ULTRASONICS

A Report on the 1963 Symposium

By J. J. G. McCue

The Ultrasonics Symposium seems now to be well established as an annual affair. The 1963 event, held on December 4, 5, and 6, at the Marriott Motor Hotel in Arlington, Va., fully met the high standard set in the previous year. These symposiums, of which the first was held in 1958, are sponsored by the IEEE Professional Technical Group on Sonics and Ultrasonics, which owes its unwieldy name partly to the merger of the American Institute of Electrical Engineers with the Institute of Radio Engineers and partly to its own recent resolve to extend its field of interest from ultrasonics to all sonic phenomena not communicating intelligence to the human ear.

The 1963 symposium dealt principally with frequencies above one megacycle; indeed, the emphasis was on frequencies in the gigacycle region, which not only offers promise of applications in communications technology, but also provides new techniques for investigation of the solid state. Papers on the older aspects of ultrasonics included delay lines, treatment of brain, and an interesting concept for a scanner that exploits acoustically induced birefringence.

J. de Klerk of Westinghouse Research Laboratories opened the program with a description of an ingenious apparatus for producing good longitudinal waves in X-cut quartz, in a helium cryostat, over the range 0.6 to 8.5 Gc/sec. The exciting signal is an oblique E-field between a wedge and two side electrodes, the wedge being aligned with its edge perpendicular to the axis of the rod. On the two sides of the wedge, the components of E along the rod (i.e., along the x-axis of the crystal) act in phase to produce a longitudinal wave. In general, the components perpendicular to the x-axis can create shear waves, but when the rod is aligned so that these components lie along the z-direction (the optic axis of the crystal), the shear is eliminated, since quartz is not piezoelectric along the z-direction. The cavities for coupling energy into the rod at one end, and out at the other, are co-axial and are tuned by adjusting the position of cylindrical beads on the center conductors; using modes such that the length of the cavity is $\lambda/4$, or $3\lambda/4$, or $5\lambda/4$, de Klerk covers the range 0.6 to 8.5 Gc/sec with only two pairs of cavities. The Q of each cavity is about 1500, and the input power is 200 watts. The equipment is being used to study the interaction of microwave phonons with the low-frequency phonons of the lattice spectrum.

In de Klerk's work, as in the pioneering experiments of Baranskii[1] and of Bömmel and Dransfeld,[2] the acoustic wave is launched in a piezoelectric material by exposing one end of it to the rapidly alternating electric field in a microwave cavity. S. Wanuga and W. Brouillette (General Electric) described an alternative method, suitable for launching either longitudinal or transverse waves in material that need not be piezoelectric. They use the magnetic field in a cavity to excite magnetostrictive films of nickel-cobalt alloy, which are applied to the material in which one wants to establish the acoustic wave. They have studied waves with frequencies up to 3 Gc/sec in silicon, germanium, gallium arsenide, and cadmium sulfide at liquid-helium temperature, as well as in ruby at room temperature.

There were a few papers on the employment of these microwave phonons in physical research. N. Tepley and M. W. P. Strandberg (MIT) described an exploration of the Fermi surface in gallium by means of oscillations in the ultrasonic attenuation as one increases the magnetic field in which the sample lies. At low temperature, a principal cause of attenuation is the transfer of lattice energy to the electrons that are on the Fermi surface. In the presence of a magnetic field, such transfer is furthered if the diameter of an electron path is an integer multiple of an ultrasonic wavelength ("geometric resonance") or if the frequency of the acoustic wave is an integer multiple of the cyclotron frequency ("ultrasonic cyclotron resonance"). The attenuation is therefore compounded of oscillatory functions, each periodic in the reciprocal of the magnetic intensity, and from the periods one can infer the effective

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electron masses and the dimensions of the Fermi surface. The method can succeed only when the wavelength of the sound is less than the mean free path of an electron. It therefore demands the use of high frequencies. Tepley and Strandberg outlined advances in technique that have enabled them to work at nine gigacycles. Since the wavelength of their sound in gallium was equal to that of orange light in air, the critical mechanical arrangements had to be of optical quality. Moreover, because of the high frequency, attenuation limited the length of the sample to about a tenth of a millimeter. By developing techniques for fabricating metal single crystals suitable for use at such a high frequency, these workers have laid a groundwork for the study of metals in which the mean free paths of electrons are too small to make the resonances detectable at lower frequencies. At nine gigacycles, it is likely that the method can even be used to find the effective electron masses, and to gauge the Fermi surface, in alloys.

Interactions between acoustic waves in solids are attracting much attention. The waves are coupled through third-order (or higher-order) terms in the lattice potential. N. S. Shiren (IBM Corporation) gave an account of some experiments on nonlinear interaction between collinear gigacycle waves in single-crystal magnesium oxide. A possible application is parametric amplification. A quartz bar with one end in a re-entrant microwave cavity is excited at 9 Gc/sec or thereabouts by a "pump" oscillator supplying a few tenths of a kilowatt. A second cavity, driven at perhaps 9.5 Gc/sec by a "signal", excites the other end of the bar, and to that end is cemented a single crystal of magnesium oxide. The quartz merely acts as a nonresonating X-cut transducer for exciting longitudinal waves along the $< 100 >$ direction in the magnesium oxide. Anharmonicity of the MgO lattice generates sum and difference frequencies, which, in turn, can generate higher-order sums and differences. As much as 70 percent of the signal power was converted to other frequencies. The sum frequency, and those that derive from it, can be suppressed by using paramagnetic resonance of impurity ions to make the lattice acoustically dispersive. In an appropriate magnetic field, the dispersion introduced at resonance by spin-phonon coupling suppresses conversion to the sum frequency, when all the waves are collinear, by preventing conservation of frequency and conservation of wave vector from being simultaneously possible. Shiren expressed a hope that such suppression of the sum frequencies would make possible the realization of gain at the signal frequency. A few weeks later, he was able to report[3] that this goal had been achieved.

Though it dealt with lower frequencies, a fine invited paper by Fred Rollins, Jr., (Midwest Research Institute) was of interest in this connection. He spoke on his demonstration[4] of the interaction of noncollinear beams of elastic waves; when two beams in an anharmonic material intersect, they can generate a third beam, provided that frequency and wave vector are conserved. For example, transverse waves with frequencies f_1 and f_2, intersecting at an appropriately selected angle, can give rise to a longitudinal wave with frequency f_1 plus f_2. The experiment was conducted successfully in fused silica, in polycrystalline aluminum, and in polycrystalline magnesium, using frequencies of a few tens of megacycles.

Attenuation of the "microwave phonons" was discussed in a number of papers. Of these, perhaps the most fully developed was presented by W. P. Mason and T. B. Bateman (Bell Telephone Laboratories), who worked at 0.3 to 0.5 Gc/sec. They have measured attenuation and velocity in germanium and silicon, with and without doping. In well-purified material, with not more than 10^{14} impurity atoms per cubic centimeter, the attenuation decreases with temperature down to about 20°K, below which it practically vanishes. The attenuation is therefore to be ascribed to phonon-phonon interactions. Since the third-order elastic moduli for germanium and silicon are known, the authors were able to calculate the attenuation to be expected for shear and compressional waves; the results agree fairly well with the measured attenuation. The effects of doping, too complex to be summarized here, were also discussed. M. Pomerantz (IBM) described a study of attenuation in germanium at higher frequency, 9 Gc/sec. He finds that the attenuation at such frequencies remains low in pure germanium at higher temperatures than it does in quartz. Doping with electron donors raises the attenuation very markedly for waves with certain polarizations, but not for other waves. From this, one concludes that, as point lattice defects, these impurities have little effect on the attenuation, and that the rise in attenuation results chiefly from electron transfer between energy valleys in k space in the germanium when their degeneracy is removed by shear.

Periodic vibration of the lattice, because it alters the electric field gradients at the nuclei, can give energy to the nuclear spins, which can thus influence the attenuation. That an injected acoustic wave can influence conventional nuclear magnetic resonance was shown nearly ten years ago by Proctor and Tantilla, who observed the effect of ultrasound on the absorption of energy from a radio-frequency magnetic field. Since the coupling between the acoustic wave and the nuclear spins is not strong, the acoustic attenuation attributable to spin-phonon interaction is too small to be detected by conventional methods; it is on the order of 0.01 decibels per kilometer. Nevertheless, direct detection of spin-phonon interaction is to be desired, since it permits the investigation of metals and semiconductors, in which the skin effect militates against the use of an rf magnetic field. D. I. Bolef (Washington University) described his technique for direct detection of acoustic absorption by nuclear spins, essentially by noting small changes in the Q of a resonator. He then showed how acoustic excitation of nuclear magnetic resonance provides a means for studying interaction between nuclear electric quadrupole moments and the lattice—even in such simple lattices as the cubic one—and therefore is a promising tool for the study of chemical binding in crystals, including metals.

As is customary at the Ultrasonics Symposium (which aspires to cover the spectrum from fundamental theory and experiment to engineering use) there were some papers on devices. T. R. Babcock and G. C. Vorie (Cornell Aeronautical Laboratory) described a proposed scanner, or image dissector, that may be suitable for picking up or displaying optical images. Two photoelastic plates between horizontal-passing polarizers are mounted face to face, but with a vertical-passing polarizer between them. Wavefronts of strain, generated by electromechanical transducers, travel vertically in one plate and horizontally in the other; light passes through the whole sandwich at the intersections where the strains coincide. The velocity of sound in the plates provides the link between the electrical waveform and the position of the transmitted light. Using a single-plate model as a camera scanning in one dimension, Babcock and Vorie showed that 25 line-pairs per inch are very plainly resolved. D. B. Fraser and R. C. LeCraw (Bell Telephone Laboratories) presented an elegant method for determining the elastic constants of solids. A sphere of the solid, a few millimeters in diameter, is placed on the top face of a ceramic shear-mode transducer, without bonding. By pulsing the transducer, one excites the sphere, and if one is near a resonant frequency for the sphere, the sphere drives the transducer after the end of the pulse. Resonant frequencies of the sphere can therefore be found, and by relating these to the calculated mode spectrum, one can determine Poisson's ratio and the Lamé constants. From the rate of decay of the vibrations, the internal friction can be measured. The method is particularly well suited to studying the variation of the elastic constants, and of the internal friction, with temperature. W. J. Spencer, also of Bell Laboratories, gave a paper on the use of x-ray diffraction to study the vibration modes of anisotropic discs. A strip of collimated x rays falls on one horizontal face of a crystalline disc, at such an angle that Bragg reflection occurs from some selected set of vertical planes in the lattice. Extinction in the plate limits the exposure received by a photographic film mounted in a horizontal plane beneath the plate. When the plate is not vibrating, the extinction is large, but when it is vibrating in one of its acoustic modes, standing waves in the plate produce lattice curvature at the antinodes of displacement; the curvature reduces the extinction and the film darkens. To provide a view of the whole plate, the film and the vibrating plate move together so that the band of x rays sweeps across the plate. Since the Bragg reflection can be made to occur from any one of several sets of vertical planes in the lattice, strain can be determined as a function of crystallographic direction. With highly perfect crystals, the resulting topographs resemble Chladni patterns. The outcome is extremely sensitive to dislocations; thus the technique seems also to offer the possibility of observing fairly directly the interaction of dislocations and acoustical waves.

A paper that elicited exceptionally high interest was one by F. S. Hickernell and N. G. Sakiotis (Motorola) on an electroacoustic amplifier. D. L. White[5] has pointed out and demonstrated the possibility of negative acoustic attenuation in a piezoelectric semiconductor. One must apply an electric field that produces an electron-drift velocity exceeding the velocity of sound in the medium. The effect is somewhat like the amplification of an electromagnetic wave in a traveling-wave tube, although in the acoustic amplifier the mean free path of the electrons is far less than a wavelength. An acoustic wave in a piezoelectric semiconductor creates a space-varying electric field that modulates the conductivity. When a strong enough drift field is applied, the phase of stress can lead the strain, and energy is delivered to the wave. In earlier work, amplification in the medium had merely diminished the net loss between electrical terminals, but Hickernell and Sakiotis reported portal-to-portal gain. In the 1-cm slab of cadmium sulfide, the acoustical gain of 75 db exceeded by 40 db the electromechanical losses. They operated in a pulsed manner at 60 Mc/sec.

E. W. Prohofsky and H. Kroger (Sperry Rand) described some of their recent work on waves of collective phonon-density fluctuation in cadmium sulfide. This phenomenon occurs under conditions of acoustic gain in the CdS; it is believed to arise from "Čerenkov-like" radiation of phonons from electrons having a drift velocity greater than that of the elastic wave. The collective wave, which could be classified as second sound, propagates $1/\sqrt{3}$ as fast as an elastic shear wave in the same medium. The authors had reported the phenomenon earlier;[6] at the symposium Prohofsky outlined his theory of the effect, and Kroger detailed the experimental elimination of various other explanations that might be adduced.

Among the half-dozen papers on delay lines was one on the use of magnetoelastic waves. These are generated by the coupling of the lattice to spin waves, which are waves of deflection of electron spins away from the ordered orientations that characterize a magnetized material. Walter Strauss (Bell Telephone Laboratories) proposes a delay line using magnetoelastic waves in yttrium iron garnet (YIG), a ferrite in which ultrasonic attenuation at room temperature is exceptionally small. The idea is appealing because the waves can be launched by setting up spin waves inside the YIG, whereas elastic waves in quartz, excited piezoelectrically as in the situations described by de Klerk and by Shiren, are launched at the crystal surface, which must therefore be finished very precisely. Furthermore, the magnetoelastic delay line would have an electrically adjustable delay, since the velocity of the spin wave depends on the strength of the magnetic field. At 4 Gc/sec the attenuation in the medium at room temperature would be only on the order of 10 db/μsec, whereas the best cable attenuates, at that frequency, by perhaps 30 db/μsec.

Another Bell Laboratories project for the design of gigacycle delay lines involves the deposition of cadmium-sulfide transducers as oriented crystals on the end faces of quartz rods, with a thin metal film at the interface in order to establish electrical contact with the CdS. This technique, carried forward by N. S. Foster, promises bandwidths of several hundred megacycles; it is thus of interest for delaying nanosecond pulses.

Occasional changes of pace were provided by some excellent speakers presenting material which, though it might be called peripheral, was also fascinating. In an after-dinner speech, Robert T. Beyer (Brown University) gave a survey of the ultrasonic work going on in various European centers. William J. Fry, speaking for himself, F. J. Fry, and G. H. Leichner (University of Illinois), told of their elaborate and painstaking development of equipment for precise application of ultrasonics for the study of structure and function of the central nervous system and for controlled modification of the human brain. Movies showed the dramatic relief that ultrasonic treatment has produced in some cases of parkinsonism. W. G. Mayer (Michigan State University) read a paper,[7] on mode conversion at plane interfaces, that will interest teachers who give courses relating to wave phenomena. While calling attention to a variety of cases of reflection and refraction involving specific materials used in industrial ultrasonics, it points out that this thoroughly classical set of problems has not yet been analyzed completely, even for materials that are isotropic. One of the summits of the three-day meeting was an invited review by T. A. Litovitz (Catholic University) of the use of ultrasonics in studying the structures of liquids.

This summary, though not exhaustive, gives an idea of the great expansion of the domain of ultrasonics and of its reach into areas that not long ago seemed to have nothing in common with acoustics. Particularly interesting is the intricate interplay of the scientific and technological sides of the subject. Much of the activity takes place in industrial laboratories—IBM, Bell Telephone, General Electric, Sperry Rand, and others—and fairly esoteric effects discovered only in the past two or three years are already being explored intensively with a view to applications. The resulting rapid progress in techniques makes possible experiments, such as those on the coupling of phonons to nuclear spins, that simply could not have succeeded if tried a few years earlier. The interplay has been particularly strong and rapid in the merger of ultrasonics with solid-state physics. It is already apparent that the 1964 symposium, to be held in Los Angeles in October, will be enlivened by new developments of this kind, though the program committee is trying to ensure that the older branches of ultrasonics—mature and ready for technological exploitation—will not be neglected.

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