lowell, Lowell, MA 01854.

We consider a magnetostatic wave transducer consisting of a thin YIG film sandwiched between two dielectric layers, both of which may be considered to be of finite thickness. The direction of the external magnetic field intensity is taken to be completely arbitrary. Employing a generalized Polder tensor, the dispersive relations are found by satisfying the natural boundary and continuity conditions. Two different relations are obtained depending on the direction and magnitude of the external magnetic field intensity and the bandwidth under consideration. In particular, forward volume waves and backward volume waves are found as special cases of one of the relations and surface waves are a special case of the other relation. Computer produced dispersion curves are obtained for the forward volume wave, backward volume wave, and surface wave cases and are in agreement with previously obtained results. Additional dispersion curves are obtained for various other configurations of the external magnetic field intensity and some of these curves can be compared favorably with previously obtained results.

[1]This work was supported by contract F19628-80-C-0029 from the U.S. Air Force ESD, RADC, Hanscom AFB, MA.

†P-6 Effects of Directional Coupling on the Magnetostatic Surface Wave Propagation, TAKURO KOLKE, Department of Electronics, Tamagawa University, Machida, Tokyo 194, Japan.

Some experimental results of the effects of directional coupling on the magnetostatic surface wave (MSSW) propagation and the application to narrow bandpass filters are described. As discussed before,[1] the value of saturation magnetization ($4\pi M_s$) is the main factor to determine the passband of the MSSW and a narrow bandpass filter can be realized by lowering the value of $4\pi M_s$. However, this method is not appropriate at higher frequencies due to a rapid increase of the group delay time. In order to solve this problem, the effects of directional coupling were studied experimentally. The experiments were performed on a sample of (LaY)IG ($4\pi M_s$ = 1760 Oe, $\Delta a^{\perp} = 0$) for various coupling lengths. At H_0 = 1770 Oe, for example, we observed the reduction of 40 to 70 percent of the 30-dB bandwidth (7.0-7.4 GHz) with the increase of the insertion loss of less than several decibels. The total insertion loss (path length = 8 mm) was less than 15 dB even after the directional coupling was employed. This method is particularly useful at higher frequencies because we can choose a material with the lowest intrinsic loss and control the bandwidth by means of the directional coupling. We believe that this will provide a new possibility to the design of magnetostatic signal processing devices.

[1] T. Koike, in *Proc. 1979 Ultrasonics Symp.*, p. 810.

P-7 Diffraction and Beam Steering of Magnetostatic Surface Waves, H. S. TUAN and J. P. PAREKH, Department of Electrical Engineering, State University of New York at Stony Brook, Stony Brook, NY 11794.

While a large body of literature exists on the diffraction and beam steering properties of surface acoustic waves (SAW's) on different piezoelectric substrates, analogous calculations for magnetostatic surface waves (MSSW's) are currently not available. The treatment of magnetostatic wave (MSW) excitation has hitherto been restricted to infinitely long transducers in the form of a single microstrip or a multielement transducer, e.g., a meander line or a grating coupler, so that diffraction effects have been excluded. A theoretical treatment is presented of the diffraction properties of MSSW's arising from the finite length of practical transducers and the beam steering arising from the pronounced anisotropy in MSSW propagation. In agreement with recent experimental observations,[1] the present calculations of diffraction patterns indicate a significantly larger beam spreading than that obtained for SAW on YZ $LiNbO_3$. The implications of the present results in terms of designing optimum transducers will be discussed.

[1] C. V. Smith, Jr., *et al., IEEE Trans. Magn.*, vol. MAG-15, p. 1738, 1979.

†P-8 A Three-Port Model for Magnetostatic Wave Transducers, J. M. OWENS, C. V. SMITH, JR., G. HASNIAN, and R. L. CARTER, The University of Texas at Arlington, Arlington, TX.

The concept of analogue signal processing directly at microwave by utilizing magnetostatic wave propagation in epitaxial YIG films has stimulated much recent research interest. Transducer design controlled bandpass filtering has resulted in only limited success. Models based on a single-bar microstrip transducer and an array factor works well for small regular arrays (number of bars <8) but fails badly as the number of bars increases. One reason for the early outstanding success of SAW technology was development of an accurate three-port model of the interdigital transducer. A three-port model has been developed for magnetostatic forward volume waves which results in a significant improvement in modeling for large transducer arrays. In this model each microstrip is represented by a three-port network having one electric port and two magnetostatic wave ports. The three-port network parameters are computed from fundamental considerations and solutions of pertinent boundary value problems. The response of a transducer array is calculated from the appropriate cascading of the individual three-port models of each element in the array. A number of transducer arrays have been numerically analyzed by digital computer and compared with experimental studies of the modeled transducer with excellent result.

P-9 MSW Terminations, C. V. SMITH, University of Texas at Arlington, Arlington, TX, J. C. SETHARES, RADC, Hanscom AFB, MA 01731, and V. L. TAYLOR, SCEE/RADC Post Doctoral Program, Hanscom AFB, MA 01731.

Nonuniform magnetic biasing fields reduced end reflections on an MSW delay line, as seen by reduced echoes in a pulse-transmission display and reduced passband ripple in the corresponding insertion loss display covering the 2.5-3.5 GHz range. For surface waves, Permalloy slugs perturbed the bias field outside the propagation path reducing passband ripple from more than 10 dB to less than 4 dB over a 400-MHz section of the band and less than 1 dB over 200 MHz. Unmatched insertion loss of 11 dB was not increased. For volume waves, considerable echo suppression was achieved. The passband ripple changed to much longer periodicity with broad insertion loss minima. Considerable improvement seems likely for volume wave performance. This method has an advantage over abrasion techniques previously reported in that the garnet strip is not modified. Experimental results and fabrication methods will be described.

†P-10 Acoustooptic Position Sensor, E. DIEULESAINT, D. ROYER, and G. SITBON, Laboratoire Acoustoélectricité Université P.&M. Curie, 10 rue Vauquelin 75231 Paris Cedex 05, France.

A measurement of the time-of-flight of an acoustic pulse along a delay line can be made the basis of a position sensor. The read-out can be effected optically, thereby obviating any need for contact between the line and the object whose position is to be determined. The classic techniques for performing this function is by the use of optically coded rods, often using a Moiré fringe detection scheme. It is difficult to obtain comparable resolution with the acoustic method. Yet the latter has two potential advantages which, in some situations, override the restricted precision. First, the acoustic signal can be coded, so as to address one of a set of position sensors. Moreover, the code can be under software control, and changed to accommodate different measurement objects. Secondly, the acoustic system can work in hostile surroundings, notably at elevated temperatures. Since fused quartz is a relatively low loss material, it can be made the basis of such a sensor. Our experiments, at frequencies up to 50 MHz are based on the use of shear waves propagating in a 10-cm long fused quartz bar. The readout is effected by observing the rotation of polarization imposed on an optical beam transmitted through the sample, as a result of the acoustooptic effect. Crossed polarizers are used, so that the arrival of the acoustic pulse becomes a threshold effect. The position sensitivity could be enhanced by using a PSK coded wave form. In the present preliminary experiments, the position resolution which we have achieved is of the order of 40 μm. We believe that this is still capable of improvement by a factor of at least four, notably by the use of a higher precision clock.

P-11 The Fabrication of an Optoacoustic Transducer for Real-Time Diagnostic Imaging, K. Y. SU and G. WADE, Department of Electrical & Computer Engineering, University of California, Santa Barbara, CA 93106.

An optoacoustic transducer consists of a planar transparent electrode, a photoconductive layer, a piezoelectric layer, and another planar electrode. This device can convert a spatial distribution of optical intensity into a corresponding distribution of acoustical amplitude. In order to operate in real time, the response time of the photoconductive layer should be about 1 μs and it should be possible to switch the resistivity from about 10^7 Ω-cm under dark conditions to about 10^2 Ω-cm for illumination. The photoconductive layer of CdS can be deposited by sputtering with a mixture of 99 percent Ar and 1 percent H_2S as the sputtering gas. Dark resistivity in excess of 10^7 Ω-cm has been obtained. A decrease of five orders of magnitude occurs in the resistance when illuminated with an Argon laser giving an intensity of approximately 2 W/cm^2. The response time is shown to be a function of the light intensity. A response time faster than 10 μs has been achieved. The adherence of CdS to piezoelectric material is excellent. The potential fabrication technique for such a transducer is described. Experimental results are presented.

P-12 Finite Beamwidth Effects in Bulk Acoustooptic Interactions, DAVID G. HAWKINS, Andersen Laboratories, Inc., Bloomfield, CT 06002.

The original theoretical treatments of the acoustooptic interaction assumed infinitely wide optical and acoustic beams and a weak interaction. Recently, various authors have presented theories that removed one or more of these assumptions. In Chu *et al.*[1] the general theory for periodically modulated layers removed the weak interaction assumption, as well as limiting the optical beamwidth, and predicted that the zero order beam would appear with a null in the middle under conditions specified by a criterion they give. We present here a method of calculating this criterion with respect to the bulk acoustooptic interaction, experimental observation of the zero order null, and an assessment of the extent to which the acoustooptic interaction follows their criterion. These results give the designer of acoustooptic devices a tool for calculating the point beyond which an interaction geometry will not follow the predictions of the plane wave theories.

[1]Chu, Kong, and Tamir, "Diffraction of Gaussian Beams by a Periodically Modulated Layer," *J. Opt. Soc. Amer.*, vol. 67, p. 1555, Nov. 1977.

P-14 Application of Tl_3AsSe_3 for Long Wavelength Acoustooptic Beam Steering Devices, M. KHOSHNEVISAN, R. L. HALL, E. A. SOVERO, Rockwell International Science Center, Thousand Oaks, CA 91360 and E. SKURNICK and W. DAVIDIAN, Riverside Research Institute, New York, NY 10023.

The choice of acoustooptic materials suitable for long wavelength ($\sim$10.6 μm) beam steering is relatively limited. Results of a study are presented in which Tl_3AsSe_3 has been examined for this application. It is shown that two distinct modes of operation, namely, a normal Bragg configuration and a degenerate birefringent configuration, both appear as very promising candidates. Resolvable number of spots that can be achieved are comparable with germanium, presently a common 10.6-μm deflector material. The efficiencies are higher for Tl_3AsSe_3 deflectors than Ge. However, access times are longer than for Ge. Efficiencies of the normal and birefringent modes of Tl_3AsSe_3 appear comparable, but there are differences in other deflector performance parameters. Theoretical considerations and experimental data on prototype deflectors of Tl_3AsSe_3 will be presented and comparisons are made of the deflector performance of the two types of Tl_3AeSe_3 deflectors with that of germanium.

P-15 A Generalized Method for Designing Acoustooptic Tunable Filters, E. A. SOVERO and M. KHOSHNEVISAN, Rockwell International Science Center, Thousand Oaks, CA 91360.

A matrix method is presented which allows the prediction of the performance characteristics of acoustooptic tunable filters (AOTF) in any general configuration. Knowledge of the following materials properties is required; index of refraction (n_o, n_e) and the matrix elements for the elastic (C_{ijkl}) and photoelastic (P_{ijkl}) tensors. Trial configurations of the AOTF are specified by three vectors as input parameters: wave vector of the incident light and its polarization direction, plus a unit vector along the acoustic phase propagation. Calculated results are obtained which predict the required acoustic wave, the direction and polarization of the scattered light beam, and the efficiency of the interaction (in terms of the effective figure of merit $M_{2\text{eff}}$). Bandwidth and the optical aperture of the device are also obtained. Variation of the input parameters allow calculation of the performance characteristics for many such configurations. Final selection of parameters can be made based on the device requirements. This method can be applied to acoustooptic crystals of any symmetry group and is more general than methods described by previous workers. Summary of the method, specific examples and experimental results will be presented.

P-16 Decay Time Constants of Photoinduced Stored SAW Patterns, H. DROPKIN, J. N. LEE, and N. J. BERG, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD 20783.

The storage of a stroboscopic image of a propagating SAW has been reported previously.[1] The storage is effected by illuminating a *Y-Z* cut lithium-niobate delay line using a 3-ns 1-J 1.06-μm writing laser while the SAW is propagating down the line. A direct detection method using the spatial separation of the beam produced by the imprinted diffraction pattern has been used to obtain the time dependence of the strength of the stored pattern; this avoids the cross correlation detection equipment needed previously and allows determination of storage amplitudes at times immediately after writing. The decay time constants of the stored signal under dark conditions, under 633-nm (HeNe Laser) reading illumination and at SAW frequencies of 10 to 90 MHz are reported. There is evidence for multiple time constants. An $f^{-1/2}$ dependence of time constants versus SAW frequency fits the data. Experiments have been conducted to determine the effects of surface cleanliness and condition on storage amplitude and time. Photoemission experiments have been carried out to verify a surface-charge storage mechanism that has been proposed.[1]

[1]J. N. Lee, N. J. Berg, and P. S. Brody, in *Proc. 1979 IEEE Ultrasonic Symp.*, p. 81.

ELASTIC CONVOLVERS II

Chairperson: C. MAERFELD

I-1. Broad-Band Phase-Compensating Transducers for Monolithic Convolvers,[1] W. R. SMITH, Hughes Aircraft Company, Fullerton, CA 92634.

A major problem in the development of broad-band monolithic convolvers has been the phase errors that result from dispersive SAW propagation in the output electrode and MSC or parabolic-horn beam compressors. We report the development of dispersive input transducers whose design provides correction of an arbitrary phase-error-versus-frequency function known to exist in a given convolver design. These transducers have the added advantage of eliminating the matching circuit (typically an impedance inverter) required to achieve a broad-band impedance match for conventional periodic transducers. Furthermore, the shape of the insertion loss function can be controlled independently of the phase correction, so that the passband can be either flat or weighted, e.g., for compensation of frequency-dependent insertion loss. A specific design example having a 3-dB bandwidth of 150 MHz centered at 300 MHz will be described. Results of simulations of the processing of 92 MHz chip rate coded MSK waveforms show no perceptible degradation in the processing gain or time-sidelobe structure. Assuming a hypothetical convolver having 60° peak quadratic phase error over 120 MHz bandwidth, we have also verified by simulation that the associated transducer design produces the desired phase correction, namely, a quadratic of identical magnitude but opposite sign. We hope to demonstrate these transducers in a convolver before the symposium.

[1]This work was supported by the U.S. Army under ERADCOM Contract DAAB07-78-C-3004.

I-2 Dispersion in Acoustoelectric Convolvers: A Time Domain Model,[1] J. H. GOLL, Texas Instruments Incorporated, Dallas, TX 75265.

A time domain model of wave packets propagating in dispersive waveguides is presented. Previous models, using frequency domain arguments, allowed calculation of the distortions in convolvers and indicated means of minimizing these distortions. The model presented here helps to elucidate the mechanism for these distortions.

[1]This work was supported by DARPA and CORADCOM.

I-3 Focused Surface Wave Transducers on Anisotropic Substrates: A Theory Developed for the Waveguided Storage Correlator, J. B. GREEN, G. S. KINO, and B. T. KHURI-YAKUB, E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305.

A new monolithic ZnO on Si narrow waveguided storage correlator has been demonstrated which when operated in the plate-to-acoustic readout mode has a correlation efficiency of $F_T^{corr} = -53$ dBm. This is 13 dB better than that reported for any other ZnO on Si storage correlator. A 100-μm wide top-plate electrode serves as a $\Delta v/v$ waveguide for the 100-μm wide acoustic beam. The surface acoustic wave itself is excited by 10 finger pair interdigital transducers. Due to the large bonding pad capacity relative to the capacity of the active portion of the transducer, this device has a 3-dB bandwidth of only 2 MHz. In order to overcome this inherently narrow bandwidth of this device, we have proposed using focused surface wave transducers instead of the narrow IDT's that we presently employ. These transducers are similar to ordinary interdigital transducers with fingers that are formed into concentric circular arcs. The focused transducers have the advantages of a large active radiation area in addition to the ability to generate a narrow acoustic beam. We have developed a theory based on Huygen's principle which predicts the radiation fields of these transducers on anisotropic substrates. The theory is valid for parabolic approximations to the slowness curve.

I-4 Elastic Convolver Using Planar Prism Waveguide Couplers, K. L. DAVIS and J. F. WELLER, Naval Research Laboratory, Washington, DC 20375.

An elastic convolver has been built on YZ $LiNbO_3$ using planar prism structures for coupling surface acoustic waves with a 60 wavelength beamwidth into a three wavelength wide acoustic waveguide. The coupler, which is analogous in operation to the optical prism coupler is a planar metallic film pattern less than one centimeter long and spaced approximately one wavelength from the waveguide. Advantages of the prism coupler include selective excitation of a single waveguide mode, no bulk wave interference in the convolver, and ease of fabrication. The measured coupler efficiency for the prisms is within 1- dB of the theoretical maximum 80 percent. The convolver has a center frequency of 300 MHz and an external efficiency factor $F = -73$ dBm. Coupling characteristics of the present prism coupler design limit the 3-dB bandwidth to less than 50 MHz. Laser probe measurements have been performed which show the beam compression, coupling efficiency, coupling rate, and propagation angle. The method used for designing the prism couplers will be described as well as design techniques for broadening the coupler bandwidth.

I-5 Characterization of SAW Metal Strip Waveguides, H. ENGAN, K. A. INGEBRIGTSEN, and A. RØNNEKLEIV, Norwegian Institute of Technology, N-7034 Trondheim, Norway.

Thin-film aluminum waveguides for surface acoustic waves on *Y*-cut, *Z*-propagating $LiNbO_3$ have been investigated. Using electrical measurements and optical probing, results will be given for guides with metal thickness in the range 18–35 nm. Frequency has varied from 150 to 400 MHz, and several waveguide structures of 5 and 10-wavelength width at the designed transducer center frequencies have been measured. Free surfaces and wide nonguiding metallized surfaces have been used as references in order to separate various contributions to attenuation and dispersion. Three different waveguide modes have been identified. The results will be discussed and compared with previous work.

I-6 Electromagnetic Long-Line Effects in SAW Convolvers,[1] E. L. ADLER,[2] Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.

In surface acoustic wave (SAW) convolvers used to process long-duration waveforms, the output electrode behaves like a lossy transmission line and the effects of electromagnetic delay and electrode resistivity must be taken into account in evaluating convolver characteristics. These transmission line effects are treated by appropriately weighting the spatial integration over the convolver length in calculating the device output voltage. The spatial weighting functions for two representative convolver configurations are derived and the corresponding output-circuit loss formulas are given. Results are presented in graphical form to illustrate the lossy transmission line effects on the spatial uniformity and efficiency of the output circuit for both a center-tapped and an end-tapped geometry. A detailed analysis of these two tapping geometries with specific impedance terminations is also given and it is shown that for the end-tapped geometry the degradation in convolver performance due to long-line effects can be compensated for by appropriately offsetting the signal and reference carrier frequencies. These results provide useful design guidelines for long convolvers.

[1] This work was supported by the Department of the Air Force.
[2] Visiting scientist, permanent address: McGill University, Montreal, PQ, H3A-2A7, Canada.

SAW RESONATOR FILTERS AND AGING

Chairperson: W. J. TANSKI

J-1 [Invited] What SAW Can Learn from BAW: Implications for Future Frequency Control, Selection, and Signal Processing, T. LUKASZEK and A. BALLATO, U.S. Army Electronics Technology and Devices Laboratory (ERADCOM), Fort Monmouth, NJ 07703.

A brief historical review of the development of bulk acoustic wave devices is given, including the influence of supporting technology on the levels of frequency stability achieved. This is followed by a qualitative comparison of bulk and surface acoustic wave generation and propagation, and a similar comparison of the technologies involved in the fabrication of each type of device. From the comparisons a strategy will be formulated for utilizing the learning curve for BAW devices to bootstrap the corresponding SAW development. Emphasis will be placed on prospects for reduction of SAW aging, development of new SAW cuts with improved temperature, pressure, and aging performance, and applicability of the improved devices to future systems' needs.

J-2 Long-Term Aging and Mechanical Stability of 1.4 GHZ SAW Oscillators,[1] M. GILDEN, G. K. MONTRESS, and R. A. WAGNER, United Technologies Research Center, East Hartford, CT 06108.

Experimental studies have been continuing with 1.4 GHz SAW delay line oscillators fabricated using a vacuum sealed all quartz packaging technique. The aging period now extends over more than 52 weeks with the best oscillators showing net changes in frequency of several ppm. The observed aging characteristics suggest that two distinct processes, with opposite rates, combine to give the overall characteristics. The sealed all quartz package, soft mounted externally with RTV, has shown good resistance to gravitationally induced changes in frequency due to changes in oscillator orientation. These measured frequency changes are typically less than .05 ppm/G. Other results will include a description of aging measurements with a modified sealing technique and work directed towards further improving oscillator mechanical stability.

[1] This work supported in part by Rome Air Development Center, Hanscom Air Force Base, MA.

J-3 Active Aging of SAW Resonators, W. R. SHREVE, Hewlett-Packard Laboratories, Palo Alto, CA 94304.

An oscillator stabilized by a surface acoustic wave resonator (SAWR) has been run continuously for a period of 20 months with a net frequency change of less than one part per million (<160 Hz at 160 MHz).

This oscillator is the best of a set built around SAWR's in copper/ceramic headers. Another oscillator has been run for 12 months with a net change of less than 0.5 ppm. It is one of a set built around SAWR's in TO headers. This is the first report of active SAWR tests for periods over one year that result in changes that are this small. Other devices in each set have aged at rates up to 5 ppm/year. The SAWR's were made with etched groove reflectors and aluminum transducers on rotated Y-cut quartz substrates. The techniques used in fabrication, packaging and testing the devices will be described.

J-4 Surface Chemistry Related To SAW Resonator Aging, J. S. SCHOENWALD, A. B. HARKER, J. WISE, and E. J. STAPLES, Electronics Research Center, Rockwell International Corporation, Thousand Oaks, CA 91360.

The electrical characteristics of surface acoustic wave devices depend critically on the physical and chemical properties of the device surface as well as on the interaction between the propagating wave in the substrate with its surrounding gaseous medium. The gas-surface interactions were carried out in a dual chamber vacuum apparatus with a SAW resonator isolated in each chamber. One resonator, kept continually under vacuum, acted as a reference, while the second resonator was exposed to a variety of gases under controlled conditions. The nature of the chemical changes occurring on the surface were confirmed by examining the device surface by X-ray photoelectron spectroscopy. Experiments have been performed to study the absorption and chemisorption of reactive gases. These experiments are needed to understand and model the aging mechanism of SAW resonator. Typical results will be presented.

J-5 Impedance Characterization and Design of Two-Pole Hybrid, SAW Resonator Filters, J. WISE, J. S. SCHOENWALD, and E. J. STAPLES, Electronics Research Center, Rockwell International Corporation, Thousand Oaks, CA 91360.

The design, fabrication, and performance of two-pole hybrid SAW resonator filters will be discussed. The hybrid device consists of a SAW resonator, matching networks in chip component form, mounted on a ceramic substrate, and hermetically sealed in a 16-pin dual in-line package. The SAW resonator is two-pole with in-line acoustic coupling, as opposed to transverse or crosscoupled two-pole structures. Chip components are used for simple LC tuning to match the device impedance and provide flat inband response and phase linearity. A transmission line model is employed to synthesize the desirable bandwidth, shape factor and stopband characteristics. After design and fabrication, the scattering parameters of the untuned SAW resonator are measured by an automated testing procedure, and the data are analyzed to yield the impedance characteristics over the bandwidth of the device. The results are then computer analyzed to determine the proper values of the chip components in the matching networks. Parasitic reactances and losses can also be included in this model. Completed device results will be presented.

PHOTOACOUSTIC IMAGING

Chairperson: R. L. THOMAS

K-1 Photoacoustic and Photothermal Imaging at Low Modulation Frequencies, T. POUSI, M. JOKINEN, M. LUUKKALA, and A. LEHTO, Physics Department, University of Helsinki, Siltavuorennenger 20D, 00170 Helsinki 17, Finland.

Photoacoustic effect can be employed to produce images or thermal maps of the sample surface if the chopped light beam is spatially scanned across the sample surface. We have built several imaging systems based on this method where we have been able to detect various types of thermal discontinuities like cracks and delaminations. The photoacoustic closed chamber has turned out to be rather impractical to use for large scale imaging except microscopy, and therefore we have been deeveloping alternative pickup methods for the thermal pulse like mounting the sample directly upon a piezoelectric pickup element. We discuss several results obtained with these photoacoustic and photothermal imaging devices.

K-2 Applications of Optoacoustic Imaging and Microscopy, G. BUSSE, ZWE Physik, Hochschule der Bundeswehr München, 8014 Neubiberg, Germany.

Scanning the optoacoustic signal as a function of the sample coordinates gives an image of optical and thermal properties of the sample. Both magnitude and phase angle of the complex signal can be used for imaging, the latter being advantageous for some applications as shown previously.[1,2] Optoacoustic imaging allows subsurface structure detection in opaque material (e.g., metal) and even depth profiling by variation of modulation frequency. Contrast can be enhanced by local modulation technique. Optoacoustic microscopy requires high resolution (some μm) which is achieved only by decreasing the optical spot size and increasing the modulation frequency to the MHz-region.[3]

[1] G. Busse, *Appl. Phys. Lett.*, vol. 35, p. 759, 1979.
[2] G. Busse and A. Ograbeck, *J. Appl. Phys.* (in press).
[3] A. Rosencwaig and G. Busse, *Appl. Phys. Lett.*, vol. 36, p. 725, 1980.

K-3 Two-Dimensional Photoacousting Mapping of Ion-Implanted and Laser Annealed Semiconductors, R. A. McFARLANE, L. D. HESS, and G. L. OLSON, Hughes Research Laboratories, Malibu, CA 90265.

Studies are being made of the amorphous-crystalline transition brought about by laser annealing of ion-implanted semiconductor materials. The presence of a damaged surface layer of several hundred angstroms thickness resulting from ion implantation is detected using photoacoustic techniques with a laser wavelength selected for optimum response. We have made extensive studies of ion-implanted GaAs and have demonstrated the ability to detect crystal damage for implant fluences as low as 10^{12} cm^{-2}. These studies were performed using a wavelength of 1.06 μm where the residual single crystal absorption is small and the amorphous layer can give rise to absorptions of 70 percent under conditions of high implant fluence ($>10^{14}$ cm^{-2}). In addition, we have demonstrated that that small PAS signals from the substrate absorption can be eliminated by correct phasing of the lock-in reference signal since they occur shifted $\pi/4$ in phase from the signals arising from the amorphous surface layer. By raster scanning the interrogating laser over samples implanted with different fluences and patterns, two-dimensional maps have been produced of the implant damage over samples 0.5 cm $\times$ 0.5 cm with spatial resolution on the order of 40 μm. Both x-y recorder perspective displays and scope monitor mapping formats are being used for data presentation. The work is being extended to ion-implanted silicon using an interrogating wavelength of 1.32 μm. Examples of recrystallization using both pulsed and cw laser annealing will be shown.

K-4 Phase and Amplitude of Photoacoustically Generated Signals in Thermal-Wave Imaging Geometry, F. A. MCDONALD and G. C. WETSEL, JR., Physics Department, Southern Methodist University, Dallas, TX 75275.

Thermal-wave imaging of subsurface features using photoacoustically generated waves has recently been reported.[1] In these experiments, light modulated at ultrasonic frequencies was absorbed by a sample, resulting in the production of thermal and acoustic waves. The amplitude and phase of acoustic waves detected by a piezoelectric transducer bonded to the sample were associated with interaction of the thermal wave with subsurface features. We have analyzed a one-dimensional model applicable to this process in an attempt to explain the sources of the amplitude and (particularly) the phase variations. The model consists of an opaque layer in which the light is absorbed, a substrate with different material properties, and a transducer bonded to the substrate. We have found that phase variations of the order of those reported can be accounted for by the model. The dependence of the amplitude and phase of the detected signal on modulation frequency, optical absorption coefficient, thermal and acoustic material parameters, and material thickness will be discussed.

[1] G. Busse and A. Rosencwaig, *Appl. Phys. Lett.*, vol. 36, 815, 1980.

K-5 Photoacoustic Microscopy-A New Technique in Biology and Nondestructive Testing, C. R. PETTS and H. K. WICKRAMASINGHE, Department of Electrical Engineering, University College, London, England.

Over the past two years, there has been a great deal of interest in photoacoustic microscopy. The original photoacoustic microscope proposed at Stanford University used the focused (low energy, high peak power) pulses from a mode-locked and Q switched YAG laser to generate the photoacoustic signal while a confocal acoustic lens was used as the receiver. More recently, there has been interest in a gas-cell type photoacoustic microscope operating at low modulation frequencies.[1] This system has the advantage that it is simple to construct and does not require critical alignment. However, we have found that the average optical power level required in order to record images in seconds rather than minutes is around 200 mW with this system and can often result in sample damage. We report on a hybrid scheme which combines the gas-cell type microscope together with high peak power low energy pulses, thereby increasing the signal strength while at the same time limiting the average laser power. By tuning the laser continuously through the visible range, we can record photoacoustic spectra of objects on a microscopic scale. A finite difference method has been used in order to calculate the temperature distribution and the photoacoustic signal strength for the pusled case. Experimental results, both biological and other, will be presented.

[1] *Electron. Lett.*, vol. 15, p. 326, 1979.

K-6 Quantitative Determination of Laser-Generated Ultrasonic Waves in a Solid,[1] J.R.M. VIERTL, Corporate Research and Development, General Electric Company, Schenectady, NY 12301.

Laser generation of longitudinal and radial shear ultrasonic waves by a Q-switched neodymium, glass laser reveals that intense ultrasonic waves are produced in a solid. The frequency spectra of these laser-generated ultrasonic waves, expressed as an absolute magnitude, are obtained by deconvolution of the response of the measurement system. In addition to the bulk longitudinal wave, the x-cut quartz disk transducer has detected an exceptionally strong radial shear wave. This wave, detected by the elastic coupling between radial and thickness deformations of the x-cut quartz disk transducer, is quantified. The energy efficiency of generating the longitudinal wave is approximately 4.5×10^{-4}. This work quantifies the laser-generated bulk elastic waves in a solid so that their usefulness in special nondestructive testing applications may be developed.

[1] This work was funded by Corporate Research and Development, General Electric Company.

K-7 Thermoelastic Wave Generation by the Heated Interface Between Two Media, G. C. WETSEL, JR., Physics Department, Southern Methodist University, Dallas, TX 75275.

Thermoelastic generation of ultrasonic waves by the heating of a thin metal film at the interface between two media has been reported.[1] In these papers, the application of the technique to nondestructive testing and the importance of acoustically constraining the heated surface were stressed. Whereas experimental results were presented which established the technique, a theory of the phenomenon was not explicitly displayed. Furthermore, the material-parameter group important to signal enhancement was not discussed. Results of the analysis of a one-dimensional model of harmonic thermoelastic wave generation are presented. The model consists of a thick sample, a surface heat source, and a backing slab of finite thickness, which might be used for acoustic impedance matching. The acoustic-wave and thermal diffusion equations were solved subject to the appropriate boundary conditions. It was found that the most important factors in signal enhancement—even more important than acoustic impedance matching—is the quantity $(\alpha_s/\mu_s + \alpha_b/\mu_b)$ where α_s and α_b are the thermal expansion coefficients of sample and backing, respectively, and μ_s and μ_b are the thermal-wave propagation factors for the sample and backing, respectively. The results of this theory are in good agreement with the reported experimental results.*

[1] R. J. von Gutfeld and R. L. Melcher, *Appl. Phys. Lett.*, vol. 30, p. 257, v1977; R. J. von Gutfeld and H. F. Budd, *Appl. Phys. Lett.*, vol. 34, p. 617, 1979.

ACOUSTOELECTRIC DEVICES I

Chairperson: E. STERN

L-1 [Invited] GaAs Monolithic SAW Devices for Signal Processing and Frequency Control, T. W. GRUDKOWSKI, G. K. MONTRESS, M. GILDEN, and J. F. BLACK, United Technologies Research Center, East Hartford, CT 06108.

GaAs technology is rapidly maturing for application to digital and microwave integrated circuits, primarily because of its high mobility and large bandgap as compared to silicon. The present work considers the additional capabilities offered by exploiting its inherent piezoelectricity for monolithic SAW device development. The approach takes advantage of the improved quality of the semi-insulating substrate material required for GaAs IC development and concentrates on SAW device configurations which may eventually be integrated together with compatible electronics on the same substrate. The basic transduction and propagation characteristics for the Rayleigh wave on (100) ⟨011⟩ GaAs will be reviewed for device operation in the 100–200 MHz frequency range. Recent developments in the design and performance of two-port resonator filters, tunable SAW phase shifters, and programmable matched filters will be presented. Potential for further development of the technology will also be addressed.

L-2 GaAs SAW Diode Storage Correlator, K. W. LOH, D. K. SCHRODER, and R. C. CLARKE, Westinghouse Research and Development Center, Pittsburgh, PA 15235.

GaAs is a promising candidate for monolithic storage correlators because of its low SAW velocity and low attenuation compared to monolithic Si correlators with ZnO films. Compared to $LiNbO_3$/Si air gap correlators, the monolithic GaAs device is smaller and cheaper. Various aspects of the GaAs correlator will be discussed. 1) Attenuation distorts the correlation signal and hence limits the signal length. SAW's propagating along the ⟨110⟩ direction on (100) oriented substrates propagate as Rayleigh waves; however, leaky waves are generated off the ⟨110⟩ direction. Laser probe measurements of leaky wave attenuation as a function of angle or semi-insulating as well as on low carrier concentration n-epitaxial layers on n^+ substrates will be presented and compared to theory. 2) The properties of high quality, low leakage current diodes in these epi-layers will be presented. 3) Experimental measurements of writing and storage times of GaAs correlators will be shown.

L-3 SAW Programmable Matched Filter Signal Processor,[1] F. S. HICKERNELL, M. D. ADAMO, R. V. DELONG, and J. G. HINSDALE, Motorola Inc., Government Electronics Division, Scottsdale, AZ 85252, and H. J. BUSH, Rome Air Development Center, (DCID) Griffiss AFB, NY 13441.

A silicon-based monolithic SAW programmable biphase correlator has been developed for use in spread spectrum communication links. The zinc oxide film layer transducers used for surface wave generation on the silicon operate at 100 MHz with a 9-MHz 3-dB bandwidth and an insertion loss of 12–15 dB. The 31 biphase piezoresistive MOSFET detector taps were fabricated using low profile silicon gate CMOS technology with a reflection loss of less than 0.1 dB/tap and a detection efficiency of 40 dB. The tap control circuitry consisting of a serial digital shift register and parallel gate voltage feeds is capable of setting arbitrary codes and amplitude weights within 3 μs. A single matched filter signal processor device was used to correlate 31-bit codes on a contiguous basis. Tap weights were controlled over a 20-dB range, correlated peak-to-sidelobe ratios of 15 dB were achieved, and the correlated peak was greater than 30 dB above the noise level of the test system.

[1]This work was supported by the USAF Rome Air Development Center, Griffiss AFB, NY.

L-4 Monolithic ZnO-GaAs Acoustoelectric Devices,[1] G. R. ADAMS, J. D. JACKSON, and J. S. HEEKS, Standard Telecommunication Laboratories Ltd., Harlow, Essex CM17 9NA, England.

Results of experimental studies in the developing field of GaAs based SAW signal processing devices are presented, and for the first time the practical realization of a monolithic ZnO-GaAs Schottky diode memory correlator are reported. Fundamental progress has been made in ZnO semiconductor technology, in particular the development of a process compatible metal-SiO_2-ZnO-SiO_2-GaAs configuration which provides near theoretical piezoelectric coupling, allows low propagation loss and efficient acoustoelectric interaction, and possesses material passivation features which enhance yield and stability. With this configuration we have made GaAs delay lines having a tuned insertion loss of 9.5 dB at a center frequency of 57 MHz, and a transducer bandwidth of 10 percent. A monolithic GaAs convolver has also been constructured by introducing a continuous space charge layer in the delay medium. Terminal efficiency of the convolver is −63 dBm, with an insertion loss of 10 dB and 6 μs delay. Work associated with the memory correlator device has concentrated on the fabrication of low leakage Schottky diode arrays. A Ti-GaAs structure has been developed and proton isolation employed as a measure against charge acquisition. With this approach we have made a monolithic GaAs memory correlator and observed storage and correlation of Barker coded signals. The 3-dB storage decay time is 12 ms.

[1]The work was supported by the Procurement Executive, UK Ministry of Defence, sponsored by DCVD.

L-5 High *Q* ZNO-on-Silicon SAW Resonators,[1] S. J. MARTIN, R. L. GUNSHOR, and R. F. PIERRET, School of Electrical Engineering, Purdue University, West Lafayette, IN 47907.

Surface acoustic wave resonators in the 100–300 MHz range have been fabricated using the ZnO-on-silicon layered configuration. The performance of the sputtered film monolithic devices indicates the feasibility of fabricating high *Q* UHF/VHF resonators directly on processed silicon wafers functioning in monolithic RF integrated circuits. Two-port resonator performance characteristics include loaded *Q* values in excess of 5000, with temperature stability coefficients in the range of −30 ppm/°C without special compensation. These performance criteria compare favorably with those obtained with lithium niobate. The implication of the high *Q* values toward an upper bound for the free surface propagation loss will be discussed. A comparison is made between various reflector array schemes, including aluminum and chrome-gold strips, as well as grooves etched in the ZnO layer. The optimum phase loaction of transducers in the resonant cavity is reported for each reflector type.

[1]This work was supported jointly by AFOSR Grant 77-3304, NSF Grant ENG 76-1129, and the NSF-MRL program.

NDE-MEASUREMENTS, SYSTEMS, AND TECHNIQUES I

Chairperson: E. P. PAPADAKIS

M-1 Ultrasonic Imaging for Nondestructive Evaluation of Composite Material with Digital Image Enhancement,[1] R. T. WEBSTER and P. DAS, Rensselaer Polytechnic Institute, Troy, NY 12181.

An acoustic transmission imaging system incorporating a trapped energy mode transducer is used for imaging composite materials. The focusing transducer is fabricated by plating a number of concentric rings of electrodes on a suitable piezoelectric plate of uniform thickness. The concentric ring structure acts as a Fresnel lens and the interelement isolation is provided by the trapped energy mode. The data for the ultrasonic images were obtained under the control of a Z-80 microprocessor based system. The images are processed by a DEANZA image processor with PRIME host computer. This image processor is capable of such functions as pseudocoloring and deconvolution to improve resolution. The graphite-epoxy composite materials studied have about their tensile resistance. The materials were subjected to tensile stresses of about 70 000 lb/in^2 before imaging them. The objective of the experiment was to study what damage the tensile stress caused on the materials. The materials also had holes drilled in them with either a carbide tipped drill or a high speed steel (HSS) drill and the damage density around the holes was also of special interest.

[1]Supported in part by NASA under Grant NGL33-018-003.

M-2 High-Temperature High-Pressure Water Level Sensor, G. N. MILLER, R. L. ANDERSON, Union Carbide Corp., Oak Ridge National Laboratory, Oak Ridge, TN 37830, L. C. LYNNWORTH, W. B. STUDLEY, and W. R. WADE, Panametrics, Inc., Waltham, MA 02154.

Equipment was developed to measure water levels over a range of 750 mm with an uncertainty of ±20 mm. Temperature ranged from 20 to 250°C; pressure ranged up to 100 atm. The sensor is SS304 flattened wire of 1.6 × 3.2-mm cross section, in which the measured torsional transit time is a function of water density ρ, level H, and temperature T. To eliminate the influence ρ and T, the extensional transit time also is measured in the same sensor. To interrogate the sensor with both modes, Joule and Wiedemann transducers are multiplexed in an alternating sequence. Synchronized blanking circuits omit spurious echoes in 4 intervals whose durations are digitally controlled in proportion to the extionsional and torsional transit times up to the first echo and, independently, between echoes.

M-3 Use of a Two-Dimensional Filter for the Imaging of Near Front Surface Flaw,[1] N. HAMANO, F. RAAM, and R. KATZ, Ultrasonic Imaging Laboratory, Department of Electrical & Computer Engineering, The University of Michigan, Ann Arbor, MI 48109.

One of the problems in pulse echo ultrasonic testing using normal incident wave is the difficulty of detecting and imaging small discontinuities located close to the front surface of a specimen. In a typical *B*-scan image, effect of the front surface appears as a bright band region which almost uniformly extends over the scanning direction of a transducer. Therefore in the two-dimensional frequency domain, spectrum of this region is concentrated in a thin slit area while that of flaw is usually spread over a larger area. Based on this observation a two-dimensional high pass filter was designed in order to eliminate the frequency components corresponding to the front surface echo. The filter was applied to a *B*-scan image of an aluminum block containing a side drilled hole (2 mm diameter) centered at 2.5 mm below the front surface, and the result indicated that most of the front surface region was eliminated while echoes from the hole were preserved. More experimental results under various testing conditions will be presented.

[1]This work was supported by the Nuclear Regulatory Commission.

M-4 Ultrasound Imaging Through Highly Reverberant Thin Layers,[1] J. SANIIE, V. L. NEWHOUSE, and E. S. FURGASON, Electrical Engineering Department, Purdue University, West Lafayette, IN 47907.

Nondestructive testing of targets consisting of finite number of thin layers using backscattered ultrasound echoes is highly desirable in material evaluation. These targets can be examined by an ultrasound pulse-echo system from which acoustical parameters sensitive to the inhomogeneity of the samples are extracted. In practice, extracting these parameters is difficult if not impossible because of 1) limitation of system spatial resolution, and 2) multiple reflection within the target. In this study the system resolution has been improved by using transducers with the largest possible bandwidth taking into account the increase in absorption and scattering, and applying appropriate deconvolution techniques when the signal-to-noise ratio is high. The reverberation echoes are identified and classified by decoupling the components of the backscattered echoes. Furthermore, an indirect approach based on the frequency spectrum of the received echoes has been used to determine the characteristics of the unknown targets. These techniques have been adapted for measuring support plate corrosion growth around steam generator tubes from inside the tubes which produce highly reverberant echoes.

[1]This work is being supported by EPRI Project SPGO-S142-1.

M-5 In-Process Ultrasonic Thickness Measurement of Electroplated Chrome, J. FRANKEL, W. KORMAN, and G. CAPSIMALIS, Benet Weapons Laboratory, LCWSL, U.S. ARRADCOM, Watervliet Arsenal, Watervliet, NY 12189.

The thickness of electroplated chrome was measured during plating without process interruption by monitoring the time of return of a 10-MHz ultrasonic pulse which was reflected off the chrome plating-bath interface after having traveled through the piece plated and the chrome plate. Changes in plate thickness of one thousandth of an inch can be observed. The measurement can be done by visually monitoring the returned echo on the delayed and expanded time base of a CRT, or by use of a counter, or a system using an oscillator with gated amplifier and balanced mixer. An output is provided for computer control and for thickness versus time plots.

M-6 Acoustic Imaging by a Sonic Phase Locked Loop, ROBERT J. REDDING, Design Automation (London) Limited, Cox Green Lane, Maidenhead, Berkshire, England.

A technique developed for ultrasonic measurements of level and flow employs VHF/FM radio techniques and circuitry applied to an ultrasonic carrier wave. The phase of the audio frequency modulation is maintained constant by a phase-locked loop and hence the system settles at a frequency which is a measure of the transit time. The use of an ultrasound carrier wave together with the "single signal" effect of an FM detector causes the strongest signal to predominate. The system is thus highly directional and selects the shortest path. However, the PLL can be characterized to respond only to a particular audio range and hence the system can see a homogenity at a chosen depth. The attenuation of the path is also made available as an analog electrical signal. Attempts to use the system for "contour plotting," for monitoring the atmosphere for fire and gas detection, and in medical diagnosis are reported.

BULK WAVE SIGNAL PROCESSING

Chairperson: E. K. KIRCHNER

N-1 Stress Induced Frequency Shifts in Thickness-Mode Quartz Resonators, B. K. SINHA, Schlumberger-Doll Research, Ridgefield, CT 06877.

A thickness-mode quartz resonator when subjected to an externally applied load, changes its resonant frequency as a result of changes in the effective elastic stiffness and geometry. A predominantly extensional or flexural deformation of the plate resonator has significantly different stress induced frequency shifts for various orientations and modes of vibration. Previous studies of such effects of different mechanical biases on the resonant frequency have been made in the past based upon several approximation techniques which have yielded results with varying degrees of success. In the present work, the biasing state is determined from a system of approximate thin plate equations for extensional and flexural deformations. A state of generalized plane stress is assumed for arbitrarily *anisotropic* rectangular plates subjected to uniform stresses along its edges. The stress induced frequency changes are computed from a perturbation procedure for small dynamic fields superposed on a static bias. The computational results would show the force-frequency effect at the room temperature for the plate resonator of various orientations and different loading configurations. Finally, a comparison of the results with the existing experimental data as well as other approximation techniques is made.

N-2 Ceramic Flatpack Enclosed *AT* and *SC*-Cut Resonators, R. L. FILLER, J. R. VIG, U.S. Army Electronics Technology and Devices Laboratory, Ft. Monmouth, NJ 07703, L. J. KERES and T. M. SNOWDEN, General Electric Neutron Devices Department, St. Petersburg, FL 33733.

The performance of ceramic flatpack enclosed *AT* and *SC*-cut (bulk wave) resonators have been studied as functions of the design and fabrication parameters. The resonators studied have been 5-MHz fundamental mode and third overtone 6-MHz fundamental, 10-MHz third overtone and 20-MHz fundamental mode. The properties studied include the short-term and long-term stability, versus the frequency temperature characteristics, the vibration resistance, the shock resistance, the warmup characteristics, the Q, the retrace at turnover temperature, and the mode spectra. The main design and fabrication parameters to be discussed include the blank geometry and surface finish, the mounting and bonding configuration, and the plating and sealing techniques. It will be shown that warmup to 1×10^{-8}, from $-40°C$ to $+90°C$, in less than three minutes, is feasible with fundamental mode ceramic flatpack enclosed resonators. Such fundamental mode resonators have also exhibited parts in 10^{12} short-term stability at 1 s, and vibration resistances ranging from $1 \times 10^{-8}/g$ to parts in $10^{10}/g$ depending on the blank geometries and mounting configurations.

N-4 A New Type Energy Trapping Caused by Contributions From the Complex Branches of Dispersion Curves, H. WATANABE, K. NAKAMURA, and H. SHIMIZU, Department of Electrical Communications, Faculty of Engineering, Tohoku University, Sendai, Japan.

The energy trapping of width-extensional vibrations in a thin piezoelectric ceramic strip is studied theoretically and experimentally, and it is shown that a new type energy trapping by contributions from complex branches occurs in the vicinity of the stationary points on dispersion curves. The trapped-energy modes have some interesting characteristics, such as 1) the resonant frequency curves as a function of the electrode-length/strip-width ratio exhibit noticeable undulations, 2) the decay of displacements with distance from the electrode edge accompanies sinusoidal oscillations, and 3) the ratio of capacitances becomes a minimum at an electrode length where the resonant frequency curve begins to undulate and increases abruptly as the electrode becomes longer. The existence of this type of energy trapping is also verified experimentally for thickness-extensional vibrations in a piezoelectric ceramic plate.

N-5 Fundamental Mode VHF/UHF Bulk Acoustic Wave Resonators and Filters on Silicon, T. W. GRUDKOWSKI, J. F. BLACK, T. M. REEDER,[1] D. E. CULLEN, and R. A. WAGNER, United Technologies Research Center, East Hartford, CT 06108.

Novel bulk acoustic wave high Q resonators and acoustically coupled resonator filters have been fabricated and operated at their fundamental half wavelength mode in the 200–500 MHz frequency range. These structures are fabricated on thin ZnO/silicon diaphragms with dimensions small enough to be incorporated within integrated circuits. Resonator Q's near 2600 have been obtained and strong interresonator acoustic coupling has been achieved yielding filter insertion loss as low as 5.5 dB. Equivalent circuit analysis and comparison with experimental results will be described.

[1]Presently at Tektronix, Beaverton, OR 97077.

N-6 Monolithic Matching for Braod-Band Microwave Delay Lines, R. A. MOORE, R. N. SUNDERLIN, Systems Development Division, Westinghouse Defense and Electronics, Systems Center, Baltimore, MD 21203, and S. LIBERMAN, Harry Diamond Laboratory, Washington, DC.

Microwave delay lines consist of a propagation medium and two film transducers. By past practice the film transducers provide an active electroacoustical aperture as required to meet the acoustical geometry of the delay line. The result has required that to achieve a suitable aperture led to an unsuitably small electrical impedance for normal circuit interfacing with resulting limitations on reproducability and bandwidth at low insertion loss. Recently Moore *et al.*[1] demonstrated that the electrical impedance could be made large enough for broadband matching by dividing the aperture into several series connected segments forming a mosaic transducer. Monolithic matching of the transducers forming effectively a microwave integrated circuit requires no post processing adjustment for broad-band matching to a VSWR of 3.1. The achieved mosaic transducer and matching element are described and results of computer modeling of the structure and matching element along with their adjustment for optimum process parameters are provided. The model identifies process parameters achieved through best fit analysis of a procedural set of limits. It identifies projected design limits through optimization for low insertion loss, bandwidth and low VSWR.

[1]Moore, Sunderlin, McAvey, and Liberman, "Gigahertz bandwidth . . . line," *Sonics and Ultrasonics Symp. Proc.*, IEEE Cat. 78CH 1482-9 SU, 1979.

PHYSICAL ACOUSTICS I
Nonlinear and Viscoelastic Phenomena

Chairperson: M. A. BREAZEALE

O-1 [Invited] Nonlinear Elastic Behavior and Instabilities in Crystals,[1] M. FISCHER, A. ZAREMBOWITCH, Université Paris VI, Paris, France, and M. A. BREAZEALE, University of Tennessee, Knoxville, TN 37916.

The pressure dependence of the elastic constants of single crystals for hydrostatic pressure smaller than 10 kbars is generally well described by using the third-order elastic constants usually determined from ultrasonic measurements. Departure from this conventional behavior is expected in crystals exhibiting instabilities, for instance, crystals with a phase transition. The possible connection between instability and an unusual nonlinear behavior is studied in three compounds: $TlCdF_3$, $CsCdF_3$, $KZnF_3$. $TlCdF_3$ exhibits a structural phase transition and the description of the pressure dependence of the elastic constants requires the third-order elastic constants and the fourth-order elastic constants even in a temperature range which is not very close to the transition temperature. $CsCdF_3$ has possibly a hindered phase transition and some departure from the conventional elastic behavior is observed. $KZnF_3$ is very stable and becomes more stable under hydrostatic pressure; no departure from the usual behavior is observed. The interest of such considerations is underlined from the technical point of view (in particular, for ultrasonic harmonic generation).

[1]This work was supported in part by NATO.

O-2 Measurement of Ultrasonically Induced Static Strain in a Solid, WILLIAM P. WINFREE[1] and JOHN H. CANTRELL, JR., NASA Langley Research Center, Hampton, VA 23665.

The solution of the nonlinear differential equation which describes the behavior of a finite amplitude initially sinusoidal ultrasonic wave propagating in a solid medium contains a static strain term in addition to the well-known harmonic terms. This static strain has been predicted theoretically to be proportional to the squares of the amplitude of the driving wave and the ultrasonic frequency.[2,3] We report the first experimental observation of the static strain in a solid ((111) direction of single crystal germanium) and find agreement with the theoretical predictions.

[1]National Research Council Resident Research Associate.
[2]R. N. Thurston and M. J. Shapiro, *J. Acoust. Soc. Amer.*, vol. 41, p. 1112, 1967.
[3]R. B. Thompson and H. F. Tiersten, *J. Acoust. Soc. Amer.*, vol. 62, p. 33, 1977.

O-3 Ultrasonic Nonlinearity Parameters of Silicon Between 300 and 4 K,[1] JACOB PHILIP and M. A. BREAZEALE, Department of Physics, The University of Tennessee, Knoxville, TN 37916.

The ultrasonic harmonic generation has been used to determine the nonlinearity parameters of silicon between room temperature and 4 K. By measuring the amplitude of the second harmonic of an initially sinusoidal longitudinal ultrasonic wave propagating along the three principal directions, the temperature dependence of three linear combinations of third-order elastic constants of silicon have been studied. Between room temperature and 77 K, the magnitude of the TOE constants does not vary much as a function of temperature. Between 77 and 4 K, C_{111} changes by 3.5 percent, $(C_{112} + 4C_{166})$ changes by 11.7 percent and $(C_{123} + 7C_{144} + 8C_{456})$ which is positive below 8 K. The negative thermal expansion behavior of silicon between 119 and 20 K does not affect these measurements greatly. The strain generalized Grüneisen parameters of silicon have been calculated from measured nonlinearity parameters and are compared with existing values.

[1]This work was supported by the Office of Naval Research.

O-5 Low Frequency Shear Elastic Properties of Smectic A Liquid Crystals,[1] M. R. FISCH,[2] L. B. SORENSEN, P. S. PERSHAN, Harvard University, Cambridge, MA 02138.

The shear elastic constant for the liquid crystal 4-n-octyloxy-4'-cyanobiphenyl (8OCB) has been measured in the smectic A phase. We have developed a technique to prepare samples with one free surface. The free surface of the samples was driven electrically at frequencies ⩽100 khz. An optical heterodyne detection scheme was used to detect the shear wave excited by this driver. Large increases in the effective shear viscosity and decreases in the elastic constant are seen near the Nematic-Smectic A phase transition.

[1]This work was supported by the National Science Foundation under Grant DMR 77-24295 and by the Joint Services Electronics Program.
[2]Xerox Predoctoral Fellow.

O-6 Transient Pressure Field of US-Phased Arrays, U. AULENBACHER and K. J. LANGENBERG, Fachrichtung 12.2, Theoretische Elektrotechnik, Universität des Saarlandes, D-6600 Saarbrücken, Germany.

A new analytical formula for the pressure step-function response of an arbitrary nonuniform piston vibrator with any geometry is presented for both near- and far-field. It is found by application of Cagniard's method to an integral representation of the pressure-field. The response for other–realistic–driving functions can be obtained by convolution with the step-function response. Numerical results are given for a rectangular uniform aperture. By superposition of the transient fields of several pistons of that kind, the results for an ultrasonic phased-array are obtained. They are pictured in three-dimensional space-time plots which represent transient beam patterns. The influence of bandwidth of excitation and distance between the elements of main-, side-, and grating-lobes is shown for various angles of beam deflection.

ACOUSTOELECTRON DEVICES II

Chairperson: R. W. RALSTON

R-1 Monolithic Sezawa Wave Storage Correlators and Convolvers,[1] J. E. BOWERS, B. T. KHURI-YAKUB, and G. S. KINO, E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305.

The results of chirp and Barker code compression experiments are presented, demonstrating 30-MHz bandwidths in a monolithic ZnO/Si convolver. The design of the broad-band matching networks required was based on a new and powerful iterative technique which can optimize the characteristics for the measuring transducer parameters and internal loss variations over the frequency band. Analytic and experimental results on the effect of dispersion on correlation, input correlation, and convolution are presented. It was found that dispersion in Sezawa convolvers limits the usable bandwidth to 20%. The variation of group velocity with frequency was measured over a 70-MHz range of frequencies and found to be in good agreement with theoretical predictions.

[1]This work was supported by the Defense Advanced Research Projects Agency and monitored by the Office of Naval Research under Contract N00014-76-C-0129.

R-2 Monolithic Schottky Diode Storage Correlator, R. L. THORNTON and G. S. KINO, E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305.

We describe the first monolithic Schottky diode ASW storage correlator. The device is fabricated using the ZnO on Si technology, with the ZnO film being deposited by sputter deposition in the magnetron discharge system. The device operates on the first order Rayleigh mode at a frequency of 125 MHz and employs a ZnO film 1.6 μm in thickness, with 1000 Å of sputter deposited SiO_2 between the diode array and the ZnO. Using PtSi Schottky barrier diodes as the storage elements, it is possible to store a signal efficiently within a single RF cycle. This is a major improvement over the pn diode configuration, which needs 10 to 100 RF cycles for efficient storage. The device has a convolution efficiency of −64 dBm and a correlation efficiency of −77.4 dBm when operated in the acoustic-to-plate readout mode.

R-3 MZOS-FET Type Convolver, KAZUHIKO MATSUMOTO, TOYOSAKA MORIIZUMI, and TSUTOMU YASUDA, Department of Electrical and Electronics Engineering, Tokyo Institute of Technology, Meguroku, Tokyo, 152, Japan.

A novel nonlinearity due to the saturation drain current of the MOS-transistor was used for producing the convolution output. The normal convolver, e.g., $LiNbO_3$/Si or ZnO/Si type, utilized the nonlinearity of the depletion layer capacitance in the Si surface. This nonlinearity, however, includes the many higher order terms and two input SAW powers are dissipated into those higher harmonics. Therefore, the convolution output includes the distortion by the harmonic generation, and the dynamic range becomes narrow and the efficiency low. On the contrary, the drain current in the MOS-transistor has only the quadratic term between the saturation current and the gate bias. Therefore, two input SAW powers are mixed only quadratically and produce the convolution output effectively without any higher order harmonics. In our experiments, the ZnO/Si structure was used, and the source and the drain regions were formed parallel to the SAW propagation direction. The gate electrode was located on the ZnO layer. The convolution output produced by the nonlinearity of the saturation drain current was about 10 dB higher than that of the depletion layer capacitance. This type of the convolver is so promising because of the higher convolution efficiency and the wider dynamic range output without any harmonics.

R-4 An Acoustoelectric Burst-Waveform Processor,[1] S. A. REIBLE and I. YAO, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.

A technique for processing Doppler-shifted burst waveforms with a programmable acoustoelectric coherent integrator is reported. A succession of subpulses imitating target returns is entered into a $LiNbO_3$ delay line. The subpulses are coherently overlaid as charge in the Schottky diode array of the device by means of a counterpropagating train of acoustic storage pulses appropriately timed for the target velocity. After all subpulses are overlayed, the stored charge pattern is read out by correlation with an acoustic read waveform. Doppler-shifted input waveforms consisting of 2 to 16 3-μs-long gated-CW subpulses having 100-μs intervals were employed. The ambiguity surface of the resultant output is consistent with the number of input subpulses and the subpulse-to-subpulse interval. The prototype coherent integrator has a 10-MHz bandwidth, a 17-μs range window, and a 10-ms coherence time. An array of such devices can provide both Doppler and range information in a number of parallel channels, with the Doppler velocity, Doppler resolution, and range swath under programmable control.

[1]This work was supported by the Department of the Army.

R-5 Acoustoelectric Mobility Measurements on Films with Neglibible Acoustic Loss,[1] R. ADLER, D. JANES, S. DATTA, and B. J. HUNSINGER, Coordinated Science Laboratory, University of Illinois, Urbana, IL 61801.

The acoustoelectric effect has been used in the past to determine the mobility of carriers in thin semiconductor films exposed to the electric field of a surface wave. The method requires measurement of the dc acoustoelectric current and of the acoustic loss caused by the mobile carriers. For very high resistance films, the acoustic loss becomes too small to measure, particularly if there is a substantial air gap between delay line surface and film. We have recast the acoustoelectric equation into a form which, instead of relating mobility to acoustic loss and dc current, relates it to ac and dc fields along the film. The ac field can be calculated from the known acoustic power density, and the dc field is found by measuring the open-circuit acoustoelectric dc voltage. We have used this method successfully on films with very high resistance (10^8–10^{10} $\Omega/\square$) and very low mobility (less than

1 cm^2/Vs), deposited on nonpiezoelectric substrates and spaced from the surface wave delay line by a convenient 12.5 μm gap.

[1]This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-C-0259.

R-6 Electron Transport by Line Acoustic Waves in GaAs:Cr,[1] M. HOSKINS, F. FLIEGEL, S. MAHON, S. DATTA, and B. J. HUNSINGER, Coordinated Science Laboratory, University of Illinois, Urbana, IL 61801.

Electrons in GaAs:Cr have been entrained by line acoustic waves and transported at the propagation velocity. The LAW's are ultrasonic waves confined within one half wavelength of an edge formed by a $\{110\}$ cleave and the surface of a $\{110\}$ cut GaAs:Cr crystal. The highly confined LAW's propagate in the $\langle 111 \rangle$ direction and produce a large traveling wave field (up to 10 V/cm). The traveling wave field drags electrons across a uniformly illuminated surface from one ohmic contact to another to produce an acoustoelectric current. This acoustoelectric current versus electric field can be made to saturate, indicating that nearly all the carriers are traveling synchronously with the acoustic wave. These results are significant for two reasons: a) they raise the possibility of a high speed gateless GaAs CCD driven by a low power acoustic wave; b) they give rise to a new approach for measuring drift mobility of disordered sheet conductors without the magnetic anomalies associated with the Hall effect.

[1]This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-C-0259.

NDE-MEASUREMENTS, SYSTEMS AND TECHNIQUES II

Chairperson: B. R. TITTMAN

S-1 Ultrasonic Characterization of the Thermal Protection Tiles for the Space Shuttle,[1] G. A. ALERS, University of New Mexico, and R. M. ZIMMERMAN, Sandia Laboratories, Albuquerque, NM 87131.

The space shuttle, being a reusable space vehicle, is covered with a permanent thermal insulation in the form of over 30 000 individual 6 × 6-in titles made from a compaction of silica fibers. In order to insure the thermal survival of the airframe structure, each tile must be nondestructively tested for its inherent strength as well as for the quality of its attachment to the structure. To complicate this inspection problem, the fabrication procedure for the tiles renders them very anisotropic and partially inhomogeneous. Special transducers and coupling procedures had to be developed for measuring the velocity of sound in the tiles and then a five-element elastic modulus tensor was developed to describe the ultrasonic wave propagation properties of the basic material. The angular dependence of the velocity of sound is used to determine the orientation of the principal axes of the material on a finished tile and it has also been found that the inherent tensile strength of the tiles can be correlated with the absolute value of the velocity of sound. A simple model to rationalize this correlation between an elastic property and a fracture mechanism has been developed.

[1]This work was supported by the Space Division of Rockwell International Corporation through its Science Center.

S-2 Nonlinear FM Coded SAW EMAT's For Nondestructive Testing of Materials, V. M. RISTIC, F. HAUSER, G. DUBOIS, Department of Electrical Engineering, University of Toronto, Toronto, ON, Canada M5S 1A4, and H. LICHT, Atomic Energy of Canada Ltd., Chalk River, Canada K0J 1J0.

The operation of linearly FM coded SAW EMAT's was demonstrated on aluminum and magnesium.[1,2] Such devices exhibit a limited SNR due to low time-bandwidth product (compression gain). Using devices with nonlinear FM coding we have been able to achieve SNR's in excess of 15 dB for compression gains as low as 10. Such devices are intended for use in laboratory for surface stress detection and in field detection of surface cracks. A transmit-receive system made of these devices is then used for detection of surface cracks of various sizes. The calibration of the system and measurements performed on Mg, Al, and Z_{r-2} are given and various aspects of device design discussed.

[1]T. J. Moran, in *1976 Ultrasonics Symp. Proc.*, pp. 26-28.
[2]V. M. Ristic, in *Industrial Materials Res. Inst. Nat. Council of Canada Seminar Proc.*, 1980, pp. 1-22.

S-3 An On-Line Method for Measuring the Physical Properties of Rigid Materials, M. F. LEACH, Physics Department, Laurentian University, Sudbury, ON, Canada P3E 2C6.

This investigation deals with the correlation of the measured resonance frequencies of materials of various shapes and the physical properties of these materials, namely, size, shape, size and shape distributions, and elastic properties related to the shear and Young's moduli. Direct analysis of acoustic signals emitted by the collisions of rigid particles provides a practically instantaneous determination of the following properties: a) size and size distribution over a range of approximately 100 μm to 1 cm diameter, b) aspect ratios of particles of elongated shape, and c) shear and Young's moduli of different materials. The use of signals generated by the materials themselves, rather than external signals which characterizes most conventional methods, offers these advantages: a) direct correlation of the material properties to those of the signals, b) much simpler and more versatile systems for measuring material properties, and c) determination of properties with greater ease, speed, and accuracy.

S-4 [Invited] Mechanism Noise,[1] S. DUBOWSKY and T. MORRIS, Mechanics and Structures Department, University of California, Los Angeles, CA 90024.

The acoustic noise of machine systems can have important effects on their marketability and the health of their users. To reduce machine noise, engineers require accurate analytical models of the acoustic-dynamic behavior of machine systems. Such models would also enable easily measured noise signatures to be used as a diagnostic tool for detecting and locating problems. The first step in analytically predicting machine noise is determining its dynamic behavior. For many machines, this dynamic behavior must include the effects of impacts within the machine's connection clearances and the elasticity of its members. These effects, along with the variable geometry found in machines make the dynamics problem nonlinear and difficult. Recent advances in the field of machine dynamics have now made the solution of this problem possible. Modern machine dynamic methods and classical acoustical techniques are combined to develop analytical procedures for predicting the noise produced by linked machine systems. A set of analytic functions called directivity functions are developed. These enable the design engineer to obtain efficiently amplitudes and spectra of the acoustical field produced. A simple model called an acoustic beam model is discussed. This model appears to be a valuable design tool. Experimental results which show good correlation with the analytically predicted values are also presented.

[1]This work was supported by NSF Grant ENG75-17359.

S-5 Optimum Processing of Broad-Band Ultrasonic Data, DICK ELSLEY, JOHN M. RICHARDSON, and BOB ADDISON, JR., Rockwell International Science Center, Thousand Oaks, CA 91360.

In order to quantitatively characterize flaws in materials or biological systems ultrasonically, it is important to determine the properties of the system under test over as broad as possible a range of frequencies despite the effects of noise and the properties of the ultrasonic transducers. By treating the signals and noise statistically, we develop algorithms for optimal extraction of the desired properties. The types of noises present in ultrasonic signals are discussed and algorithms are derived for extending the bandwidth of single-transducer data by optimally combining the data from several transducers at different frequencies, for improved flaw detection by means of matched filtering, and for deconvolution of ultrasonic transducers to a "standard transducer." Application of these techniques to flaw characterization are present.

S-6 Analysis of Lamb Wave Diffraction by a Finite Crack Using the Method of Generalized Scattering Matrices, S. ROKHLIN, Department of Materials Engineering, Ben-Gurion University of the Negev, Beer-Sheva, P.O.B. 653, Israel.

The method of generalized scattering matrices for analyzing the diffraction of Lamb waves by a finite crack parallel to surfaces in an elastic layer is discussed. The solution reduces to finding the elements of a generalized infinite scattering matrix. The finding of this element is equivalent to solving an infinite system of algebraic equations, the coefficients of which are formed from previously obtained scattering matrices for a semi-infinite crack. It is shown that the solution obtained by the method of generalized scattering matrices is identical with the solution obtained previously by the author from the generalized Wiener-Hopf method. The region of the plate containing the crack forms an open resonator of elastic vibrations. The radiation losses from the resonator zone are partially associated with the radiation of a resonating wave during multiple diffraction by the edges of the crack and with transformation of the resonating wave into other modes, which are subsequently radiated from the resonator zone. Approximations of the solution, associated with incorporation of a finite number of waves excited in the region of the crack, are discussed. Simple approximate equations are presented for finding the resonance frequencies.

ACOUSTOOPTIC SIGNAL PROCESSING

Chairperson: E. G. LEAN

†T-1 [Invited] Acoustooptic Time Integrating Correlators, TERRY M. TURPIN, Department of Defense, Fort Meade, MD 20755.

Over the past few years there has been an exponential increase in interest in analog processing technology. This is largely due to economics. The cost of digital processing at very high data rates is often prohibitive. In addition many of the components required for optical processing have matured to the "off-the-shelf" stage. A significant portion of the effort in optical processing has shifted from components development to processing architecture. The time integration architecture offers the following advantages. 1) It makes the most efficient use of CCD arrays as sensors. 2) It often produces a significant data rate reduction (output rate is often orders of magnitude below the input rate) 3) It does not require a two-dimensional electrooptic modulator to implement two-dimensional operations. Several classes of processes that use the time integration concept are described. It is hoped that this paper will provide enough of a foundation in this philosophy to allow its readers to formulate their own processing problems in terms of this extremely flexible architecture. Finally, it should be noted that the time integrating architecture is not limited to optics, but can be implemented with charge coupled devices and surface acoustic waves.

T-2 Acoustooptic Diffraction from Acoustic Anisotropic Shear Modes in Gallium Phosphide, D. L. HECHT and G. W. PETRIE, Applied Technology Division of Itek Corporation, 645 Almanor Avenue, Sunnyvale, CA 94086.

The collimation of acoustic beams in anisotropic modes is extended in proportion to the reciprocal of the curvature $(1 - 2b)$ of the slowness surface.[1] Acoustooptic (AO) deflector transducer height and drive power required are proportional to $\beta = |1 - 2b|^{1/2}$ for the slowness cross section normal to the optical propagation vector $\overline{K}_0$. For the slow shear mode propagating along [110] in GaP with $\overline{K}_0$ along [111], $\beta = 0.187$, so that efficiency is enhanced by 5.3X or aperture extended by 28x. To demonstrate extended collimation a 2.4-μs aperture device was fabricated at 150 MHz with a transducer height of only 0.1 mm. Acoustic attenuation measurements by optical probing were made on wide-band devices: 2 dB/μs at 1 GHz and 7 dB/μs at 2.5 GHz. The standard AO figures of merit relative to fused silica $\overline{M}_1, \overline{M}_2, \overline{M}_3$, and $\overline{M}_4$ are 4.9, 4.5, 7.2, and 5.3. Rotating the optical beam to [110] raises these to 17.8, 16.4, 26.0, and 19.4; however, $\beta = 0.678$ in that case. If the optical beam is rotated 2.5° from [111] toward [110], $\beta = 0$ is obtained. This results in ideal collimation up to limits set by fourth-order terms in the wavevector equation.

[1]M. G. Cohen, *J. Appl. Phys.*, vol. 18, p. 3821, Sept. 1967.

T-3 Acoustooptic Time-Integrating Correlation Using Guided-Wave Anisotropic Bragg Diffraction,[1] C. C. LEE, K. Y. LIAO, C. L. CHANG, and C. S. TSAI, School of Engineering, University of California, Irvine, CA 92717.

Some experiments on acoustooptic time-integrating correlation using guided-wave *isotropic* Bragg diffraction was reported earlier.[2] A hybrid structure for integrated optics implementation and its projected performances were also discussed more recently.[3] We report on an alternate hybrid structure which utilizes *anisotropic* Bragg diffraction.[4] This new structure requires a waveguide substrate of much smaller dimension along the direction of optical propagation. Experimental results using Ti-diffused $LiNbO_3$ waveguide and SAW at 396 MHz center frequency are reported.

[1]This work was supported in part by the AROD and the NSF.
[2]I. W. Yao and C. S. Tsai, in *Proc. 1978 Ultrasonics Symp.*, p. 87, IEEE Cat. 78CH 1344-1 SU.
[3]C. S. Tsai, J. K. Wang, and K. Y. Liao, *SPIE*, vol. 180, p. 160, 1979.
[4]C. S. Tsai, I. W. Yao, B. Kim, and Le T. Nguyen, in *1977 Int. Conf. Integrated Optics and Optical Fiber Communications, Dig. of Technical Papers*, p. 57.

T-4 Interferometric Surface-Wave Acoustooptic Time-Integrating Correlator, I. J. ABRAMOVITZ and N. J. BERG, US Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD 20783.

A novel structure for a coherent-interferometric acoustooptic (AO) time-integrating correlator, similar to that originally proposed by Montgomery, has been implemented using a single SAW device with tilted transducers to reduce intermodulation terms. The SAW device was fabricated on Y-Z $LiNbO_3$ with a center frequency of 175 MHz, bandwidth of 60 MHz, and time aperture of about 10 μs. The instantaneous bandwidth of the AO correlator is determined by the spacing density of the photodetector array. A bandwidth of 60 MHz has been achieved, with a potential of 120 MHz. Typical integration times are 30 ± 40 ms, providing processing gains in excess of 10^6. Such a device is very useful in providing fast synchronization of a spread-spectrum communication link, via the sliding correlation technique. In addition, the device can demodulate to baseband and simultaneously act as a synchronization lock monitor for moderate data rates. Where processing may be limited by Doppler shifts, a two-dimensional architecture has been proposed to allow full processing gain.

T-5 High-Speed Adaptive Filtering and Reconstruction of Broad-Band Signals Using Acoustooptic Techniques, JOHN N. LEE, N. J. BERG, and P. S. BRODY, US Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD 20783.

Processing of broad-band signals requires the removal of strong, narrow-band interfering signals. Narrow-band interference has been eliminated using a Bragg-cell receiver with an electroded, cubic-phase, PLZT wafer at the frequency plane. The surface-electrode pattern on the wafer is comprised of 300 channels in the form of interdigitated fingers in the active region. Each channel is independently controllable and has an obscuration factor of 0.16. Channel width is slightly larger than the Bragg-cell diffraction spot size. Control of the channels is provided by a parallel-readout fiber-optic coupled detector array which samples the frequency plane via a beamsplitter. The temporal characteristics of the broad-band signal are recovered by imaging the filtered light distribution and a reference beam onto a wide-area photomultiplier tube to allow coherent detection.

PHYSICAL ACOUSTICS II–ATTENUATION

Chairperson: M. LEVY

U-1 Acoustic and Dielectric Loss Processes in PVF_2, P. RAVINET, J. HUE, G. VOLLUET, P. HARTEMANN, D. BROUSSOUX, and F. MICHERON, Thomson-CSF Research Center, Domaine de Corbeville, 91401 Orsay, France.

Acoustic and dielectric properties of homemade and commercial piezoelectric PVF_2 have been measured for samples with thicknesses between 26 and 260 μm using the conventional acoustic resonator method. The influence of temperature from –40 to 90°C has been shown up for frequencies between 2 and 50 MHz. At room temperature the acoustic losses exhibit a linear dependence versus frequency which proves that the intrinsic phonon-phonon coupling losses are negligible in this material since they would cause a square law dependence of losses versus frequency. This feature of PVF_2 is confirmed by computed values of losses due to such a process. The frequency independent term of acoustic losses has been attributed to a macromolecular chain relaxation tail with a characteristic relaxation frequency smaller than the operating frequencies at room temperature. Dielectric measurements associated with thermostimulated currents and internal friction measurements have shown that these losses are related to the glass temperature shift with frequency. The thermostimulated measurement techniques in which no driving voltage nor strain is used does not exhibit such a linear dependence of losses versus frequency. It is concluded that the periodic driving voltage applied to the piezoelectric resonator involves a supplementary loss mechanism which can be interpreted as a nonlinear behavior of the viscosity associated, for instance, with a hyteresis-type process in the macromolecular chain motion.

U-2 Ultrasonic Attenuation in the Carrier Hopping Regime in p InSb at Low Temperature,[1] J. D. N. CHEEKE and G. MADORE, Département de Physique, Université de Sherbrooke, Sherbrooke, PQ, Canada J1K 2R1.

Results of ultrasonic attenuation for three concentrations (10^{14}, 2×10^{15}, and 8×10^{16} cm^{-3}) of Ge in InSb are presented. The measurements were made for longitudinal waves for frequencies in the range 30–600 MHz, magnetic fields 0–7.5 T, and temperatures 1.5–20 K. A relaxation peak is observed near 10 K followed by a region of excess absorption at lower temperatures attributed to election phonon scattering. A marked decrease of attenuation with magnetic field was observed which correlates with the behavior of the magnetoresistance; measurements of the temperature and magnetic field dependence of the electrical conductivity enable us to identify the conductivity regimes ϵ_1, ϵ_2, and ϵ_3 and leads us to associate the excess attenuation to localized carriers in the ϵ_3 hopping régime. The excess absorption is compared with theory regarding magnitude, frequency, and field dependence. Finally, we discuss the observed strong field dependence of the relaxation peak which implies the existence of a field dependent relaxation time.

[1] This work was supported by the Natural Sciences and Engineering Research Council of Canada.

U-3 Phenomenological Theory of Attenuation and Propagation Velocity of Elastic Waves in Rocks, J. M. RICHARDSON and B. R. TITTMANN, Rockwell International Science Center, Thousand Oaks, CA 91360.

A phenomenological theory of velocity and attenuation of elastic waves in rocks is proposed and applied to several rock types. The theory is based upon the two main assumptions: a) that the macroscopic elastic behavior can be modelled as a superposition of linear nonresonant dissipative processes, and b) that these processes involve thermal activation with a flat distribution of activation energies over a range whose endpoints depend on the partial pressure of the volatile to which the rock is exposed.

U-4 Lattice Attenuations in CdS Measured by Acoustic Domains, Y. TOKUNAGA, Kanazawa Technical College, Nonoichi, Ishikawa 921, Japan, and T. HATA and T. HADA, Kanazawa University, Kotasuno, Kanazawa 920, Japan.

It is well-known that the room temperature frequency dependence of lattice attenuation α_1 in CdS is proportional to $f^{2.0}$ (f: sound frequency) as Akhiezer expected. However, the various data measured by acoustic fluxes in acoustic domains have been proportional to $f^{1.0-1.8}$ rather than $f^{2.0}$ in the application of square pulse voltage. The relation of $\alpha_1 \propto f^{2.0}$ has been only satisfied in the case of employment of special techniques such as a double pulse or a slow rise-time pulse. We describe the simple and accurate measurement technique of α_1 in the case of square pulse voltage. The α_1 measurement was carried out by ultrasonic injection technique and Brillouin scattering one. The data obtained by our technique show clearly that not only is α_1 proportional to $f^{2.0}$ in broad ranges from 0.4 GHz to 2 GHz, but also α_1/f^2 is found to be about 2.4×10^{-18} NPs^2/cm which coincides with the data obtained from the special techniques above.

[1] This work was supported by 1980 Grant-in-Aid for Scientific Research from the Ministry of Education in Japan.

U-5 Acoustic Properties of Amorphous SiH_x-Films, M. VON HAUMEDER, K. L. BHATIA, and S. HUNKLINGER, Max-Planck-Institut für Festkörperforschung, Heisenbergstr. 1, D-7 Stuttgart, Germany.

Some amorphous dielectric materials like a-Si can only be prepared in the form of thin films. Similar to bulk materials amorphous films exhibit surprising thermal and acoustic anomalies at low temperatures. These anomalies have been attributed to the existence of a broad distribution of two level systems (TLS), which interact strongly with phonons. Rayleigh waves are particularly sensitive to thin films since the elastic energy is restricted to the surface. We report here acoustic measurements of the attenuation, and of the variation of the sound velocity in reactive sputtered films of amorphous Si and SiH_x using Rayleigh waves. By variation of the hydrogen contents we found a shift of the thermal activated relaxation in silicon towards higher temperatures in SiH_x. In addition, other relaxation contributions appear which we attribute to SiH and SiH_2-centers. A correlation between the magnitude of this relaxation and the atomic percentage of hydrogen is observed.

†U-6 Ultrasonic Surface Wave Investigation of Superfluidity in Thin Helium Films,[1] P. MORISSEAU and J. D. N. CHEEKE, Département de Physique, Université de Sherbrooke, Sherbrooke, PQ, Canada J1K 2R1.

Thin helium films (1–20 monolayers) have been grown on lithium niobate substrates in the range 1.3–2.1 K. Interdigital electrodes resonant at 82 MHz were deposited in line about 1 cm apart on the substrate; the transducer on one end was used as the generator for 413 MHz RF pulses and the signal was detected in the other two enabling measurements of acoustic attenuation due to the helium film between these two. We observe a small but reproducible variation at the onset of superfluidity which has been determined by previous workers by other methods. The position and width of the onset is discussed in terms of the Kosterlitz Thouless theory for two-dimensional systems. In addition we also observe an anomaly of unknown origin rather closer to the saturated vapor pressure. Results are also presented of attenuation due to bulk helium as a function of temperature and pressure. Due to the high compressibility of liquid helium a sensitive test of the theory of leaky wave losses can be made.

[1] This work was supported by the Natural Sciences and Engineering Research Council of Canada.

†U-7 ***Ultrasonic Attenuation in Sodium, Potassium and Copper at* Low Temperatures,** O. N. AWASTHI, Physics Department, Regional College of Education, Mysore-570006, India.

The measurements of ultrasonic attenuation in metals at low temperatures (below 20 K) provide significant information about the electron-electron and electron-phonon interactions. The recent measurements of ultrasonic attenuation in single crystals of sodium, potassium, and copper at low temperatures (2.5–20 K) generally confirm the frequency and temperature dependence of the attenuation predicted by the theory, but the absolute magnitude has been found to exceed the calculated values by about 60 percent. In the theory it is generally assumed that the relaxation time involved for the attenuation is the same as is encountered in the electrical conductivity of metals. This particular assumption, if not valid, will certainly affect the theoretical estimates of the attenuation. We have tried to improve upon the theory by including the contribution of the electron–electron interactions to the ultrasonic attenuation in sodium, potassium & copper at low temperatures. Here we have used a simplified spherical fermi-surface model with an istropic umklapp transition probability for these metals. We find an improvement in the theoretical values of these metals.

SAW FREQUENCY ANALYZERS

Chairperson: J. H. CAFARELLA

V-1 [Invited] A Review of Current and Future Components for Electronic Warfare Receivers, J. H. COLLINS and P. M. GRANT, Department of Electrical Engineering, University of Edinburgh, Mayfield Road, Edinburgh EH9 3JL, UK.

Electronic warfare (EW) receivers for the passive gathering of radar and communications intelligence are discussed. The operational parameters of conventional system architectures are reviewed, including crystal video; instantaneous frequency measurement (IFM) and scanning superheterodyne receivers. Advances due to modularity, digital control and component integration are highlighted. The impact of new componentry based on surface acoustic wave (SAW) and acoustooptic Bragg cell technology is then discussed, particularly in relation to channelized receivers, microscan receivers, and IFM's. Finally, a number of conclusions are drawn covering likely trends in EW receivers and the need for continuing development of very high speed silicon integrated circuits (VHSIC's) for overall digital management of back-end signal processing and sorting.

V-2 A 1-GHz Bandwidth SAW Compressive Receiver, G. L. MOULE and R. A. BALE, Royal Signals and Radar Establishment, Malvern, England.

Analysis of modern radar signals demands the ability to handle short time coincident pulses at widely differing frequencies. The surface acoustic wave compressive receiver offers a compact solution with moderate resolutions over bandwidths in excess of 1 GHz. The choice of transform parameters is a compromise between short pulse capability and high resolution and must take into account the problems encountered with the chirp implementation of the Fourier transform of wide-band signals. Results for SAW compressive receiver subsystems developed to include specially designed output data handling circuits show a 1-GHz bandwidth, 4-MHz resolution capability.

V-3 Self-Aligning SAW Chirp-Fourier-Transform System,[1] D. R. ARSENAULT and V. S. DOLAT, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.

A SAW chirp-Fourier-transform system is described which utilizes active closed-loop control to adjust system timing and thereby maintain the accuracy of its output complex Fourier transforms even when device characteristics change due to temperature shifts and aging. Three separate adjustments, the timing of the input window over which the transform is taken, the timing of the output samples relative to the transform, and the phase used for I and Q demodulation, are required. The input window and the output sample timing are aligned by independently controlling the timing of post- and premultiplying chirps, respectively. For efficient device utilization one RAC expander generates both chirps so that each channel of this continuous "ping-ponged" system needs only one of these devices. Both channels share the same RAC compressor. I and Q phase is adjusted by digitally controlling the phase of the impulse RF source. Adjustments are made under active closed-loop control utilizing algorithms that derive error corrections from properly chosen test signals. These techniques have been implemented in a system which accepts digital data at a continuous 10-Mword/s rate, D/A converts this data and delivers its 256-point Fourier transform to A/D converters. The system processes complex words consisting of eight bits real and imaginary and maintains accuracy to 1 percent.

[1] This work was supported by the Department of the Air Force.

V-4 Wide-Band Instantaneous Frequency Measurements (IFM) Using SAW Devices, Y. BAR-NESS, Department of Systems Engineering, University of Pennsylvania, Philadelphia, PA 19104 and H. MESSER, School of Engineering, Tel Aviv University, Israel.

Frequency measuring systems are important in many applications. One method of performing such measurements is to autocorrelate the signal to be measured using a fixed value of delay. A disadvantage to this approach is that ambiguities of measurement result. This can be avoided only by imposing a limit on the signal frequency range. Using a SAW voltage controlled delay line (VCDL) instead of the fixed delay line makes it possible to get a very wide-band instantaneous frequency measurement (IFM). We consider the use of variable delay for IFM. The correlator output is filtered and fed back to control the delay line. This feedback system that mathematically recalls FM feedback can, in fact, be used in other applications as well, such as in wide-band FM detection. The work includes setting up the dynamic equations of the system with different loop filters. Phase plane representations shows the singular stable points of the system and helps to compare the performance with different loop filters. Computer simulations and experimental results support the theory. It is shown that with proper selection of the chirp filters used in the VCDl, the input frequency to voltage output conversion is unique, and hence the ambiguity is eliminated. It is also shown that the frequency measuring bandwidth, which is practically the VCDL bandwidth, is essentially large and depends only on the chirp filters parameters.

V-5 A UHF Fast Frequency Synthesizer Using SAW Filters, M. BEN ZAKEN, N. ZILBERMANN, E. KOGAN, P. ROMICK, and E. SOFER, Tadiran, Israel Electronics Industries Ltd., P.O.B. 648, Tel Aviv 61000, Israel.

A fast frequency synthesizer utilizing the SAW filter bank technique was designed and constructed. The synthesizer operates by mixing the outputs of the 10-channels SAW filter bank to generate 100 frequencies over a 100-MHz bandwidth at UHF. The achieved spurious signal level is below -70 dBc. The noise floor measured is -140 dBc/Hz at 10 kHz apart from the carrier. A switching time of 3 μs has been demonstrated. Small size has been achieved due to the use of hybrid technology. The reasons leading to the choice of the direct frequency synthesis method will be explained with emphasis on the required performance. It will be shown that the SAW filter bank approach is superior where a combination of high spectral purity, fast switching time, and low power consumption is important. This approach also enables the simultaneous generation of several frequencies. The design trade-offs required by SAW technology will be pointed out. Utilization of a SAW filter bank to generate frequencies at 10 MHz and 1 MHz spacing will be shown. Hybrid modules with SAW filters will be demonstrated. The inherent compactness, lightness and low power consumption makes the presented technique attractive in a wide range of applications.

NDE-MEASUREMENTS, SYSTEMS AND TECHNIQUES III

Chairperson: G. S. Kino

W-1 Measurement Techniques in Elastic Wave Scattering Experiments,[1] B. R. TITTMANN and L. A. AHLBERG, Science Center, Rockwell International, Thousand Oaks, CA 91360.

Techniques are described for measurements for the radiation pattern of elastic waves scattered by complex bulk defects. The problems addressed are sample preparation, system calibration, data acquisition, and data processing. The sample preparation technique is discussed in terms of the diffusion bonding process (developed by Paton, Science Center). Samples have been fabricated with such diverse defects as multiple voids, voids with rough surfaces and small protuberances, elliptical cracks, and combinations of voids and cracks. The description of system calibration emphasizes the transducer response and treats regimes of application and relative merits of various reflectors for calibrating the frequency response of transducers (included are results of calculations by Richardson and Thompson, Science Center). Data acquisition and processing are discussed in terms of digitizing the waveforms, decomvolving the waveforms to remove the transducer response, and calculating the magnitude and phase of the Fourier transform and the time impulse response function with the use of ISP (an interpretive signal processor developed by Elsley, Science Center). The various elements of the techniques are demonstrated with recently obtained examples of the Science Center's NDE program.

[1] This research was sponsored by the Center for Advanced NDE operated by the Science Center, Rockwell International, for ARPA/AFML under Contract F33615-80-C-5004, F33615-74-C-5180.

W-2 Semiadaptive Approach to the Extraction of Low-Frequency Properties from Scattering Measurements, J. M. RICHARDSON and R. K. ELSLEY, Rockwell International/Science Center, Thousand Oaks, CA 91360.

At sufficiently low frequencies, the scattering amplitude for any elastic wave scattering process from a localized scatterer can be written in the form $A(\omega) = \Sigma A_n \omega n$. In general, we can set $A_0 = A_1 = 0$. There are two low frequency properties of particular interest for characterizing scatters, namely, a) the coefficient A_2 describing the Rayleigh scattering regime and b) the ratio $\tau = A_3/iA_2$ which locates the center of the scatterer by giving the arrival time that an impulse would have if scattered from a point scatterer at the position of the center. In a previous paper the authors gave a detailed discussion of the problem of estimating A_2 and τ from scattering measurements. Use was made of a measurement model in which a possible measured waveform is represented as a superposition of the true signal and stationary Gauasian noise. In this treatment the noise power spectrum includes a term representing random errors in the modelling of $A(\omega)$. The so-called semiadaptive approach involves estimating the model error parameter C_8 on the same footing as A_2 and τ. Computational results based upon experimental and synthetic test data will be discussed.

W-3 Perturbation Method for Analyzing the Effect on Ultrasonic Echo Returns of Rough Surfaces in Material Cracks and Voids,[1] B. A. AULD and S. AYTER, Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305.

The effect of surface roughness of a crack or a void is investigated by means of Brekhovshikh's surface perturbation theory. Surface roughness is modeled as a nonvanishing spatially varying normal stress on an ideal smooth flaw. The perturbation formulation permits one to express this stress in terms of a function describing the deviation of the actual rough surface away from the ideal surface. Application of the reciprocity relation translates the perturbed stress function into a perturbation of the reflection coefficient. Applications to a number of different problems are discussed. The method can be used to determine the change in the angular scattering spectrum in terms of the scattering function, i.e., diffuse scattering. Taking the crack roughness as a statistical parameter, one can express the uncertainty inversion measurements in relation to the statistics of the roughness function, both for small k_a and large k_a cases. Crookedness of a crack may also be treated as a special case of roughness. Examples will be given.

[1] This work was supported by the Rockwell International Science Center under Contract RISC BO-FO 1243-3.

W-4 Normal Mode Variational Method for Two- and Three-Dimensional Acoustic Scattering in an Isotropic Plate,[1] B. A. AULD and M. TAN, Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305.

A method is presented for solving two- and three-dimensional acoustic scattering problems in an infinite isotropic elastic plate. Two- and three-dimensional plate Green's functions have been developed in terms of plate elastic wave mode expansions, using the elastodynamic reciprocity relation to carry out the expansions. In the three-dimensional case the angular spectrum of radiated waves is converted to "waveguide" format by imposing periodic boundary conditions transverse to the "waveguide axis." General properties of these Green's functions are discussed and they are then applied to the formulation of thin crack scatterers. A variational principle is developed for the modal reflection coefficients. Numerical examples are given for two-dimensional problems in which only the dominant modes propagate. Problems of convergence and truncation of the mode expansion series are considered and a method for removing the singularity from the Green's function modal expansion is presented. Extension to three-dimensional problems is discussed.

[1] This work was supported by the National Science Foundation under Grant ENG 79-14623.

W-5 Ultrasonic Detection and Sizing of Planar Weld Flaws in the Long Wavelength Limit,[1] C. M. FORTUNKO, Fracture and Deformation Division, National Bureau of Standards, Boulder, CO 80303.

An ultrasonic inspection scheme is described for detecting and sizing planar flaws in girth welds of cross country gas pipelines. The scheme is based on the inversion of long wavelength scattering data obtained with shear horizontal (SH) waves. Electromagnetic acoustic transducers (EMAT's) are used to excite and detect 470-kHz SH wave focused beams with a wavelength of 7.4 mm (0.290 in). The system has been used with excellent results to identify lack of sidewall fusion (LOF) flaws in 1.5 mm (0.060 in) in depth and incomplete penetration (IP) of approximately 0.5 mm (0.020 in) at the root of girth welds of 15.9 mm (0.625 in) in thickness. The presence of a "high-low" condition could also be detected. Also described are the physical principles of the technique, the operation of the demonstration system, and calibration procedures. A brief discussion is included of the complementary use of high resolution ultrasonic techniques to supplement the long wavelength scattering data for improved flaw characterization.

[1] This work was supported by the Materials Transportation Bureau of the Department of Transportation.

W-6 Experimental Study of the Two Bulk Compressional Modes in Water-Saturated Porous Structures, T. J. PLONA, Schlumberger-Doll Research, Ridgefield, CT 06877.

Recently, it has been experimentally observed that two bulk compressional modes can propagate in a water-saturated porous medium at frequencies near 1 MHz.[1] Based on the theory of Biot, the compressional wave of the first kind (i.e., the fast or normal wave) corresponds to an in-phase motion of the fluid and solid, while the compressional wave of the second kind (i.e., the slow wave) corresponds to an out-of-phase motion. First the experimental procedures which demonstrate that the slow wave is indeed a bulk compressional wave are described. Second, bulk wave velocities (i.e., fast compressional, slow compressional, and shear) are reported for several different types of porous structures including laboratory prepared samples of sintered glass spheres as well as commercially available porous materials frequently used in filtration applications. The porosities of the materials range from 10 to 40 percent, while the fluid permeability ranges from 1 to 55 μm^2. The speed of the slow compressional wave is observed to increase as the porosity and permeability simultaneously increase. The slow wave speed is less than the sound speed in water and measures about one-third to one-fourth the fast compressional speed. Observation of slow waves are shown to be limited at high frequencies due to scattering effects and at low frequencies due to viscous skin depth effects. Applications of slow waves to determine fluid properties in porous structures are discussed.

[1] T. J. Plona, *Appl. Phys. Lett.*, vol. 36, pp. 259-261, 1980.

SAW PROPAGATION

Chairperson: G. W. FARNELL

X-1 Visualization of SAW Propagation with the Scanning Electron Microscope, R. VEITH, G. EBERHARTER, H. P. FEUERBAUM, and U. KNAUER, Siemens AG, Forschungs laboratorien, München, Germany.

We developed a new technique to observe SAW propagation on piezoelectric substrates with the scanning electron microscope. Previously, only standing wave patterns could be observed using the voltage contrast mode. By adding a fast beam blanking system and synchronizing it to the SAW transducer driving voltage, we obtained stationary images of propagating waves. Additional information on the direction of propagation was obtained by continuously phase shifting the beam blanking with respect to the transducer driving voltage. This resulted in slowly moving wavefronts that could be displayed on a TV monitor. The very fast technique was applied to separately investigate diffraction, beam steering, reflection, spurious wave excitation, and material imperfections. Examples will be shown for the analysis of transversal filters on Y-Z-$LiNbO_3$ with center frequencies up to 500 MHz.

X-2 Phase Contrast Optical Filtering for Mapping SAW Second Harmonic Fields, A. ALIPPI, A. PALMA, L. PALMIERI, G. SOCINO, and E. VERONA, Istituto di Acustica "O.M.Corbino" CNR, Roma, Italy.

The extensive use of acoustic nonlinearities in SAW devices or else their undesired effects limiting the dynamic range of acoustoelectric devices ask for a precise knowledge of the harmonic generation and propagation in crystals. A complementary view to the studies of nonlinear coupling coefficients[1] may be represented by a mapping of the acoustic fields where nonlinear effects are present in the near field region. An optical filtering technique has been devised which permits one to select in the Fourier plane of the diffracted light the contributions due to the first order of the second harmonic from that due to second order of fundamental wave. The technique is similar to that used in contrast phase microscopy, where an optical plate retards and attenuates the zeroth order central spot by proper amounts. The light signal is directly collected by a photomultiplier on a plane, where a suitably magnified image of the acoustic field is scanned. The electrical signal at 2ω frequency is processed by etherodyning techniques. First results are presented relative to longitudinal and transversal scanning of SAW nonlinear fields in $LiNbO_3$ samples.

[1] A. Adamou *et al.*, "Parametric Mixing of Surface Acoustic Waves," *J. Appl. Phys.*, vol. 50, p. 4120, 1979.

X-3 Nonlinearly Coupled Modes of Surface Acoustic Waves,[1] N. P. VLANNES[2] and A. BERS,[2] Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.

A general coupled-amplitude equation is derived for surface acoustic waves. The derivation accounts for the propagating character and surface exponential decay of the uncoupled waves by using orthogonality relations to separate the interacting modes. Coupling constants for nonlinear mixing are derived from nonlinear material constants and normalized electric and strain fields and depend only on propagation direction of the linear normal modes. For conservative coupling, a single coupling constant describes a given three-wave interaction. Coupling constants of collinear harmonic generation are power independent and scale as fundamental frequency squared. For YZ-$LiNbO_3$, a consistent theoretical basis for single-nonlinear-parameter models of multiharmonic generation is established, and due to amplitude phase-locking, energy balance methods are shown applicable to most harmonic generation experiments. An experiment was done with an electrostatic surface probe to measure the magnitude of the nonlinear coupling constants for noncollinear interactions and examine the wave profiles. Waves at 36-MHz and 214-MHz were launched in the Z direction and 10°-off Z, respectively, on Y-cut $LiNbO_3$. The magnitude of the coupling constant of a resonant interaction that generates a 250-MHz wave was found to be $(7.4 \pm 1.6) \times 10^8$ m/s^2 $W^{1/2}$.

[1] This work was sponsored by the Department of the Army.
[2] Current addresses: Massachusetts Institute of Technology, Cambridge, MA 02139.

X-4 An Approximate GTD Technique for Computing SAW Diffraction for General Anisotropic Media,[1] W. A. RADASKY and G. L. MATTHAEI, Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106.

The geometric theory of diffraction (GTD) provides a remarkably simple means for computing the diffracted field from an aperture in terms of a geometric optics beam plus contributions from scattering centers at the edges of the aperture.[2] To our knowledge this method has not previously been applied to anisotropic media, except for the special case of a uniaxial medium[3] in regions away from the beam edges. (At the beam edges a singularity occurs in the GTD solution unless correction terms are added.) A method has been found for applying the GTD to general anisotropic media such as YZ $LiNbO_3$. Also, methods for removing the beam-edge singularities, which were developed for isotropic media,[4] have been adapted for the anisotropic case. Comparison of results computed by the GTD with results obtained by the plane-wave spectrum method for the case of $LiNbO_3$ is promising. It is anticipated that the GTD should provide a means for rapidly computing diffraction patterns of SAW transducers on media like $LiNbO_3$ where the parabolic anisotropic approximation is not valid.

[1] This work was supported in part by NSF Grant ENG77-28526.
[2] J. B. Keller, *J. Appl. Phys.*, vol. 28, pp. 426-444.
[3] B. Rulf and L. B. Felsen, *PIB Symp. Proc.* 1964, pp. 107-127.
[4] R. G. Kouyoumjian, *Topics in Applied Physics*, vol. 3. 1975, pp. 174-183.

SAW FILTERS
SIGNAL PROCESSING
PHYSICAL ACOUSTICS

Chairperson: R. A. MOORE

Q-1 Field Induced Effects on Surface Acoustic Waves in a Semiconductor Coupled Piezoelectric Substrate and Electronic Control SAW Transducer, S. K. LAHIRI, Department of Electronics and Electrical Communication Engineering, I.I.T., Kharagpur 721302, India, and A. CHAKI, Jhargram Raj College, Jhargram, Dist. Midnapur, West Bengal, India.

The effect of changing the surface condition of an adjacent gap-coupled semiconductor substrate on the propagation characteristics of surface acoustic waves over a piezoelectric substrate ($LiNbO_3$) has been studied using a new and simple technique for producing the MOS field effect. A modified SAW convolver with improved figure of merit has been realized. The effect of semiconductor gap coupling on an interdigital transducer (IDT) has also been studied. The field-effect control of the semiconductor surface has resulted in an electronically controlled IDT, which may provide additional flexibility in the realization of SAW filters. The results are discussed theoretically.

Q-2 The Application of Electrostatic Analysis to Generalized SAW Transducers,[1] R. C. PEACH, GEC Hirst Research Centre, Wembley, Middlesex, England.

The problems posed by the theory of SAW transducers have received much attention in recent years, and considerable advances have been made in the derivation of electrostatic solutions in a number of cases. These solutions permit most of the relevant circuit parameters of the transducer to be derived. The electrostatic problems associated with arbitrary transducer structures are considered from the point of view of complex variable analysis, which provides a very powerful analytic tool and also gives great insight into the construction and properties of the solutions. General formulas are derived, and a class of finite transducer geometries is considered for which a complete analytic solution for the electric field is possible. Explicit formula for the element factor of the infinite periodic array are derived as a limiting case.

[1] This work was supported by Procurement Executive, Ministry of Defence, sponsored by DCVD.

Q-3 New Theory of SSBW Devices, E. DANICKI, Military Academy of Technology, 00-908, Warsaw 49, Poland.

Interdigital transducer is considered lying on a surface of *Y*-rotated quartz substrate. An equivalent surface permittivity (ESP) as a function of r/r–wave vector tangential to the surface/ is analyzed in a first approximation. It is shown that the function of ESP has square-root inhomogeneity at that value of r where bulk wave group velocity is parallel to the surface. This inhomogeneity plays the same role in theory of surface-skimming bulk wave (SSBW) devices as a pole of EPS in theory of SAW devices. The trans-admittance relations of transducers are derived, the only difference of that for SAW case is a dependence on the distance between transducers. The trapping energy effect is also discussed. Some numerical and experimental results will be presented for *ST* quartz substrate.

†Q-4 SAW-LAW Multistrip Mode Converter,[1] S. DATTA, M. HOSKINS, R. ADLER, and B. J. HUNSINGER, Coordinated Science Laboratory, University of Illinois, Urbana, IL 61801.

Line acoustic waves (LAW) are ultrasonic waves that propagate nondispersively along the sharp edge of a polished substrate. LAW's carry very intense fields and are useful for nonlinear devices such as convolvers. Direct broad-band generation of LAW's has proven to be difficult and the SAW to LAW multistrip mode converter described may be a significant improvement. The conventional multistrip coupler cannot be used directly for mode conversion because surface and line waves travel at significantly different velocities. This difficulty is overcome in a multistrip mode converter (MSMC) by allowing the waves to interact periodically over limited regions; in principle, complete conversion may be achieved over a limited bandwidth. This is a well-known technique employed in certain traveling wave tubes but, to our knowledge, has not been used in acoustics before. A bandwidth of 5 percent and a conversion efficiency of 30 percent have been measured in the first experimental device. Significant improvements in bandwidth and efficiency are foreseen.

[1] This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB-07-C-0259.

Q-5 Use of Apodized Metal Gratings in Fabricating Low Cost Quartz RAC Filters,[1] G. W. JUDD and J. L. THOSS, Hughes Aircraft Company, Fullerton, CA 92634.

A straightforward design technique for making low cost RAC filters on quartz substrates is described. This approach utilizes a simple apodization scheme to control the response of metal reflection gratings that can be made with conventional photolithographic processes. A set of quartz RAC lines having a 20 percent operating bandwidth at 51.2 MHz, and a dispersive time delay of 50 μs have shown that this technique is capable of producing modest time-bandwidth product devices with excellent performance characteristics. The results of series of experiments that were conducted to determine the 90° reflection characteristics of shorted metal gratings on various rotated *y*-cut quartz substrates will also be reported. Data used to determine the single stripe reflection coefficient of aluminum stripes on *y*-cut substrates with rotation angles of 32° to 42.75° is presented together with measurements of the temperature coefficients of delay for these materials. A new technique for determining the stripe angle required to obtain 90° reflections on a given substrate material is described and its use in measuring the desired stripe angle for the above rotated *y*-cut substrates is summarized.

[1] This work was supported by the Electronics Research and Development Command under Contract DAAB07-78-C-3004.

Q-6 Automatic Time Domain Testing of SAW Devices, K. LANGECKER and R. VEITH, Siemens AG, Forschungs laboratorien, München, Germany.

Testing of SAW devices requires time domain measurements to differentiate spurious signals such as electromagnetic leakage, triple transit, and other reflections. The most common method, measuring the impulse response with an oscilloscope is limited in dynamic range and does not render itself for automation. Fast Fourier transformation of amplitude and phase frequency response is too time consuming for a larger quantity of devices. A new technique has been developed that makes use of a standard automatic networkanalyzer set up and pulse modulation at both input and output of the test device. Two modes of measurement exhibiting 70-dB dynamic range are possible. In the first mode spurious signals can be excluded from real time frequency response measurements. This method has proved to be a valuable tool for experimental analysis of SAW devices. In the second mode an impulse response measurement is made within 10 ms. This mode has enabled an automatic 100-percent test of SAW TV IF filter impulse response in production.

Q-7 Effect of Static Electric Field on Propagation of Surface Acoustic Waves in Piezoelectric Media, SHRINIVAS G. JOSHI, Marquette University, Milwaukee, WI 53233.

The effect of an externally applied electric field on the propagation of surface acoustic waves in a piezoelectric medium is considered. The electric field produces strain, which leads to a change in the time delay of the device. This has been used to fine tune the time delay of a delay line and the center frequency of a SAW resonator. Experiments performed with fields up to 2×10^6 v/m indicate a linear relationship of the form $\Delta t_d/t_d = K E$, where K is a material constant. K has the same order of magnitude as the relevant piezoelectric constant, d_{ij} where i denotes the direction of the applied electric field and j denotes the component of longitudinal strain in the propagation direction. This effect may also be useful as a device for measuring very high voltages.

Q-8 A Surface Acoustic Wave Application for a PAM-FM Communication Modem, S. NANAYAKKARA, Wayne State University, Detroit, MI and C. K. CAMPBELL, McMaster University, Hamilton, ON, Canada.

A method is proposed for the implementation of a pulse amplitude modulation-frequency modulation (PAM-FM) communications system modem, using surface acoustic wave device techniques. The transmitter stage for generating the message-carrying signal and a non-coded synchronization signal, includes a feedback loop control incorporating a SAW bandpass filter, a SAW delay equalizer, and a SAW sampling frequency-to-voltage converter.[1] In the receiving modem, the PAM-FM synchronization signal is first extracted with the aid of a SAW convolver and CW reference signal. The correlated output pulse is then used as the gating pulse into the sampling SAW F/V converter, during each conversion segment and waveform restoration. In this way, synchronization problems should be minimized, and error rate lessened. The proposed circuit is discussed, together with possible enhancement of signal-to-noise performance.[2]

[1] S. Nanayakkara and C. K. Campbell, "A method of converting frequency to voltage using a surface acoustic wave device," *IEEE Trans. Sonics Ultrason.*, vol. SU-26, pp. 419-422, Nov. 1979.
[2] S. Nanayakkara and C. K. Campbell, "Evaluation of signal and noise performance of a sampling wideband SAW FM discriminator," in *Proc. 1979 Ultrasonics Symp.*, 1979, pp. 738-740.

Q-9 Analog Encoded Signal Transmission Using Position-modulated Linear Chirps,[1] M. KOWATSCH, J. LAFFERL, and F. J. SEIFERT, Institut für Physikalische Elektronik, TU Wien, A-1040 Vienna, Austria.

For analog signal transmission to be encoded by linear chirps (linear FM) the most appropriate type of modulation is pulse position modulation (PPM), i.e., the starting-point of consecutive chirps with equal amplitude, length, center frequency, and dispersive slope is varied according to the sampled data. Chirp duration and sampling rate are properly chosen to yield permanent overlapping of several FM pulses. To recover the baseband signal in the receiver separation of consecutive chirps by pulse compression in a matched filter is required. Synchronization is attained by phase-locking the receiver reference quartz oscillator to the PPM mean frequency. A conversion of PPM into pulse amplitude modulation in the receiver demodulation process permits a maximum information bandwidth to be transmitted at a given sampling rate, yet keeping nonlinear distortions in the restored baseband signal low. In our system using SAW dispersive delay lines with a time-bandwidth product of 180 centered at 60 MHz, we achieve a signal bandwidth from 200 Hz to 600 kHz with a sampling rate of 1.3 MHz. The dynamic range is greater than 40 dB, and the amplitude characteristic is constant within 0.5 dB over the entire desired baseband signal spectral range.

[1] This work was supported by the Austrian Ministry of Defense and by the Fonds zur Förderung der wissenschaftlichen Forschung, Vienna, Project S-22/11.

Q-10 Transverse Acoustoelectric Voltage Inversion in a Simple Model Semiconductor,[1] I. J. FRITZ, Sandia National Laboratories, Albuquerque, NM 87185.

The interaction between a surface acoustic wave, propagating on a piezoelectric substrate, and an adjacent semiconductor leads to dc acoustoelectric fields in the semiconductor. The resulting transverse acoustoelectric voltage (TAV) has been recalculated, following closely the procedure used in the original calculation of Gulyaev *et al.*[2] The simple model used for the semiconductor assumes a single carrier type, flat bands, and no traps. It is found that the TAV has a different dependence on ω/ω_c (where ω is the wave frequency and ω_c the conductivity frequency) than given originally.[2] In the limit $\omega/\omega_c << 1$ the TAV has the opposite sign from that predicted by the original calculation, in agreement with recent experiments and with the low-frequency expression given by Morita *et al.*[3] Furthermore, the calculations indicate that the TAV changes sign as a function ω/ω_c, a fact which does not appear to have been pointed out previously. Proper interpretation of experiments where acoustoelectric voltage inversion is observed requires taking into account this intrinsic effect, and doing so appears to explain some previously puzzling results.

[1] Work was supported by the U.S. Department of Energy under Contract DE-AC04-76-DP00789.
[2] Yu. V. Gulyaev, A. Yu. Karabanov, A. M. Kmita, A. V. Medved', and Sh.S. Tursunov, *Sov. Phys.-Solid State*, vol. 12, p. 2085, 1971.
[3] S. Morita, K. Tsubouchi, and N. Mikoshiba, *Japan. J. Appl. Phys.*, vol. 15, p. 1019, 1976.

†Q-11 A SAW Multiple-Channel Filter for Underwater Acoustic Signals, P. H. SCHOTTLER, Sperry Research Center, Sudbury, MA 01776.

A system for applying a surface acoustic wave (SAW) transversal filter to the filtering of multiple channels of underwater acoustic signals is described. Time-division multiplexed and frequency heterodyned outputs from a number of sonar channels are applied to a single SAW filter processing channel, and the SAW filter output is demultiplexed to obtain filtered versions of the input signals. Since the mux/demux is done on sampled-data signals (digitally), while the filtering is done on a continuous-time signal, this SAW multichannel filter system is a sampled-data/analog hybrid. Because of the mismatch between the bandwidths (10-20 kHz) of the acoustic signals to be processed (assumed to be at baseband) and the operating frequency (10 MHz to 1 GHz) and bandwidth (MHz) of a typical SAW transversal filter, time-base modification (bandwidth expansion/contraction) and frequency heterodyning are required at the input and output interfaces to the SAW filter. The filter operates on blocks of time-compressed data from each channel; the blocks from different channels are interleaved and overlapped in such a way that "seam-free" processing of each input channel is achieved. Several issues associated with the SAW hybrid multichannel filter are treated: 1) the signal processing aspects of the SAW hybrid system which involve matching the processing capability of a SAW transversal filter to the processing of multiple channels of underwater acoustic data; and 2) the memory requirements and multiply rate requirements of an all-digital system which has the same throughput as the SAW hybrid system.

Q-12 A Technique for Increasing the Number of Transform Points in SAW Chirp-Fourier-Transform Processors, P. TORTOLI, G. F. MANES, Istituto di Elettronica, Florence, Italy, and C. ATZENI, IROE, Consiglio Nazionale Richerche, Florence, Italy.

The high-speed high-data-rate capability of SAW chirp Fourier transform processors have made attractive the use of hybrid configurations, where an analog SAW CFT subsystem, with D/A and A/D converters interface, is employed to process digital data in alternative to digital FFT. According to the classical MCM transform architecture, the number of transform points is determined by the width of the processing window imposed by the premultiplying chirp, the maximum number being equal to one quarter of the chirp filter time-bandwidth product. A new technique is introduced capable of providing a significant increase of the number of transform points by postprocessing the transformed data. Basically, the technique consists in sequentially analyzing adjacent input data blocks, and in recombining the output transform data blocks after previous multiplication by proper phase factors. The procedure can be flexibly employed for increasing the resolution capability over the analyzed bandwidth or, conversely, for extending the analyzed bandwidth with unaltered resolution.

Q-13 Charge Distribution and Memory Effect of Piezoelectric Gates,[1] M. E. MOTAMEDI, A. F. CSERHATI, E. J. STAPLES, and T. C. LIM, Electronics Research Center, Rockwell International Corporation, Thousand Oaks, CA 91360.

The MIS structure with a piezoelectric ZnO in the gate has many potential applications in signal processing and sensor devices. Various structures were fabricated and used as simple capacitors and field effect transistors. A theoretical model is developed to predict the electrical and mechanical properties of the device when a ZnO film is sandwiched between two layers of SiO_2. Results such as surface barrier of ZnO-SiO_2 interface, distribution of charge in ZnO, and storage capacity or memory effect of a piezoelectric gate will be presented.

[1] This work was supported by BMDATC under Contract DASG60-78-C-0095.

Q-14 An Ultrasonic Method for the Evaluation of Multiphase Binary Diffusion, Z. RONEN, S. ROKHLIN, Department of Materials Engineering, Ben-Gurion University of the Negev, and M. P. DARIEL, Department of Materials Engineering, Ben-Gurion University of the Negev and Nuclear Research Center-Negev, Beer-Sheva, Israel.

The application of an ultrasonic method for the assessment of the thickness of a binary diffusion zone is described. The mathematical analysis of the interaction of an acoustic wave with the diffusion on zone shows that the amplitude and the phase of a reflected ultrasonic signal are strongly dependent on the zone parameters, i.e., its elastic properties and its thickness. The characteristics of the reflected signal can, therefore, be used to deduce information on the diffusion zone. In order to verify this prediction, we have chosen to investigate the interaction of ultrasonic waves with the interface in Al-Cu diffusion couples. According to the phase diagram of this system several intermetallic phases are formed at the interface of the diffusion couple. The nature of these compound layers were examined by metallographic, scanning electron microscope, and electron microprobe techniques. Good agreement was observed between ultrasonic and direct measurements of the diffusion zone thickness. Further development of this new technique may allow its utilization for the monitoring of binary diffusion reactions.

Q-15 A New Ultrasonic Method for Measuring the Shear Modulus of Thin Interface Films, S. ROKHLIN and M. ROSEN, Department of Materials Engineering, Ben-Gurion University of the Negev, Beer-Sheva, P.O.B. 653, Israel.

A thin elastic film separating two identical half spaces is capable of localizing the energy of an elastic wave, provided that the shear modulus of the film is smaller than the shear modulus of the substrates. The formed interface wave is the low-frequency limit for the first antisymmetric mode in a system with an elastic layer separating two solid half spaces. When the film is thin, the velocity of the interface wave depends on the shear modulus of the film, its density and thickness, and also on the properties of the substrates. When the film thickness tends to zero, the velocity of the interface wave tends to the velocity of the shear wave of the half spaces. It is shown that, if the thickness of a film of a viscous fluid is smaller than the thickness of the hydrodynamic boundary layer, the film behaves as a solid. If the film thickness exceeds the thickness of the boundary layer, then the film behaves as a liquid, and the velocity of the interface wave is close to the velocity of the Rayleigh wave in the material of the substrates. It is shown that the interface wave can be used to estimate the elastic and dissipation properties of thin interface layers. Experimental results of the complex shear modulus for viscoelastic materials are presented.

Q-16 Electrically Tunable Narrow-Bandwidth SAW Filter, JEANNINE HENAFF and MICHEL FELDMANN, CNET PAB, Department DTS/MAE, 196 Rue de Paris, 92220 Bagneux, France.

SAW voltage controlled oscillators are very easily implemented using a conventional hybrid junction and varactors. Taking advantage of this, a similar device may be designed for use as an electrically tunable filter. The device consists of a SAW delay line with moderate insertion loss and closed through a low-noise amplifier in order to maintain the loop losses to a few decibels. In addition, a phase-shifter is inserted in the loop to match the overall phase. The input is typically the input of the amplifier, while the output may be similarly the output of the amplifier, for low loss, or an auxilliary SAW transducer designed to compensate for the frequency response of the delay line. This is a very agile narrow bandwidth filter, capable of meeting the requirements of the future vehicular communication system with frequency around 900 MHz. This type of tunable SAW filter has been first implemented at about 100 MHz on Lithium Tantalate ($LiTaO_3$) and Berlinite (AL PO4). Experimental results concerning both frequency response and stability will be reported.

SSBW AND SAW OSCILLATORS

Chairperson: M. F. LEWIS

Y-1 High Frequency Temperature Stable SBAW Oscillators,[1] K. F. LAU, K. H. YEN, R. S. KAGIWADA, and A. M. KONG, TRW Defense and Space Systems Group, Redondo Beach, CA 90278.

Oscillators at 1, 2, and 3 GHz have been developed using shallow bulk acoustic wave (SBAW) delay lines as the frequency controlling element. The SBAW delay lines were fabricated on rotated Y-cut quartz with rotation angle near 36°. For these substrates, the SBAW has a high wave velocity on the order of 5100 m/s. It has a zero first-order temperature coefficient of delay near room temperature. Both fundamental and third-harmonic transducer were implemented in the transducer design. The key to obtaining low insertion loss high frequency devices was found to be the use of thin metallization (~ 300 A Al) and embedded transducers. The oscillators were constructed with discrete components. Their short term stability was evaluated by measuring the frequency stability in the time domain and by measuring the phase noise in the frequency domain. The temperature stability was evaluated as a function of substrate angle and metallization thickness. The long term aging was also investigated. The applicability of SBAW in high frequency oscillators is demonstrated. By using SBAW technology, oscillators above 1 GHz can be fabricated reproducibly in large quantities and at a relatively low cost.

[1] This work was partially supported by ARO Contract DAAG26-78-C-0043 and NASA Contract NAS5-26002.

Y-2 S-Band SSBW Delay Lines for Oscillator Applications, D. L. LEE,[1] Raytheon Research Division, Waltham, MA 02254.

Because certain crystal orientations for the SSBW exhibit a 60-percent higher velocity than their SAW counterparts, these waves are likely candidates for delay line oscillators operating in the 1.5 to 3.0 GHz frequency range. For low noise applications, optimal transducer separation is dependent on attenuation due to both material losses as well as bulk wave scattering from the transducer fingers, with values of these losses determining device Q and insertion loss. Experimental data are presented on both of these loss mechanisms for the SSBW. Further, it is shown that SSBW's relatively small radiation resistance requires the transducer aperture be reduced until it is diffraction-limited, resulting in a transducer design whose geometry is nearly uniquely determined by specifying operating frequency. It is shown that useful devices with insertion loss and Q values comparable to SAW devices are obtainable up to 3 GHz. Results are presented for a 2.7 GHz delay line having a tuned insertion loss of 23 dB with a Q value of 4000.

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Y-3 Suppression of Reflection Effects in Surface Skimming Bulk Wave Devices, P. D. BLOCH, E. G. S. PAIGE, and M. W. WAGG, Department of Engineering Science, University of Oxford, Parks Road, Oxford, England.

A drawback to the use of surface skimming bulk waves (SSBW) in device structures is the occurrence of spurious signals due to strong reflections from crystal edges (up to 100 percent reflectivity). Suppression of the reflected SSBW by conventional SAW absorption techniques has been shown to be ineffective and even after metallization of the surface, this approach is inadequate. This paper presents results on the suppression of spurious signals by angling the reflecting crystal edge. After reflection at non-normal incidence, the effect of the reflected wave may be reduced by 1) geometric factors, 2) reduced piezoelectric coupling, 3) attenuation due to failure to satisfy the elastic boundary condition, 4) mode conversion, and 5) surface absorption. A theoretical and experimental comparative study of these effects leads to the conclusion that for many applications the combination of 1) and 2) provides an effective method of suppression.

Y-4 A 120-MHz SAW Resonator Stabilized Oscillator with High Spectral Purity,[1] L. PENAVAIRE, D. SEGUIGNES, C. LARDAT, Thomson-CSF, Cagnes/Mer 06802, France, and J. J. BONNIER, J. Y. CHEVALIER, and Y. BESSON, Thomson-CSF, 178, bd Gabriel Péri, 92240 Malakoff, France.

We discuss the design and fabrication of a 120-MHz oscillator which is stabilized by a SAW grooved resonator, in order to optimize the phase noise spectral density. The performances of the two-port resonators we fabricated (Q, insertion loss, and frequency adjustment) and the characteristics of the associated electronics are given. A specialized measurement bench for amplitude and phase spectral noise density is described. This setup uses two identical oscillators whose frequencies differ by an intermediate frequency. Its demonstrated sensitivity is better than −182 dBc/Hz down to 1 kHz from the carrier. The last part compares the experimental noise measurements and the theoretical predictions. The flicker noise influence is emphasized and we show the advantage of filtering the oscillator output with an another resonator with identical characteristics. Measurements show a phase spectral density better than −160 dBc/Hz and −180 dBc/Hz, 4 kHz and 15 kHz from the carrier, respectively.

[1] This work was sponsored by DRET (France).

Y-5 Observations on the Short-Term Stability of a SAW Delay Line Oscillator,[1] C. K. Campbell, Communications Research Laboratory, McMaster University, Hamilton, ON L8S 4L7, Canada.

Time domain short-term stability measurements are reported for an unlocked 183 MHz SAW delay line oscillator with output power 0 dBm into 50 Ω. An untuned insertion loss ~29 dB was obtained for the Lewis-type delay line on ST-X quartz, with an input reactive impedance of 50 Ω. The output reactive impedance of 250 Ω was series tuned with a 0.3-μH inductor. The computed unbiased Allan variance $\sigma_y^2(2, \tau, \tau)$ exhibited a dependence $\sigma_y^2(2, \tau, \tau) \propto \tau^{-2}$ over the range $10^{-3} \leqslant \tau \leqslant 1$ s with a fractional standard deviation $\sigma_y(\tau) \sim 8 \times 10^{-12}$ for $\tau = 1$ s, at 40°C. This result compares favorably with short-term stabilities for conventional quartz oscillators. From considerations of possible noise mechanisms influencing $\sigma_y^2(2, \tau, \tau)$, it was concluded that additive Johnson noise was the dominant one in this particular circuit. The SAW oscillator and measurement configurations are described, together with other details of oscillator performance. Design considerations are discussed, for effecting a possible further improvement of the above short-term stability.

[1] This work was supported in part under DOC Contract 0SU77-00111 with the Communications Research Centre, Ottawa, ON, Canada.

Y-6 Dynamic Thermal Sensitivity of SAW Quartz Oscillators,[1] D. HAUDEN[2] and G. THEOBALD, Laboratoire de Physique et de Métrologie des Oscillateurs du CNRS associé á l'Université de Franche-Comté-Besancon, 32 Avenue de l'Observatoire, 25000 Besancon, France.

In general, temperature variations of acoustic devices are considered slow enough to have a uniform thermal distribution in the volume of the crystal. In this case the usual model using a polynomial expansion up to the third order versus temperature is quite sufficient to describe thermal effects. On the other hand, fast thermal variations introduce nonuniform temperature distributions and thermal gradients which modify propagation properties of the wave. Calculations of thermal effects in SAW oscillators must take into account the spatial temperature distribution resulting from internal thermal variations and heat diffusion along transducers, connections, mounting and the crystal itself. Thermal stresses and strains are thereby introduced which change the wave velocity by nonlinear coupling due to the third-order elastic constants. It is shown that corresponding wave velocity variations (and thus oscillator frequency shifts) are proportional to the time derivative of the internal temperature. This model allows the calculation of the dynamic thermal sensitivity of SAW delay lines (or SAW resonators) built from singly and doubly rotated quartz cuts. An oven under digital temperature control from a computer is used to perform measurements. Applied temperature variations can be step or sinusoidal function of time.

[1] This work was supported by RADC, Hanscom AFB, MA.
[2] Current address: Rome Air Development Center/EEA, Hanscom AFB, MA 01731.

Y-7 Injection Locked SAW Oscillators,[1] D. J. DODSON, N. D. BRUNSMAN, and R. W. KERR, TRW DSSG, Redondo Beach, CA 90278.

SAW oscillators are finding increased application in direct frequency synthesizers due to their excellent phase noise and good temperature stability. In such applications it is often desirable to injection lock a bank of SAW oscillators to a single reference to establish coherence and improve stability. The injection locking properties of SAW oscillators have therefore been investigated. It has been found that with minor restatement, Adler's[2] development of injection locking applies directly to SAW oscillators. As the theory predicts, phase slope is the delay line characteristic which establishes the injection locking properties of SAW oscillators. Injection locking bandwidth can be calculated from phase slope and the ratio of injected voltage and oscillator signal levels. Data are presented showing the excellent fit of theoretical and measured injection locking bandwidth for SAWs of various delay times. Based on this understanding of the injection locking, a bank of SAW oscillators has been fabricated and locked to a comb generator. Data for this circuit are also presented.

[1] This work was supported in part by US Army Communications and Electronics Materiel Readiness Command.
[2] R. Adler, "A study of locking phenomena in oscillators," *Proc. IRE*, vol. 34, pp. 351-357, June 1946.

NDE-ARRAY TRANSDUCERS AND PROBE TRANSDUCERS

Chairperson: J. LARSON

Z-1 [Invited] PVF_2 Transducers,[1] H. J. SHAW, D. WEINSTEIN, L. T. ZITELLI, C. W. FRANK, and R. C. DEMATTEI, Stanford University, Stanford, CA 94305.

PVF_2 is of interest for ultrasonic transducers because of its high piezoelectric coefficient, of the order of that of crystalline quartz, its flexible thin film format, and its low acoustic impedance which provides excellent bandwidth and impulse response when radiating into, or receiving from, water or materials of similar impedance. Simple transducers fabricated from these films exhibit nearly classical thin layer transducer behavior in close agreement with theory. We show that transducers of high performance can be achieved that are easily made by films hot-pressed from commercial PVF_2 resins available from a number of sources. Prospects for practical transducers in the frequency ranges of importance for nondestructive evaluation of materials and structures, and for clinical medicine, are discussed, as is the applicability of PVF_2 films to transducer arrays for electronically controlled ultrasonic imaging. Methods of synthesizing PVF_2 material from the monomer are summarized, together with prospects for increased mechanistic understanding and enhancement of piezoelectric properties through further investigation of polymerization procedures. Prospects for improving the properties of PVF_2 films through changes in the manipulative history are also discussed.

[1] This work was supported by the Office of Naval Research under Contract N00014-75-C-0582, the Air Force Office of Scientific Research under Grant AFOSR-77-3386, and the NSF-MRL Program through the Center for Materials Research at Stanford University.

†Z-2 Acoustical Arrays with Nonuniform Element Spacing and/or Elevation, J. M. RICHARDSON and R. C. ADDISON, JR., Rockwell International Science Center, Thousand Oaks, CA 91360.

Several analyses are made of the radiation patterns produced by one-dimensional arrays of CW acoustical transducer elements whose positions are subject to three possible kinds of nonuniformity: a) nonuniform horizontal spacing between elements; b) nonuniform vertical elevation of elements; and c) combinations of both. For the sake of mathematical convenience, infinite arrays with a kind of Gaussian apodization are considered. Particular emphasis is put on the behavior of grating lobes. The effects of random position and phase errors are discussed.

Z3 Pseudorandom Codes for Multimode Operation of Phased Arrays,[1] B. B. LEE and E. S. FURGASON, Electrical Engineering Building, Purdue University, West Lafayette, IN 47907.

Previous work[2] has shown that noise signals and correlation detection can be used in phased arrays to simultaneously transmit and receive in a number of modes at a time (multiple beam directions, multiple focal points, etc.). In this investigation a comparison is made between noise signals and various pseudorandom codes, as applied to simultaneous transmission. Comparisons between the various types of transmitted signals made use of computer generated codes stored in a programmable signal source, and a digital correlation flaw detection system. Measured signal-to-noise ratios were compared to theoretical results. Preliminary results indicate that pseudorandom codes and noise signals are essentially equivalent under low input signal-to-noise ratio situations. Under high input signal-to-noise ratio situations, the pseudorandom codes appear to be better due to their nonrandom time sidelobes; finite correlation of noise signals produces random time sidelobes due to self interference.

[1] This work was supported by EPRI Project RP1395-4.
[2] B. B. Lee and E. S. Furgason, "The use of noise signals for multimode operation of phased arrays," *J. Acoust. Soc. Amer.*, July 1980.

Z-4 Thin-Film ZNO-MOS Transducers with Virtually DC Response, P.-L. CHEN, R. S. MULLER, R. M. WHITE, and R. JOLLY, Department of Electrical Engineering and Computer Sciences, and Electronics Research Laboratory, University of California, Berkeley, CA 94720.

One can combine thin piezoelectric films with MOS transistors in various ways to make sensitive ultrasonic transducers for bulk and surface waves. It has been found that by encapsulating the thin-film sputtered ZnO and the MOS device in either sputtered or CVD-produced silicon dioxide, the low frequency response of these devices can be greatly extended. Time constants as large as one week have been measured. Characteristics such as frequency response, sensitivity, dynamic range, and stability of bare and insulator-encapsulated transducers will be given and compared for devices having ZnO in the gate region or adjacent to the MOS transistor.

ACOUSTIC MICROSCOPY

Chairperson: R. C. ADDISON

AA-1 Acoustic Microscopy in High Pressure Gases, H. K. WICKRAMASINGHE and C. R. PETTS, Department of Electrical Engineering, University College, London, England.

The resolution of a scanning acoustic microscope can be shown to be roughly 2/3 the wavelength attainable in the coupling medium. The commonly used coupling medium is water, and the shortest wavelength that has been achieved in a water based acoustic microscope is 0.5 μ. We report on a system that uses a gas. This brings about several advantages; the main one being that the acoustic wavelength in gases is typically five to ten times smaller than that in liquids at the same frequency. Thus using a gas with the same absorption coefficient as water should make it be possible to improve the resolution of the microscope by a factor of five to ten over that in water. However, most gases have absorption coefficients that are about 100 to 1000 times higher (at atmospheric pressure) than those in liquids. What makes gases such as argon and xenon particularly useful is the fact that their absorption decreases as P^{-1}. Thus using argon at 40 bar, we can achieve a resolution that is a factor of two below the minimum value achieved in water. Alternatively, using xenon at the same pressure it should be possible to achieve a resolution which is a factor of four below that in water. Initial results in argon will be presented.

AA-2 Microscope Lens Using Conversion of Rayleigh to Compressional Waves,[1] G. W. FARNELL and C. K. JEN, Department of Electrical Engineering , McGill University, Montreal, PQ, Canada.

In the prototype lens, converging Rayleigh waves generated by a circular interdigital transducer on the interface between a liquid and a piezoelectric substrate are converted to compressional waves in the liquid in the form of a hollow conical beam. The cone angle is determined by the phase-match condition between the surface wave on the interface and the compressional wave in the liquid. The focal spot size is of the order of a wavelength, and the sidelobes depend on the propagation length of the Rayleigh wave and are intermediate between those of an annular and a standard full aperture lens. Conversion efficiency depends primarily on the electric-to-acoustic conversion of the electrodes as a surface-wave transducer. Calculations include the effects of substrate anisotropy, but the experimental lenses have been simple concentric circular interdigital transducers of two or three fingers on Y-cut $LiNbO_3$ and thus of very wide bandwidth. Since the lens is planar and defined by the electrodes, geometries of nested circles or distorted circles can be designed to vary the position or shape of the focal spot by switching electrodes or varying the frequency of excitation.

[1] Research supported by Natural Sciences and Engineering Research Council of Canada.

AA-3 Acoustic Micrography of Elastic Constants,[1] I. R. SMITH and D. A. SINCLAIR, University College, London, England.

The images derived from microscopy arise from an often complex interplay of various contrast mechanisms. For some applications of acoustic microscopy, it would be desirable to produce images which would map the elastic constants of the object. If one sacrifices a little of the maximum attainable resolution, one can, following a theory due to Bennett, derive the required constants in a rather simple manner from recorded amplitude and phase data. The accuracy of the technique has been assessed using liquid slab specimens. The method has also been developed so as to allow measurements on solid slabs and has given encouraging results. The overall capability of the method will be assessed, including a discussion of the trade-off between resolution and accuracy. Preliminary results on the use of the method for tissue characterization and for cellular imaging will be presented.

[1] This work was supported by the Science Research Council and by the Medical Research Council.

AA-4 Measurement of Acoustic Transmission Through Air Cavity Using Acoustic Microscopy,[1] J. K. WANG, C. S. TSAI, and C. C. LEE, School of Engineering, University of California, Irvine, CA 92717.

We had earlier used a transmission scanning acoustic microscope (SAM)[2] operating at a fixed frequency of 150 MHz to detect voids and inclusions in thick specimens of both specially made material joints[3] and production-line hybrid microelectronic components.[4] We have most recently used the same SAM in swept-frequency mode to study the transmission characteristics of air cavities imbedded in host materials such as glass and steel. Strong acoustic transmission has been shown to occur within a few megahertz band centering at 90 MHz. The measured frequency separation between adjacent peaks of the transmission spectra is found to relate to the longitudinal dimension and the acoustic velocity of the air cavity by a simple resonance formula. Measurement technique and the results obtained are described in detail. Potential applications of this technique for nondestructive detection and characterization of defects, and for measuring acoustic velocity of a variety of materials are also discussed.

[1] This work was supported in part by the MRL Section of the NSF under Grant DMR 72-03297-A03.
[2] R. A. Lemons and C. F. Quate, *Appl. Phys. Lett.*, vol. 24, p. 163, 1974.
[3] C. S. Tsai, J. K. Wang, and C. C. Lee, *Appl. Phys. Lett.*, vol. 31, p. 317, 1977.
[4] C. S. Tsai, C. C. Lee, and J. K. Wang, in *Proc. 1979 Reliability Physics Symp.*, IEEE Cat. 79 CH 1425-8 PHY, p. 178.

†AA-5 Quantitative Flaw Size Determinations with the Scanning Laser Acoustic Microscope (SLAM),[1] D. E. YUHAS, C. L. VORRES, and L. W. KESSLER, Sonoscan Inc., 530 East Green Street, Bensenville, IL 60106.

Accurate methods for determining flaw size are necessary for establishing accept/reject criteria for nondestructive testing of ceramics. The scanning laser acoustic microscope (SLAM) produces orthographic projection images of internal features. Due to diffraction spreading of the acoustic beam and focusing effects, the image size of a buried structure may differ from its actual size. The observed image size depends on actual flaw size, flaw type, depth from the surface, and the acoustic properties of the host material. Silicon nitride samples with implanted solid inclusions were imaged as the sample thickness was reduced by grinding. Measurements of flaw depth from the surface were made after each thickness reduction by simple stereoscopy techniques. In addition, micrographs of the flaw were recorded showing the variation of the image as a function of depth. A relationship between actual flaw size and the image size is derived and compared with that predicted based on scattering theory.

[1] This work was supported by DARPA/AFML Center for NDE, Rockwell Science Center.

†AA-6 Dark Field Imaging with the Scanning Laser Acoustic Microscope (SLAM), L. W. KESSLER and D. E. YUHAS, Sonoscan Inc., 530 East Green Street, Bensenville, IL 60106.

Acoustic bulk wave energy impinging on a surface flaw (e.g., crack) from within a sample is partially mode-converted to waves which propagate parallel to the surface. In bright field acoustic microscopy, both the transmitted bulk wave and a portion of the mode-converted wave are detected. Because the waves are coherent and overlap spatially, the images are characterized by a fringe pattern (spatial beat note) superimposed on a bright background. An alternate detection method, dark field imaging, involves electronically rejecting the bulk wave and visualizing only the scattered component. Rejection is possible because of the action of the laser scanning which perceives an electrical frequency Doppler shifted from that of the incident acoustic wave. The Doppler shift, of course, is determined by the direction of the laser scan and the direction of the scattered acoustic waves. The dark field method is found to be a more sensitive means of detecting small surface flaws (relative to bright field). We describe the SLAM dark field imaging technique, and compare bright and dark field images of the same flaws.

MULTISTRIP AND GRATING DEVICES

Chairperson: L. P. SOLIE

BB-1 Temperature-Stable RAC,[1] D. E. OATES and D. M. BOROSON, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.

Recently, a new cut of quartz was proposed for fabrication of temperature-stable dispersive delay lines in the reflective-array-compressor (RAC) configuration. We report here the first experimental results for RAC's fabricated using this cut. Measurements of the temperature dependence of the chirp slope and group delay will be presented. Preliminary results show variations of less than 10 ppm/°C. These first RAC's use interdigital transducers (IDT) and have time-bandwidth products of up to 125. The bandwidth using IDT's is limited; therefore, wide-band and edge-bonded transducers have been developed for use in temperature-stable RAC's with fractional bandwidths of up to 50 percent. Measurements and calculations of diffraction and beam steering for the new cut will be presented. A new and efficient method for calculating planar diffraction fields on general anisotropic materials has been developed. Because the SAW beam profile is merely the Fourier transform of a particular function of the input transducer shape and the phase velocity of the material, the entire beam profile can be quickly calculated using fast Fourier transform algorithms. A 2048-point beam profile can be calculated approximately two orders of magnitude more quickly than with direct numerical integration.

[1] This work was supported by the Departments of the Army and the Air Force.

BB-2 The Analysis of the Grating Structures by Coupling-of-Modes Theory,[1] H. A. HAUS and P. V. WRIGHT, Department of EECS and RLE, Massachusetts Institute of Technology, Cambridge, MA 02139.

The analysis of grating structures is greatly simplified by the use of the coupling-of-modes theory. We discuss the approximations inherent in such an analysis and the conditions under which it is valid for grating structures. It is shown that the theory is valid for the analysis of most practical gratings. Solutions are given for all the phase and amplitude responses of a normal-incidence grating. These solutions include the effects of multiple bounces within the grating. A relatively simple method for analyzing grating structures to second-order (in grating depth) by means of the coupling-of-modes theory is given. The latter permits both the second-order coupling coefficient and the reduction in grating wave velocity to be obtained in closed form for both normal- and oblique-incidence gratings. Finally, a coupling-of-modes approach for analyzing "U" and "Z" path gratings when multiple-reflection effects are important is proposed. The great simplicity of the analysis compared with the commonly used "unit-cell" approach clearly demonstrates the power of the coupling-of-modes theory.

[1] This work was supported by the National Science Foundation under Grant ENG7909980.

BB-3 A Closed-Form Analysis of Reflective-Array Gratings,[1] P. V. WRIGHT,[2] Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173 and H. A. HAUS, Massachusetts Institute of Technology, Cambridge, MA 02139.

A complete analysis of low-loss reflective-array gratings is presented which includes the effects of multiple reflections and stored energy in deep gratings. Closed-form solutions are derived for all the waves in a "U"-path grating and also those in a reflective-array compressor (RAC). This is the first time that such a complete and fundamental analysis of the RAC has been reported. The analysis is performed for a 45° oblique-incidence grating on an isotropic substrate either with a constant spatial period or with a linear-chirp. For an arbitrary input, closed-form solutions are obtained for the waves both transmitted and reflected by the grating, using the coupling-of-modes theory. By invoking an equivalent isotropic Poisson ratio, the analysis is extended to include typical anisotropic materials. The theory is then compared with experimental data taken on practical devices. In particular, the effect on RAC performance of multiple reflections in deep gratings is studied. Finally, the reflection coefficient at oblique incidence is calculated to second-order to determine the importance of stored-energy effects in RAC devices.

[1] This work was supported by the Department of the Army and the National Science Foundation.
[2] Permanent Address: Massachusetts Institute of Technology, Cambridge, MA 02139.

BB-4 The Use of Frequency-Selective Multistrip Couplers in Surface Acoustic Wave Transversal Filters, R. J. MURRAY, Philips Research Laboratories, Redhill, Surrey, RH1 5HA, UK and J. SCHOFIELD, Mullard Central Materials Laboratory, Mitcham, Surrey, CR4 4XY, UK.

The way in which frequency-selective multistrip couplers can be used to maximum practical advantage in surface acoustic wave transversal filters is described. It is shown how multistrip couplers incorporating a geometric jog in one track may be designed to introduce notches into a filter characteristic or to suppress unwanted harmonic responses without imposing design restrictions on the transducer geometry. It is also shown that part of the filter selectivity can be obtained from a weighted bandpass multistrip coupler; this eases the selective requirements on the interdigital transducers, which allows minimization of the transducer length and reduces the number of small sources. A technique for the incorporation of harmonic suppression into a weighted bandpass multistrip coupler is described in detail. Methods for the synthesis and analysis of bandpass multistrip couplers are discussed. Experimental measurements on filters incorporating third harmonic suppressed bandpass multistrip couplers are reported and are shown to be in good agreement with theoretical predictions.

†BB-5 Diffraction in TV-IF Filters Using Multistrip Couplers,[1] W. MADER, Institut für Physikalische Elektronik, TU Wien A-1040 Vienna, Austria, H. STOCKER and G. TOBOLKA, Siemens AG, Research Laboratories, FL FES 11, Otto-Hahn, Ring 6, D-8000 Munich, Germany.

In high performance SAW TV-IF filters multistrip couplers (MSC) are used to suppress unwanted spurious bulk mode transmission. Small maximum finger overlap is chosen to keep filter cost low due to small substrat square dimensions. Because of the small apertures diffraction becomes severe on 128° rotated Y cut lithium niobate. As recently published scanning electron microscope investigations show, parts of the waves launched by the apertures of the input transducer are spread into the track of the output transducer. Experiment shows that these detected spurious waves are only about 40 to 50 dB down compared to the midband transmission. This is perfectly verified by calculations using the parabolic anisotropic diffraction formulas. In filter analysis transmission by the MSC with regard to diffraction cost between the MSC and each transducer and transmission by direct coupling of spurious diffracted waves from the input to the output transducer were taken into consideration. Both contributions were summed up allowing for the phase shift due to the MSC behavior to give the transfer function of the filter.

[1] This work was supported by the Fonds zur Förderung der wissenschaftlichen Forschung, Vienna, Project S-22/11.

IMAGING–I

Chairperson: S. LEES

CC-1 [Invited] Real-Time Synthetic Aperture Imaging System,[1] G. S. KING, D. CORL, S. BENNETT, and K. PETERSON, E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305.

The principles of a real-time synthetic aperture acoustic imaging system operating with a center frequency of 2.5 MHz will be described. The device employs a multiplexer to address individual elements of a transducer array. The pulse is transmitted from one element and received on the same one, then read through an A-to-D converter into a RAM. This process is repeated in turn for 32 transducer elements. All information read from the region to the imaged is stored in a set of RAM's. The time delays required for image processing are then syntheaized by adding the signals from appropriate points in the RAM's. This process can be carried out in real-time at 30 Hz frame rate. Images taken with the system in a water tank, with surface waves, on metals, and with bulk waves in metals will be shown. A discussion will be given of the kinds of images to be expected from such imaging systems and of their relation to typical optical images. One major difficulty with systems of this kind is the imaging of specular reflectors. The relation between the point response of such systems and the response to specular reflectors will be discussed.

[1] This work is supported by the Air Force Office of Scientific Research under Contract F49620-79-C-0217.

CC-2 A Three-Dimensional Synthetic Focusing System, K. LIANG, B. T. KHURI-YAKUB, and G. S. KINO, E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305.

Synthetic focus acoustic imaging techniques are being developed to reconstruct three-dimensional acoustic images of flaws inside silicon nitride. The following geometries have been examined: flat disk samples 0.635 cm diameter and 10 cm long. Computer simulations based on theoretically calculated backscattered waveforms from spherical voids, iron, and silicon inclusions have been carried out. Two- and three-dimensional reflectivity distributions are reconstructed from the pulsed echo data on a computer using a selective back-projection scheme. For the flat disk geometry, a square 8 × 8 element aperture with sampling points two wavelengths apart is used. For the cylindrical case, an open-ended cylindrical aperture consisting of a stack of 16 rings two wavelengths apart with each ring having 32 evenly distributed sampling points is used.

CC-3 Acoustic Imaging with Two-Dimensional Arrays,[1] K. M. LAKIN, WILLIAM SHEPPARD, and K. TAM, University of Southern California, Los Angeles, CA 90007.

A reconstruction of the ultrasonic scattered fields in the zone near the scatter constitutes an image of the scatterer or flaw. In a real case the reconstruction zone may contain more than one distinct scatterer and accordingly the entire group form the image. At a remote location the scattered fields form a complicated diffraction pattern which will yield the image if operated on by a suitable set of mathematical operations. The measurement of the remote fields is of major interest as it affects the image quality. Unlike phased array systems, the transducer spacing, hence measurement sampling density, is determined by the spatial frequencies of the diffraction pattern and sampling theory. This paper will describe the implementation of a 64 × 64 two-dimensional array and the results obtained in imaging the phase and magnitude of source and scattered fields.

[1] This work was supported by the DARPA/AFML Interdisciplinary Program on Non-Destructive Evaluation.

CC-4 A SAW-Based Programmable Transversal Filter with Application to Ultrasound Imaging, G. F. MANES, D. GERLI, P. MATTERA, Istituto di Elettronica C. ATZENI, IROE, Consiglio Nazionale Ricerche, Florence, Italy.

A SAW tapped delay line operated in the baseband region is used to implement a programmable transversal filter. Programmability is achieved by controlling the tap weights through DAC multipliers.

A prototype system capable of implementing a variety of processing functions, including real-time Hilbert transformation and inverse filtering is described. The system is particularly intended for application to pulsed ultrasound imaging.

CC-5 Acoustical Imaging via Coherent Reception of Spatially Coloured Transmissions, P. TOURNOIS, Thomson-CSF, ASM Division, 06802 Cagnes-sur-Mer, France.

If the transducers of an antenna transmit different signals simultaneously, the insonified space is "coloured" since a particular resulting signal corresponds to each direction. At the receiver's end, classical beamforming is performed as if insonification was isotropic. Next, each formed beam output is fed into the filter matched to the signal transmitted into that particular direction; a gain of the order of two in angular resolution results, similar to that of the product of the transmit-receive antenna patterns, but no directional transmission was required. The applications of this general principle to the field of acoustical imaging is reviewed.

THIN FILMS

Chairperson: A. J. SLOBODNIK

DD-1 Attenuating Thin Films for SAW Devices,[1] A. C. ANDERSON and V. S. DOLAT, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173.

Conventional surface acoustic wave (SAW) transducers are bidirectional and launch waves which, when reflected by crystal edges, can result in spurious device responses. To prevent spurious signals, these unwanted waves are typically damped with grease or tape placed on the substrate. There is a need for a stable, rugged, contamination-free means of attenuating SAW's, especially for space-qualified devices. High-resistivity thin films deposited on the surface of a piezoelectric crystal interact with the electric field which accompanies the surface wave. The loss resulting from the induced current flow rapidly attenuates the wave. The properties of sputter-deposited thin cermet film (e.g., $Cr\text{-}Cr_2O_3$) of controlled resistivity on the surface of $LiNbO_3$ crystals have been investigated. Attenuation of up to 0.3 dB/wavelength has been achieved for YZ $LiNbO_3$. These films are very rugged and have been used to suppress unwanted waves in reflective array compressor (RAC) devices. Additional process control may allow amplitude trimming of RAC response as well. A comparison of the theoretical expectation and experimental results for attenuation produced by these films will be presented.

[1] This work was supported by the Department of the Army.

DD-2 High-Frequency and Low-Dispersion SAW Devices on AlN/Al_2O_3 and AlN/Si for Signal Processing, K. TSUBOUCHI, K. SUGAI, and N. MIKOSHIBA, Research Institute of Electrical Communication, Tohoku Univ., Katahira 2-1-1, Sendai 980, Japan.

A single-crystal film of AlN on the basal plane of sapphire, which shows a RED pattern of individual spots and Kikuchi lines, has been grown by metalorganic chemical vapor deposition at ~1200°C under the adequate gas flow pattern, but under inadequate conditions the hillock-like misoriented grains have appeared and these grains gave the degradation of electromechanical coupling. (ZX)AlN/(ZY)Al_2O_3 SAW device showed the lower dispersion than previously reported on sapphire substrate. It was of slightly "slow on fast" type, i.e., the phase velocity decreased from 5706 m/s to about 5650 m/s as the film thickness increased. On (111) Si substrate (n-type, $\rho = 2.3\ \Omega \cdot cm$), a single-crystal film of (0001) AlN has been grown at ~1200°C. We have measured C-V and G-V characteristics of MIS structure of Al/AlN/Si and obtained the following results which show sufficiently stable MIS structure: V_{FB} (flat band voltage) = +0.9 V, ΔV (C-V hysteresis) $\lesssim$ 0.05 V, N_{ss} (surface state density) at depletion region $\sim 10^{11}\ eV^{-1}\ cm^{-2}$, σ_n (electron capture cross section) $\sim 10^{-17}\ cm^2$. The AlN/Si SAW device also exhibits high-frequency and low-dispersion characteristics and has especially potential advantages for wide-band signal devices with acoustoelectric effects such as convolvers and correlators.

DD-3 Low Temperature Growth of Piezoelectric AlN Film for Surface and Bulk Wave Transducers by RF Reactive Planar Magnetron Sputtering, T. SHIOSAKI, T. YAMAMOTO, T. ODA, and A. KAWABATA, Faculty of Engineering, Kyoto University, Kyoto, Japan.

A single-crystalline AlN film is grown on a basal plane sapphire substrate and also *c* axis oriented AlN films are grown on glass and gold-film substrates at substrate temperatures as low as from 50°C to 500°C by using reactive RF planar magnetron sputtering, the film quality being equally good at temperatures between 100°C and 500°C. Surface acoustic waves are generated and detected for the first time by IDT's at the interface between an AlN film and sapphire substrate, besides by IDT's on the top of the AlN film. The SAW coupling factor k^2 is 0.09 and 0.12 percent at $h/\lambda = 0.3$, respectively, for these IDT locations. The AlN films sputtered on gold electrodes on Kovar glass (glass transition temperature 502°C) rod and sheet are also piezoelectric and used as bulk and surface acoustic wave transducers, respectively. Several electromechanical constants for AlN have been measured by using thin AlN plates of several tens of microns in thickness removed from the glass and gold film substrates, showing AlN is really a promising piezoelectric material at high frequency. Ultrasonic velocities: $v_1^l E = 9.65$ km/s, $v_3^l D = 11.3$ km/s; elastic constants $S_{11}E = 3.30 \times 10^{-12}\ m^2/N$, $C_{33}D = 4.17 \times 10^{11}\ N/m^2$, $C_{33}E = 4.04 \times 10^{11}\ N/m^2$; coupling coefficients: $k_{33}t = 17.3$ percent, $k_{31} = 9.2$ percent; dielectric constant: $\epsilon_{33}T = 11.4\ \epsilon_0$.

DD-4 SAW and Boundary Wave Properties for SiO_2 $LiTaO_3$ Structure Fabricated by Plasma-CVD, K. SHIBAYAMA, K. YAMANOUCHI, and W. CHUJO, Research Institute of Electrical Communication, Tohoku University, Sendai, Japan.

The propagation characteristics of the layered structure consisting of SiO_2 film on $LiTaO_3$ (126° rotated *Y*-cut, *X*-propagational) are investigated. SiO_2 films are fabricated by plasma-CVD techniques. Rayleigh waves are launched and received by regular IDT fabricated on crystal plate. By use of SiH_4-N_2O plasma-CVD system, we have obtained an excellent result not only for temperature characteristics (≈ -2 ppm/°C) but also for frequency response. In this case, the gas flow ratio is $N_2O:SiH_4 = 1:30$, and the film thickness H is $H/\lambda \simeq 0.14$ (λ: wavelength of Rayleigh wave). This thickness corresponds to approximately half of the theoretical expectation ($H/\lambda \simeq 0.25$). We have also investigated the character of piezoelectric acoustic boundary waves (PABW). When the SiO_2 film is increased to as much as $H/\lambda = 0.416$, and in the same gas flow ratio as above, the PABW response is only observed, and the frequency response surpasses the SAW response given by no film condition. Moreover, $SiO_2/LiTaO_3$ (36° rotated Y-X) and $SiO_2/LiNbO_3$ (128° rotated Y-X) structures fabricated by plasma-CVD show a similar tendency as stated above.

DD-5 PVF_2 Elastic Constant Evaluation, R. S. WAGERS, Texas Instruments Incorporated, Dallas, TX 75265.

The elastic constants of the piezoelectric polymer polyvinylidene fluoride, PVF_2, are determined from the experimental Lamb wave mode spectra of PVF_2 delay lines. The first five Lamb waves of PVF_2 thin plates are excited by interdigital transducers at temperatures from -50°C to -175°C. Numerical values for the elastic constants c_{11}, c_{13}, c_{33}, and c_{55} are presented. The results obtained for c_{33} and c_{55} are in agreement with those of previous investigators. Results for c_{11} and c_{13} are presented for the first time.

DD-6 Low Frequency Acoustic Propagation in Anisotropic Thin Polymer Films, ED BALIZER, PHILIPP KORNREICH, and STEPHEN KOWEL, Department of Electrical and Computer Engineering, Syracuse University, Syracuse, NY 13210.

We have studied wave propagation in thin anisotropic linear viscoelastic polymers. The equations of motion of the waves for thin plates were derived by generalizing Mindlin's variational and truncation methods[1] to include linear viscoelastic dissipative forces. The dispersion relations were found from these equations for the three modes of lowest frequency, in the limit of a semi-infinite plate geometry. Experimental measurements for each of these modes were taken on biaxially oriented PVF_2 and will be discussed in terms of the theory.

[1] R. D. Mindlin, "An Introduction to the Mathematical Theory of Vibrations of Elastic Plates," Signal Corps Engineering Laboratories, Fort Monmouth, NJ (1955).

ACOUSTIC SENSORS

Chairperson: C. S. TSAI

EE-1 Gyroscopic Effect in Surface Acoustic Waves, B. Y. LAO, Bendix Advanced Technology Center, Bendix Corporation, Southfield, MI 48076.

The effect of rotation on surface acoustic waves is derived theoretically in a perturbation treatment of the Coriolis force for an isotropic medium. The linear effect on the propagation velocity V in terms of $(\Delta V/V)/(\Omega/\omega)$, where Ω and ω are the rotation and SAW frequencies, respectively, is found to depend only on the Poisson's ratio of the medium and varies between 0.27 and -0.2. A dual-resonator gyroscope based on this effect will give a phase angle output equal to a maximum of 54 percent of the system attitude to be measured. The stability of the state-of-the-art SAW resonators implies a gyroscope resolution of 1/10 earth rotation rate.

EE-2 Acoustic Surface Wave Accelerometer and Rotation Rate Sensor,[1] H. F. TIERSTEN, D. S. STEVENS, and P. K. DAS, Rensselaer Polytechnic Institute, Troy, NY 12181.

In inertial guidance the movement of a vehicle is directed using measurements from sensing devices. These measurements do not entail the determination of fields outside the vehicle. Two types of sensing devices are used; accelerometers and gyroscopes. The possibility of implementing both of these devices using surface waves in an essentially monolithic fashion is investigated. If three surface wave resonators such as those used in the surface wave pressure transducer are loaded by means of large masses, which when subject to acceleration can impart large biasing loads to the substrates and thereby cause changes in the resonant frequencies, the structure is an accelerometer. The function of the gyroscope can be simulated if rotation rate can be sensed. It is well-known that if a point moves with a velocity relative to a rotating substrate the moving point experiences the Coriolis acceleration, which is linear in and normal to both the angular velocity of the substrate and relative velocity of the moving point. Consequently, the velocity of propagation of a surface wave will vary with the angular velocity of the substrate. Thus, by monitoring the velocity of three distinct surface waves, the angular velocity can in principle be determined. The results of measurements are presented and compared with calculations based on a perturbation procedure.

[1] This work was supported in part by ONR Contract N00014-76-C-0368 and NSF Grant ENG 7827637.

EE-3 Progress in the Development of SAW Resonator Pressure Transducers,[1] D. E. CULLEN and G. K. MONTRESS, United Technologies Research Center, East Hartford, CT 06108.

The dual oscillator SAW resonator pressure transducer is a promising candidate for high performance, moderate cost pressure sensor applications. The design, fabrication, packaging, and circuitry of this device will be described, with emphasis on recent modifications leading to improved sensor performance. Temperature compensation techniques and the effects of high Q SAW resonators on device stability will be discussed. Sensor data illustrating frequency output versus pressure, pressure sensitivity, nonlinearity, hysteresis, thermal sensitivity, and stability will be presented.

[1] This work was supported in part by the Naval Avionics Center, Indianapolis, IN.

EE-4 [Invited] Fiber Optical Sensor Development, T. G. GIALLORENZI, Optical Sciences Division, Naval Research Laboratory, Washington, DC 20375.

During the past few years, a significant noncommunications alternative use of optical fibers has evolved. This new application involves the use of fibers to sense acoustic, magnetic, temperature, acceleration, and rotation perturbations. As an example of the potential of these sensors, fiber acoustic sensors offer an order of magnitude increase in performance in terms of threshold detectability when compared with the best piezoelectric ceramic/polymer sensors. These fiber acoustic sensors offer other advantages such as revolutionary geometric versatility. In the case of fiber magnetic sensors, threshold detectabilities of 10^{-12} G appear feasible; sensitivities which rival the best superconducting SQUID sensors. Furthermore, state of the art fiber accelerometers with submicro-g performance have been demonstrated. The various aspects of this evolving technology and the present experimental status of the fiber sensor field are reviewed. Emphasis is placed on acoustic sensor configurations.

EE-5 PVF_2 Phase Shifters and Modulators for Fiber Optic Sensor Systems,[1] E. F. CAROME and K. P. KOO, Physics Department, John Carroll University, Cleveland, OH 44118.

We have conducted studies of the use of thin-film PVF_2 elements attached to single mode optical fibers as phase shifters and modulators. There are many applications for such devices in current technology and because of their flexibility, low weight and other factors, the PVF_2 elements appear to be more versatile than the piezoelectric plates and cylinders that have been employed by other workers. Details of the design and operational characteristics of the type of device we have developed are illustrated in terms of its use in fiber optic sensor systems. In this application it may be employed as an optical phase shifter to hold a Mach-Zender type optical interferometer in quadrature so that the sensor's sensitivity is maintained at a maximum; in addition, the PVF_2 element may be used as a modulator if heterodyne detection techniques are to be employed. Various methods of configuring these devices are discussed and data are presented on their sensitivity and frequency response.

[1] This work was supported in part by the Office of Naval Research.

EE-6 Detection of Ultrasonic Waves in Solids by an Optical Fiber Interferometer, R. O. CLAUS[1] and JOHN H. CANTRELL, JR., NASA Langley Research Center, Hampton, VA 23665.

An optical fiber interferometer has been developed for the detection of ultrasonic waves in solids. The optical paths in both signal and reference arms of the interferometer are through the cores of similar 2 m lengths of ITT-110 single mode fiber mode-stripped at both input and output. Light from the output ends of the reference fiber and the signal fiber which was embedded in a 2.54 cm disk of plastic resin 1.1 cm thick were superimposed to form a straight line interference fringe pattern. Instantaneous fringe translation is proportional to the strain produced by ultrasonic bulk waves generated in the disk and is integrated along the fiber path in the solid. By spatially filtering the moving fringe pattern and synchronously demodulating the filtered optical signal, strain sensitivity two orders of magnitude greater than that reported[1,2] is predicted. Direct calibration at dc indicates a minimum theoretical detectable strain of less than 10^{-10}.

[1] Permanent address: Department of Electrical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061.
[2] J. H. Cole, R. L. Johnson, and P. G. Bhuta, "Fiber-optic detection of sound," *J. Acoust. Soc. Amer.*, vol. 62, p. 1136, 1977.
[3] C. D. Butler and G. B. Hocker, "Fiber optics strain gauge," *Appl. Opt.*, vol. 17, p. 2867, 1978.

SAW TRANSDUCERS

Chairperson: W. R. SMITH

FF-1 An Optimal SAW Filter Design Using FIR Design Technique, M. MORIMOTO, K. KOBAYASHI, and M. HIBINO, Transmission Division, Nippon Electric Co., Ltd., Kawasaki, Japan.

An optimal design involving the minimum number of transducer fingers in SAW filters was developed, using the FIR (finite impulse response) approximation technique. Design procedures are segregated into three steps. First, estimate the minimum transducer fingers which satisfy the symmetric or the asymmetric SAW filter specifications. Next, the design of SAW apodized transducer geometries is computed by utilizing the linear phase FIR approximation. Conventionally, for the apodized-apodized transducer geometries, two impulse responses from transmitting and their receiving transducer were independently computed, cascade connection assures the desired impulse response. In other words, the frequency response of the transmitting (or receiving) transducer satisfies the half of the log magnitude specification. On the contrary, in our method, a transfer function satisfying the full specification is first designed and then the composition of transmitting and receiving transducer geometry are made by analyzing the root of that transfer function in Z-plane. Then, the filter response of these transducer geometries is analyzed by using the equivalent circuit model. It can reduce the transducer fingers to less than several tens of percents compared with that of the conventional technique, which has been confirmed by the calculation and the experimental results. These calculation steps are perfectly carried out by the design automation technique.

FF-2 SAW Bandpass Filters with Withdrawal Weighted Transducers, E. KOGAN and P. ROMIK, Tadiran, Israel Electronics Industries Ltd., 3 Hashalom Road, P.O.B. 648, Tel Aviv 6100, Israel.

Several types of SAW bandpass filters using exclusively withdrawal weighted (WW) transducers were designed and fabricated on *ST* quartz. The filters include either identical or different WW transducers. The filters were designed for fundamental center frequencies between 35 MHz and 70 MHz, with fractional bandwidths of 0.7–2.5 percent. The filters were successfully operated at the fundamental and third harmonic frequencies, and different matching networks were evaluated. Some of the filters exhibited an excellent phase linearity, with deviations of less than 0.5^0 and group delay variation of 50 ns. This makes them well suited for IF filtering applications. In others, sidelobe rejections of up to 60 dB were achieved over a large frequency interval, for application in a direct fast frequency synthesizer. The insertion loss has b been reduced in one filter by means of a three transducer configuration. The design procedure is presented including the WW algorithm and the effect of the spectral weighting model and the matching networks on the predicted frequency response. The computer prediction will be compared to the experimental filter performance. The role of the WW design in reducing the filter complexity, phase ripple and size, and consequently group delay variation, will be pointed out. The importance of matching networks in reducing the sidelobe and spurious level, together with the insertion loss, will be discussed. Finally, experimental results achieved on a production basis, with two IF filters for a UHF radio link, will be presented.

FF-3 Phase Weighting for Low Loss SAW Filters, M. HIKITA, Y. KINOSHITA, H. KOJIMA, and T. TABUCHI, Central Research Laboratory Hitachi, Ltd., Kobunji, Tokyo, 185 Japan.

Finger length apodization of IDT's is widely used to provide required frequency responses for SAW filters, but use of this procedure for low loss filters, such as resonant filters or group type filters, increases insertion losses. We have developed a new low loss method. Since this method is based on conventional finger apodization, it has nearly equivalent performance, but there is essentially no increase in losses. In the passband, SAW transversal amplitudes over an IDT are orderly added in phase and form almost a plane wave. Over the stopband, the transversal amplitudes are added in various phases. This method should be called phase weighting of IDT's compared with conventional amplitude apodization. Use of phase weighting provides the frequency response of conventional transversal filter without an increase in losses. We applied this method to a broad-band resonant filter. The resonant filter used a TTR (twin turn reflector) structure and surface shear wave modes on a 41°–64° rotated Y cut X propagation $LiNbO_3$ substrate. Low loss (2–3 dB) and broad bandwidth (4–6 percent) were achieved without using outer inductors. TTR filters have many sidelobes due to the reflection characteristics of the turn reflectors. To suppress these sidelobes, we use phase weighting. High out of band rejection (55 dB) is obtained with a negligible increase in insertion losses.

FF-4 Acoustic Surface Wave Filters Using New Distance Weighting Techniques, K. YAMANOUCHI, T. MEGURO, and K. Shibayama, Research Institute of Electrical Communication, Tohoku University, Sendai, Japan.

Weighting techniques of acoustic surface wave filters are well established practices for shaping the frequency response of bandpass filters and for reducing time sidelobes in pulse compression filters. The most popular method for achieving these weighting techniques, so called apodization techniques, has been by varying the overlap between adjacent electrodes. We propose a new technique, that is, a distance weighting technique, which has better characteristics than apodization techniques. In the distance weighting technique an interdigital transducer is divided into several sections and the weighting is performed by varying the propagation distance between input and output transducer of each section. The distance weighting technique works best for reducing the weighting loss and diffraction error and getting the same values of impedance for input and output transducers. This technique is applicable to a wide variety of devices. Several filter examples are described.

FF-5 Charge-Superposition Analysis of Multiphase SAW Transducers, D. P. MORGAN, B. LEWIS, and R. G. ARNOLD, Plessey Research (Caswell) Limited, Caswell, Towcester, Northants, NN12 8EQ, UK.

The charge superposition principle offers a convenient and flexible method for analysis of SAW transducers.[1] The application of the method to multiphase unidirectional transducers is described, taking account of the networks used to obtain appropriate phasing and matching. The theory gives the admittances between the three transducer terminals, the conversion coefficient and directivity for a launching transducer and, for a receiving transducer, the conversion, reflection, and transmission coefficients. For unapodized transducers at the centre frequency, analytic expressions for these parameters are obtained. It is found that, for relatively wide bandwidths, significant triple transit ripple can occur at the band edges. Confirmatory experimental results are presented.

[1] D. P. Morgan *et al.*, *Electron. Lett.*, vol. 15, p. 583, 1979.

FF-6 A SAW Step-Type Delay Line for Efficient High Order Harmonic Mode Excitation, P. NARAÎNE, C. K. CAMPBELL, and Y. YE, Communications Research Lab., McMaster University, Hamilton, ON L8S 4L7, Canada.

A SAW step-type delay line has been developed for efficient high order harmonic mode excitation. A circuit advantage of this delay line type, which offers application in high frequency SAW delay line oscillators, is in the suppression of spurious harmonic modes. The step-type delay line also offers more tolerance in the lithographic artwork stage, than does the conventional high frequency transducer. For excitation of the Mth harmonic, each finger in the step transducer is arranged into M displaced segments, with λ_0/M displacement between each. The metallization ratio is selected to conform with the desired harmonic. For odd harmonic modes, the single fingers of the input transducer are stepped. The output transducer can be of the uniform single finger type, or it can be stepped also. For even harmonics, a three-finger step-type input transducer is required, in conjunction with a Kerbel-type three-finger output transducer. A review of the theory is given, together with measurements which include comparative ones on a fifth harmonic step-type line with an untuned insertion loss ~17 dB at f_5 = 114 MHz, and a fifth harmonic Kerbel-type 3–4 finger delay line with insertion loss ~23 dB at the same f_5 value.

[1] This work was supported in part by an operating grant from the Natural Sciences and Engineering Research Council of Canada to C. K. Campbell.

IMAGING II

Chairperson: K. M. LAKIN

GG-1 An Acoustic Imaging System for Medical Use, H. EDWARD KARRER, FLEMING DIAS, JOHN D. LARSON, RICK PERING, Hewlett-Packard Laboratories, Palo Alto, CA 94304, SAMUEL MASLAK, 2776 Kipling, Palo Alto, CA, DAVID A. WILSON, SRI International, Menlo Park, CA.

An experimental linear phased array acoustic imaging system has been developed for cardiac, obstetric, and radiological use. This is a real-time pulsed B scan system using either a 2.5 MHz or a 3.5 MHz hand-held transducer. The display format is a sector scan with dimensions of $90^\circ \times 20$ cm and the system is dynamically focused. The system uses an analog heterodyne architecture which greatly simplifies the electronics for a densely packed array and also allows use with transducers of different frequencies. With a 20-mm aperture, the system achieves a 6-dB resolution at 7 cm in water of 2.5 mm in azimuth, 1-mm in range, and 5 mm in elevation. Emphasis was put on a system with wide dynamic range; extremely low side lobe levels of the array beam plot have been achieved over the sector. A digital scan converter is used to convert the sector scan to a raster display and is also used for image processing. Images will be shown to demonstrate system performance.

GG-2 An Image Display Algorithm for Use in Real-Time Sector Scanners with Digital Scan Converters, H. G. LARSEN and S. C. LEAVITT, Hewlett-Packard Corp., Andover, MA 01810.

In real-time sector scanners, the data is typically sampled at discrete intervals along radial rays so that the precise polar (R, θ) coordinates are known. These are then converted to rectangular (X, Y) coordinates and the data value (grey level) is translated to the nearest display point (pixel) in the digital scan converter (DSC). As a result of this mapping process, a number of artifacts manifest themselves in the displayed image, including the well-known Moiré pattern, and a subsequent "digital," or "blocky" appearance of the image. B-scanners have largely overcome this problem by increasing the density of radial rays, and performing some signal processing (averaging, peak detection) at the pixel level. We consider a different kind of mapping algorithm appropriate to real-time sector scanners which eliminates the sources of these previously mentioned artifacts. The resulting image no longer has Moiré voids or the steppy and blocky appearance often associated with digital ultrasound images. Specific examples will be shown.

GG-3 A Fast Electronically Scanned Two-Dimensional Array for Acoustic Imaging[1], F. GELLY and C. MAERFELD, Thomson-CSF DASM, BP 53, 06802 Cagnes/Mer, France.

A new way of building a two-dimensional 16×16 array to be used in a lens acoustic camera is presented. This retina is made of a stack of one-dimensional arrays working at 2 MHz, each one having its own multiplexer, amplifier, filter, and detector. An external fast multiplexer scans the detectors and yields the video output. The resulting resolution (1.5 mm) is similar in both directions. This technique allows for fast scanning (0.1 μs/point) and good sensitivity since the integration time on each point is equal to the scanning time of one line. Later, it will be extended to a 100×100 array, then the whole scanning time will be as low as 1 ms.

[1] This work was sponsored by DRET (France).

GG-4 Spectral Analysis of Doppler Flowmeter Signals in Atherosclerotic Disease, P. J. BENDICK, J. L. GLOVER, and R. S. DILLEY, Wishard Memorial Hospital, Indiana University School of Medicine and Regenstrief Institute, Indianapolis, IN 46202.

Currently used noninvasive vascular diagnostic techniques, based on hemodynamically significant flow disturbances, are generally only reliable for detecting atherosclerotic lesions with a diameter reduction of greater than 50 percent. Real time spectral analysis of audio signals obtained from the peripheral arterial system using the ultrasound Doppler flowmeter appears to be a simple yet sensitive technique to detect stenotic lesions early in their development. A signal just distal to a subcritical stenosis has a spectrum with a well defined systolic peak and a low frequency diastolic flow, both characteristic of a normal spectrum, but the peak systolic frequency is significantly elevated compared to that proximal to the lesion. Slight changes in audio spectra between sites proximal and distal to a subcritical stenosis have been best appreciated using a pulsed Doppler flowmeter which allows localization of velocity information to the center of the lumen where disturbances are greatest. Preliminary analysis of approximately 75 patients indicates relative peak frequency to be a reliable indicator of stenosis; careful angiographic correlation will better define other spectral parameters, such as a broadened systolic peak or elevated diastolic frequencies with a decreased fall-off rate, sensitive to stenotic lesions.

GG-5 A Linear Stepped Doppler Ultrasound Array for Real-Time Two-Dimensional Blood Flow Imaging, J. W. ARENSON, R. S. C. COBBOLD, and K. W. JOHNSTON, Institute of Biomedical Engineering, University of Toronto, Toronto, ON, Canada M5S 1A4.

Current Doppler ultrasound blood flow imaging systems using single-crystal or two-crystal transducers typically take 10–30 minutes to obtain a satisfactory carotid artery image. This long scanning time is due both to the pulsatile nature of the flow and the need to manually scan the transducer over the region to be imaged. To effect a major reduction in scan time, we have designed a linear stepped Doppler ultrasound array for real-time two-dimensional imaging of blood flow through the carotid artery. The array consists of 32-2-mm × 8-mm PZT5 5MHz crystals arranged on a staircase backing such that the step size is an integral number of wavelengths while the staircase rises at approximately 30°. A grouping of six crystals are used at a time, the two middle crystals as receivers and the four outer crystals as properly phased transmitters. This arrangement of crystals interrogates a narrow beam of tissue at an angle of approximately 60° from the array axis. The lateral resolution of the array (defined as the beamwidth −6 dB from the peak value at a given distance) was determined by computer simulations and in water tank tests to be better than 4.5 mm for depths ranging from 4 cm to 10 cm. Stepping down the array one crystal at a time images one dimension of blood flow information. A rotating mirror located in front of the array sweeps out the second dimension of the image.

GG-6 Directional CW Doppler Ultrasound Using a Double-Heterodyne Demodulator,[1] M. S. KASSAM, C. W. LAU, R. S. C. COBBOLD, and K. W. JOHNSTON, Institute of Biomedical Engineering, University of Toronto, Toronto, ON, Canada M5S 1A4.

Continuous wave Doppler ultrasound velocity meters are often used to record blood flow velocity waveforms from peripheral arteries, extracranial cerebral arteries, or the aortic arch, in order to noninvasively assess patients with arterial occlusive disease. Most commercial bidirectional velocity meters employ the phase quadrature demodulation technique, and this generally results in inadequate suppression between the forward and reverse flow channels. Moreover, this technique requires a dual channel spectral analysis system. A single-channel bidirectional Doppler velocity meter has been constructed using a double-heterodyne demodulation technique which overcomes the above limitations. It also allows the use of either a 4- or 8-MHz transmitting frequency.

[1] This work was supported in part by the Medical Research Council, the Ontario Heart Foundation, and the Natural Sciences and Engineering Research Council of Canada.

SPUTTERED ZnO FILMS

Chairperson: J. S. SCHOENWALD

HH-1 [Invited] ZnO Processing for Bulk- and Surface-Wave Devices, FRED S. HICKERNELL, Motorola Inc., Government Electronics Division, Scottsdale, AZ 85252.

Zinc-oxide thin-film transducers are used in a variety of microwave acoustic device applications for the generation and detection of bulk and surface acoustic waves. High coupling factor–low acoustic loss films are characterized by their dense fine grain, well ordered crystallite structure, optical clarity, and smooth surface texture. Sputtering the films using a compound ZnO target at moderate rates, with low reactive gas pressures, on heated substrates, have produced films whose piezoelectric and acoustic properties approach those of single crystal zinc oxide. Several diagnostic techniques such as XRD, RED, SEM, TEM, optical, chemical, and electrical have been used to characterize acoustic quality. Process conditions which lead to high quality film growth and diagnostic measures which best predict transducer performance are discussed.

HH-2 Sputter Deposition of ZnO Thin Films Using Glow Discharge Mass Spectrometry, C. R. AITA, Gould Laboratories, Rolling Meadows, IL 60008.

A review is given of the ZnO film fabrication research effort carried out at Gould Laboratories in support of the surface acoustic wave device development program. A 99.999-percent ZnO target was RF diode sputtered at various RF forward power levels, O_2/Ar sputtering gas mixtures, and substrate temperatures. Both (111) oriented Si and (111) Al coated-(111) oriented Si substrates were used. During the course of a deposition, glow discharge mass spectrometry (GDMS) was used to determine the characteristics of the various sputtering plasmas, in particular the plasma potential and the type and number of positive ions which were incident upon the substrate plane. The resulting film structure was analyzed by X-ray diffraction and scanning electron microscopy. The results are discussed in terms of the average depostion rate, the relative number of Zn^+ to ZnO^+ ions incident on the growth interface, and bombardment of the growing film by secondary electrons emitted from the target. The results of a post-deposition annealing study carried out at temperatures up to 700°C are also discussed.

HH-3 Reactive Magnetron Sputtering of ZnO,[1] B. T. KHURI-YAKUB and J. SMITS, E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305.

A planar magnetron system is used to sputter zinc oxide on a variety of substrates. A zinc target is used, and sputtering is done in an oxygen atmosphere. The zinc oxide films are evaluated by bulk and surface acoustic measurements, scanning electron microscopy, and reflection electron diffraction. Zinc oxide films are grown on a variety of substrates such as gold, aluminum, platinum, fused quartz, and silicon dioxide on (111) and (100) silicon. Highly oriented films are obtained on all the substrates with a typical standard derivation in the rocking curves of the order of 0.2–0.5°. Typical sputtering parameters are RF power = 1.25 kW, sputtering rate = 10–15 μm/h, oxygen partial pressure = 7 μm, substrate temperature = 450–500°C, and target to substrate spacing = 4–7 cm.

[1] This work is supported by the Defense Advanced Research Projects Agency and monitored by the Office of Naval Research under Contract N00014-76-C-0129.

HH-4 ZnO Transducers for Microwave Bulk-Wave Devices, E. K. KIRCHNER and D. K. GILL, Teledyne MEC, Palo Alto, CA 94304 and B. T. KHURI-YAKUB, Stanford University, Stanford, CA 94305.

ZnO transducers have been produced for both microwave acoustic bulk-wave delay devices and acoustooptic components using dc triode sputtering. Sputtering of the ZnO film is achieved at gas pressures near one micron, with a premixed 20-percent oxygen, 80-percent argon reactive atmosphere. Deposition rates of 2.5–3.5 μm/h are typical with unheated substrates, with a target to substrate spacing of 4 cm, and with dc power of 150 to 250 W. The value of the standard deviation angle of the C axis orientation obtained from X-ray rocking curves has a minimum of approximately 1.5° which is larger than that reported for RF planar-magnetron sputtering.[1] The dc triode sputtered films are used in devices over the frequency range of 200 MHz–16 GHz. Electromechanical coupling coefficients of 0.235 (84 percent of the bulk ZnO value) are typical. RF performance of the ZnO transducers will be discussed.

[1] T. Yamamoto *et al.*, *J. Appl. Phys.*, vol. 51, pp. 3113–3120, 1980.

HH-5 ZnO Film Analysis, B. R. McAVOY, Westinghouse Research and Development Center, Pittsburgh, PA 15235.

Piezoelectric thin films have become increasingly important for a diversified array of devices such as microwave delay lines, integrated SAW and acoustooptic components. The continued interest in these devices depends, in large part, on the consistent high quality of the films produced. A number of refined analysis techniques can be used to insure that the ZnO film deposition systems are performing satisfactorily. These techniques include scanning transmission electron microscopy (STEM) with microelectron diffraction, electron spectroscopy chemical analysis (ESCA), and Auger analysis in addition to the more commonly used reflection electron diffraction (REED) and X-ray diffraction. These results are correlated with systems mass analyzer data and glow discharge spectroscopy. This program of analysis has been used to 1) identify system contamination, 2) examine the microstructure of the ZnO, and 3) compare systems performance. Three types of systems, for which experimental data is available, are compared: RF diode with cryopump, magnetron with cryopump and RF diode with a turbomolecular pump.

HH-6 UHF Composite Bulk Wave Resonators,[1] K. M. LAKIN and J. S. WANG, University of Southern California, Los Angeles, CA 90007.

At VHF and UHF the fabrication of bulk wave resonators and monolythic filters by conventional techniques is difficult or impossible due to the thin fragile nature of the required structure. A class of miniature bulk wave resonators fabricated using thin-film and micro-electronic materials processing techniques is described. The resonators are composed of a thin sputtered ZnO film on a thin single-crystal membrane that in turn is supported by the bulk of the Si substrate or wafer. The resonators have fundamental mode resonant frequencies near 500 MHz and have exhibited Q's as high as 9000. The resonator area is less than 150 μ square and with supporting substrate is less than 1 mm square. The supporting theory for the resonators shows that they have the unique property of operation on both even and odd overtones in contrast to conventional thickness mode resonators which offer only odd overtone operation.

[1] This research was supported by the Air Force Office of Scientific Research under the Joint Services Electronics Program.

SAW FILTERS

Chairperson: R. S. KAGIWADA

II-1 $LiNbO_3$-Surface Acoustic Wave Edge Bonded Transducers on *ST* Quartz and ⟨001⟩-Cut GaAs,[1] D. E. OATES and R. A. BECKER, Lincoln Laboratory, Lexington, MA 02173.

The ability to generate wide-band surface acoustic waves (SAW) on a variety of substrates is important to develop a wider selection of devices, both acoustic and acoustoelectric, with performance characteristics appropriate to the signal-processing requirements of real systems. While edge-bonded transducers (EBT) have been used before, we report the extension of this technology to GaAs. In addition, a new model has been developed which allows, for the first time, an accurate description of EBT behavior. We have fabricated $LiNbO_3$ EBT's on both *ST* quartz and ⟨001⟩-cut GaAs, with efficient transduction and fractional bandwidths of 50 percent and 91 percent, respectively, at center frequencies of approximately 100 MHz. Single-transducer conversion loss as low as 4 dB has been obtained on *ST* quartz. These experimental results for both substrates are in good agreement with the model, which uses the Mason method to describe the behavior of the $LiNbO_3$ bulk shear wave transducer and uses normal modes to treat the conversion of shear wave energy to SAW energy at the transducer–substrate interface. A description of this model, as well as fabrication and experimental details will be presented.

[1] This work was supported by the Department of the Army.

II-2 Low Loss 0.9–1.9 GHz SAW Filters with Submicron Finger Period Electrodes, K. ASKAWA, M. ITOH, H. GOKAN, S. ESHO, K. NISHIKAWA, T. NISHIHARA, Nippon Electric Co., Ltd., Kawasaki, 213 Japan, and S. URABE, Yokosuka E. C. L., N. T. T., Yokosuka, 238 230-03 Japan.

Two kinds of low loss GHz SAW filters with submicron finger-pitch double electrodes and a 1-mm square pattern size have been developed. One was a 1-μm pitch 0.9 GHz filter with 5 dB insertion loss and the other a 0.5-μm pitch 1.9 GHz one with a 9.5 dB loss, both having non-unidirectional transducers on a 128° Y-X $LiNbO_3$ substrate. These filters were realized by a new fabrication process. The process consists of direct wafer electron beam writing, two step mask transfer and ion beam etching. Mask transfer from electron resist PMMA to photoresist AZ-1350J ensures the mask having high accuracy and high resistivity to aluminum electrode ion-beam-etching. The insertion loss was lowered mainly by optimizing ion beam etching conditions to decrease acoustic propagation losses due to electrode edge geometries, ion etched surface damages, and electrode film absorption. Lead wire inductance usage as a tuning element contributed to both insertion loss decrease and package miniaturization. The 0.9 GHz filter developed here satisfies all of the specifications for bandpass filter in a high capacity mobile telephone system in Japan and has a possiblity for practical usage in the system.

II-3 SAW Comb Filter for TV Frequency Synthesizing Tuning System, K. KISHIMOTO, M. ISHIGAKI, K. HAZAMA, and S. MATSUMURA, Consumer Products Research Center, Hitachi, Ltd., Yokohama, Japan 244.

We have developed a more advanced version of the SAW comb filter, by which quite a new concept of TV frequency synthesizing tuning system has been completed, based on the technologies of TV channel indicating systems with SAW comb filters, reported at the 1979 Symposium. Since the local oscillator frequency absolutely depends on filter characteristics, this new filter chip is fabricated on a $LiTaO_3$ substrate for a better temperature stability. This brought us new targets which we had to overcome, the larger insertion loss of the filter, due to the relatively small coupling constant. In order to reduce the loss over the very wide frequency range, the filter chip has been designed with three sets of chirp type transducers, corresponding to VHF low (150–162 MHz), VHF high (230–296 MHz), and UHF (530–824 MHz). In addition, thin-film impedance matching inductors for UHF band are fabricated on the same substrate for the better performance. The filter has the following superior performances: 1) insertion loss is less than 35 dB over the whole TV band; 2) frequency accuracy is within ±0.25 MHz ± 0.03 percent; 3) frequency temperature coefficient is –25 ppm/°C; 4) frequency intervals of comb characteristics are 1 MHz in VHF band and 2 MHz in UHF band. The color TV equipped with this new tuning system will be placed on the domestic market in the fall of 1980.

II-4 Highly Reliable ZnO Thin-Film SAW Nyquist Filters for TV, O. YAMAZAKI, K. WASA, and S. HAYAKAWA, Materials Research Laboratory, Matsushita Electric Industrial Co., Ltd., Moriguchi, Osaka, 570, Japan.

ZnO thin-film SAW Nyquist filters for TV sets and demodulators for TV stations are described. The filters comprise a layered structure: a sputtered ZnO thin piezoelectric film is overlaid on a borosilicate glass substrate. Al interdigital electrodes are inserted between the ZnO film and the glass substrate, and Al counter electrodes are positioned on the ZnO film surface. Thickness of the ZnO film is about three percent of SAW wavelength. Apodization is carried out by shaping the counter electrodes. An advanced SAW design for TV-VIF filters is found to reduce their inevitable insertion loss so that the VIF stage can operate without any preamplifier. Precise design realizes a standard demodulator for TV stations, flatness of amplitude $< \pm 0.05$ dB and ripple of group delay $< \pm 10$ nS at passband. These filters show an excellent frequency stability < 10 ppm/°C and a drift < 100 ppm/25 000 h. The present SAW filters are now in production.

SAW delay lines are unique because they provide microseconds analog memory for broad-band signal processing. Since all spectral components have to be preserved in the delayed signal, large bandwidth, flat frequency response, and high spurious signal suppression are simultaneously required. Advances achieved in meeting these requirements are reported. SAW delay lines have been developed with frequency response flat to ±0.1 dB within 58 percent fractional bandwidth, octave 3 dB andwidth centered at 240 MHz, 34 dB insertion loss on Y-Z-$LiNbO_3$, spurious signal suppression better than 50 dB, and time delays up to 10 μs. This performance has been achieved in three major steps. First, second-order effects were minimized using two inclined chirp transducers in a nondispersive configuration with split finger electrodes. In the second step, first-order design formulas were applied to compute finger electrode overlap functions in an iterative design procedure. The third step comprised device fabrication where a minimum linewidth of 1.2 μ had to be controlled to ±0.1 μ in order to achieve the desired flat frequency response. 150 delay lines have been fabricated with a total yield of 75 percent using automatic photoresist processing, 10x projection printing, and lift off technique.

II-6 Compensation of Diffraction Effects on Group Delay Time and Stopband Rejection,[1] W. MADER, Institut für Physikalische Elektronik, TU Wien, A-1040 Vienna, Austria, H. STOCKER, and R. VEITH, Siemens AG, Research Laboratories, FL FES 11, Otto-Hahn-Ring 6, D-8000 Munich, Germany.

SAW bandpass filters for application in IF stages of microwave radio systems have to satisfy very strict quality requirements, especially in respect of minimum amplitude and group delay time distortion. Small square dimensions of the device are also desired, so that diffraction effects due to finite finger overlap become severe and demand for compensation. Both amplitude and phase errors have to be compensated to achieve satisfying results. Two methods, both using a discretized Newton iteration algorithm, are shown to improve the filter characteristic, eliminating group delay time ripples, increasing stopband rejection and restoring passband symmetry. Split-finger transducers allow compensation of phase errors without changing the finger positions, which has important advantages in the technology process of SAW device production. The correction procedure reduces calculated delay time ripple from about 7 ns to only 0.5 ns and improves stopband rejection by about 20 dB. Experimental results are in good agreement with theory.

[1] This work was supported by the Fonds zur Förderung der wissenschaftlichen Forschung, Vienna, Project S-22/11.

NDE-MEASUREMENTS, SYSTEMS, AND TECHNIQUES IV

Chairperson: H. M. FROST

JJ-1 Improved Correction for Continuous Wave Ultrasonic Phase Velocity Measurements in Solids Using Two Bonded Transducers, ENGMIN J. CHERN,[1] JOHN H. CANTRELL, JR., JOSEPH S. HEYMAN, and WILLIAM P. WINFREE,[2] NASA Langley Research Center, Hampton, VA 23665.

An improved correction formula for continuous wave ultrasonic phase velocity measurements in solids using two bonded transducers is derived from the transmission line theory. The effect of coupling bonds is quantitatively considered even though it is often neglected due to the difficulty of accurately determining the bond thickness. Computer simulated experiments for different transducer-sample configurations show that the improved correction for the transducers and bonds is more accurate than previous corrections. We report experimental measurements using noncontacting capacitive transducers to obtain a reference value of the ultrasonic phase velocity in a polycrystalline aluminum sample. Experimental measurements using contacting transducers with the present bonded transducer correction formula are compared to the capacitive transducers measurements. The results of the experiments verify the validity and accuracy of the improved correction formula.

[1] Permanent address: College of William and Mary, Williamsburg, VA 23185.
[2] National Research Council Resident Research Associate.

†JJ-2 Radiation Damage to Conventional Transducers and the Consideration of Using Nonconventional Transducers for a High Radiation Environment Application, JAMES N. C. CHEN, Ontario Hydro Research Laboratory, Toronto, Ontario, M8Z 5S4, Canada.

More than 50 ultrasonic transducers have been tested in 10^6 R/h radiation field for more than 200 hours. The result suggests that most of the commercial ultrasonic transducers are not suitable for this high radiation environment application. Our destructive analysis of the irradiated transducers reveals that the conventional damping disk is the transducer component most susceptible to radiation attack. It becomes apparent that transducers of a few alternative designs, which do not use the conventional damping disk, can be reliably used for inspection purposes in this high radiation environment. The design features and the engineering parameters of three types of transducers are explored.

JJ-3 Multiparameter Characterization of Fatigue Damage in Graphite/Epoxy Composites from Ultrasonic Transmission Power Spectra, JOHN H. CANTRELL, JR., WILLIAM P. WINFREE,[1] JOSEPH S. HEYMAN, and JOHN D. WHITCOMB, NASA Langley Research Center, Hampton, VA 23665.

Fatigue damage in graphite/epoxy composite samples is quantitatively examined from ultrasonic transmission power spectra. The spectra were obtained with a new measurement system which combines the phase insensitive acoustoelectric transducer with the frequency-tracked tone-burst spectroscopy technique. A mathematical model of the transmission spectra was employed which parametrized the reflection coefficient, the attenuation coefficient, and the phase velocity. A computer code was developed which least-squares fit the mathematical model to the measured transmission spectra and generated simultaneous values of the model parameters. This multiparameter characterization technique is shown to provide significant quantitative information on early fatigue damage in graphite/epoxy composites.

[1] National Research Council Resident Research Associate.

JJ-4 Ultrasonic Velocity Characterization of Fatigue and Impact Damage in Graphite/Epoxy Composites,[1] H. I. RINGERMACHER,[1] NASA Langley Research Center, Hampton, VA 23665.

Ultrasonic velocity measurements have been made on graphite/epoxy composite specimens subjected to low velocity impact damage and on specimens subjected to load cycle-induced fatigue damage. In addition, the effects of impact followed by fatigue as well as fatigue followed by impact were examined with regard to damage susceptibility. The ultrasonic velocity was evaluated as a sensitive parameter for the characterization of damage in fiber composites.

[1] National Research Council Resident Research Associate.

JJ-5 [Invited] Recent Material Property Measurements by Acoustic Techniques,[1] J. R. QUINN, Electric Power Research Institute, Palo Alto, CA 94303 and P. B. HILDEBRAND, Spectron Development Laboratory, Costa Mesa, CA 92626.

A review of recent efforts to measure residual stress distributions and related material properties in structural metals will be presented. The emphasis shall be on experimental techniques. Specific approaches to be presented are acoustic time of flight tomography, differential phase contrast imaging of residual stress, and measurement of the conservation integrals J, L, and M. Limitations of the acoustic approach to the measurement of stress and fracture mechanics parameters will be presented.

[1] This work was supported by the Electric Power Research Institute.

BIOPHYSICS I

Chairperson: J. G. MILLER

†KK-1 [Invited] Nonlinear Acoustic Phenomena at Biomedical Frequencies and Intensities,[1] EDWIN L. CARSTENSEN, Department of Electrical Engineering, University of Rochester, Rochester, NY 14627.

As finite amplitude ultrasonic waves propagate, harmonics of the source frequency are generated in the medium and the wave suffers losses in excess of that which would be predicted by linear acoustic theory. The magnitudes of these effects increase with source intensity, with distance from the source and with frequency. In the extreme case, a hard shock, characterized by a sharp discontinuity in the pressure, is formed. Nonlinear phenomena may play an important role in certain biomedical applications of ultrasound. In biological effects studies, the subjects may be exposed to a line spectrum of frequencies rather than the source frequency alone. Media, such as water, which ordinarily may be considered to be dissipationless, become lossy and their nonlinear properties set upper limits for the acoustic energy which can be delivered to samples of biological material. The absorption coefficients of tissues become functions of intensity. The thresholds for lesion production in tissues are lower than would be predicted on the basis of the linear properties of those tissues.

[1] This work was supported in part by U.S.P.H.S. Grant GM09933.

KK-2 A Computer Analysis System for Ultrasonic Backscatter from Liver and Kidney,[1] F. L. LIZZI, E. FELEPPA, N. JAREMKO, Riverside Research Institute, 80 West End Ave., New York, NY 10023, D. L. KING and P. WEI, College of Physicians and Surgeons, Columbia University, New York, NY 10032.

A clinical digital acquisition and processing system has been implemented for studying ultrasonic backscatter from abdominal organs. The system uses a PDP 11/55 and employs techniques similar to those developed for opthalmic applications. RF echoes obtained from a clinical ultrasonic scanner are digitized, stored, and used in several forms of processing. The 100 KBytes of data from a single scan can be acquired and stored on disk in less than 1 s. Processing can then proceed on three levels. First, image processing can be performed on video signals derived from the digitized data. Second, tissue characterization can proceed from spectrum and cepstrum analysis of RF data from areas demarcated on an image by a joystick. Third, processing can be applied prior to image formation to improve resolution (deconvolution) or to depict computed tissue parameters.

[1] This work was supported in part by Public Health Service NIH Grant GM-26850.

KK-3 Hyperthermia Induction and Its Measurement Using Ultrasound, M. FABRI, O. PRAKASH, J. M. ESCANYE, M. DROCOURD, M. L. GAULARD, and J. ROBERT, Division de Technologie Médicale-Service de Médecine Nucléaire-18, rue Lionnois 54000-Nancy, France.

This communication epitomizes some of the preliminary findings obtained under a recently commenced program for construction of a compact device for generation and measurement of hyperthermia using ultrasound. The first part deals with the constructional details of the device and test of the unit. The second part discusses temperature dependent velocimetric measurements. To test the efficacy of application of ultrasound as a nonconventional thermometric technique, tissue type behavior towards temperature dependent velocity has been investigated *in vitro* in some tissues–e.g., liver, muscle, intestines–during hyperthermal exposures. The temperature coefficient of ultrasound velocity is almost constant for many soft tissues.

†KK-4 Is Bone a Cosserat Solid?,[1] HYO SUB YOON and J. LAWRENCE KATZ, Center for Biomedical Engineering, Rensselaer Polytechnic Institute, Troy, NY 12181.

In a viscoelastic composite material and bone, acoustic waves are dispersed by two distinct mechanisms as they propagate through the material, i.e., geometric dispersion and viscoelastic dispersion. The viscoelastic dispersion is characterized by increase in phase velocity with increase in frequency, while the geometric dispersion is well-known since the investigation by Kelvin, Brillouin, and many others. By comparing the dispersion data on these types of materials, we have noticed that increases in the ultrasonic velocities for human bones[2,3] are much larger than those for simple viscoelastic solids[4] and composites,[5] difficult to explain by the viscoelastic dispersion alone. This suggests that there may be involved another dispersion mechanism in addition to the viscoelastic contribution. Mindlin[6] has developed a theory on the Cosserat continuum with microstructure, which can explain this additional dispersion in bone, even in its low frequency approximations. Recently, in their torsion experiment, Yang and Lakes[7] have determined the new material constant of bone, which has the dimension of length and embodies all the difference between analogous equations with/without couple stresses.

[1] Supported by the Whitaker Foundation and USPHS thru NIDR Grant 5 T32-DEOR05404.
[2] Yoon and Katz, in *1976 Ultrason. Symp. Proc.*, pp. 48–50.
[3] Fry and Barger, *J. Acoust. Soc. Amer.*, vol. 63, pp. 1576–1590, 1978.
[4] Asay *et al., J. Appl. Phys.*, vol. 40, pp. 1768–1783, 1969.
[5] Sutherland, *J. Acoust. Soc. Amer.*, vol. 57, pp. 870–875, 1975.
[6] Mindlin, *Arch. Rational Mech. Anal.*, vol. 16, pp. 51–78, 1964.
[7] Yang and Lakes, to be presented at 1980 ASME Winter Meeting.

KK-5 Clinical Application of Acoustic Emission Techniques to Bone Abnormalities,[1] H. S. YOON, B. CARACO, H. KAUR, and J. L. KATZ, Center for Biomedical Engineering, Rensselaer Polytechnic Inst., Troy, NY 12181.

Based on our previous work on fresh animal bones of several different species and different types within the same species, attempts have been made to apply acoustic emission (AE) techniques clinically to animal and human bones. Since "conventional" acoustic emission techniques are not truly noninvasive, they had to be modified in the following way. Instead of applying loads to the bone under test, which will be uncomfortable to live subjects, low-intensity ultrasonic pulses are introduced to the bone through an AE transducer, while another receiving AE transducer provides necessary AE parameters, such as amplitude, pulsewidth, counts, energy distributions, and cumulative counts versus time. Defective bones are simulated by varying degrees of sawing and drilling, and by different amounts of marrow in the long bone. The obtained AE parameters were clearly distinguishable between normal and abnormal bones, and between different degrees of abnormalities. When these modified acoustic emission techniques were applied to living human subjects and anesthetized dogs, the velocities data of externally applied "AE" signals appear to indicate that they have traveled in a surface wave mode, which is consistent with the results by others.

[1] This work was supported in part by the Whitaker Foundation, in part by USPHS through NIDR Contract 5 T32-DEOR05404, and in part by the Children's Hospital Medical Center, Boston, MA.

TEMPERATURE COMPENSATED MATERIALS

Chairperson: P. H. CARR

LL-1 [Invited] New Piezoelectric Ceramics with Zero Temperature Coefficients for Acoustic Wave Applications, H. TAKEUCHI, Y. ITO, S. JYOMURA, K. NAGATUMA, and S. ASHIDA, Central Research Laboratory, Hitachi Ltd., Tokyo, Japan.

Lead titanate ($PbTiO_3$) ceramics having zero temperature coefficients in various acoustic wave modes are developed by addition of Nd_2O_3, In_2O_3 and MnO_2. Chemical formulas of these ceramics are generally expressed by $(Pb_{1-(3/2)x+(1/2)z}Nd_x)(Ti_{1-y-z}Mn_yIn_z)O_3$. These ceramics have very small temperature coefficients of surface wave delay time (less than $1 \times 10^{-6}/°C$) over a wide temperature range (-10° to +60°C) at appropriate compositions. Furthermore, it is possible to reduce the temperature coefficients of resonance frequencies in bulk wave modes (radial mode, thickness mode, flexure mode) to the same order as for surface wave by changing the combination of Nd, Mn, In concentration appropriately. The new ceramics have large electromechanical coupling factors for surface wave ($k_s \sim 0.16$) and thickness modes ($k_t \sim 0.50$). The propagation loss of surface wave is 4 dB/cm at 60 MHz, which is the lowest value yet reported for ceramics. These modified $PbTiO_3$ ceramics are thus potential materials for acoustic wave applications. As examples of application, SAW filters (60 ~ 300 MHz), tuning fork resonators (30 kHz) and thickness mode resonators (4 MHz) are fabricated using these ceramics.

LL-2 Crystal Chemistry of Ferroelectric Materials for Surface Acoustic Wave Devices,[1] R. R. NEURGAONKAR, T. C. LIM, E. J. STAPLES, Electronics Research Center, Rockwell International, Thousand Oaks, CA 91360 and E. L. CROSS, Materials Research Laboratory, Pennsylvania State University, University Park, PA 16802.

The crystal chemistry concept has been applied and shown to be successful in improving the temperature stability of surface acoustic wave (SAW) materials. It is known that α - quartz and $LiNbO_3$, the most commonly used materials in SAW devices, have disadvantages for certain applications. For example, the relatively poor electromechanical coupling constant ($K^2 = 0.0016$) of quartz renders it unsuitable for devices requiring large bandwidth while the poor temperature coefficient (90 ppm/°C) of SAW velocity on $LiNbO_3$ renders this material unsuitable for many applications where environmental stability is important. The crystal concept involves determination of the role of different ions which are substituted for Li^+, Nb^{5+} or both in the $LiNbO_3$ structure. Na^+-modified films grown by the liquid phase epitaxy technique were studied in detail and it was found that the addition of 1 mole% Na^+ improved the stability by almost 40 percent without affecting the coupling constant K^2. In addition preliminary work on the tungsten bronze solid solution $Sr_{1-x}Ba_xNb_2O_6$ showed that these ferroelectric single crystals have higher electromechanical coupling constant than $LiNbO_3$ and possess temperature compensated orientations, indicating they could be potentially important future materials in the area of temperature stable SAW resonators. The results will be reviewed and discussed in terms of materials: crystal structure, crystal chemistry, and the problems associated with their growth.

[1] This work was supported by DARPA Contract F49620-78-C-0093 and AFOSR Contract F4962-77-C-0081.

LL-3 A Phenomenological Theory for Predicting the Temperature Dependence of Elastic Dielectric and Piezoelectric Properties in Simple Proper Ferroelectric Crystals,[1] T. R. SHROUT, L. E. CROSS, P. MOSES, H. A. MCKINSTRY, The Pennsylvania State University, University Park, PA 16802, and R. R. NEURGAONKAR, Electronics Research Center, Rockwell International Corporation, Thousand Oaks, CA 91360.

The Landau: Ginsburg: Devonshire phenomenological theory for proper ferroelectrics has been extended to include sixth order electrostrictive coupling in the prototype (paraelectric) structure. These higher order terms lead to contributions to the stiffened elastic compliances S^P_{ijkl} which are quadratic in polarization P, so that in the ferroelectric phase the strong temperature dependence of P_s the spontaneous polarization is reflected into the elastic response. The analysis has been applied to the tungsten bronze ferroelectric $Ba_{0.39}Sr_{0.61}Nb_2O_6$ and sixth order electrostriction constants measured in the prototype phase used to derive elastic behavior in the ferroelectric form. A feature which makes the phenomenology valuable is that the higher order stiffnesses and coupling terms do not change markedly with temperature or with cationic makeup, thus in principle it is possible to predict from a single family of prototypic constants quantitative trends for the dielectric, piezoelectric, elastic, and thermal constants for a very wide range of bronze ferroelectric compounds.

[1] This work was supported by DARPA Contract F49620-78-C-0093 and AFOSR Contract F4962-77-C-0081.

LL-4 SAW Propagation Characteristics of Complete Cut of Quartz and New Cut with Zero Temperature Coefficient of Delay, Y. SHIMIZU and Y. YAMAMOTO, Tokyo Institute of Technology, Tokyo, 152 Japan.

We report the following five results of SAW propagation characteristics on quarts. 1) The new first-, second-, and third-temperature coefficients of the stiffnesses for alpha-quartz were obtained for better agreement with experiments. 2) Sets of maps are presented showing the value of SAW velocity, electromechanical coupling constant, power flow angle, and temperature coefficient of delay. 3) One method is explained for selecting the optimum cut for SAW propagation characteristics by these maps. 4) Experimental results of temperature coefficient of delay are shown for several new cuts with smaller temperature coefficient than *ST* cut, obtained from the theoretical prediction. 5) Metalization effect upon temperature property of SAW was theoretically analyzed for aluminum or gold film on quartz.

LL-5 High Temperature Stable Overlay Configuration on 46° X-Rotated Quartz,[1] R. LEC, J. F. VETELINO. F. JOSSE, D. S. BAILEY, M. EHSASI, Electrical Engineering Department, University of Maine, Orono, ME 04469 and W. SOLUCH, Tele and Radio Research Institute Ratuzowa 11 03-450 Warsaw, Poland.

In SAW devices requiring high temperature stability, it is very desirable to have the temperature coefficient of delay (TCD) equal to zero over a very wide range of temperatures. Orientations exist in the X-rotated cut of quartz where first and second order temperature coefficients are zero. One particularly attractive cut is the 46° rotated X-cut. In this cut TCD has a cubic behavior with temperature, similar to the bulk AT cut, in which TCD is zero over a wide range of temperature. However, this temperature range is significantly higher than room temperature. The effect that metallic layers of aluminum and gold have on TCD are studied. Experimentally, it is found that the flat region of the TCD curve is shifted downward to room temperature for certain metal layer thicknesses. This results in a high temperature stable (TCD = 0) configuration over a wide range of temperature near room temperature. The experimental results are substantiated by theoretical calculations. The implications this configuration might have in SAW devices is also discussed.

[1] This work was supported by the National Science Foundation under Grant ENG-7826941.

LL-6 Temperature Stable SAW Devices Using Doubly Rotated Cut of Quartz,[1] D. F. WILLIAMS and F. Y. CHO, Motorola Government Electronics Division, Scottsdale, AZ 85252.

Results of a numerical study of the properties of surface acoustic waves (SAW) on doubly rotated cuts of quartz are presented. Areas with low temperature coefficient of frequency (TCF) from previous study are studied in finer grids of one degree increments during this study. Experimental measurements of TCF with transducers oriented by 0.2-degree increments were obtained for selected orientations. The results of Sinha and Tiersten's approach are correlated with the finite difference method and used to find cuts with zero first-order TCF. Families of cuts on alpha quartz with SAW temperature stability superior to that found on ST cut quartz are identified.

[1] This work is supported by U.S. Army Electronics Command, Fort Monmouth, NJ, Contract DAAK 20-T9-C-0275.

NDE-MEASUREMENTS, SYSTEMS AND TECHNIQUES V

Chairperson: L. W. KESSLER

MM-1 Signal Processing Methods for Transmission Ultrasonic Computerized Tomography,[1] J. F. GREENLEAF and R. C. BAHN, Mayo Foundation, Rochester, MN 55901.

Transmission ultrasound compter-assisted tomography (UCAT) requires measurements of signal transit time and amplitude from pulses of ultrasound directed through the tissue from a pleurality of directions within a plane. The extreme dynamic range (90 dB) of typical signals require specialized methods of signal acquisition and conditioning along with algorithms for digital linear and nonlinear filtering of resulting data. A transmission UCAT instrument has been constructed for clinical tests in breast cancer detection. Signal transit time is measured over a range of 150 μs with an accuracy of ± 5 ns. Signal amplitude is measured with a precision of 12 bits over a logarithmically compressed range of 90 dB. Techniques of real time multifrequency attenuation measurements have been developed and applied to tissue equivalent phantoms and tissues. Reconstruction of two-dimensional distributions of acoustic speed and attenuation within breasts of patients with and without cancer have been obtained.

[1] This was was supported by the National Institute of Health under Grants CA 24085, HV 72928, GM24994, HL 0060.

MM-2 Spatial Moments of the Ultrasonic Intensity Distribution for the Purpose of Quantitative Imaging in Inhomogeneous Media, THOMAS A. SHOUP, GARY H. BRANDENBURGER, and J. G. MILLER, Washington University, St. Louis, MO 63130.

As an approach toward characterizing the ultrasonic field at a receiving aperture for the purpose of quantitative imaging, we investigated the spatial moments of the ultrasonic intensity distribution. In principle, the output of each element of an array of point-like piezoelectric elements can be squared to estimate the local intensity $I(\vec{r})$ in order to calculate the nth spatial moment $\vec{M}_n = \int(\vec{r})^n I(\vec{r})dA$. M_0, the average intensity, is the same quantity measured by an acoustoelectric receiver which was shown previously to eliminate phase cancellation errors. $\vec{M}_1$ permits an estimate of the average refraction experienced by the transmitted beam and M_2 permits an estimate of the lateral beam broadening due to transmission through the medium. To evaluate this approach, we simulated an array by mechanically scanning a 1-mm diameter piezoelectric receiver. Transmission measurements were made on well characterized test objects and quantitative images were reconstructed using standard methods of computer assisted tomography. Results obtained using the method of spatial moments were compared with those obtained using an acoustoelectric receiver and with conventional piezoelectric detection. Results obtained using the method of spatial moments exhibited freedom from phase cancellation errors and provided reliable estimates of attenuation, the extent of refraction and beam broadening. Consequently, the method of spatial moments represents a potentially useful approach to quantitative ultrasonic imaging in inhomogeneous and irregularly shaped media.

MM-3 A New Approach to Transmission and Emission CT, A. J. DEVANEY, Schlumberger-Doll Research, P.O. Box 307, Ridgefield, CT 06877.

Nonimaging techniques for determining the internal structure of spatially incoherent sources and weak scatterers from far-field data are presented. These techniques are based on rigorous formulations of the inverse source problem[1] and inverse scattering problem[2] and have direct application to emission CT (inverse source problem) and transmission CT (inverse scattering problem). The proposed techniques appear to be especially suitable in applications involving ultrasound since they are based on rigorous formulations of the inverse source and scattering problems and thus account for diffraction and refraction of the radiated or scattered fields.

[1] A. J. Devaney, *J. Math. Phys.*, vol. 20, p. 1687, 1979.
[2] E. Wolf, *Optics Commun.*, vol. 1, p. 153, 1969; A. J. Devaney, *J. Math. Phys.*, vol. 19, p. 1526, 1978.

MM-4 The Design of Broad-Band and Efficient Bulk Wave Transducers, C. H. CHOU, J. E. BOWERS, A. R. SELFRIDGE, B. T. KHURI-YAKUB, and G. S. KINO, E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305.

The basic design criteria for bulk wave transducers in nondestructive evaluation and medical imaging is the compactness of the impulse response. This criteria is different from the usual 3-dB bandwidth criteria because a flat bandwidth response does not necessarily imply a compact impulse response. We use electric circuit components to tune transducers with low impedance backing and no quarter-wave front matching layers. An iterative optimization computer program is used to determine the optimum values for the circuit elements. The optimization is done in the time domain with a criteria of reducing the length of the impulse response of the transducer. The impulse response is thus reduced from about 15 cycles to three cycles and has an almost Gaussian frequency response. The increase in the round trip insertion loss of the transducer due to the tuning is of the order of a few dB. Transducers have been constructed at 5 and 50 MHz with a backing of epoxy ($Z = 3$ kg/m^2 – S) and no front matching layer; the agreement between theory and experiment is excellent. Our technique has also been used to design transducers with quarter wave matching layer where the optimization is carried out for both the electric circuit components and the impedance and thickness of the matching layer.

†MM-5 Multimodal Excitation for Improved Angular Response in Photolithographed Ultrasonic Arrays, M. D. FOX, University of Connecticut, Storrs, CT 06268.

Ultrasonic phased array imagers have evolved rapidly in recent years. A key element in determining quality of such imagers is the array itself, particularly its focussing and angular response characteristics. Traditionally, such arrays have been formed from separate, individually machined elements, to reduce crosstalk. However, such elements often do not behave as pure thickness mode radiators, leading to degraded angular response. We have found that it is possible to photoetch high resolution ultrasonic arrays on monolithic piezoceramic substrates without having serious crosstalk between elements. Such arrays must be analyzed as multimodal surface wave generators, which can lead to improved angular response characteristics over conventionally manufactured arrays. Such arrays have the additional advantages of uniformity, high resolution, and ease of fabrication. Point probe scans of the transmit field patterns of a number of configurations will be presented and compared with theoretical analysis.

[1] This work was supported by the National Heart, Lung and Blood Institute under Contract NO1-HV7-2929.

MM-6 Fundamental Concepts in Acoustic Transducer Array Design,[1] A. R. SELFRIDGE, G. S. KINO, and B. T. KHURI-YAKUB, E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305.

Ceramic strip resonators with rectangular cross section have been made with aspect ratios (width to height ratios) from 0.1 to 30. The short and open circuit resonant frequencies have been plotted as a function of aspect ratio with good agreement between experiment and a simple coupled mode theory. The effect of loading these resonators acoustically with solids and liquids has also been examined. The resonators we have measured had a center frequency of near 3 MHz and widths down to 0.12 wavelengths in water at this frequency. We have demonstrated for the first time that when the resonators are less than a wavelength in width, a complex acoustic load impedance must be used to accurately predict the electrical impedance of the resonator which is measured. Our theory used to derive this complex acoustic load impedances will be described.

[1] This work is supported by the Electric Power Research Institute under Contract RP 609-1 and by the Air Force Office of Scientific Research under Contract F49620-79-C-0217.

MM-7 Basic Pitfalls in Numerical Reconstruction of Flaws with Acoustic Holography, D. BROCK and K. J. LANGENBERG, Fachrichtung 12.2, Theoretische Elektrotechnik, Universität des Saarlandes, D-6600 Saarbrücken, Germany.

In nondestructive evaluation of flaws with acoustic holography numerical reconstruction schemes are mostly based on the one- or two-dimensional Rayleigh-Sommerfeld integral, its Fresnel approximation or matched filter techniques. It can be easily demonstrated that the first and latter formulations are identical. Yet a basic difficulty of both is to extract the real crack size from the reconstructed image; the reconstruction properties of Fresnel transforms have been shown under incorrect assumptions. An analytical relationship in terms of a convolution integral exists between the velocity potential distribution on the surface of the object and its reconstructed image; therefore, the so-called ambiguity function of a point object has always a 3-dB width of the order of the wavelength, even for an infinite aperture. We present computations and reconstructions of synthetic holograms of linear crack models being based on the first-order approximate solution of the underlying integral equation and show how the reconstructed crack size additionally depends on the aperture width. It turns out that the Fresnel approximation of the integral transforms is sufficiently valid for all practical applications.

BIOPHYSICS–II

Chairperson: W. D. O'BRIEN, JR.

†NN-1 [Invited] Acoustic Medical Imaging Through Aberrating Media, J. W. HUNT, F. S. FOSTER, and M. ARDITI, The Ontario Cancer Institute and Department of Medical Biophysics, University of Toronto, 500 Sherbourne Street, Toronto, ON M4X 1K9, Canada.

When scanning across the body using traditional ultrasound systems, the poor beam lateral resolution is displayed by streaking images. The beam width δ at the focus of a transducer is mainly limited by the diffraction,and given by

$$\delta = 1.41\,(c/\upsilon)(f/d) = 1.41\,(c/\upsilon)(f\text{-number})$$

in which f is the focal length, d is the transducer diameter, c is the speed of sound in the medium, and υ is the average frequency of the ultrasound beam. Tissue attenuation limits the frequency used; therefore, improved resolution is best obtained by designing large aperture (i.e., small f-number) acoustic systems. Improved focusing is a compromise since poor depth-of-field is obtained. A phased annular ring system, coupled to a zone focusing technique has improved the lateral resolution by two to three times. Recently, an exciting approach has been developed, in which the lateral resolution and depth-of-field limitations are greatly reduced. Essentially, a cylindrical or conical transducer produces a sharp line-focus inside the body. A second receiving transducer is placed in line with this focus and detects the scattered waves in depth of the tissue. Lateral resolution of better than 0.5 mm has been demonstrated both in a water bath and in tissue samples. As well, several novel image techniques have been tested in the laboratory, in which the annoying "speckled" images can be averaged out without loosing spatial resolution.

†NN-2 Degration of Acoustic Images in Mammalian Tissue, K. N. BATES, Hewlett-Packard Laboratories, Palo Alto, CA 94304.

It has long been recognized that ultrasonic images of the body are far worse than what would be expected based on measurements made with an imaging system in a water tank. Measurements in tissue phantoms provide closer but far from perfect correlation. Numerous *in vivo* and *in vitro* measurements in animal tissues are described. These measurements were obtained by comparing the line response in water of the imaging system developed at H.P. Labs with that obtained in tissue. Previously reported effects of Rayleigh scattering and speckle were confirmed. However, beam spreading effects at low F numbers were observed that were not attributable to frequency dependent attenuation. To test the validity of the measurements in excised tissue, the experiments were repeated in an anesthetized pig. The results through muscle agreed well with those of the excised tissue. Measurements through the liver showed a fourfold loss of resolution believed to be due to refractive effects at the different tissue boundaries.

NN-3 Parallel-Focusing and Speckle Reduction in Medical Ultrasonic Imaging,[1] H. E. MELTON, JR., Department of Pathology, Medical College of Wisconsin, Milwaukee, WI 53226.[2]

Focusing to improve resolution using electronic delays led to the development of dynamic focusing so that resolution as a function of range was nearly uncompromised. Unfortunately, such a method of focusing was sensitive to phase cancellation whether derived from aberration or from targets. A new method of focusing was developed which led to a reduction of phase cancellation effects or speckle. Instead of dynamic focusing independent focus-sums were formed each with a different focus. Each sum was detected separately and then added together to form the final video signal. This method completely removed the need for focus-updating, and thereby it removed the lack of congruence between focus-update range and out-of-position focus due to aberration. Also this method reduced correlation between focus-sum signals of the same range which in the final video led to a reduction of speckle and led to an apparent improvement in the resolution of structure within tissues which scatter ultrasound.

[1] This work was supported in part by N.I.H. Grant FD 01007 and the Department of Pathology, Medical College of Wisconsin.
[2] Current address: Department of Electrical Engineering, University of Iowa, Iowa City, IA 52242.

NN-4 The Speed of Sound as a Function of Temperature in Mammalian Tissue, R. L. NASONI, T. BOWEN, M. DEWHIRST, H. ROTH, and R. PREMOVICH, Division of Radiation Oncology, University of Arizona Health Sciences Center, Tucson, AZ 85724.

The speed of sound in mammalian (canine) tissue was measured as a function of temperature to determine whether these measurements have the stability, repeatability, and freedom from artifact to qualify speed as a scan parameter in a CT ultrasound thermal mapping system. This system would provide thermal dosimetry for the treatment of cancer using hyperthermia; a modality which is receiving the wide acceptance by the medical community, but has been hampered by inadequate dosimetry. Measurements were made of the speed as a function of temperature over temperatures ranging from 35° to 45°C on canine tissues both *in vitro* and *in vivo* using a 5-MHz pulse transmission velocimeter. Twenty-five *in vitro* and 14 *in vivo* runs were made on kidney, liver spleen, muscle, and stomach including an *in vivo* run made on blood. The speed of sound was also measured *in vivo* in six canine tumor types at a fixed temperature and over a temperature range for another type. For *in vitro* runs, the fractions of water, lipid, collagen and protein in the insonified volumes were determined. Speed was fit to a linear regression model on these components and temperatures. Conclusions are 1) the speed of sound as a function of temperature can be measured *in vivo* with stability and freedom from artifact; 2) lack of repeatability from tissue to tissue makes speed an improbable thermal scan parameter; however, 3) because of repeatability in slope the temperature coefficient of ultrasound may have possible use in thermal dosimetry.

NN-5 Echo Enhancement Techniques Similar to Optical Staining,[1] J. ABRAMSON, A. DYBBS, I. GREBER, and D. HAZONY, Case Institute of Technology (CWRU), Cleveland, OH 44106.

A broad-band 25-MHz transducer (pulse length approximately 100 ns) has been coupled through glucose Ringer's solution to detect the epithelium-Bowman's membrane-stroma interface of the bovine cornea. Ordinarily the echo from this boundary is barely detectable. After application of glycerine for two minutes, the echo from this interface is easily detected. Furthermore, the glycerine reduces the thickness of the corneal layers. Typically the epithelium is reduced to 120 μ from 150 μ while the stroma is reduced to 900 μ from 950 μ crons. As the treatment wears off the corneal layers start to swell. Hypertonic solutions such as 5 percent saline have similar effects. Local dehyration is probably responsible for the echo enhancement that occurs and thus these techniques may be used to study changes in both epithelial and stromal thickness *in vivo*. A large amount of data and photographs will be presented.

[1] This work was supported in part by NIH Grants RR–07113-12, GM-075-35 and Gould Inc. Moreover, the support and comments of Dr. Edward W. Purnell and his staff are much appreciated.

†NN-6 Differentiation of Abdominal Organs and Pathologies by the Analysis of A-Mode Ultrasound Waveforms, J. P. JONES, V. GONZALEZ, and R. KOVACK, Department of Radiological Sciences, University of California Irvine, Irvine, CA 92717.

We have implemented a computerized data anlaysis system for ultrasonic tissue characterization. One important feature of this system is its ability (via a fast ADC) to record both the phase and amplitude of A-mode waveforms selected through regions of interest on a conventional B-mode ultrasonogram. The results of comprehensive measurements taken *in vivo* on over 30 nomral human subjects as well as several subjects with confirmed cirrhosis of the liver are described. All measurements were limited to abdominal organs and included liver, pancreas, and spleen. Various signal processing procedures have been applied to the data including amplitude histogram, intensity histogram, power spectrum, autocorrelation, cross correlation, historgram of the first peaks in the autocorrelation of the power spectrum, real cepstrum, and harmonic product spectrum. The results of the various signal analysis schemes will be compared and evaluated and the problems associated with the development of a generalized characterization scheme noted. Almost all of the signal processing techniques tried could differentiate between liver, pancreas, and spleen and could differentiate between normal and cirrhotic liver.

Author Index