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A Short History of Microwave Acoustics

JEFFREY H. COLLINS, FELLOW, IEEE

***Abstract*—Microwave acoustics may be defined as the subject embodying the propagation of acoustic waves in solid-state materials at micron-order wavelengths where analysis, design, and componentry realizations are similar to those used by the microwave engineer exploiting electromagnetic waves. Microwave acoustics has a short history, being about 25 years old, but is underpinned by the theory of sound propagation due to Lord Rayleigh of 100 years ago. Microwave acoustic components inherently have several distinct physical origins including volume acoustic waves in solids excited by piezoelectric thin-film transducers and magnetic propagating modes in yttrium iron garnet, both at conventional microwave frequencies; the later surface acoustic-wave (SAW) technology for operation at VHF/UHF; and the realm of acoustooptics, which can embody any of the earlier three. Over its 25-year history, microwave acoustics has matured to become a necessary building-block in many radar and communication systems for efficiently carrying out real-time analog signal processing. Contributions to microwave acoustics have been truly international and have spanned many diverse disciplines. The growth of this subject has led to the formation of several companies dedicated to its application.**

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I. INTRODUCTION

IN WRITING a guest editorial on microwave acoustics for the TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES in November 1969, Al Bahr [1] posed the question, "What has acoustics to do with G-MTT?" and answered it through a quote from the G-MTT constitution of the time, namely that "Microwave theory and techniques are related to electromagnetic waves usually in the frequency region between 1–100 GHz; other spectral regions and wave types are included within the scope of the Group whenever basic microwave theory and techniques can yield useful results. Generally, this occurs in the theory of wave propagation in structures with dimensions comparable to a wavelength, and in the related techniques for analysis and design."

Indeed, microwave acoustics has over the years demonstrated all these attributes. However, in "microwave acoustics," the "micro" part of "microwave" is normally

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associated with micron-dimension wavelengths. Because microwave acoustics is based exclusively on solid-state technology, and since the velocity of a sound wave in a crystal is of the order of 3–5×10^3 m/s, a factor 10^5 slower than an electromagnetic wave, wavelengths of 100 μm are realizable down to 30 MHz, and yet a wavelength of a few microns falls genuinely in the microwave frequency range between 500 MHz and a few gigahertz!

Experimentally, microwave acoustics is a young subject, being about 25 years old. However, the theory of sound propagation that underpins it, due to Lord Rayleigh, is more like 100 years old. Microwave acoustics has had many realizations in its short history. These range through volume wave excitation by surface piezoelectricity and magnetostiction, and later by half-wavelength-thick thin-film piezoelectric transducers; efficient volume (bulk) wave nondispersive delay lines; yttrium-iron garnet (YIG) dispersive devices utilizing combinations of acoustic and magnetic propagation; and acoustooptic Bragg diffraction cells. All these operate genuinely at microwave frequencies. Then came the decade of the 1970's, which was dominated by surface acoustic-wave (SAW) devices operating at VHF and UHF frequencies which have proved of great relevance to IF processing of microwave signals. The history of microwave acoustics is truly international, with researchers making major contributions from such diverse countries as Canada, France, West Germany, Japan, Russia, the U.K., and the U.S.A.

Two prime reasons can be associated with man's interest in microwave acoustics: the obvious one of scientific curiosity and the truly dominant one of the quest for compact signal processors, exemplified by the attainment of microseconds of delay in a volume of a few cubic inches with an insertion-loss penalty readily overcome by today's solid-state amplifiers. The development of microwave acoustics has been recorded over the past 20 years in several Special Issues of IEEE Journals. The reader is particularly referred to the Proc. IEEE Issue of October 1965, guest-edited by Gerald McCue and Dick Damon [2]; the MTT-17 Issue of November 1969, guest-edited by Al Bahr [1]; the MTT-21 Issue of April 1973, guest edited by Tom Reeder [3]; the Proc. IEEE Issue of May 1976, guest edited by Lou Claiborne, Gordon Kino, and Ernest Stern [4]; and the MTT-29 Issue of May 1981, guest edited by Dick Williamson and Tom Bristol [5]. Interestingly, all three MTT Special Issues on microwave acoustics were jointly sponsored by the IEEE Sonics & Ultrasonics Group. Most notably, however, the Proc. IEEE Issue of October 1965 saw the birth of microwave acoustics when traditional devices for the 10-MHz to 500-MHz range involving complex quartz handcrafting manufacturing methods became deemphasized by the reporting of significant results in the new field of microwave acoustics utilizing reproducible manufacturing methods akin to those of microelectronics. This changeover in emphasis has never subsequently been reversed.

II. Microwave Bulk Acoustic-Wave Delay Lines

A. Introduction

The basic *bulk* acoustic-wave delay line for gigahertz frequencies consists of a cylindrical rod, typically of 3-mm diameter and a few centimeters length, of suitable single-crystal transmission material for the propagation of the acoustic wave. At the ends of the rod are transducers for converting the electromagnetic to acoustic energy; these over the years have taken several forms. Electrical networks, or filters, are attached to each of the transducers for coupling to the microwave circuits, both in and out. The term "bulk acoustic wave" describes acoustic propagation in a medium whose transverse dimensions may be considered infinite, that is, equivalent to electromagnetic propagation in unbounded space. The theory of acoustic-wave propagation in solids, although traceable back to Lord Rayleigh, was first thoroughly laid out in 1958 in the series of books by Warren P. Mason entitled "Physical Acoustics and the Properties of Solids," published by Van Nostrand [6]. Importantly, two classes of bulkwaves can exist in single-crystal materials, namely longitudinal waves and shear waves; both are nondispersive.

B. The Early Experiments

In 1957, Baranskii [7] of the Soviet Union succeeded in exciting sound through the piezoelectric coupling constant of quartz up to a frequency of 2 GHz and used diffracted light as a means of detecting the presence of the acoustic column. In 1958, Bommel and Dransfield [8] demonstrated the generation of coherent longitudinal and shear waves via surface piezoelectricity in quartz with a reentrant cavity at one end of a crystalline rod (Fig. 1). A conversion loss of about 40 dB and delays of several microseconds per centimeter were observed. This experimental configuration proved the forerunner of many academic investigations aimed at identifying the basic mechanisms for acoustic losses in solids as a function of temperature. In 1959, Bommel and Dransfield [9] reported the use of a 1.8 μm-thick evaporated nickel film on a quartz rod to generate 1-GHz phonons by ferromagnetic resonance. The same year, using similar procedures, Jacobsen [10] of General Electric reported the excitation of 10-GHz longitudinal waves at low temperatures in quartz bars. In 1962, a complementary magnetic experiment by Spencer, Denton, and Chambers [11] of Bell Telephone Laboratories demonstrated the excitation of plane shear waves via surface magnetostiction in a magnetically biased yttrium iron garnet (YIG) rod. These shear waves were found to have a remarkably low attenuation, about 0.25 dB/μs at 1 GHz and room temperature, and stimulated the belief that cumbersome electromagnetic delay lines at microwave frequencies would be superceded by miniature acoustic solid-state delay lines, providing efficient transducers with large bandwidth could be realized. It was recognized that the

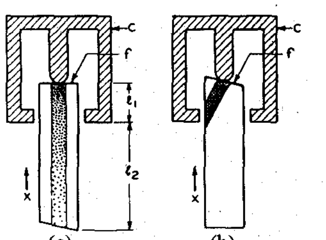

Fig. 1. Configuration used in 1958 by H. E. Bommel and K. Dransfield, [8, fig. 2] of Bell Telephone Laboratories, to measure acoustic longitudinal wave propagation by light diffraction through a rectangular crystalline quartz rod, $4\times1\times0.5$ cm, at 1 GHz excited through the electric field of a coaxial cavity. Acoustic attenuation was estimated to be of the order of 2 to 4 dB/cm, or 1 to 1 dB/μs. The experiment shown in (b) aims to verify theories of acoustic beam steering in crystalline quartz.

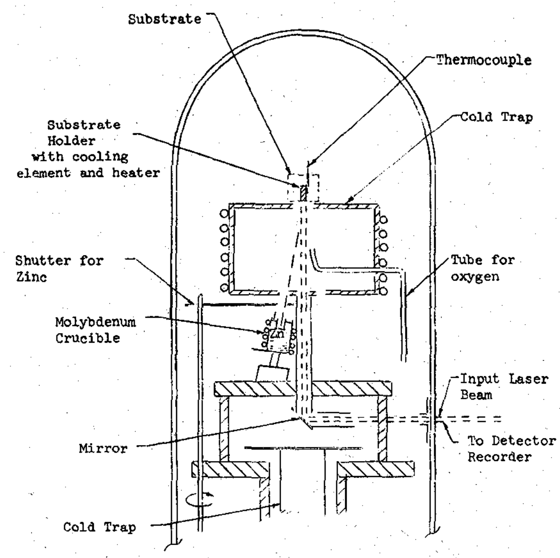

Fig. 2. Schematic of vacuum station for deposition of cadmium sulphide (CdS) thin piezoelectric films. Figure is taken from Ph.D thesis entitled "Acoustic generation with reactively deposited piezoelectric thin films," of R. W. Malbon, Microwave Laboratory, Stanford University, dated December 1968.

obstacle was technological in that resonant plates bonded to the acoustic substrate, the favored excitation technique for ultrasonic delay lines in the frequency range 5–100 MHz, could not be fabricated in a similar way at gigahertz frequencies due to the micron-order plate-thickness dimensions involved. Nevertheless, Sittig *et al.* [12], using mechanical polishing after bonding of the resonant plate, obtained fundamental mode excitation at 0.8 GHz.

C. Thin-Film Transducers

Microwave bulk acoustic-wave delay lines took a major practical step forward with the suggestion made by Norman Foster of Bell Telephone Laboratories at the 1963 IEEE Ultrasonics Symposium that *thin* piezoelectric films, one-half acoustic wavelength thick, might make efficient transducers concomitant with large bandwidth ($>$ 500 MHz). The basic configuration for the subsequent experiments required that the thin piezoelectric film be made to vibrate in one or more pure one-dimensional acoustic modes by application of a harmonic potential to the metal top and counter electrodes. Acoustic energy generated by the piezoelectric thin-film would then radiate into the single-crystal acoustic substrate such that the initial beam size was defined by the dimensions of the top electrode. Transducers satisfying the above description were readily analyzed using again the ultrasonic methods described in the series of books by Warren P. Mason [6].

The first successful experiments on thin-film transducers used cadmium sulphide (CdS) layers and were reported in 1965 by Foster [13] and John de Klerk [14] of Westinghouse Research Laboratories. CdS was deposited by thermal evaporation with the addition of sulphur to obtain the necessary high resistivity. The layers were found to be polycrystalline, with the film Z axis deposited at the same angle relative to the acoustic substrate as the directional evaporant beam. CdS films with Z normal to the substrate were found to excite a pure longitudinal wave, whereas films deposited with the Z axis aligned approximately 39° away from the substrate normal produced predominantly shear waves. These results produced a flurry of research activity, and notably, in 1966 at Stanford University, Mike Malbon, Don Winslow, and John Shaw [15] deposited many high-quality CdS films on sapphire, fused quartz, and metal film surfaces by direct beam evaporation of cadmium and sulphur (Fig. 2).

These successes led immediately to investigations of the material zinc oxide (ZnO), which has a higher value of shear and longitudinal piezoelectric coupling constants than CdS. High-quality films were prepared by reactive sputtering of polycrystalline ZnO targets in an argon/oxygen atmosphere by Foster and Rozgonyi [16]. The Stanford University team [17] followed in 1967 by reporting the deposition of good ZnO films for longitudinal wave excitation through the thermal evaporation of zinc in a carefully controlled atmosphere of oxygen. Finally, both aluminium nitride (AlN) and lithium niobate ($LiNbO_3$) films for piezoelectric transduction were demonstrated, respectively, by Wauk and Winslow in 1968 [18] and Foster in 1969 [19]. Interest in AlN was stimulated by its longitudinal wave velocity being approximately twice that of CdS and ZnO, leading potentially to a doubling of operating frequency for microwave acoustic delay lines for given transducer dimensions: interest in $LiNbO_3$ was stimulated by its exceptionally high piezoelectric coupling constant.

Many efforts were made in the late 1960's to optimally design broad-band low-loss microwave bulk acoustic-wave transducers. The work conducted at Teledyne MEC and Stanford University of Tom Reeder and Frank Olson [20] was particularly significant. Fig. 3 shows a 1968 result for conversion loss and VSWR for a broad-band L-band transducer utilizing a three-resonator matching network and a longitudinal mode thin-film transducer of gold, ZnO, gold, Z-oriented sapphire. The achieved minimum conversion loss of 7 dB over a 31 percent, 3-dB bandwidth, points

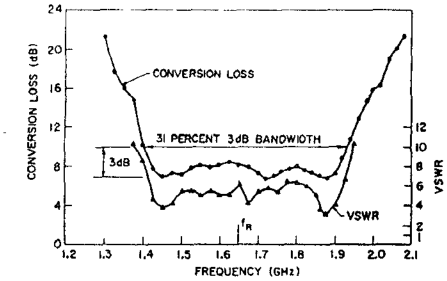

Fig. 3. Conversion loss and VSWR for a broad-band *L*-band transducer utilizing a three-resonator electrical matching network. Figure is taken from article by T. M. Reeder and D. K. Winslow which appeared in the *IEEE Trans. Microwave Theory Tech.*, Special Issue on Microwave Acoustics, November 1969, Figure 15, page 935.

up that the age of microwave acoustic delay lines had arrived.

D. Delay Lines

In parallel with the development of piezoelectric thin-film transducers in the mid-1960's went measurements by several research groups of acoustic attenuation versus frequency, by both pulse-echo and optical-diffraction techniques, on favored materials such as sapphire and rutile [21], and the growth of high-quality new single-crystal materials like yttrium aluminium garnet (YAG) and the ferroelectrics: lithium niobate, lithium tantalate (Li Ta O_3), and bismuth germanium oxide (Bi_{12} Ge O_{20}), to which Ballman of Bell Telephone Laboratories made most significant contributions [22].

Unfortunately, only very simple physical models proved possible for the behavior of acoustic attenuation versus frequency at room temperature, thus negating the possibility of synthesizing the lowest acoustic-loss material. Nevertheless, both theory and practice showed that acoustic loss generally increased approximately as the square of frequency [23]. This result, of course, had been known for quartz from the early experimenters, but its loss of about 1 dB/μs at 1 GHz was considered too high for microwave acoustic delay-line applications. The whole scene then became bounded by YAG, which was found to have the lowest acoustic attenuation for shear waves of around 10 dB/μs at 10 GHz (Fig. 4).

With the dual realization of reliable fabrication procedures for thin-film piezoelectric transducers, coupled with their acoustic and electrical matching networks, and crystalline materials with known acoustic attenuation, it rapidly became possible in the mid-1960's to build microwave bulk acoustic-wave delay lines. Table I shows some typical performance specifications issued in the 1966/1967 time-frame. The first four entries were low-power devices from the manufacturer (Teledyne MEC), the maximum allowable peak input power being a few watts due to voltage breakdown in the thin-film transducers. In these devices, the electromagnetic feedthrough was more than 30 dB below the desired signal, and the second-time-around signal was more than 10 dB down. The weight of these devices was about 3 oz, and they occupied volumes of less than 3 in^3. The last three entries in the table are drawn from an IEEE Spectrum review paper of 1967 [24] by Dick Damon of Sperry Rand Research Laboratories, and refer to higher power devices. Later results are contained in an article by Frank Olson published in the *Microwave Journal* of March 1970 [25].

Microwave bulk acoustic-wave delay lines first found practical application in systems around 1970 as a direct replacement for bulky conventional coaxial and waveguide delay lines [26] in altimeters, and in newer applications like simulating a target return for radar ranges between 500 ft and 60 000 ft; and as delayed local oscillator in a fixed-range spread spectrum radar for proximity fuses [25].

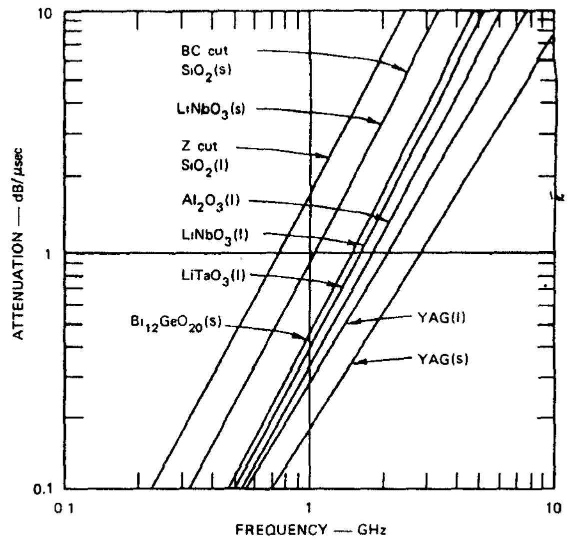

Fig. 4. Frequency dependence of acoustic attenuation at room temperature in delay-line materials for shear waves (s) and longitudinal waves (l). Graph is taken from report entitled "Principles and applications of praetersonics," by A. Bahr, I. Court, A. Karp, and L. Young, prepared by Stanford Research Institute in January 1969 for the Office of Naval Research, Washington, D.C.

TABLE I
PERFORMANCE SPECIFICATIONS OF TYPICAL MICROWAVE ACOUSTIC DELAY LINES

Frequency (GHz)	Bandwidth (GHz)	Delay (μsec)	Insertion Loss (dB)
Low Power			
1.3	0.2	2.0	25 ± 4
1.5	1.0	2.0	60 ± 4
2.5	1.0	2.3	50 ± 4
2.25	1.5	4.0	57 ± 4
High Power			
L-Band*	0.02	1.5 to 120 (max)	70 130
C-Band	0.4	2.8	100
X-Band	0.75	3.5	112

*Multiple-pass device, with gate selection of desired echo.

Another important application was in deception repeaters for electronic warfare systems. Here, the microwave acoustic delay line was used in conjunction with a traveling-wave tube or solid-state amplifier in an octave bandwidth feedback loop to affect stealing of the hostile radar's range gate [27].

III. Yttrium Iron Garnet Microwave Delay Lines

The 1956 discovery of ferromagnetism in the insulating material, yttrium-iron garnet (YIG), by Bertaut and Forrat in France, and its later growth in substantially sized crystals by using the molten flux technique pioneered by Nielsen at Bell Telephone Laboratories [28], led to polished spheres, biased to ferromagnetic resonance, finding widespread and dependable microwave component applications as electronically tunable bandpass filters from the early 1960's [29]. The 1962 experiments of Ed Spencer *et al.* (11), referred to in Section II-B, immediately created great interest in YIG as a microwave delay-line material.

These experiments led researchers in the 1964–1967 timeframe, such as Ernst Schlomann at Raytheon, Rick Morgenthaler at M.I.T., Walter Strauss at Bell Telephone Laboratories, Herman van de Vaart and Dick Damon at Sperry Rand, Frank Olson at Teledyne MEC, Bert Auld at Stanford University, and a research team at the University of Glasgow under Jeff Collins, to investigate YIG as a delay medium much more closely. All these researchers used one basic configuration, namely the axially biased YIG rod, of 3-mm diameter and 10-mm length, excited normally between 1 GHz and 4 GHz at one polished end face by a shorted fine-wire coupler. The results that were found were truly amazing and led to an entirely new dimension of thinking about delay lines as versatile signal-processing elements.

A fundamental point was that the YIG rod geometry, unlike the YIG spheres used in microwave filters, was nonellipsoidal, thus leading to a nonuniform internal dc magnetic field [30]. Experiments conducted at fixed frequency showed that three distinct modes of propagation could exist as the external magnetic field increased, namely two-port dispersive magnetostatic waves, one-port dispersive magnetoacoustic waves (often called magnetoelastic in the papers), and finally two-port nondispersive shear acoustic waves as originally discovered by Ed Spencer (11). The theory of magnetostatic mode propagation for uniformly magnetized YIG had been earlier worked out in 1961 by Dick Damon and John Eshbach [31]. The key confirmatory experiments here on YIG were performed by Olson and Yaeger [32], but available delays were limited to about 1 μs.

Undoubtedly, the most difficult problem proved to be the explanation for the one-port magnetoelastic delay-line performance. Here, the experiments were conducted by Walter Strauss [33], the explanation of energy conversion processes were found by Bingul Yazgan and Jeff Collins [34] to be electromagnetic wave–spin wave–acoustic wave–spin wave–electromagnetic wave as depicted in Fig. 5; and the detailed theory of spin-wave to acoustic-wave conversion was worked out by Ernst Schlomann [35]. Experimental results showed low conversion losses (3 to 7 dB) but relatively high propagation loss varying typically from 6 dB/μs at 1 GHz to 20 dB/μs at 9 GHz.

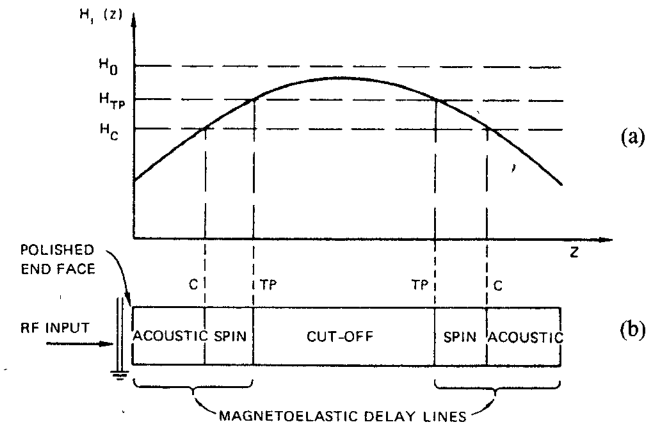

Fig. 5. Operating principles of a one-port magnetoelastic YIG delay line. (a) Plot of internal magnetic field H_i along the axis of when the applied field is H_o. (b) Schematic representation showing the regions in which different types of waves propagate. H_{TP} defines the position in the rod, called the turning point, at which the wave vectors for spin and shear waves are equal. Figure is taken from [38, fig. 1], published in 1968.

The obvious application for dispersive YIG delay lines at microwave frequencies was as matched filters in pulse-compression radar systems. Preliminary one-port *S*-band experiments using the magnetoelastic mode were reported in 1965 by Collins and Neilson [36] followed by one-port *X*-band experiments by Van de Vaart [37], typical dispersive delays being 1/μs at bandwidths of 100 MHz. Operational difficulties associated with the one-port configuration led rapidly to a whole series of possible two-port configurations for pulse-compression applications, which were documented by Collins and Zapp [38]. Unfortunately, practical applications fell on stony ground due to lack of reproducibility of the YIG crystals and difficulties in tailoring the dc magnetic field to give both linear-dispersion characteristics and low time sidelobes after pulse compression. Nevertheless, the versatility of microwave YIG delay lines was certainly not at an end. In a definitive paper of 1968 [39], Bert Auld and coworkers demonstrated that signal processing in a nonperiodically time-varying medium such as provided by biased YIG rods could yield the functions of frequency translation and coding: variable delay and recall, gating, time-scale stretching or shrinking, and time reversal.

Real applications of YIG as a delay-line medium had to await a technological development which could overcome the nonellipsoidal geometries inherent in all earlier experiments. This happened in 1969, when the enormous interest in the quite different field of magnetic bubble domains led to the reliable epitaxial growth of YIG in film thickness up to 20 μm on single-crystal gadolinium gallium garnet by Jack Mee and coworkers at Rockwell International [40].

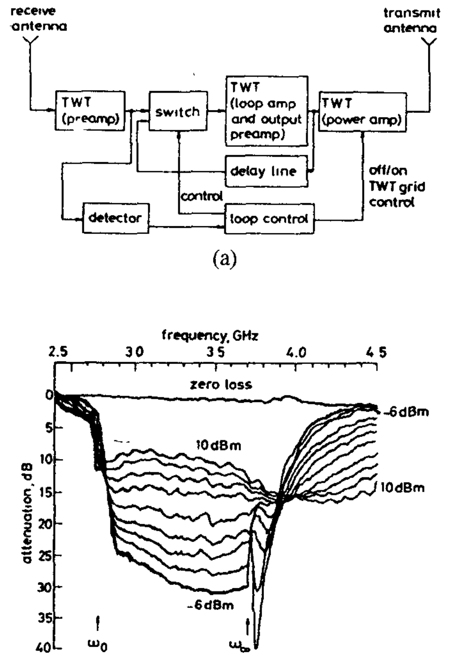

Fig. 6. (a) Block diagram of electronic warfare deception repeater employing a memory loop. (b) The YIG magnetostatic wave signal/noise enhancer is placed in series with the microwave acoustic delay line. Note that low-level (noise) signals suffer much greater attenuation than the high-level required signals. Full details of the YIG device are given in [43], published in 1980.

However, it was *not* microwave acoustics that came to the fore but rather microwave magnetostatic (MSW) delay lines in the 1–10-GHz range closely obeying the Damon and Eshbach theory [31]. Here, again, was versatility in the form of three distinct propagating waves: the magnetostatic surface wave when the dc bias field is in the plane of the YIG film normal to the direction of propagation, and two classes of magnetostatic volume waves when the dc bias field is along the direction of propagation—the so-called magnetostatic backward volume wave, and, perpendicular to the film, the so-called magnetostatic forward wave. Full experiments on these were reported by Bongianni in 1972 [41].

However, the major thrust in applying these YIG films for microwave applications did not arrive until the late 1970's and early 1980's when the nonrecursive transversal filter principles inherent in the surface acoustic-wave (SAW) devices described in Section IV were applied to magnetostatic waves, notably by John Owens and coworkers at the University of Texas at Arlington; and by J. P. Castera and P. Hartemann and coworkers at Thomson-CSF, Paris [42]. One notable exception to this was the use by Douglas Adam at Westinghouse of YIG magnetostatic waves to serve as a signal-to-noise enhancer [43] in a deception repeater for the electronic warfare application deploying a microwave acoustic delay line mentioned in Section II-D (Fig. 6). Finally, it is interesting to note that today microwave MSW devices constitute an important area of U.S. Government research activity [44].

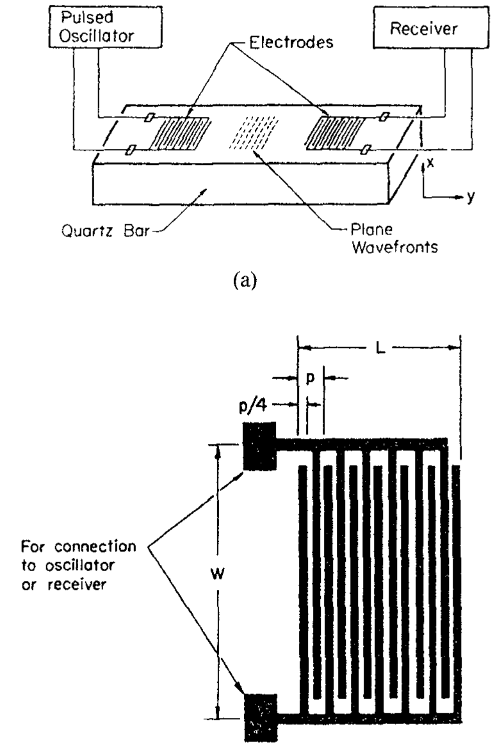

Fig. 7. The original demonstration of direct piezoelectric coupling to surface acoustic waves by White and Voltmer in 1965 [46]. (a) The arrangement for transduction by electrodes on a crystalline quartz bar. (b) The electrode pattern of the interdigital transducer used at 15 MHz and 45 MHz. Approximate dimensions in inches were: $p = 0.008$, $W = 0.095$, $L = 0.079$.

IV. Surface Acoustic Waves

A. Early Experiments

In the late 1960's, the coming to product maturity of microwave acoustic bulk wave delay lines, and the practical deemphasis of YIG delay lines due to their modest performance, led acoustic researchers to search for a new area with considerable potential in analog signal processing: the answer lay in surface acoustic-wave (SAW) devices.

It was Lord Rayleigh who in 1885 [45] first proved that waves of mechanical displacement could propagate nondispersively on the surface of a solid. As an example, earthquakes furnish sources for propagating these waves on the earth's surface. Remarkably, it was not until 1965 that a key experiment for directly exciting surface acoustic waves (SAW) was performed by Dick White and F. W. Voltmer at the University of California at Berkeley [46]. They demonstrated at 15 MHz and 45 MHz that SAW's propagated between a pair of spaced interdigital electrode transducers (IDT's) deposited on both crystalline quartz and cadmium sulphide (see Fig. 7). In an invited paper [47] delivered at the 1967 G-MTT International Microwave Symposium in Boston, Eric Ash of University College London reported the first results on the achievement of linear dispersion at a center frequency of a few megahertz in a layered Rayleigh-type structure and went on to predict

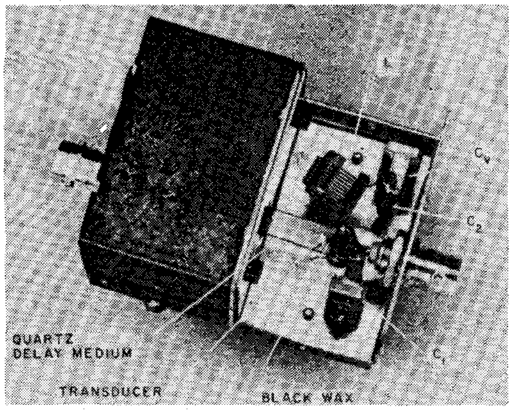

Fig. 8. The original Stanford University surface acoustic-wave quartz delay line due to Collins *et al.* in 1968 [48]. The spacing between transducers was 1.200 in. Black wax was used for the acoustic terminations at the end of the quartz bar. Note the electrical matching network to achieve matching to 50 Ω.

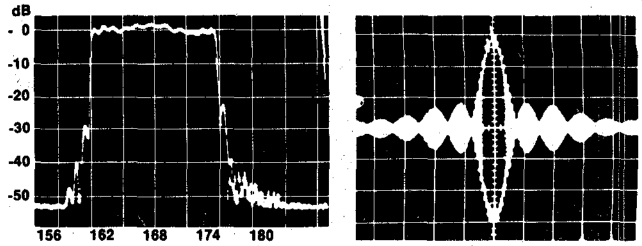

Fig. 9. High-selectivity SAW bandpass filter developed at Texas Instruments, circa 1972. The left-hand oscilloscope trace shows the frequency response 12-MHz (7 percent) bandwidth, 14-dB insertion loss. The right-hand oscilloscope trace is a sin x/x impulse response which indicates linear phase and rectangular bandpass.

that several forms of passive electronic components, like resonators and filters, would be realized. These results led John Shaw at the Microwave Laboratory of W. W. Hansen Laboratories at Stanford University later in 1967 to start a program with Hank Gerard, Ken Lakin, and Jeff Collins to investigate more fully SAW devices because of their inherent virtues of relying on photolith technology similar to but simpler than used in the fabrication of silicon integrated circuits. In September 1968, impressive results were reported on frequency filtering [48]. Twelve similar SAW delay lines had been built on crystalline quartz for 100-MHz operation using periodic electrode IDT's with an insertion loss of 10 dB, delay of 9.6 μs, 3-dB bandwidth of 3.5 MHz, 50-Ω input and output impedance with 90-dB isolation, and spurious signals greater than 20 dB down. This original device structure is shown in Fig. 8. It was noted at the time that 6 dB of the 10-dB insertion loss was directly attributable to the bidirectional nature of the two IDT's. To stimulate interest in SAW, the Stanford group then sent most of these twelve delay-line filters to U.S. companies and Government agencies, and the take-off for SAW device technology followed rapidly and raised the topic internationally to 'band-wagon' status. For this reason, this section of the paper is confined to the mainstream developments.

Meantime, at the theoretical level, there had been considerable activity in understanding the IDT excitation of SAW. Notable was the work of Ingebrigtsen in Norway [49], Coquin and Tiersten at Bell Telephone Laboratories [50], and most importantly that of Campbell and Jones [51] at Hughes Aircraft. In particular, Campbell and Jones carried out the computer calculations of the SAW velocity on a number of cuts and orientations of the strong piezoelectric coupling material, lithium niobate, with the surface free and then metallized. This small difference in velocity Δv, divided by the free velocity v, was shown experimentally by Hank Gerard [52] to be half the square of the electromechanical coupling constant allowing the bulkwave model of coupling developed in Warren Mason's books [6] to be used for calculating the behavior of IDT's. This work was published in the November 1969 Special Issue of MTT [1] by Dick Smith and co-workers, along with the significant result that the optimum fractional bandwidth achievable in Y—cut, Z—propagating lithium niobate for minimum conversion loss was 20 percent compared with the 3.5 percent of YX quartz used in the earlier experiments.

B. Some Key Device Experiments

It was soon recognized that the ability to arbitrarily tap a surface acoustic wave along its propagation path by electrical means and to sum the tap outputs formed, in fact, a Kallman nonrecursive transversal filter which allows independent control of the phase characteristic for different amplitude characteristics, and that, further, both frequency and time-domain filters could be realized. Unfortunately, however, the width of the metal IDT electrodes at 1 GHz would be typically only 1 μm, and thus the technology was primarily limited to frequencies less than 500 MHz.

A major commercial opportunity for SAW devices was described in 1970 by Adrian de Vries at Zenith, Chicago [4] using piezoelectric ceramics, and by Rick Mitchell at Philips Research Laboratories, U.K., using lithium niobate [53] for filters to provide the major part of the channel selectivity in color TV sets. This opportunity was later seized on by a number of other companies, notably Plessey in the U.K. (now manufactured by Signal Technology Ltd.), Siemens in Germany, and Japanese companies, with great success. Today, SAW filters are a standard fit in most color TV sets.

In parallel, Texas Instruments Central Research Laboratories, in the persons of Lou Claiborne and Clint Hartmann, made notable contributions to both the technology and a most useable theory (the so-called "impulse model") of SAW frequency filters [3]. An outstanding result of 1972 vintage is shown in Fig. 9. The frequency response is centered at 168 MHz and has a 12-MHz 3-dB bandwidth and 13.5-MHz 40-dB bandwidth. The skirt selectivity of this device exceeds 80 dB/MHz for the first 25 dB, and its midband insertion loss is 14 dB. Built on crystalline quartz for high-temperature stability, this filter measured only 12 mm by 5 mm by 1 mm. Another important development at Texas Instruments was the technical realization of a multi-

TABLE II
PULSE-COMPRESSION PERFORMANCE USING A SAW-MATCHED FILTER FOR A CENTER FREQUENCY OF 60 MHz, BANDWIDTH OF 25 MHz, AND TIME DURATION OF 5 μs: THE COMPRESSOR WEIGHTING FUNCTION IS 30dB TAYLOR

	Specification	Experimental Result	Theoretical Ideal
Max. sidelobe level	< -30 dB	-30 dB	-30 dB
Far out sidelobes	< -35 dB	-45 dB	-45 dB
-3 dB pulse width	< 60 ns	50 ns	45 ns
-30 dB pulse width	No spec.	150 ns	128 ns

phase unidirectional transducer to remove the 6-dB bidirectionality loss. Table II summarizes their SAW bandpass filters capabilities in 1973.

The military field also provided a major, but quite different, application for SAW devices, namely in matched filtering for radar pulse-compression systems and spread spectrum communication systems during the 1969–1973 timeframe. For radar pulses compression, major effort was devoted in the U.K. by Ted Paige and Dennis Maines at the Royal Signal and Radar Establishment (RSRE) using dispersive, graded periodicity, IDT's on crystalline quartz for time-bandwidth products of around 100 [54], by Tom Bristol and co-workers at Hughes Aircraft using lithium niobate as the host material [55], and by Dick Williamson and Ernest Stern at M.I.T. Lincoln Laboratories using ion-milled reflective array structures to produce the dispersion with, again, lithium niobate as the host material for time-bandwidth products around 1000 [56]. Notable also during this period was the work on both bandpass filters and pulse-compression filters by Roger Tancrell and Mel Holland at Raytheon [57]. What was truly remarkable was the agreement between theory and practice on pulse-compression performance. By way of illustration, just two results are chosen which are shown in Table II for an RSRE device of 125:1 pulse-compression ratio; and in Fig. 10 for an M.I.T. device of near 5000:1 pulse-compression ratio, with a sidelobe level of better than 40 dB [4]. These devices were rapidly deployed in applications like airborne radar. Fig. 11 shows a photograph of a complete pulse-compression subsystem using SAW filters which both generates the IF waveform and compresses it due to MESL, Edinburgh, in 1973.

The next important device was the practical development of the SAW oscillator in 1974 by Marion Lewis of RSRE, U.K. [58]. The oscillator consisted of a SAW delay line with an amplifier in the feedback loop to achieve net loop gain, a structure used by Dennis Maines *et al.* at RSRE as early as 1969 to measure delay-line phase variations with temperature [59]. Lewis showed the SAW oscillator to have a stability and modulation capability between those of *LC* oscillators and conventional quartz-crystal oscillators but a number of advantages over both for operation in the 20-MHz to 2-GHz range. The advantages included operating frequency determined accurately by the IDT pattern, ruggedization, convenient heat sinking, and

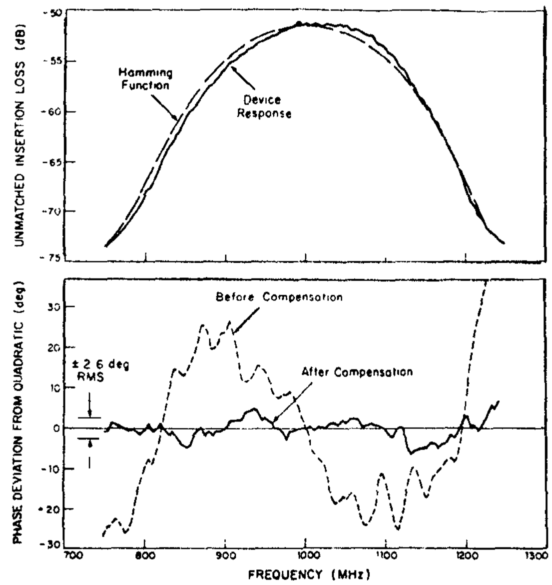

Fig. 10. Performance of 512-MHz bandwidth, 10-μs duration pulse-compression filter utilizing a SAW reflecting array device due to M.I.T. Lincoln Laboratories for the Alcor radar [4]. Note the Hamming weighting used to provide 40-dB sidelobes; and that the rms phase error is compensated to less than 1.2°.

FM capability which could be tailored to user needs. Fig. 12 is a photograph of an early 720-MHz RSRE oscillator which illustrates many of these points. The amplifier chip is housed in the lower TO 5 can, while the delay line is just discernable in the upper TO 5 can through the glass window. Frequency stability was, of course, a major concern in the performance of SAW oscillators. Marion Lewis's early device had an excellent short-term stability of approximately 10^{-9} measured over 1 s. The medium-term stability was <1 ppm over $\pm 4°$C, but the long-term stability was about 10 ppm/month, one or two orders of magnitude greater than conventional quartz-crystal oscillators. In recent years, much effort has been expended in improving both the medium- and long-term performance of SAW oscillators to the point where they seem destined to be a frequency reference source in global position satellite (GPS) receivers [60].

Advances in SAW oscillators and narrow-band SAW filters were made possible by the invention of the two-port SAW resonator first described [61] by Ed Staples and co-workers from Texas Instruments at the 1974 IEEE Ultrasonics Symposium. By using a long etched set of periodic grooves at both ends of an otherwise conventional SAW delay line, a Fabry–Perot-type of bandpass resonator filter was created. Typical Q parameters envisaged were 2000–5000 with device insertion loss less than 5 dB and 35-dB sidelobe suppression.

In parallel with the development of linear dispersion SAW filters for pulse compression there had been considerable activity in building SAW tapped lines as analog matched filters for the generation and correlation of pseudo-noise phase shift-keyed signals employed in spread-spectrum communications systems. The first experiments were performed in 1969 by Constanza *et al.* at

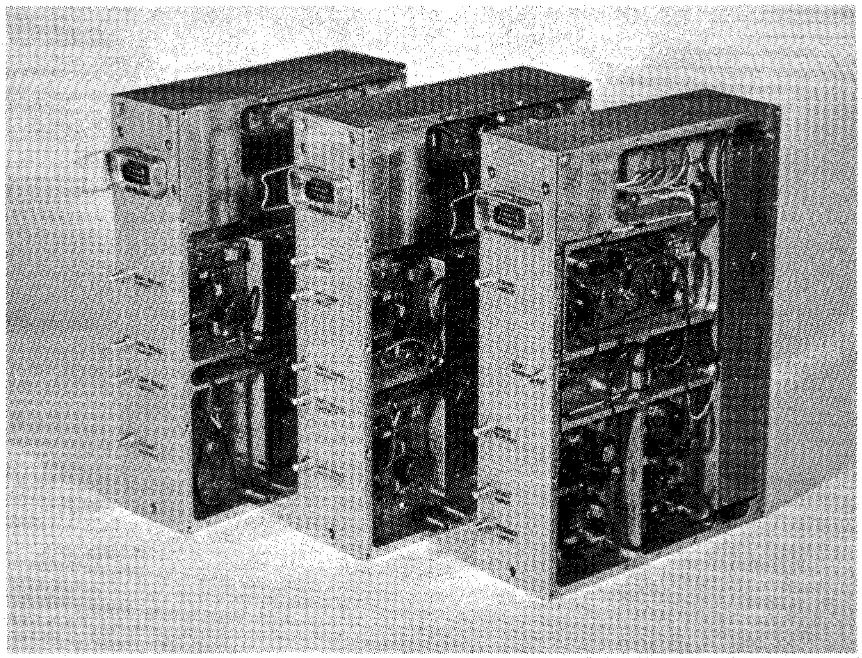

Fig. 11. Photograph of a complete pulse-compression subsystem utilizing SAW expansion and compression filters developed for airborne radar applications by MESL Edinburgh, circa 1973.

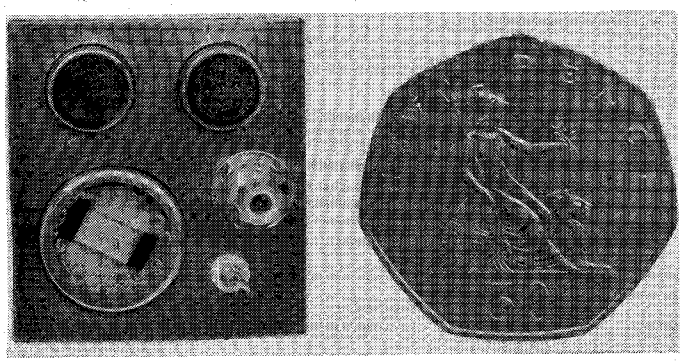

Fig. 12. Photograph of an early 720-MHz RSRE SAW oscillator due to Lewis in 1973 [58].

Rockwell International [1]. Although successful for sequence lengths up to 255 at 10-megachip rates, they had the inherent disadvantage of lack of programmability. This was overcome to some extent by the ability to switch the phase of the taps according to a set of stored codes. Notable in the early 1970's was the technological work of Barry Darby and Peter Grant at the University of Edinburgh [62]. A major breakthrough was obtained by Maury Luukkala and Gordon Kino at Stanford University when, in 1971, they observed the convolution of SAW in lithium niobate [63]. Here, two SAW beams launched in opposite directions interacted through an acoustic nonlinearity to generate a product term which was spatially stationary but at twice the frequency of the two SAW beams and, hence, tappable on the lithium niobate substrate using a capacitor structure. The important signal-processing concept was that this spatial integral of the product was mathematically the convolution of the two inputs. A signal waveform could then be correlated, like a matched filter, if the reference input (one of the SAW beams) was made proportional to the time-reverse of the required signal to be correlated (the second SAW beam). Unfortunately, the efficiency of the early devices was very low, typically 90-dB insertion loss for a 0-dBm reference level and correlation of a waveform with 20-MHz bandwidth and 10 μs duration. Some 40–60-dB better efficiencies were later obtained by Gordon Kino and co-workers using a semiconductor coupled to the SAW propagation surface [3] and by Tom Reeder in connecting a series of taps to diodes in which the nonlinear interaction takes place [64].

Finally, in this brief review of some key SAW-device developments, is the multistrip coupler (MSC) devized by Graham Marshall and Ted Paige at RSRE, U.K., in 1971 [65] which was fully described in the 1973 IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES Special Issue [3] and which was awarded the Microwave Prize in 1974. The MSC became the 'directional coupler' of SAW's and consisted of a simple array of parallel metallic strips on a piezoelectric substrate. However, many other applications for the MSC were described, including highly reflective mirrors, unidirectional transducers, triple-transit suppressors, and most importantly beam-width compressors which were effectively SAW impedance transformers. These beam-width compressors have recently found major application within SAW convolvers, which also include acoustic waveguides, akin to open structure electromagnetic waveguides, to improve their efficiencies substantially [65].

Any reader who wishes to find a more detailed exposition of the 1200 or so publications on surface acoustic-wave devices for the 1968–1973 timeframe is referred to the book by D. P. Morgan [66], and four excellent review articles by R. M. White [67], G. S. Kino and H. Matthews

[68], J. B. Maines and E. G. S. Paige [69], and M. G. Holland and L. T. Claiborne [70]. For details of surface velocities, the reader is referred to the excellent *Microwave Acoustic Handbooks* by Andy Slobodnik and co-workers [71].

C. Chirp Transform Modules

The availability of high-performance large (1000:1) time bandwidth (TB) product linear dispersion (chirp) SAW filters in the early 1970's led, as stated earlier, immediately to their application in pulse-compression radars. However, in the mid-1960's, several workers, typified by Harry Hewitt at Stanford University [72] and Peter Butson at GEC, U.K. [73], identified the potential use of chirp filters in combination with swept local oscillators as a tool for spectrum analysis. Quite fundamental to this application, and a much wider range of applications, was the chirp-Z transform, the definitive paper on which was published by Rabiner and co-workers from Bell Telephone Laboratories in 1969 [74]. It was the advent of passive SAW technology for analog signal processing that first allowed easy practical realization of the chirp transform to effect Fourier transforms in real-time.

The SAW chirp transform realization and specific applications were described in the 1973–1975 timeframe by several workers including Ted Paige at RSRE, U.K. [75], Jim Alsup at NOSC, San Diego [76], Bob Hayes at Texas Instruments [77], and Carlo Atzeni and co-workers at the University of Florence [78]; in fact, the chirp transform had become the second SAW "band-wagon!"

In essence, the SAW chirp transform algorithm begins with the multiplication of the input signal by a linear FM (chirp) waveform. Next, the product is filtered through a linear FM compression filter having the same chirp slope as the premultiply waveform. This simple process produces an output signal that corresponds in both amplitude and phase to the Fourier transform of the input signal. Significantly, no A/D or D/A conversion is used and no clocks are required, and the SAW components allowed a unique broad-band processing capability at extremely low power consumption. The range of applications of individual SAW chirp transform processors is shown in Table III, which is taken from the review paper on the subject by Mervyn Jack and co-workers published in 1980 [79]. Further sophistication can be introduced by interconnecting two processors such that the transform output from the first can be modified or edited under the control of an externally programmed function, prior to Fourier transformation in the second processor. When the second processor performs an inverse Fourier transform, simple gating can be used to produce a bandstop/bandpass filtering function. Alternatively, logarithmic amplification of the power spectrum at the output of the first processor with subsequent Fourier transformation gives the power cepstrum of the input waveform: the cepstrum has direct application in waveform detection and classification.

Limitations of space preclude doing justice to this highly important topic. Nevertheless, from the myriad of excellent published results, one will be chosen, due to Gerard and Otto of Hughes aircraft [80] in 1977, to illustrate the power and sophistication of SAW chirp transform modules. Here, the goal was to realize a single programmable correlator through the configuration shown in Fig. 13 which used only four SAW reflective array filters for pulse compression of a library of quasi-linear FM waveforms that range up to 60 MHz in bandwidth and up to 60 μs in duration.

TABLE III
APPLICATIONS OF SAW CHIRP TRANSFORM PROCESSORS

PROCESSING FUNCTION	TRANSFORM	APPLICATION	SYSTEM
Spectrum analysis	Temporal	Signal classification	Radar/ECM
Network analysis	Temporal	System and component analysis	Communication Links
Beamforming	Spatial	Surveillance	Sonar
Special signal generation	Temporal (inverse)	Frequency to time conversion	Spread spectrum signalling

(a) Individual.

INTERMEDIATE OPERATION	OVERALL SIGNAL PROCESSING FUNCTION	APPLICATION AREA
Switch on/off with external pulse	Programmable bandpass/ bandstop filter	Spectral weighting for interference suppression
Logarithm	Cepstrum	Signal classification
Multiply with conjugate Fourier transform of input	Programmable correlator	Correlation of unknown input

(b) Combined.

V. ACOUSTOOPTIC INTERACTIONS

A. Early Experiments

As stated in Section II, Bommel and Dransfield [8] used light to measure the properties of the acoustic beams they generated at microwave frequencies through reentrant cavity excitation of quartz rods. Indeed, the diffraction of light in this way was predicted theoretically by Brillouin in 1922 [81]. A review article published by Slater in 1958 [82] pointed out that the frequency of the scattered light is Doppler-shifted by an amount equal to the acoustic frequency, and the maximum scattering occurs when the light is incident upon the acoustic wavefront at the Bragg angle.

The advent in the early 1960's of the laser, giving coherent light, and experimental techniques for generating coherent acoustic waves at gigahertz frequencies rekindled interest in acoustooptics. In 1965, Cal Quate, Don Winslow, and Chris Wilkinson of Stanford University reported the first definitive experiments conducted under these conditions [2]. They used a helium neon laser (6328Å) for the light source. The acoustic waves were generated using a RF cavity with either piezoelectric disks bonded to the substrate or by cadmium-sulphide films evaporated on the substrate with the substrate acoustically terminated in a

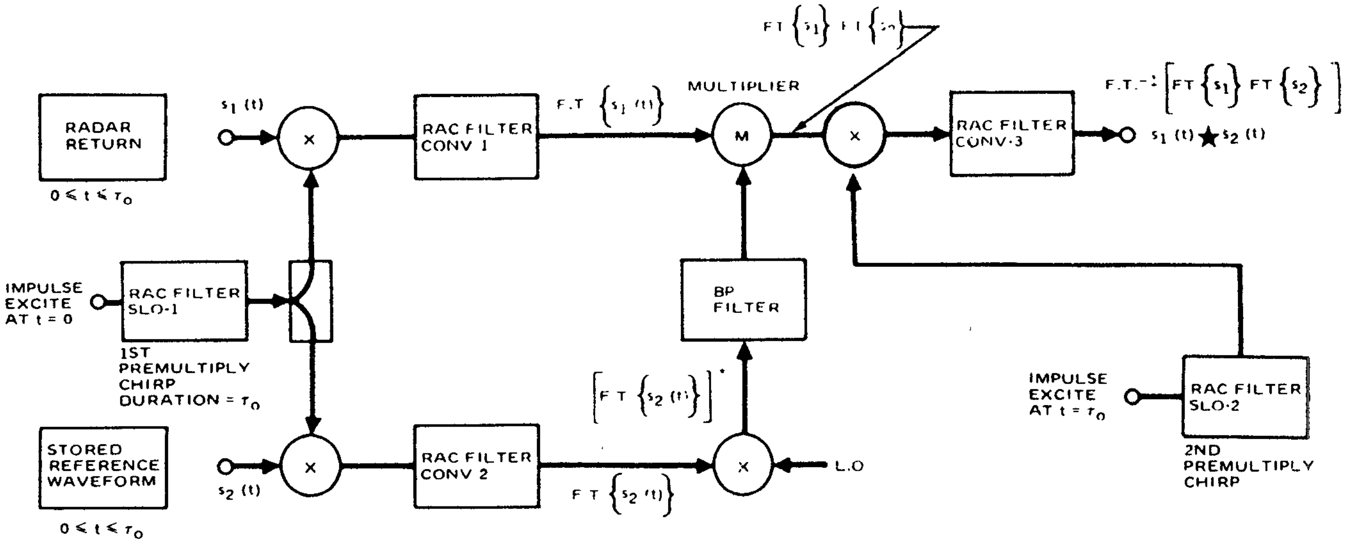

Fig. 13. Block diagram of the radar chirp transform correlator due to Gerard and Otto in 1977 [80]. Impulse excitation is applied to the SAW reflective array filter, SLO-1 (left). This is frequency doubled to yield the premultiply chip. A 30 segment of the first premultiply chip is gated for use as the second premultiply chip. Pulse compression follows.

pool of mercury. The diffracted light was detected using a phototube. The 700-MHz experimental configuration and the Fabry-Perot etalon used to measure the frequency shift of the diffracted light are shown in Fig. 14. Several significant results were found, namely that the Bragg angles were conveniently large (1–10°) and were proportional to the input acoustic frequency, some 10 percent of the light beam could be diffracted, the diffracted light intensity was linearly proportional to input signal power, and the Bragg cell frequency resolution was approximately equal to the reciprocal of the acoustic transit time through the crystal. Moreover, acoustooptical processing was a classic example of parametric interactions with traveling waves with the power transfer between the waves governed by the Manley-Rowe relations so familiar to microwave engineers of the day in low-noise parametric amplifiers.

Many experiments followed rapidly aimed at optimizing the light diffraction efficiencies in a wide range of crystalline materials having low-bulk acoustic-wave attenuation at microwave frequencies. However, the spur to all these was the goal of performing versatile signal-processing functions, and, again, pulse compression came to the fore. Using a divergent light source, McMahon [83] at Sperry Rand Research Laboratories and Schulz *et al.* [84] at Raytheon were able to detect a pulse-compression waveform by focusing it on a phototube. An alternative scheme by Eric Lean *et al.* [85] achieved the same result using a parallel optical beam and harnessing the anisotropic nature of the crystalline medium. These experiments demonstrated that time-bandwidth products of about 100 could be processed directly at microwave frequencies over bandwidths of typically 100 MHz, but the time sidelobe performance was poor. More sophisticated experiments were also attempted; see, for example, Squire and Alsup [1] on an acoustooptical transversal filter.

B. Spectrum Analyzers

The acoustooptic Bragg Cell was identified by workers at GTE, Sylvania, and ATI Santa Clara in the early 1970's as being essentially a spatially channelized filter or a spectrum analyzer with the powerful capability of being able to resolve simultaneous RF signals with close to 100-percent intercept probability. Further, lithium niobate was demonstrated to have a 500-MHz bandwidth and a frequency resolution of order 0.5 MHz for center frequency operation of 1 GHz, rendering it suitable for radar intercept applications; and tellerium dioxide to have a 20-MHz bandwidth and a frequency resolution of order 30 kHz, rendering it suitable for communications intercept applications [86]. However, it was only in the later 1970's and early 1980's that this technology came of age with the availability of 2000-diode photodetector arrays (effectively equal to the time-bandwidth) product on a single substrate with the necessary IC circuitry for nonreal-time read-out.

Recently, and quite complementary to the bulk acoustooptic spectrum analyzer, effort has been directed to the integrated acoustooptic spectrum analyzer (IOSA). Here, SAW transduction on lithium niobate has been used together with abutted semiconductor injection lasers, geodesic lenses for beam collimation, and abutted photodetector arrays with charge-coupled device (CCD) read-out. This research continues in several places, most notably at Hughes Aircraft and University College, London.

Finally, the work of Turpin is noteworthy in the area of the joint transform time-integrating correlator which essentially used the chirp transform described in Section IV-C. The key feature of this spectrum analyzer is that the frequency resolution is the reciprocal of the output integration time without any loss of bandwidth when compared with the conventional acoustooptic spectrum analyzer giv-

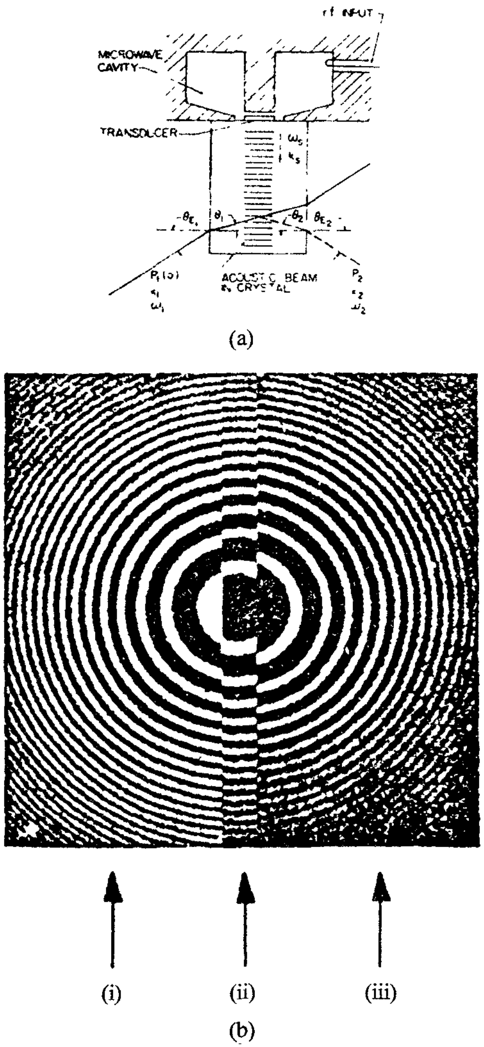

Fig. 14. (a) Illustration of experimental device used by Quate, Winslow, and Wilkinson [2] for measuring Bragg diffraction of light by microwave sound in 1965. (b) Fabry-Perot rings from a 5-cm etalon. (i) Rings from the undiffracted beam which serves as a reference. (ii) Rings from the diffracted light where the acoustic wavefronts are approaching the laser source. The increase in radius represents an increase in the optical frequency by 790 MHz. (iii) Rings from the diffracted light when the acoustic wavefronts are receding from the laser source.

ing time-bandwidth products, in principle, as high as 10^5 to 10^6.

VI. Conclusions

The history of the technology underpinning microwave acoustics is just 25 years old, but its significance in real-time analog signal processing in microwave radar, weapon guidance, and communication systems; color TV sets, and emerging areas like cable TV, has been quite dramatic in the past 10 years. Although the subject has received considerable military funding internationally in the large "vertically-integrated" companies, it has, interestingly, led to the emergence of brand new commercial enterprises such as RF Monolithics and SAWTEK in the U.S.A., and Signal Technology in the U.K. Microwave acoustics has achieved considerable maturity and great credibility in an age now dominated by silicon digital signal processing, and has led to the widespread use of new materials like lithium niobate in other areas like optoelectronics.

It is a subject of great refinement in terms of the detailed theory that has been built up and also in terms of the computer-aided design (CAD), computer-aided manufacturing (CAM), and integrated-circuit procedures that are now deployed akin to microelectronics. It has, thus, brought persons together from a wide range of scientific and engineering disciplines to interact profitably, a new example of this being acoustic microscopy. Further developments in microwave acoustics can be confidently expected, particularly in the related area of the use of the very familiar material to microwave engineers, yttrium iron garnet, for direct signal processing at microwave frequencies via magnetostatic waves.

It is humbly acknowledged with profound regret that this short history of microwave acoustics has done scant justice to the many major contributions to this subject made by friends and co-workers around the world. However, it would be quite incomplete without reference to the book of my mentor, B. A. Auld of Stanford University, CA, entitled *Acoustic Fields and Waves in Solids* (New York: Wiley, 1973).

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The Birth of Lightwave Technology and Its Implications to Microwaves

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EVER SINCE the invention of lasers [1] in the late 1950's, the use of coherent optical radiation for communication and signal processing with multigigahertz bandwidth has been a major research goal in electron devices, microwaves, quantum electronics, and optics. In order to realize that goal, the key issues that need to be addressed include a) how to transmit optical radiation with low propagation loss and signal distortion, b) how to effectively interface optical devices with electronic devices, c) how to modulate, multiplex, switch, and detect optical radiation at such high data rates, and d) how to solve the materials and fabrication technology problems. In the early 1960's, research on optical communications was concerned primarily with transmission of laser radiation through the atmosphere and the pipes. These methods had numerous disadvantages, including atmospheric turbulence and system complexity. The initial work on low-loss optical fibers reported by Kao of the Standard Telecommunication Laboratories in England in the late 1960's [2], followed by intense research efforts at the British Post Office, Bell Laboratories, Corning Glass Works, Nippon Electric Company, Nippon Sheet Glass Company, Siemens, and AEG-Telefunken, finally produced a breakthrough in the early 1970's when Kapron, Keck, and Maurer of the Corning Glass Works announced the achievement of losses under 20 dB/Km in optical fibers hundreds of meters long [3]. The birth of the low-loss fibers added a new impetus to optical communication and signal-processing research. The advent of low-loss and low-cost multimode optical fibers means that inexpensive optical communications through fibers may soon be used, much as we now use coaxial cables, applied to existing, as well as future, communications needs. No longer is it necessary to have a large number of customers on a single transmission path in order

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