# Microsound components, circuits, and applications*

Acoustic analogues of conventional microwave transmission line (microsound) components on the surface of crystalline substrates should find application in wideband, high-capacity signal and data processors.

These microsound transmission lines, hybrids, and couplers interconnect microsound transducers, amplifiers, isolators, and phase shifters to form microsound circuits capable of autocorrelation, Fourier transformation, and matrix permutation functions.

Compatible component configurations are proposed and evaluated which perform the basic functions of wave guidance, amplification, isolation, and transduction. The anticipated difficulties with their realization are discussed, and the status of critical problems, including the epitaxial growth of acoustic thin films and sub-micron etching procedures, will be given. Several circuits capable of autocorrelation, cross correlation, Fourier transformation, and matrix permutation are described.

## INTRODUCTION

During the past decade, an increasing amount of research and development has been directed toward the realization of wideband acoustic components partly because of the needs of modern signal and data processing systems and partly because of the unique properties of the sound waves themselves.

It is the purpose of this paper to restrict discussion of these devices and properties to those high-capacity signal processing and data processing components whose bandwidth exceeds 100MHz, and to those phenomena in which the signal energy is acoustic and not in some other form as optical, spinwave, or electrical disturbances. The latter restriction has been imposed because it is believed that it is possible to achieve simpler and more effective acoustic counterparts to the magneto-acoustic[1] and acousto-optic[2] devices.

Most of the effort until recently has been associated with realizing bulk acoustic wave components and, in particular, nondispersive[3] and dispersive[4] delay lines and bulk acoustic wave amplifiers.[5] The typical bulk wave device consists of a crystalline block to which opposing piezoelectric transducers are attached. The piezoelectric transducer emits a narrow beam of acoustic energy into the material. If the crystal is a piezoelectric semiconductor, then the presence of conduction electrons and an accelerating electric field may amplify[5] the acoustic wave.

Bulk devices have several features in common. They have input and output transducers which convert the electrical signal to acoustic energy. The acoustic energy is beamed through the medium from the input to the output transducer. In all bulk devices it is almost impossible to tap, switch, vary the delay, vary the amplitude, or otherwise manipulate the acoustic energy during transit. Consequently, applications have been restricted in the main to passive dispersive and nondispersive delay lines, and to where the manipulation is done with electronic circuits.

It is also possible to propagate sound on the surface of crystals; such a disturbance is called a Rayleigh[6] wave. The physical difference between a bulk and a surface wave is small; the technological difference is very large indeed, because the acoustic signal is accessible for manipulation throughout its path. The subject matter of this paper is the exploitation of this difference. The wave-like character of the surface disturbance permits the utilization of waveguides and a host of associated components and techniques heretofore restricted to microwave circuits. Such waveguides can transmit the acoustic signal to the components which transduce, amplify, delay, and isolate the signal.

It is proposed that these sound wave analogues of microwave components and circuits be called microsound components and circuits.

The discussion that follows contains a description of the four basic microsound components as they exist today, followed by a description of how the transducer, isolator, amplifier, and waveguide may look within a year or two as a result of the efforts presently under way.

## SURFACE WAVE COMPONENTS

Rayleigh waves, in contrast to bulk waves, are localized to the surface of solids. The typical particle motion is retrograde elliptical, and the amplitude decays exponentially into the body of the medium. The phase velocity of the Rayleigh wave is about 95% of the bulk shear wave velocity in most media. Particle displacements are miniscule; a typical displacement is a fraction of an Ångstrom. At UHF frequencies the wavelengths are comparable to optical wavelengths (several microns at 1GHz).

These surface acoustic waves were first described by Lord Rayleigh. At low frequencies, such waves can be generated with a wedge transducer in which the shear wave in the wedge is mostly reflected at the interface and absorbed, and a small portion of the energy is refracted as a surface wave on the substrate. The comb transducer[7] (Fig 1), an improvement over the wedge, has teeth one Rayleigh wavelength apart. The incident longitudinal waves couple to a standing surface wave on the substrate, which radiates into the bulk and in opposite directions on the surface. The conversion

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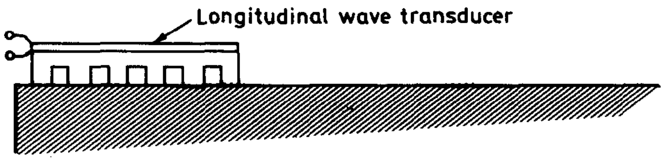


**Fig 1 Rayleigh wave comb transducer**

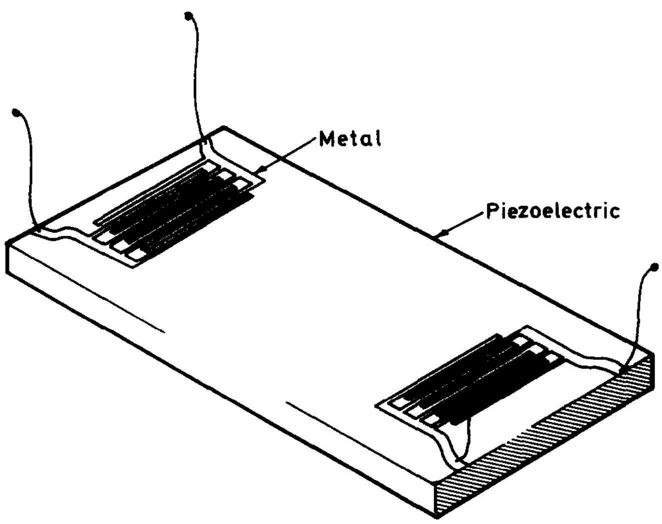


**Fig 2 Interdigital transducers on a piezoelectric block**

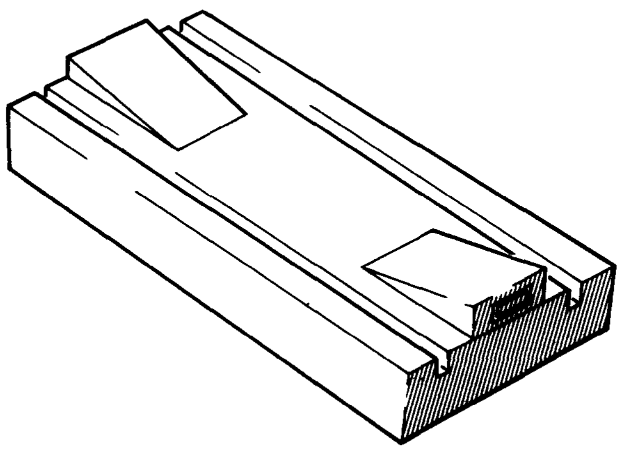

**Fig 3 Slot transmission line**

loss is quite large, and at frequencies in the GHz range the wavelengths are on the order of 3μm, or 1.2 × $10^{-4}$in. Teeth of that size would be difficult to fabricate and, because of their size, would be very fragile.

The interdigital transducer[8] shown in Fig 2 was developed for use on piezoelectric substrates. The signal leads are connected to the terminals of the transducer, and the adjacent fingers are located one-half acoustic wavelength apart. The alternating signal voltage interacts with the piezoelectric substrate and produces an acoustic standing wave. If the transducer consists of n evenly spaced finger pairs, the transducer is n wavelengths long. A null in radiation is obtained at frequencies where the transducer is n + ½ wavelengths long. Consequently, the fractional bandwidth is equal to 1/n. This transducer has found wide application in laboratories because it is simple to fabricate and efficient. For example, [9] bandwidths in excess of 30% and conversion losses of less than 4dB, of which 3dB is caused by the bi-directivity of the device, have been realized with five finger-pairs at 100MHz. Also 1GHz operation[10] has been achieved, but with reduced efficiency.

1MHz surface acoustic waves have been guided by a pair of grooves[11] as shown in Fig 3. The two wedge transducers were placed far apart on a metal substrate. A 1MHz signal was transmitted from one to the other and the insertion loss noted. Then the two grooves were inscribed and the loss dropped 10dB. The reduction of loss was attributed to wave guidance. Another form of waveguide, an acoustic analogue of the dielectric microwave guide, is shown in Fig 4a. It consists of a dense material,[12] which is acoustically slow, deposited onto a faster acoustic substrate. The acoustic energy is bound to the vicinity of the overlay, and it follows the guide around gradual bends. Another version of this transmission line [13] is a slot cut into a fast overlay on a slower substrate (Fig 4b). In these structures, nearby transmission lines are loosely coupled to each other, making feasible such devices as directional couplers.[12,14]

The bulk acoustic wave amplification mechanisms[15] found in a piezoelectric semiconductor have been adapted to surface acoustic waves[16] (Fig 5). Here a surface acoustic wave is generated on a surface of the high resistivity cadmium sulphide crystal, a piezoelectric semiconductor. Electrodes are deposited athwart the acoustic beam, and optically pumped conduction electrons are accelerated with the applied electric field. Amplification is obtained when the electron drift velocity exceeds the velocity of the surface acoustic wave. This amplifier has limitations that are similar to those of the bulk wave amplifier in that the substrate must

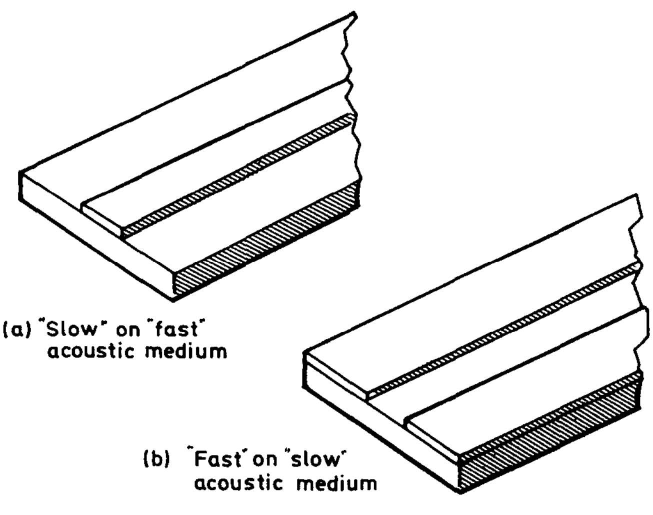


**Fig 4 Overlay transmission lines**

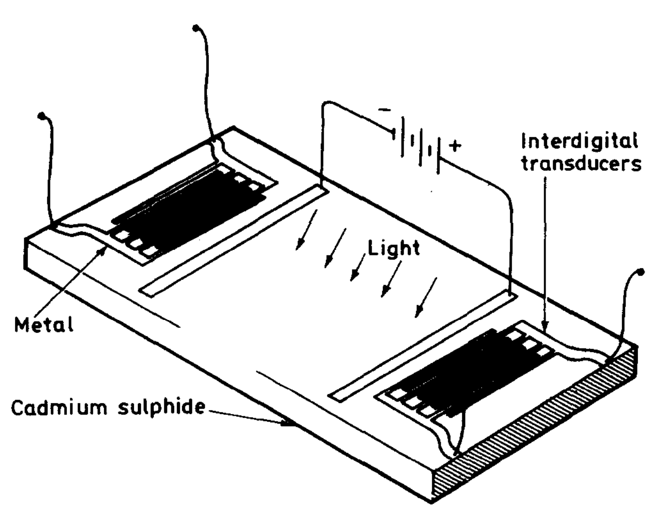


**Fig 5 Surface wave amplifier on a block of CdS**

incorporate the three qualities of acoustic conduction, piezoelectric transduction, and semiconduction. For example, CdS is a particularly good piezoelectric material, and it is a very poor acoustic and semiconducting medium at UHF.

## MICROSOUND COMPONENTS

Suppose that, for the moment, we hold in abeyance our critical faculties and consider what microsound components might look like if we ignore the limitations of present-day technology.

The losses found in acoustic media generally increase with frequency. For example, metals are lossy above a few MHz, ceramics above a few tens of MHz, and only certain non-conducting single crystals exhibit low losses in the frequency range from 500-5000MHz. Suppose that it is possible to obtain epitaxial overlays of one low-loss acoustic medium onto another. At 1GHz a typical wavelength is about 3μm. Consequently, the principal cross-sectional dimensions of a waveguide are of that order, and if the waveguide is to perform well, these dimensions should be held to a tolerance of a small fraction of 1μm. Since the diffraction limit of light is of that order, conventional photo-resist methods cannot be used, and a new technique must be employed. These techniques are described under the section headed Problems.

### *Transmission Line Components*

A microsound analogue of a microwave transmission line and filter network, shown schematically in Fig 6, contains sections of transmission line that act as coupled cavity resonators in the filter network. The surface acoustic wave energy is bound to the vicinity of the overlaid waveguide. The transmission-line discontinuities, which establish the limits of the resonators, are designed to reflect energy only in the fundamental transmission-line mode, and do not scatter energy into body waves or higher-order waveguide modes.

Suppose that most of the energy is contained within an acoustic wavelength on either side of the overlay region, and the velocity of sound in the guide is $v_g$. If the transmission line is curved at a radius, r, then the acoustic energy a wavelength away and on the outside of the curve propagates at a velocity $v_m(1 + \lambda/r)$. If this peripheral velocity exceeds the surface wave velocity of the substrate, $v_s$, then the peripheral energy continues to propagate in the initial direction and is lost to the transmission line. Consequently, the radius of curvature must be larger than $\lambda/(v_s/v_m - 1)$. It is desirable to have a small radius of curvature for many applications and, in those instances, the ratio $v_s/v_m$ should be as large as possible. For example, an epitaxial layer of zinc oxide, a particularly slow medium, on a substrate of beryllium oxide, a particularly fast medium, would meet these requirements very well.

The directional coupler in Fig 7 couples a small portion of the energy travelling from 1 to 2 into terminal arm 3. If the energy flow is reversed (from 2 to 1), the coupled sample appears at 4. A low-frequency version of the coupler[12] has been demonstrated at 10MHz with gold overlay on fused quartz.

Energy into terminal 2 of the hybrid coupler is divided equally between 5 and 6, and the signal in 6 lags by 90° the energy in 5. The device is reciprocal; two signals of equal amplitude and 90° out of phase emerge at 2. If the phase relationship between 5 and 6 is reversed, the signal emerges at 7. These characteristics can be used to fashion a switch if a means is employed to reverse the phase of the signals into ports 5 and 6. Some of the features of the hybrid coupler have been demonstrated[14] with a grooved guide at 1MHz.

### *Isolator, switch, and gyrator*

The nonreciprocal interaction of circularly polarized body shear waves with spin waves[17,18] may be adaptable to surface acoustic waves. If the surface disturbances are

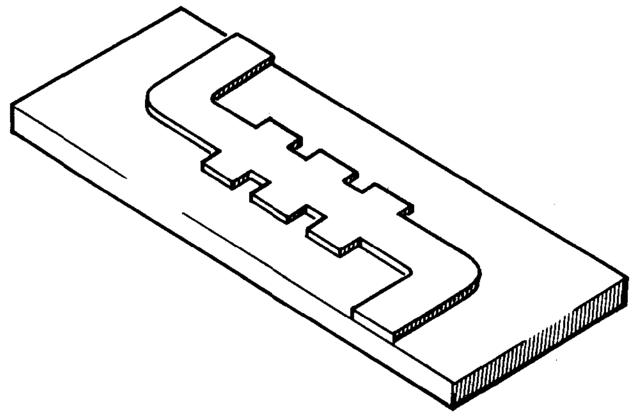

**Fig 6 Microsound transmission line, bends and filter. The dimensions of the lines at 1GHz are about 2μm wide, 1μm high, with an edge definition of ±0.05μm**

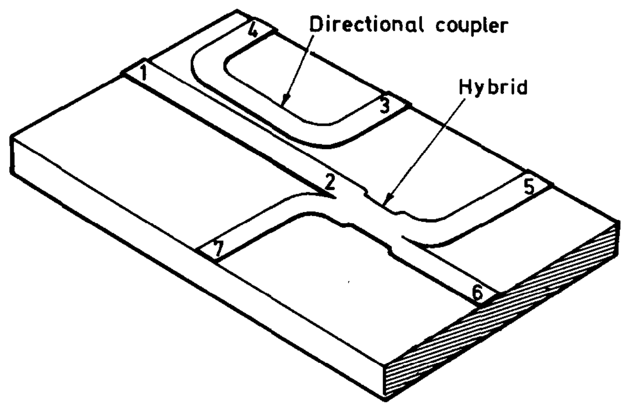


**Fig 7 Directional and hybrid couplers**

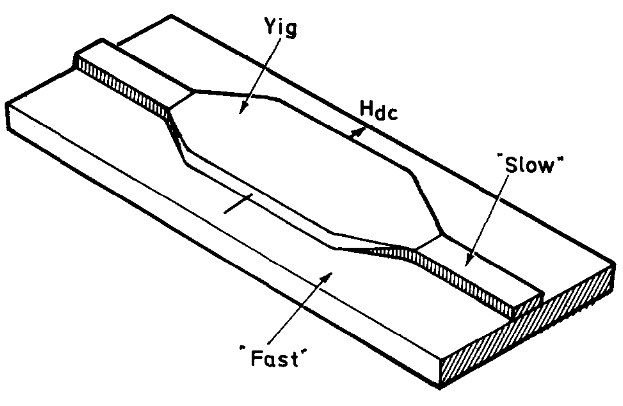


**Fig 8 Magneto-acoustic isolator or phase shifter**

viewed in a direction lying in the plane of the surface and perpendicular to the propagation, then the particle motion is elliptical retrograde. This is a fairly close approximation to the particle motion of a circularly polarized shear wave.

A transmission line made of a magneto-acoustic material such as yttrium iron garnet and magnetized to the magneto-acoustic crossover point by a field lying in the plane of the surface and normal to the propagating direction (Fig 8) should exhibit greater insertion loss to a wave propagating to the left than to a wave propagating to the right. This effect can be used to minimize the effects of multiple reflection in the transmission line. It should also be feasible to make nonreciprocal phase shifters with the same structure. Here, the phase shift of signals traveling from left to right differs from the phase shift of signals traveling from right to left. If this difference is 90°, a switch circuit becomes feasible (Fig 9); the energy into 1 emerges at 3, and if the field directions are reversed, energy in 1 emerges at 4. Energy into 2 emerges at the complementary ports.

Reciprocal phasers may be feasible with piezoelectric transmission lines, since the phase velocity of sound in piezoelectrics is related to the sense and to the direction of the electric stress. Such phasers are similarly suited to the construction of switches

*Amplifiers*

A wave propagating on the surface of a piezoelectric medium may have dipolar electric fields[19] that extend out of the surface for a distance of about one wavelength. The electric fields could, in principle, penetrate into a semiconducting layer and interact with the conduction electrons.[20] The amplifier mechanism has been analyzed,[21] and a working model with 20dB electronic, 6dB net gain has been obtained at 100MHz.[22] A microsound version of this amplifier is shown in Fig 10. The acoustic energy in the waveguide is radiated into the piezoelectric pad, where the electric field associated with the wave penetrates into the overlayer of semiconductor. Carriers in the semiconductor interact with the applied dc and microsound electric fields. The conduction carriers drift in the direction of the electric field, which is parallel to the sound wave propagation direction. If the drift velocity of the carriers exceeds that of the sound wave, electronic gain is obtained.

In a bulk wave amplifier, it is necessary to use a piezoelectric semiconductor such as cadmium sulphide. These materials have relatively low mobilities and high acoustic losses at frequencies above 1GHz. Consequently, it is necessary to apply very large voltages to overcome the low mobility and, since a considerable amount of acoustic energy is absorbed, the net gain of the amplifier is also reduced. Because of the relatively low mobility and requisite high electron density, a considerable amount of dc dissipation occurs in the crystal, and suitable amplifiers have worked only in a pulsed mode at UHF frequencies because of extreme heating of the crystals. In the composite amplifier, it is possible to select a low-loss, crystalline piezoelectric substrate with a high piezoelectric coupling constant such as lithium niobate and a semiconductor overlay with high mobility. In this way, it is possible to optimize the piezoelectric and the semiconducting components of the amplifier independently. A considerable improvement in amplifier performance should be obtainable by this strategy. Obtaining semiconducting surfaces of high mobility presents a special problem and may require extensive investigation of surface and interface properties of semiconductors.

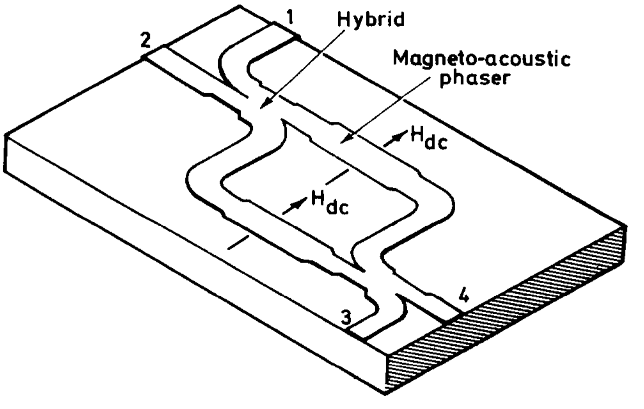


**Fig 9 Microsound double-pole double-throw switch**

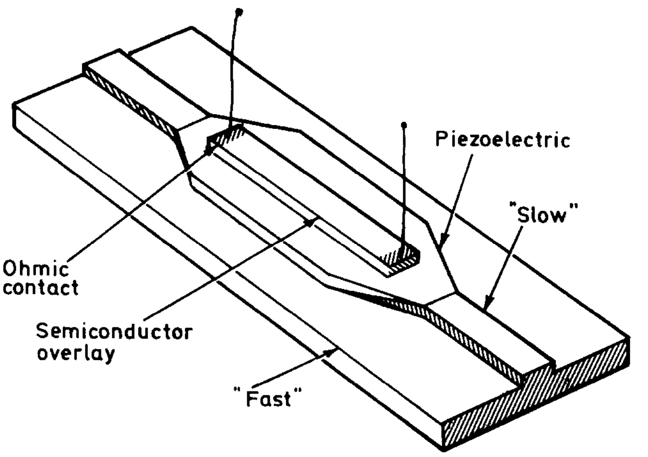


**Fig 10 Microsound amplifier**

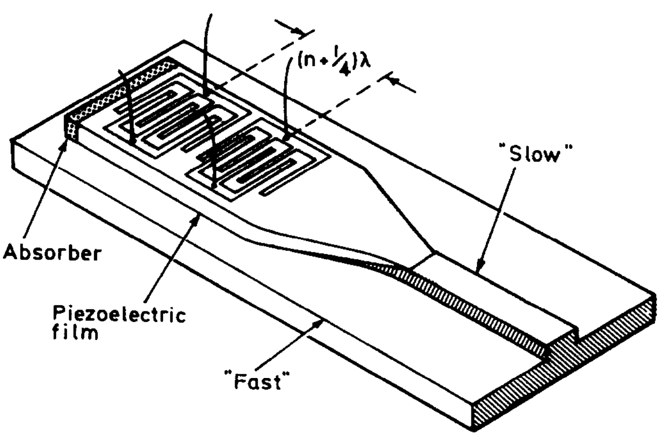


**Fig 11 Microsound directional transducer**

*Transducer*

The transducer in Fig 11 consists of a piezoelectric overlay and a metallized interdigital structure. A suitable matching structure is inserted between the piezoelectric pad and the waveguide. This transducer[23] is directional—the two sections are driven in phase quadrature and are located one-quarter wavelength apart. Constructive interference in the desired direction and destructive interference in the opposite direction are obtained by this configuration.

APPLICATIONS

The microsound components can be interconnected to form specialized circuits for signal and data processing applications. One example is the parallel delay line[24] (Fig 12) for digital computer applications. The circuit satisfies the need for precisely matched parallel delay lines which are compatible with digital computer circuits in which the bits in a word travel on parallel paths, and the bits in each time frame constitute a word. Also, it is desirable to provide fast access time to the stored information in these high-capacity delay lines. The access time could be reduced at will by using microsound couplers (not shown) along the microsound delay line.

Matched digital delay lines require delay times which are equal within one time frame. It has not been feasible to construct bulk delay lines with this precision and, as a result, parallel delay lines are not ordinarily employed for memory applications. With microsound circuits, precise matching is feasible because the lines are accessible for trimming operations. In the figure, the resonant ring oscillator generates UHF acoustic energy which is distributed to the delay lines via the directional couplers. The electrical control signal opens the switch modulators, and pulses of acoustic signals propagate along the line. The acoustic signals are transduced and detected at the tap points. The detected electrical signals are processed by the microelectronic circuitry. The microelectronic circuits are compatible with the microsound circuit structures. If it is desirable, both circuits could be deposited on the same substrate.

Another example of how the microsound components can be interconnected is a tapped delay line in which the electrical signal is converted to microsound with a suitable transducer and the acoustic signal is passed through a transversal equalizer which compensates for the residual dispersion of the transmission-line components. Reflections and resonances are suppressed by the microsound isolators. The main signal energy in the transmission line is delayed, amplified, and converted to an electrical signal which, in turn, could connect to another tapped delay line. Samples of the signal may be obtained with directional couplers that couple a small portion of the main line signal to a tap which, in turn, might consist of a filter network, an amplifier, and a transducer.

The amount of delay obtained by these means is limited principally by the size of the substrate, by the permissible radius of curvature in the transmission line, and by the limitations of the available etching technology.

The transversal equalizer (Fig 13), a simple ladder structure, is used to compensate for the dispersion and the errors in the transmission lines. The equalizer is used to correct for one effect of delay line error, which is to transfer energy into the time sidelobes of short impulses. The distorted impulse is fed into the line on the left and is suitably delayed along the upper path way. A portion of the pulse is coupled into the ladder structure below. Each one of the rungs provides a suitable amplitude and phase adjustment to the signal which coincides with a particular time sidelobe at the output end of the equalizer. The corrective signals destructively interfere with the unwanted time sidelobes of the impulse.

Another application of microsound is the Fourier transformer of Fig 14. It is a Blass[25] array, which is capable of forming over a relatively wide bandwidth the Fourier transform of a signal. The array consists of equally spaced, concentric transmission lines and an overlay of radial transmission lines with a directional coupler at each crossover. The inputs are connected to the concentric lines, and the outputs emerge at the ends of the radial lines. If the radial line is at an angle of 1 rad, then the distance from the output to every input terminal is the same, and the coupled signals will arrive at all inputs at exactly the same instant of time. The converse is also true; if a signal is injected into all inputs at the same instant (or the same phase), then most of the energy will appear at output 1. Suppose energy is put into output $\theta_1$. The path-length difference to adjacent inputs is equal to $\Delta R(\theta_1 - 1)$, where $\Delta R$ is the difference in radius between adjacent concentric lines, and $\theta_1$ is the angle of the radial line. The reciprocal condition also applies; if the inputs are sequentially delayed by an amount produced by a line length $\Delta R(\theta - 1)$, then most of the energy will emerge at the $\theta_1$ output.

Suppose the input signals are obtained from the taps of an equally spaced delay line with a delay of $\tau$ seconds between taps. If the delayed sinusoidal signal frequency $\omega_0 = 2\pi n/\tau \, \mathrm{rad.\,s^{-1}}$ (n is an integer), then all the tapped signals are in phase and the signal emerges from output 1. If $\omega = \omega_0 + \Delta\omega_1$, where $\Delta\omega_1 = k_a \Delta R(\theta_1 - 1)/\tau$, and $k_a$ is the propagation constant of the transmission line in the Blass array, then most of the signal emerges at output $\theta_1$. Similarly, other frequency components of the signal will coalesce at output terminal $\theta_i$, as defined by the equation $\theta_i = 1 + \Delta\omega_i \tau / k_a \Delta R$. The outputs constitute the Fourier components of the signal. The converse is also true; the signal will emerge from the delay line if the Fourier components are injected into the outputs.

The tapped delay line as described above and the Blass array in Fig 14 could be combined to produce a microsound correlator. If the phase shifts are set to zero and the gain of all

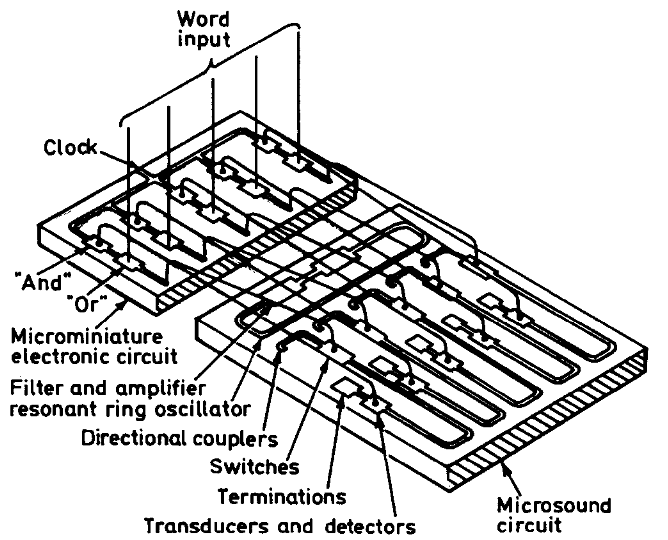


Fig 12 Microsound parallel digital delay lines

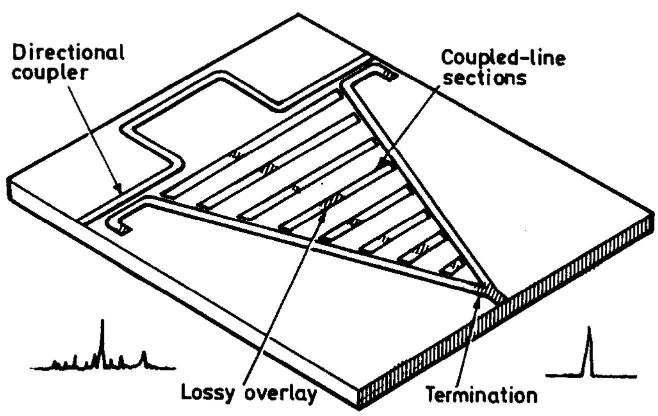


Fig 13 Microsound transversal equalizer

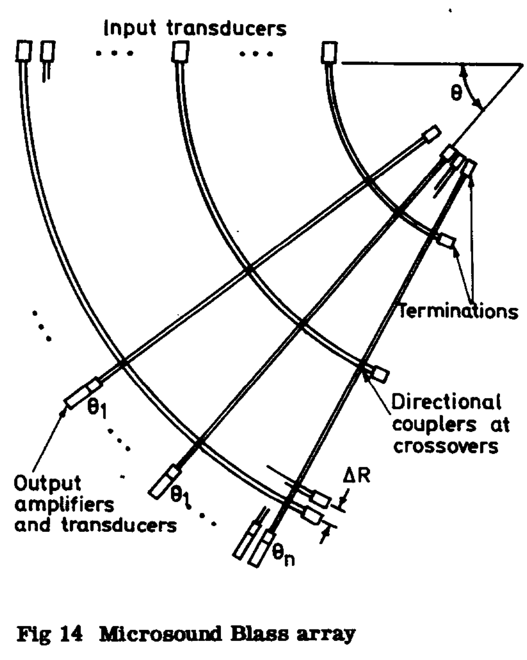


Fig 14 Microsound Blass array

the amplifiers is set to the same value, the circuit behaves as a Fourier transformer or autocorrelator. If a second circuit is used to form the Fourier transform of $f_2(t)$, and if the phase and amplitude of the output phasers and amplifiers are set to the conjugate of the Fourier transform $F_2^*(\omega)$, then the outputs are the product $F_1(\omega) \times F_2^*(\omega)$. The inverse transform produces the cross correlation function of two independent signals.

If a phase slope is inserted into the input phasers, a signal of a particular frequency can be made to emerge at any output. It is possible to form a multi-throw switch by these means, or to tune a spectrum analyzer to a different portion of the spectrum.

Signal-switching matrices are also feasible through the utilization of phasers and couplers. Such circuits could perform matrix permutation, variable signal delay and the like. For example, the circuit shown in Fig 15 performs the function of variable delay. The input signal is routed either through the shorter lower pathway or through the longer upper pathway. By selecting the routing, it is possible to establish a differential delay path ranging from 0-63$\Delta$L in incremental steps of $\Delta$L.

These circuits are examples of what may be done with microsound components. Many other applications are possible which require the small size, high storage capacity, ready access, and flexibility of microsound circuits.

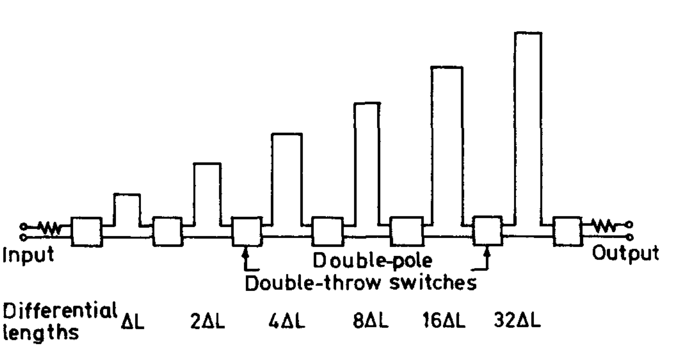


**Fig 15 Schematic diagram of a digital microsound variable time delay circuit**

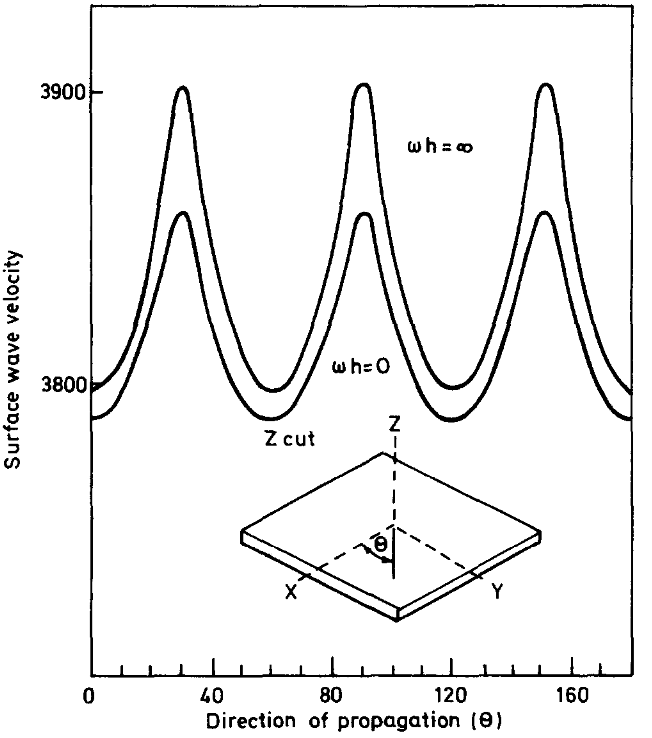


**Fig 16 Surface wave velocity vs propagation direction on z-cut lithium niobate (courtesy of W. R. Jones)**

## PROBLEMS

The realization of microsound components in the frequency range from 500-5000MHz is limited by a number of considerations which include problems with design, manufacture, and measurement.

High-frequency components should be built with epitaxial films of piezoelectric, semiconducting, and magnetoacoustic materials on low-loss crystalline substrates. A particular example of such a film is the YIG film on YAG substrates.[26] This example is particularly noteworthy because it represents an achievement that goes beyond the complexities of depositing simpler materials as $Z_nO$, $B_eO$, and $G_e$ on suitable substrates. This technology should be employable to make new combinations of materials such as zinc oxide films on $B_eO$ or $S_i$ on $Z_nO$.

Detailed analysis of surface waves on various crystalline materials and combinations of materials is desired. An example of the kind of analysis that is needed is the phase velocity graphs[27] as a function of direction on lithium niobate (Fig 16). Without precise knowledge of the propagation constants of the materials (and the dominant mode in the waveguide), such elaborate waveguide circuits as the Blass array of Fig 14 would not be feasible.

Photo-etching methods are limited by light diffraction to an accuracy of about 0. 5$\mu$m. This restricts the operating frequency of microsound components to less than several hundred MHz. New techniques are required which yield precision at least one order of magnitude greater than obtainable with photo-etching methods if components in the GHz frequency range are to be achieved. Electron beam etching methods should provide this precision. One notable achievement in this area is the grid of wires 0. 25$\mu$m wide and on 0. 25$\mu$m centres produced with the aid of a scanning electron beam microscope by A. N. Broers.[28]

## CONCLUSIONS

A great deal of technology is available in the microwave acoustics, solid-state, integrated circuit, and microwave engineering disciplines which bear on the problems just enumerated. For example, the microwave acoustic technology provides a great deal of information on the deposition of piezoelectric films and low-loss substrates. The solid-state discipline has perfected the epitaxial deposition of semiconducting materials by the vapour transport, vacuum, and sputter deposition techniques. The analytic techniques of microwave engineering associated with electromagnetic waveguides and transmission lines and with couplers, matching networks, terminations, transitions, radiators, and the like could be applied to the design of their acoustic analogues.

In conclusion, the utilization of acoustic analogues of microwave circuits and concepts can provide components and circuits with substantially greater signal and data processing capacity than is now available. These components and circuits utilize well-known and well-understood physical properties of materials and interactions in these materials. A good deal of the necessary technology for the realization of these circuits and components is currently available in somewhat different form in allied disciplines. A relatively modest effort is required to bend this technology toward the realization of microsound components and circuitry.

These components have considerable advantages over bulk wave devices because they can be used to perform signal processing functions that are virtually impossible with bulk waves. Although electromagnetic microwave circuits can perform the same functions as microsound circuits, their great size (1km$^2$ is equivalent to 1cm$^2$ of microsound circuitry), high losses, and high cost make the microsound approach more attractive.

## REFERENCES


1 Van der Vaart, H., and Damon, R., 1967 G—MTT Symposium Proceedings, Boston, (1967) p 206

2 Shultz, M. B., Holland, M. G., and Davis, L., Jr., Applied Physics Letters, Vol 11, (1967) p 237

3 Rodrique, G. P., Proceedings of the IEEE, Vol 53, (1965) p 1428

4 Coquin, G. A., and Tsu, R., Proceedings of the IEEE, Vol 53 (1965) p 581

5 McFee, J. H., 'Physical Acoustics', Vol 4, Part A, (Ed W. Mason) Academic Press, New York (1966)

6 Lord Rayleigh, Proceedings of the London Mathematical Society, Vol 17, (1885) p 4

7 Viktorov, I. A., 'Rayleigh and Lamb Waves: Physical Theory and Applications', Plenum Press, New York (1967)

8 Coquin, G. A., and Tiersten, H. F., Sonics and Ultrasonics Symposium, Cleveland, USA, Paper N-6 (1966)

9 Auld, B. A., Collins, J. H., and Shaw, H. J. Sonics and Ultrasonics Symposium, New York, Paper A-2 (1968)

10 Armstrong, D. B., Sonics and Ultrasonics Symposium, New York, paper A-3 (1968)

11 Ash, E. A., G-MTT Symposium Proceedings, Boston (1967) p 194

12 White, D. L., Sonics and Ultrasonics Symposium, Vancouver, (1967) Paper N-1

13 Tiersten, H. F., Private Communication, Bell Telephone Laboratories

14 Ash, E. A., and Morgan, D., Electronics Letters, Vol 3, (1967) p 462

15 Hutson, A. R., McFee, J. H., and White, D. L., Physics Review Letters, Vol 7, (1961) p 237

16 White, R. M., and Voltmer, F. W., Applied Physics Letters, Vol 8, (1966) p 40

17 Mathews, H., and LeCraw, R. C., Physics Review Letters, Vol 8, (1963) p 397

18 Strauss, W., Journal of Applied Physics, Vol 36, (1965) p 118

19 White, R. M., IEEE Transactions—Electron Devices, Vol ED-14 (1967) p 181

20 Gulyaev, Yu., V., and Pustovoit, V. I. Soviet Physics, JETP, Vol 20, (1965) p 1508

21 Ingebrigtsen, K. A., ELAB Report TE-94, The Norwegian Institute of Technology, Trondheim, Norway (1967)

22 Collins, J. H., Private communication

23 Engan, H., ELAB Report TE-91, The Norwegian Institute of Technology, Trondheim, Norway (1967)

24 Suggested by T. Bially

25 Blass, J., IRE International Convention Record, Vol 8, Part 1 (1960) p 48

26 Mee, J. E., Applied Physics Letters, Vol 10 (1967) p 289

27 Campbell, J. J., and Jones, W. R., TP 68-14-7, Hughes Aircraft Co., Fullerton, California, USA (1968)

28 Broers, A. N., Microelectronics and Reliability, Vol 4, (1965) p 103