14 January 1972, Volume 175, Number 4018 SCIENCE

Microsonics

Devices using acoustic surface waves at microwave frequencies are altering signal processing.

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Microsonics offers the engineer a new way to control and manipulate energy. Among its virtues are miniaturization, reliability, and ease of device fabrication. Thus acoustic surface waves at microwave frequencies (microsonics) will very likely be of major importance to electronics engineers. Potential applications range from simple delay lines to special-purpose signal processors. In this article we review their nature, generation, and manipulation, and further discuss their application. But first we must establish a perspective from which to view this emerging technology.

The goal of the electronics engineer may be broadly defined as control and manipulation of energy, in general economically, reliably, and in as little space as possible. Historically, electronics engineers have not confined their attention solely to electrical energy. They have exploited chemical energy in batteries and fuel cells; vibrational energy in loudspeakers, styli, and microphones; electromagnetic energy in space, wave guides, and transmission lines; optical energy in phosphors and diodes; mechanical energy in motors and generators; and thermal energy in thermionic and thermoelectric converters. The approach has always been to combine the forms of energy best suited to accomplish a desired function.

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As one more means of achieving this goal in an economical, reliable, and space-saving manner, microsonics becomes relevant to electronics engineers. The physical basis of acoustic surface waves has long been known. Lord Rayleigh provided a full analytical treatment of it in 1885 (*1*). However, its utility for the electronics engineer remained limited until recent advances were made in materials science and fabrication technology (*2*).

Characteristics and Features

In an elastic, isotropic solid, vibrational energy propagates in three basic modes, namely longitudinal, shear V, and shear H (Fig. 1). In the longitudinal mode, the vibrating element moves with velocity v_p parallel to energy V_E. This is the mode of the common sound wave in air. In the shear V mode, the vibrating element moves transverse to the energy flow vector and perpendicular to the free surface of the solid. In the shear H mode, the elemental motion is still transverse to the energy flow, but it is parallel to the free surface. (This notation is useful to seismologists where the free surface is that of the earth.) In general, when a medium will support simple modes, it will also support combinations of these simple modes.

A typical example of such a combination is the hybrid mode which consists of a shear V and a longitudinal component; this combination is the Rayleigh wave, the most familiar type of surface wave (Fig. 2). In the simplest case, a Rayleigh wave on the surface of an isotropic medium, the elemental motion is retrograde and elliptical; the amplitude decreases to $1/e$ of its surface value within one wavelength from the surface; and the velocity of the surface wave V_S is smaller than the velocity V_B of bulk shear waves. In the general case of an arbitrary direction on an anisotropic medium, a complex variety of modes may exist.

From the characteristics of the surface waves stem some extraordinarily significant features.

1) The energy is physically accessible. It can be tapped, guided, and generally manipulated without requiring penetration of the medium by any kind of a probe. In contrast, interaction with bulk waves is quite difficult because of their inaccessibility.

2) The power density is high because of confinement to the surface. For a given power, the power density increases with frequency. It is axiomatic that measurement problems ease as power density increases, so this feature also simplifies experiments.

3) Since the surface wave propagation velocity is 10^5 slower than that of electromagnetic waves, for a given frequency, the wavelength is also smaller by a factor of 10^5 and all functions which scale with wavelength are smaller by the same factor. We will call this demagnification. For example, at 400 megahertz, the wavelength in lithium niobate is about 8 micrometers, compared with 80 centimeters for electromagnetic waves in space. The 8-micrometer wave is comparable to dimensions commonly encountered in integrated electronics. This geometric compatibility will enable combining microsonic signal processing elements with large-scale integrated (LSI) and hybrid electronics to provide compact subsystems.

4) An additional compatibility exists with LSI technology—process compatibility. Schemes for achieving generation, guidance, and amplification of microsonic surface waves all depend on a fabrication technology which is similar to that used in producing LSI arrays.

Generation and Reception

There is, then, sufficient motive to develop and apply these Rayleigh waves. The first requirement is development of techniques of generation and reception. While a variety of approaches are available, the interdigital transducer on a piezoelectric substrate (*3*) is presently the most widely used. Figure 3 shows the important features. A geometric resonance is employed by spacing the fingers one-half wavelength apart. Very efficient conversion from electrical to acoustic energy (less than 1 decibel loss) is possible (*4*). The device functions as follows. The electrical field between adjacent fingers fringes into the piezoelectric crystal. A strain occurs in response to the applied field. As the field alternates, so does the strain, and the surface wave is launched.

The interdigital transducer has been thoroughly analyzed at Stanford University (*5*). The Stanford group has constructed an equivalent circuit transducer model and experimentally established the validity of the model. For a simple inductive tuning circuit, one which resonates the transducer capacitance at the center frequency, the transducer efficiency is directly proportional to K^2 (the electromechanical coupling coefficient) and to N (the number of finger pairs). The half-power bandwidth is related to $1/N$, so that the bandwidth-efficiency product is approximately invariant with N. The curve in Fig. 4 is an experimental one. It clearly validates the bandwidth relation, demonstrates the modest in-out insertion loss, and emphasizes the steep slopes of the transducer band-pass characteristic. (The 14-decibel insertion loss shown in Fig. 4 includes 6 decibels which may be attributed to the bidirectional radiation pattern of the transducers, 1 decibel of propagation loss, 1 decibel of ohmic loss in the transducer electrodes, and perhaps 2 decibels of impedance mismatch loss. Thus the electromechanical conversion loss at each transducer is small.)

Guidance and Amplification

Once a wave is launched, it must be guided. This can be accomplished a number of ways (*6, 7*). One attractive approach is to deposit a thin-film strip of metal on the substrate. If the acoustic velocities in the metal are slower than they are in the substrate, the film will load the substrate and the surface wave velocity beneath the film will fall

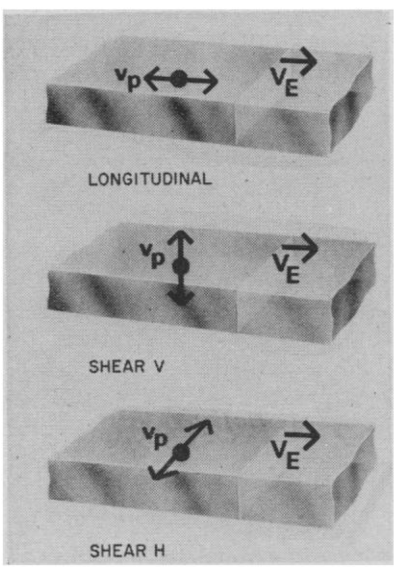


Fig. 1. Simple elastic waves in solids. Vibrational energy propagates in an isotropic, elastic medium in three simple modes. These are characterized by the relative direction of particle velocity v_p and the direction of energy flow V_E.

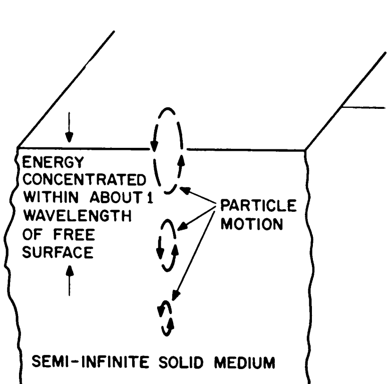


Fig. 2. Surface waves. At a free surface, a hybrid form of two simple modes is permissible. A hybrid of a shear V and a longitudinal wave is a Rayleigh wave.

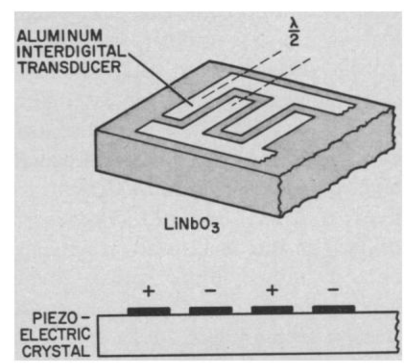


Fig. 3. Generation and transduction. Acoustic surface waves can be efficiently launched on piezoelectric surfaces by interdigital transducers. The bandwidth (B) and efficiency (η) are related to the number (N) of finger pairs in the transducer. The effective electromechanical coupling coefficient (K) is fixed by the medium.

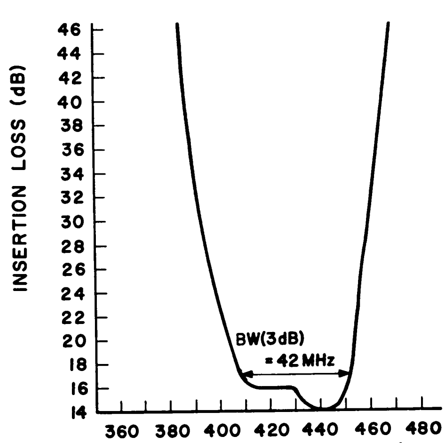


Fig. 4. Frequency response of ten-finger-pair aluminum interdigital transducer on $LiNbO_3$ substrate.

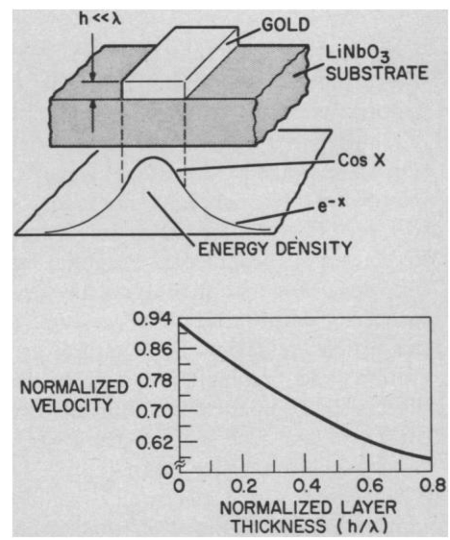


Fig. 5. Guidance. The surface wave can be guided by a thin film of metal, because the wave velocity under the metal is smaller than it is on the free surface. Some energy extends beyond the guide edges; this permits coupling to adjacent guides.

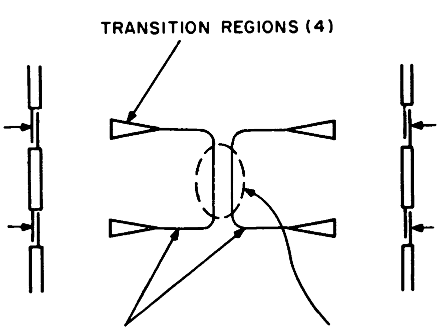


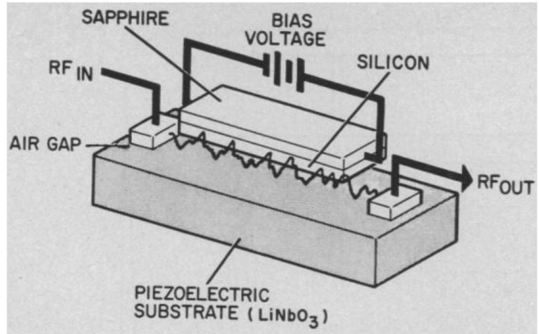
Fig. 6. Wave-guide configuration used to study the effects of a number of parameters on coupling. Arrows at left and right mark transducers.

below that on the free surface. The film will also short the piezoelectric field, reducing local stiffness and causing a further reduction in surface wave velocity. The wave is then trapped not only in its depth dimension but also in its horizontal extent. The effect is analogous to a light guide; the surface wave is bound under the strip. Figure 5 shows the variation in velocity with normalized film thickness, as well as the energy distribution under the metal. The exponential decay beyond the guide edge has an advantage—it permits transfer of energy between adjacent guides (*8*). A second strip can be made to overlap the exponential region and effectively couple energy out of it. Thus, guidance and coupling can both be achieved.

Figure 6 shows a configuration used in our laboratory to study the significance of radius of curvature, film thickness, line separation, length of coupling region, and horn taper. Similar structures have been studied by Van den Heuvel *et al.* (*9*). Even though analysis has been carried out by Tiersten (*7*) and several other investigators, the problem remains mathematically very difficult and a certain amount of empiricism may be expected. At present it cannot be definitely stated that the feasibility of surface wave guidance schemes has been adequately demonstrated.

One more function is essential to the full utility of surface wave technology—amplification. This goal, frequently sought but seldom realized with bulk acoustic waves, has been spectacularly realized with a surface wave approach (*10*). Figures 7 and 8 show the configuration and some typical data obtained at Stanford University (*11*). The gain comes about in the following way. A surface wave is launched in the piezoelectric material. As it propagates, electric fields are generated in regions of strain. These fields extend out of the surface and into the thin film of silicon which is carefully positioned above them. A d-c field, which is colinear with the surface wave vector, is maintained in the silicon; it causes electrons in the conduction band to drift in the direction of surface wave propagation. If the electric field is made large enough, the electron drift velocity will exceed the surface wave velocity.

Under this condition, the kinetic energy of the electrons is transferred to the acoustic system and distributed gain occurs. (This has a parallel in the action of a traveling wave tube). This approach permits independent optimiza-



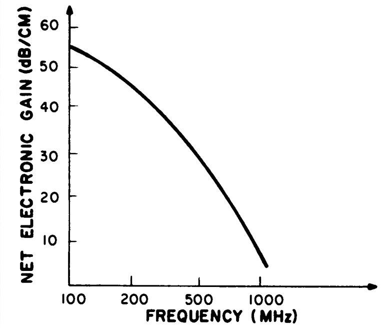


Fig. 7 (left). Integral amplification. Because transduction and propagation are not lossless, amplification is desirable. This configuration leads to transfer of energy from the electrons in the silicon to the phonon system in the $LiNbO_3$. Fig. 8 (right). Typical data obtained at Stanford showing amplification in a surface wave device.

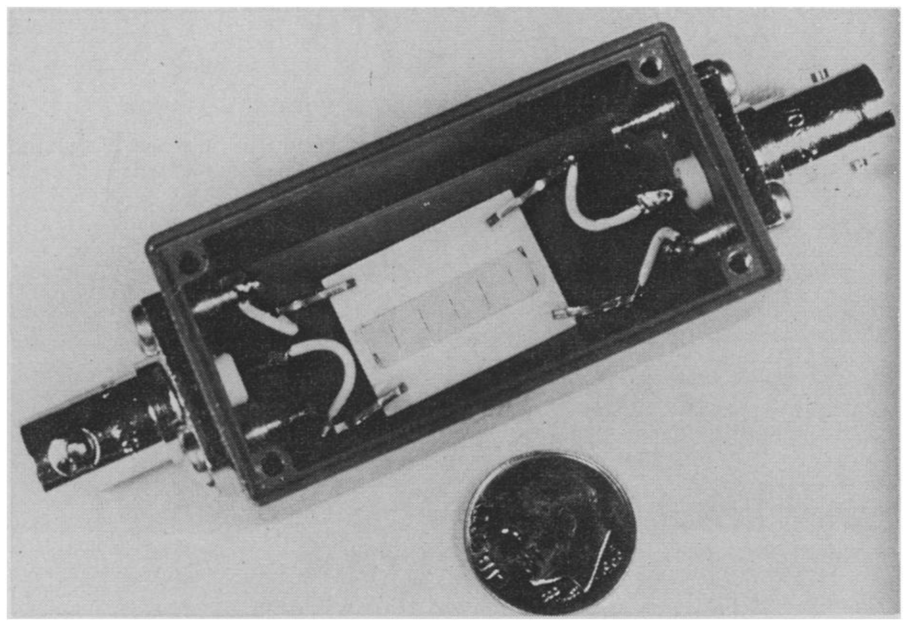


Fig. 9. Microsonic delay device. Frequency response is given in Fig. 4.

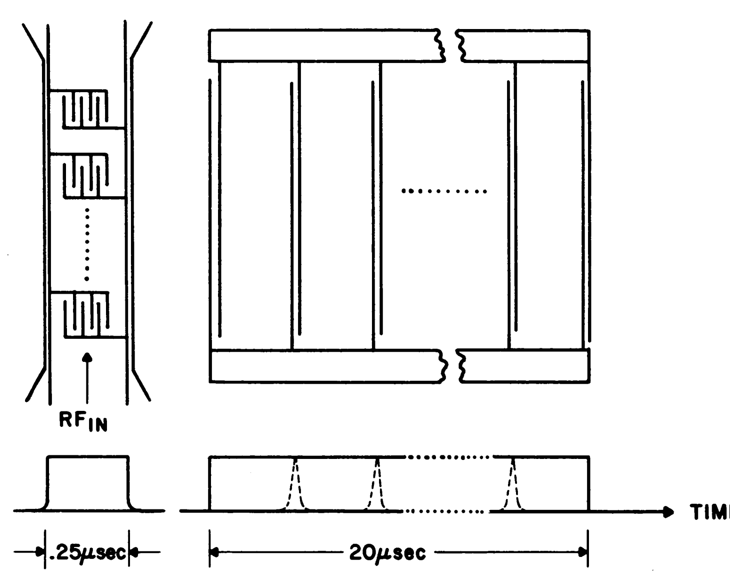


Fig. 10. Tapped delay line. Tapped microsonic delay lines are readily achievable. The configuration shown here leads to a pulse stretcher. It includes a parallel, broadband input transducer.

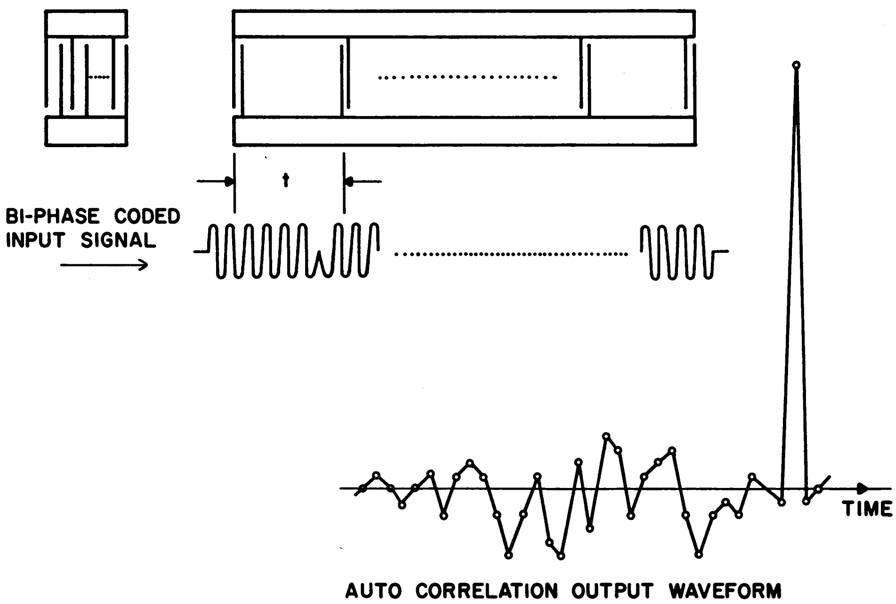


Fig. 11. Biphase correlator. This biphase correlator consists of a simple broadband input transducer and a complex output transducer. The latter has a series of single pair elements of selected polarities to accomplish correlation.

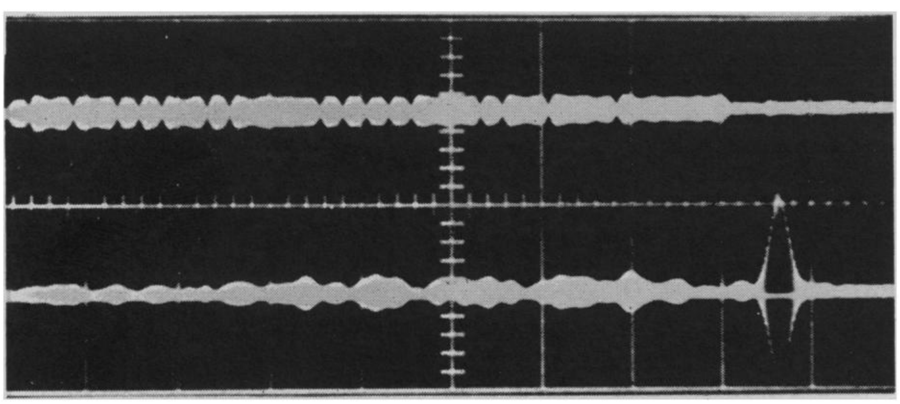


Fig. 12. Biphase correlation. The top tracing shows a sequence generated by application of an impulse to a 32-bit, phase-coded, tapped delay line. The bottom tracing shows the autocorrelation observed when this sequence is input to the conjugate device.

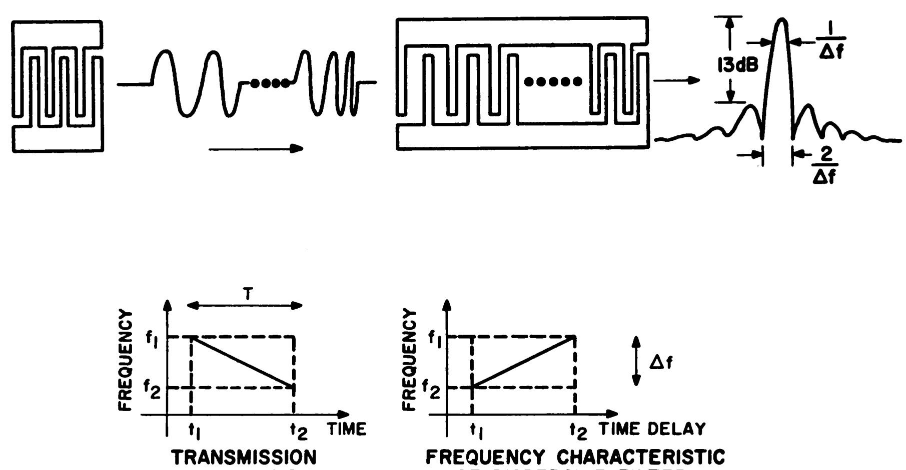


Fig. 13. Pulse compression. Pulse compression is accomplished by resonating and summing several different output transducers simultaneously. Large time-bandwidth products are achievable by diiving and summing many such subsystems in parallel on a single crystal.

tion of the piezoelectric and semiconducting properties, something which is not possible in bulk wave amplifiers. Even more important is the large ratio of surface area to interaction volume, which minimizes thermal problems and makes continuous operation possible.

Applications

Certainly the earliest and most obvious use of surface waves is as linear delay lines (*4*). Simple arithmetic shows that 0.25 microsecond of delay requires approximately 50 meters of wave guide, but less than 1 millimeter of $LiNbO_3$. Figure 9 is a photograph of a simple delay line. Nowhere is the advantage of demagnification more clearly demonstrated. The tapped delay line is a next step, which exploits one of the great advantages of surface waves, namely, the continuous accessibility of the signal along its entire propagation path. Figure 10 is a schematic representation of a tapped delay line in a "pulse stretcher" configuration in which all of the taps are connected to common output lines. When a short pulse (equal in duration to the propagation time between taps) is applied to this line, it will stimulate each tap in succession and the output signal will be a "stretched" version of the input pulse. The duration of the output will be equal to the product of the number of taps and the duration of the input. Also illustrated in Fig. 10 are (i) an input transducer in which broadbanding is accomplished by means of a parallel combination of transducers and (ii) "weak tap" output transducers containing only a single finger pair each.

A variation on the tapped delay line leads to the biphase correlator (*12*) of Fig. 11. Assume that a 60-megahertz carrier for transmitting biphase-encoded information at a 10-megabit rate has been launched. This means six cycles correspond to a bit, with phase differences of 180 degrees signifying 1's and 0's. The fingers of the output transducer are connected to the sum lines according to a predetermined code pattern. As th: phase-coded signal moves along the delay line, the autocorrelation function is observed at the output, with the correlation peak occurring when each bit in the signal is spatially registered with a tap of appropriate polarity. A schematic representation of the autocorrelation is shown in Fig. 11.

Some results achieved in our lab-

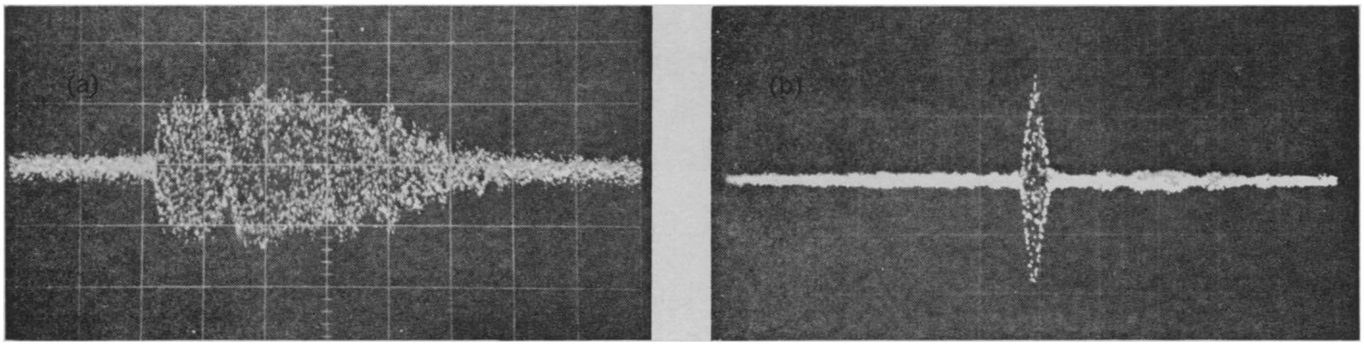


Fig. 14. Pulse compression filter. (a) Frequency-modulated signal generated by application of an impulse to a dispersive transducer. (b) Compressed output observed when this frequency-modulated signal is input to the conjugate device (100 nanoseconds per scale division).

oratories with surface wave correlators are illustrated in Fig. 12. A 32-bit sequence generated by application of an impulse to a phase-coded, tapped delay line is shown in the upper trace. The autocorrelation observed when this sequence is input to a conjugate phase-coded line is shown beneath.

A programmable correlator has also been developed (*13*). This device employs switches between the taps and the radio-frequency sum lines so that the phase of a given tap may be changed by 180 degrees, thus permitting complete code flexibility. Yet another type of tapped delay line is worth mentioning—the frequency-modulated pulse compression filter employing dispersive transducers (*14*). Since surface wave propagation is nondispersive, the dispersive (frequency-dependent) time delay is accomplished through the transducer geometry in the manner indicated in Fig. 13. Note that one end of the output transducer is sensitive to low frequencies and the other end is sensitive to high frequencies. The transition from low to high occurs gradually along the length of the transducer. Since different components must travel paths of different lengths between input and output, one has, in effect, frequency-dependent time delay. When a frequency-modulated signal is input to such a device, an approximate sin X/X output is observed, with a peak occurring when each spectral component in the signal is spatially registered with the portion of the dispersive transducer most sensitive to that particular frequency.

Results of some experiments performed in our laboratories are shown in Fig. 14. Figure 14a shows the frequency-modulated signal generated when an electrical impulse is applied to a dispersive transducer. Although not discernible in the photograph, the frequency varies from about 360 to 440 megahertz over a period of 0.5 microsecond. Figure 14b shows the compressed output of the dispersive transducer for a frequency-modulated signal as an input. Note the characteristically large main lobe and smaller side lobes.

There are many other important and challenging applications. An excellent concentrated collection of state-of-the-art papers has been published (*15*) and White has written a comprehensive review (*16*). It is neither possible nor appropriate to consider all possible applications here; but speculating a little on the future, one may envision: (i) switchable correlators used in integrated communication, navigation, identification (CNI) systems; (ii) simple correlators used in light-weight radar systems; (iii) large time-bandwidth delay lines, incorporating gain, for use in electronic warfare and radar systems; (iv) band-pass filters in color television systems; and (v) parallel processors employing long, complex transmission paths. Microsonic parallel processing requires additional explanation. Inasmuch as metal films alter the surface wave velocity, just as glass alters the velocity of light, surface waves can be manipulated with planar analogs of optical elements (*8*). It should thus be possible to beam split, focus, diffract, and refract these waves. Also Fourier transformation, convolution, autocorrelation, and all other optically achievable mathematical transforms and operations should be possible.

This analogy encourages speculation about surface wave, special-purpose processors. Quite recently nonlinear interactions between acoustic wave trains have been investigated. Newhouse has suggested that two acoustic beams crossing at right angles in a dispersive medium will generate a sum frequency beam in a direction determined by the ratio of their frequencies (*17*). The effect makes possible new techniques for switching and correlation.

Summary. A long-known wave mode is becoming practical because of new technology, thereby making another energy-managing technique available to engineers. Geometric and process compatibilities with LSI arrays will advance the utility of both microsonic and LSI arrays. A number of potential applications exist and, as in all previous cases, this new control and manipulatory capability will lead to accomplishments and functions not yet imagined.

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