the sake of simplicity, that the wave-vector curve \( C \) is a circle. Requiring that the exponential function shall be, by a certain margin, the most rapidly varying factor in the integrand of (94), we find
\[
\frac{2r}{\lambda} \gg \theta_i^{-2}, \tag{109}
\]
In the opposite extreme when \( 2r/\lambda \ll \theta_i^{-2} \), the plane wave approximation given by (104) is a fair approximation for the power density within the acoustic beam. It is worth noticing that in many reported laboratory experiments, the distance between transmitter and receiver has been in the intermediate range where neither approximation is applicable.

REFERENCES

Microsound Components, Circuits, and Applications

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Invited Paper

Abstract—Surface acoustic wave components have been realized which perform the functions of transduction, amplification, and coupling. Applications are suggested which make use of these components.

Experioratory work in connection with surface acoustic waveguides suggests the feasibility of acoustic analogs of conventional microwave transmission line (microsound) components on the surface of crystal and substrates. These microsound transmission lines, hybrids, and directional couplers interconnect microsound transducers, amplifiers, isolators, and phase shifters to form microsound circuits capable of autocorrelation, Fourier transformation, and cross correlation functions.

Compatible component configurations are proposed and evaluated which perform these basic functions. The anticipated difficulties with their realization are discussed and the current status of critical problems including the epitaxial growth of thin films and submicron etching procedures will be given. Several circuits capable of performing correlation functions are given.

I. INTRODUCTION

The exigencies of modern warfare require the acquisition and processing of immense quantities of data in very short periods of time. Perhaps the most demanding military problem is associated with antiballistic missile radar sensors in which the available information consisting of hundreds of thousands of microwave echoes with large bandwidths has to be processed in a few minutes. These sensors require delay-line systems with a bandwidth-delay time product perhaps as large as \( 10^4 \).

Similar problems also exist in the civilian sector. For example, if the cost of computer memory were reduced by a factor of 100, then large scale computer-aided education might become economic. The cost of computer memory has decreased with the size, bandwidth, and operating time of the individual components. Long wideband delay lines with fast access time may contribute to the cost reduction of circulating memory for special purpose computers. The interaction of acoustic and magneto-resistant films may lead to substantial cost reduction [1] of general computer memories. It may also be feasible to integrate acoustic and electronic circuits for more effective data processing.

The utility of sound for these applications in solids is related to the low propagation velocity and the excellent transmission characteristics of acoustic media. Sound travels five orders of magnitude more slowly than electromagnetic waves. It is possible to store a signal within one centimeter of crystal which ordinarily requires a 1-km long air-filled transmission line. The high \( Q \) of acoustic media permits delay times perhaps one hundred times that feasible with low-loss electromagnetic waveguide. Also, the wave-like nature of
sound permits the effective use of gratings and transducer arrays for achieving such special signal processing circuits as pulse compressors, filters, and auto-correlators.

Most of the effort until recently has been associated with realizing bulk acoustic wave components and, in particular, nondispersive [2] and dispersive [3] delay lines and bulk acoustic wave amplifiers [4]. The typical bulk wave device consists of a crystalline block (Fig. 1) 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 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. The signal manipulation is done with external electronic circuits.

Ready access to the signal is obtained if the acoustic energy is transferred to the surface of the crystal. Microwave techniques for the manipulation of electromagnetic waves are available that should be adaptable for the manipulation of acoustic energy. It is proposed that these sound wave analogs of microwave components and circuits be called microsound components and circuits.

The analogy between microwave components and microsound components derives from their common frequency range of 0.1 to 10 GHz, from having cross section dimensions on the order of a wavelength, and from being many wavelengths long. The main difference between them is that the transverse dimensions of the microsound components are measured in micrometers in contrast to decimeters for the microwave components. The microsound components are a long range goal of the efforts at Lincoln Laboratory and at other laboratories. Surface acoustic beams many wavelengths wide could be manipulated with gratings, mirrors, lenses, and other sound wave analogs of optical components and techniques. Surface wave components are available now which could be used directly for several immediate applications.

II. Surface Wave Components

Rayleigh waves, in contrast to bulk waves, are localized to the surface of solids. The typical particle motion is elliptical, and the amplitude decays exponentially into the body of the medium. The phase velocity of the Rayleigh wave is between 85 and 95 percent of the bulk shear wave velocity in most media. Particle displacements are miniscule; a typical displacement is measured in angstrom units. At UHF frequencies the wavelengths are comparable to optical wavelengths (several microns at 1 GHz).

These surface acoustic waves were first described by Lord Rayleigh [5]. At low frequencies, such waves are generated with the wedge transducer [6] shown in Fig. 2. Here, 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. 3), 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 downward into the bulk and to the left and right on the surface. The conversion loss is quite large, and at frequencies in the GHz range the wavelengths are on the order of 3 microns, or 1.2 × 10⁻⁴ inches. Teeth of that size are difficult to fabricate and, because of their size, are very fragile.

The interdigital transducer [8] shown in Fig. 4 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. For example [9], bandwidths in excess of 30 percent and conversion losses of less that 4 dB, of which 3 dB is caused by the bidirectivity of the device, have been realized with five finger-pairs at 100 MHz. If an identical transducer is located ½ wavelength away, and adjacent to the first transducer, and if this secondary transducer is driven in phase quadrature with the first, the energy will interfere constructively in the desired direction [10]. Such unidirectional [11] transducers have operated with bandwidth of 2 percent and a conversion loss of less than 1 dB. Electron beam pattern generation techniques have been employed to manufacture microwave transducers at a frequency of 2 GHz [12] with a conversion loss of approximately 10 dB, and with a narrow bandwidth. The fingers and gaps are less than 3000 angstroms wide in this device.

The bulk acoustic wave amplification mechanisms [13] found in a piezoelectric semiconductor have been adapted to surface acoustic waves [14] (Fig. 5). Here a surface acoustic wave is generated on a surface of the high resistivity cadmium sulfide crystal, a piezoelectric semiconductor. Electrodes are deposited athwart the acoustic beam, and photoconductive 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 incorporate the three qualities of acoustic conduction, piezoelectric transduction, and semiconduction. For example, CdS is a par-
Fig. 2. Surface wave wedge transducer. Most of the shear wave energy is reflected at the interface and absorbed; a small portion is coupled to a Rayleigh wave.

Fig. 3. Rayleigh wave comb transducer. The comb teeth are separated by one Rayleigh wavelength. The longitudinal wave energy in the comb teeth is coupled to two Rayleigh waves propagating to right and left, and to a longitudinal wave into the substrate.

Fig. 4. Interdigital transducers on a piezoelectric block.

Fig. 5. Surface wave amplifier on block of CdS. Gain is obtained when the light produces carriers in high-resistivity CdS which are accelerated to a drift velocity in excess of the Rayleigh wave velocity by the electric field.

Fig. 6. Silicon wafer used in conjunction with lithium niobate delay line in an electroacoustic composite amplifier. The wafer is mounted on a BeO heat sink.

Fig. 7. Piezoelectric gap coupler. The piezoelectric field between the separated plates provides the means for transferring surface wave energy across the gap.

particularly good piezoelectric material, and it is a very poor acoustic medium at UHF, with a mobility of 200, and acoustic attenuation coefficient of 50 dB per centimeter at 1 GHz.

A mechanical disturbance propagating on the surface of a piezoelectric crystal block (Fig. 4) has associated with it an electrostatic field. This field extends into the medium as well as outside the medium with a decay rate of an acoustic wavelength. This field penetrates into an adjacent semiconducting block and interacts with the drifting carriers in the semiconductor. We have built such a configuration, and have obtained continuous 30 dB/cm acoustic gain at 200 MHz with an input dc power for the drift field of 30 watts. The amplifier attenuates acoustic signals at a rate of 20 dB/cm if the acoustic propagation is opposite to the drifting carriers. This feature is useful for suppressing the effect of unwanted reflections. Fig. 6 shows the semiconducting wafer used in this experiment. Note the elaborate heat sinking provisions for carrying away the 30 watts. In this structure the semiconducting wafer is three thousandths of an inch (75 microns) thick. The interaction depth at 200 MHz, however, is no more than a few microns. Consequently, most of the dc power is uselessly dissipated outside the interaction region.

A thin semiconducting layer about 1 micron thick on a suitable insulator provides a substantially more efficient means for transferring the input dc energy to the acoustic wave. Such an amplifier [15] was recently assembled; it achieved 50 dB acoustic gain per centimeter with an input power of less than 7 watts at 100 MHz.

The electrostatic field can also be used to transfer acoustic wave energy from one piezoelectric surface onto an adjacent piezoelectric surface [16] as shown in Fig. 7. The acoustic energy propagates on the upper surface on the left hand crystal, and couples across a small air gap onto the under surface of the adjacent crystal with less than 2 dB conversion loss and bandwidth of 30 percent.

These three basic components could be employed in an
extended tapped acoustic delay line as shown in Fig. 8. The delay line features the principal advantages of surface acoustic wave components: an efficient amplifier which compensates for the losses associated with the acoustic wave and which suppresses reflections; a gap coupler to transfer energy from one crystal plate onto an adjacent one in order to circumvent the limitations of crystal size; and acoustic taps which provide ready access to the signal.

Many new and interesting digital and analog components and systems are configurable with these three basic components. A fourth component not yet developed, but of potentially great utility, is an efficient Rayleigh wave reflector. With presently available photolithographic techniques, it should become feasible to store as many as \(10^6\) bits/cm\(^2\) of crystal surface (Fig. 9), or obtain a bandwidth-delay time product on the order of \(10^4/\text{cm}^2\) through the utilization of these currently available transducers, amplifiers, gap couplers, and the soon to be realized reflectors.

III. MICROSOND COMPONENTS

One-MHz surface acoustic waves have been guided by a pair of grooves [17] as shown in Fig. 10. Here two wedge transducers were placed far apart on a metal substrate. A 1-MHz signal was transmitted from one to the other and the insertion loss noted. Then the two grooves were inscribed and the loss dropped 10 dB. The reduction of loss was attributed to wave guidance. Another form of waveguide, an acoustic analog of the dielectric microwave guide, is shown in Fig. 11(a). It consists of a dense material [18] that 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 [19] is a slot cut into a fast overlay on a slower substrate. In these structures nearby transmission lines are loosely coupled to each other, making feasible such devices as directional couplers [18], [20]. The metal waveguides [21] are much thinner than an acoustic wavelength, and the propagating mode is essentially a perturbed Rayleigh wave.

Another form of the overlay waveguide [22], in which all the acoustic energy is contained within a relatively thick overlay, has also been analyzed. The dispersion relation of the propagating modes corresponds in many respects to their microwave analog.

Suppose that for the moment we hold in abeyance our critical faculties and consider what microsound components
Fig. 10. Slot transmission line. The insertion loss between widely separated wedge transducers decreases dramatically when slots deeper than a Rayleigh wavelength are inscribed.

Fig. 11. Overlay transmission lines. The phase velocity in the slow medium is less than in the fast medium.

Fig. 12. Microsound transmission line, bends, and filter. The dimensions of the lines at 1 GHz are about 2 microns wide, 1 micron high, with an edge definition of ±0.05 micron.

Fig. 13. Directional and hybrid couplers. Energy into 1 goes mostly to 2, and a small portion is coupled to 3. If the flow is reversed (from 2 to 1), energy is coupled to 4. Energy into hybrid terminal 2 emerges from 5 and 6 equal in amplitude and 90° out of phase. Two equal signals 90° out of phase emerge at 2; if the phase relationship is reversed (−90°), the energy emerges at 7.

might look like using the thick waveguide 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 nonconducting single crystals exhibit low losses in the frequency range from 500 to 5000 MHz. Suppose that it is possible to obtain epitaxial overlays of one low-loss acoustic medium onto another. At 1 GHz a typical wavelength is about 3 μ. Consequently, the principal cross-sectional dimensions of a waveguide are on that order, and if the waveguide is to perform well, these dimensions should be held to a tolerance of a small fraction of one micron. Since the diffraction limit of light is on that order, conventional photo-resist methods cannot be used, and new techniques must be employed. These techniques are described in Section V.

A. Transmission-Line Components

A microsound analog of a microwave transmission line and filter network, shown schematically in Fig. 12, 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.

The directional coupler in Fig. 13 couples a small portion of the energy traveling from 1 to 2 into terminal arm 3. If the energy flow is reversed (from 2 to 1), the sample signal appears at 4. A low-frequency version of the coupler [18] has been demonstrated at 10 MHz 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 1 MHz.

B. Isolator, Switch, and Gyrator

The nonreciprocal interactions of circularly polarized body shear waves with spin waves [23], [24] may be adaptable to surface acoustic waves. If the surface disturbances are 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 magnetoacoustic material such as yttrium iron garnet and magnetized to the magneto-
Fig. 14. Magnetoacoustic isolator or phase shifter. At the surface of YIG in a microscopic region, the particle motion in a plane perpendicular to $H_{dc}$ approximates the motion of an elliptically polarized shear wave. Since positive rotation couples more strongly to the spin wave manifold than negative, nonreciprocal transmission characteristics are anticipated.

Fig. 15. Microsound double-pole double-throw switch. Power into 1 and 2 exits at 3 and 4, respectively. If the field $H_{dc}$ is reversed, the power emerges at 4 and 3.

Fig. 16. Microsound amplifier. The acoustic energy in the piezoelectric produces electric fields which extend out of the surface and into the semiconductor, where they couple to the carriers.

Fig. 17. Microsound directional transducer. Two bidirectional transducers are separated one quarter wavelength and driven in phase quadrature to obtain radiation in one direction only.

acoustic crossover point by a field lying in the plane of the surface and normal to the propagating direction (Fig. 14) 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 $90^\circ$, a switch circuit becomes feasible (Fig. 15); the energy into 1 emerges at 3, and if the field directions are reversed, energy into 1 emerges at 4. Energy into 2 emerges at the complimentary 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.

C. Amplifiers

A microsound version of the amplifier discussed in Section II is shown in Fig. 16. 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.

D. Transducer

The transducer in Fig. 17 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 [10] 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.

IV. APPLICATIONS

The microsound components can be interconnected to form specialized circuits for signal and data processing applications. One example is the parallel delay line [29]
(Fig. 18) 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 (Fig. 19). The electrical signal is converted to a microsound signal with a suitable transducer; 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. 20), 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 pathway. 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. 21. It is a lens [30] which is capable of forming over a relatively wide bandwidth the Fourier transform of a signal. The input and output arrays consist of waveguide feeds spaced less than a wavelength apart. The time sampled signals are fed into the input array located at the focal plane. It is the property of an ideal lens that the amplitude distribution of one focal plane is the Fourier transform of the amplitude distribution of the other focal plane. Consequently, the Fourier transform components emerge out of the waveguide feeds at the right.

Suppose the time samples are obtained with a tapped uniformly spaced delay line. At a particular frequency $f_0$ the samples are in phase and the energy emerging from the input array converges at the centrally located horn in the output array. At a frequency $f$ the energy converges at a horn displaced approximately $(f_0-f)L/(aF)$ from the central horn, where $L$ is the delay line length between taps, $a$ the distance between radiators of input array, $F$ is the focal length of lens, and the aperture $D< F$. Notice the resolving power of this Fourier transformer is proportional to either $L$ or $F$.

The delay line in Fig. 19 and the lens transformer in Fig. 21 could be combined to produce the microsound correlator shown in Fig. 22. If the phase shifts are set to zero and the gain of all 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 $f(t)$, and if the phase and amplitude of the output phasers and amplifiers are set to the conjugate of the Fourier transform $F_2*(w)$, then the outputs are the product $F_1(w) X F_2*(w)$. 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 multithrow 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. 23 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 to $63\Delta L$ in incremental steps of $\Delta L$.

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

V. PROBLEMS

The realization of microsound components in the frequency range from 500 to 5000 MHz 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 magneto-acoustic materials on low-loss crystalline substrates. A particular example of such a film is the YIG film on a YAG substrate [26] (Fig. 24). This example is particularly noteworthy because it represents an achievement that goes beyond the complexities of depositing simpler materials as ZnO, BeO, and Ge on suitable substrates. This technology should be employable to make new combinations of materials as ZnO on BeO or on BiGeO$_2$.0.
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 are the phase velocity graphs [31] as a function of direction on lithium niobate (Fig. 25). Without precise knowledge of the propagation constants of the materials (and the dominant mode in the waveguide), such elaborate waveguide circuits as the phased array of Fig. 21 would not be feasible.

Photo-etching methods are limited by light diffraction to an accuracy of about 1/2 micron. 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 that 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 1 micron wide and on 1/2-micron centers produced with the aid of a scanning electron beam microscope by A. N. Broers [32] (Fig. 26).

VI. CONCLUSIONS

A great deal of technology is available in the microwave acoustics, solid-state, integrated circuit, and microwave engineering disciplines which bears 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 vapor 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 analogs.

The utilization of acoustic analogs 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 (one square kilometer is equivalent to one square centimeter of microsound circuitry), high losses, and high cost make the microsound approach more attractive.

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