SURFACE ACOUSTIC WAVE DEVICES FOR COMMUNICATIONS

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Summary. Many surface acoustic wave (SAW) devices are now sufficiently well-developed that they can have a significant impact on systems design. This paper reviews the properties and limitations of SAW devices which seem particularly well suited to communications. The simple bandpass filter is considered in detail as it will undoubtedly see the widest usage of all SAW devices. The application of SAW analog matched filters in phase-shift-keyed synchronization and data demodulation is also discussed. Finally, SAW resonators and oscillators are briefly considered. A number of examples are included which show how system performance can be improved through use of SAW technology.

I. Introduction. Properties of waves of mechanical displacement, i.e. acoustic waves, propagating on the surface of a solid have been studied for more than seventy years by those investigating the physical consequences of earthquakes.[1] However, it was not until the late 1960's that the major breakthroughs occurred which were to transform this work into the now rapidly expanding field of surface acoustic wave (SAW) signal processing. In 1968 a group at Stanford University[2] with the help of computations by Campbell and Jones[3] used a new electrical to acoustical energy transducer (the interdigital transducer) devised by White and Voltmer[4] to demonstrate SAW devices with a less than 10 dB insertion loss over a 20% fractional bandwidth. Subsequently, the Stanford group developed an equivalent circuit model of the transducer[5] which made simple, accurate device design possible. The potential for performing VHF-UHF signal processing with relatively low loss over substantial bandwidths in a compact, rugged geometry spurred SAW R&D efforts in most of the major electronics firms in this country and abroad. The technology now appears ripe for application to the communications field. This paper, after a brief discussion of the basic SAW delay line, will review those SAW components which should be of greatest significance to this field.

II. Fundamental Limitations of SAW Devices. An understanding of many of the performance limitations of SAW-based signal processing devices can be gained by reviewing the operation of the basic SAW delay line, shown in Figure 1. The delay line consists of two metallic interdigital transducers on a highly polished surface of a piezoelectric cyrstal. When a sinusoidal electrical voltage is applied to the input terminals of the device, the electrical field between adjacent fingers of the transducer fringes into the substrate producing an alternating strain field and consequently an acoustic wave. Acoustic waves propagate away from the transducer along the surface in both directions perpendicular to the fingers. The forward propagating wave which is generated by the input transducer is partially converted to an electrical signal at the output transducer by the inverse piezoelectric effect. Waves either propagating in the reverse direction from this transducer or propagating past the output transducer are damped by the acoustic absorbing material. In this basic device the bidirectional nature of the transducers therefore limits the minimum attainable insertion loss to 6 dB.

The physical constants most important in the design of SAW devices are given in Table I for the most widely used piezoelectric materials. Since all single crystal materials are anisotropic, and acoustical properties have a significant orientational dependence, both the crystalline plane of propagation and the direction of propagation must be specified.

TABLE I
Physical Constants for Selected SAW Materials
(after Holland and Claiborne[6])

Material and Orientation	velocity ($x10^5$cm/sec)	k^2 percent	Delay Time Temperature Coefficient in ppm/°C
$LiNb0_3$(YZ)*	3.48	4.5	91
Quartz (ST,X)	3.15	0.16	0
$Bi_{12}Ge0_{20}$(111)(011)	1.65	1.7	128
LiT_a0_3(YZ)	3.22	.74	.37

*Symbols parentheses are the orientation of the surface normal, and the direction of wave propagation.

The acoustic wave velocity determines both the delay per unit length and the transducer periodicity. In general the SAW velocity is five orders of magnitude less than its electromagnetic counterpart. Because of this feature SAW devices are capable of extremely high information density, enabling complex signal processing to be carried out in small physical dimensions.

Of the commonly used materials bismuth-germanium-oxide possesses the smallest velocity hence the largest delay per unit length, six microseconds per centimeter. Crystals up to 25 cm. can be processed hence delays to 150 microseconds are achievable with a simple delay line. Longer delays can be realized with special folding schemes. For example, by rounding the ends of the crystal and forcing the acoustical wave to propagate in a helical path around the crystal delays of 1 millisecond have been demonstrated with 62 dB insertion loss.[7]

The practical range of operating frequencies is also determined by the SAW velocity. Most efficient acoustical excitation occurs when the frequency is such that the period of the electrical signal equals the time required for the acoustic wave to travel one transducer period (See Fig.2). At this frequency a propagating wave is reinforced by each finger under which it passes. With equal finger and space widths, the most commonly used configuration, a quarter acoustic wavelength fabrication capability is necessary. Since the SAW geometry is planar, conventional microelectronic photolithography with a resolution limit of about one micron can be employed. For the "fastest" known material, a composite structure of $A\ell N$ on $A1_20_3$,one micron resolution places an upper limit of 1.5 GHz on the frequency obtainable. For the more widely used materials, quartz and lithium niobate, the limit is about 750 MHz. With a modest increase in fabrication complexity, i.e. utilization of flexible photomasks with conventional photolithography, the resolution capability can be extended to .5 microns.[8] For still finer resolution, electron beam or x-ray photolithography, can be employed. $LiNb0_3$ devices operating at 2.5 GHz have in fact been demonstrated.[9] In general, the vast majority of SAW applications have been below 800 MHz, principally because of fabricational considerations but also because acoustic attenuation becomessignificant above this frequency.[10]

Another important material parameter noted in Table I is the temperature coefficient of delay. Where temperature stability is of paramount concern, ST quartz is employed since it exhibits a zero parts per million (ppm) per degree centigrade temperature dependence at room temperature. Over the temperature range -50°C to +80°C, however, the ST-quartz surface wave velocity can vary as much as 80 ppm.[11]

A third material parameter noted in Table I is the electromechanical coupling constant, k^2. k^2 gives a measure of the efficiency which electrical energy can be converted to acoustical energy. A SAW delay line can be matched over the fractional bandwidth.[12]

$$\frac{\Delta f}{f_o} = \sqrt{\frac{4k^2}{\pi}} \qquad (1)$$

The midband insertion loss of this device will be 6 dB, due to the transducer bidirectionality, plus minor contributions from acoustic diffraction, ohmic losses, etc., typically ~1 dB. This high degree of matching is seldom done because it results in high multiple reflections within the device; furthermore, it is frequently desirable to let the SAW device rather than the electrical matching network set the device performance. In general, insertion loss can always be traded for increased bandwidth. Outside the bandwidth given in equation 1, the loss increases at a rate of 12 dB per octave.

There are many second order effects which may be important in SAW device design[10,12] e.g. diffraction, beam steering, spurious mode excitation, parasitic capacitance and resistance and acoustic attenuation, but all are now well characterized. Although design can be quite complex, it can nevertheless be straightforwardly carried out to a high degree of accuracy.

From the above discussion it is obvious that there is no “universal” acoustic material; the “best” material is dictated by its intended application. In practice, the most widely used materials are ST-quartz, because of excellent temperature and spurious response characteristics, and $LiNb0_3$, because of a high coupling constant. However, for specialized applications, such as those requiring a long delay or high frequency, other materials are employed.

III. SAW Components. A. Introduction. Despite-their relatively short history, SAW devices have found their way into a number of systems and subsystems. However, apart from the TV filter to be discussed below, by far the widest usage of SAW devices has been in the field of radar, a field to which the time delays and bandwidths of SAW devices are well suited. The SAW pulse compression filter has been particularly significant; this component is now widely used in operational radar systems. Communications systems tend to require smaller bandwidths ($\leq$ 10 MHz) and longer time delays (> 1 ms) than radar systems, parameters for which SAW devices are not in general well suited. However, for some applications SAW devices offer clear advantages over competing technologies. These applications will be highlighted in the remainder of this section.

B. Bandpass Filters. An extremely wide variety of bandpass filter responses can be realized with SAW delay lines by proper design of the interdigital transducer. The design engineer uses two parameters to achieve the desired bandpass shape--the electrode separation and overlap (Fig.2). The former determines the frequency of maximum response and the latter the amplitude contribution of any given set of electrodes. The actual design procedure relies on the property that the spatial pattern of the transducer is equivalent to its impulse response. Mathematically, the frequency response, H(ω) and the impulse response, h(t), are a Fourier
transform air. I.e.

$$H(\omega) = \int_{-\infty}^{\infty} h(t) e^{-j\omega t}\, dt \qquad (2)$$

The frequency response of a transducer made up of N uniformly spaced, unweighted electrode-pairs is sinx/x with a 3 dB bandwidth of 1/N. To produce a rectangular frequency bandpass, the electrodes must be weighted in a sinx/x spatial pattern. The finite transducer length causes ripples in the bandpass which can be minimized with proper additional weighting functions. Ripples can also be caused by acoustic phase front distortion, electromagnetic feedthrough and spurious mode excitation.

Of the wide variety of SAW bandpass filters the one receiving the most attention is the TV filter since it is the first SAW device which has the potential of finding a wide commercial market. The Zenith version of the filter,[13] whose frequency response is shown in Figure 3, is not a complicated filter by SAW standards. Deep traps at 39.75 MHz and 47.25 MHz are necessary to remove the upper adjacent channel picture carrier and the lower adjacent channel sound carrier, respectively. In general, the electrical performance of the filter is excellent as compared to conventional IF filters. The main concern has been its economic viability; the filters must be manufactured for ~ $2 apiece. Recent indications are that its use is imminent, however.[13]

The group at Edinburgh University has identified several communications s stems which could advantageously be retrofitted with SAW filters.[14] Specifications for two such filters are given in Table II, one an IF filter for a 2700 channel analog repeater and a second a gaussian response IF filter for a 32 channel PCM system. Both can be realized with high quality state-of-the-art design and fabrication procedures. Besides the usual SAW device advantages of lightweight, compactness and ruggedness use of SAW IF filters can eliminate the time consuming adjustments required for lumped element filters. Furthermore, any reproducible group delay distortion can be designed out in the filters themselves.

TABLE II
Specifications for IF Filters for a) 2700-Channel Repeater and b) 32-Channel PCM System

	a)	b)
Center Frequency	140 MHz	70 MHz
Insertion Loss	< 8 dB	--
Passband Width	±15 MHz(-1 dB) ±25 MHz(-3 dB)	±2.5 MHz (-3 dB)
Passband Ripple	< .1 dB (±15 MHz)	--
Stopband Attenuation	> 50 dB (±40 MHz)	> 35 dB (±7.5 MHz)
Group Delay Variation	.1 ns.(±15 MHz)	3 ns.

Table III presents a recent tabulation of SAW bandpass filter characteristics divided into three categories--those now practical, those demonstrated in the laboratory and those which should ultimately be realizable. Not all parameters can be achieved simultaneously e.g. low insertion loss and low phase ripple are currently not feasible. In order to achieve less than 6 dB insertion loss multi-phase transducers have been developed. However, their complexity and lack of flexibility has precluded their wide use to date. Most of the limitations in Table III follow directly from the material and fabrication considerations discussed in Section II.

TABLE III
SAW Bandpass Filter Ca:)abilities
(after Claiborne[15])

Parameters	Practical	Developmental	Projected
Center Frequency	10 MHz-1.0 Ghz	10 MHz-1.5 GHZ	1 MHz-2 GHz
Bandwidth	50 kHz-0.4 f_o	50 kHz-0.4 f_o	20 kHz-0.8 f_o
Minimum Insertion Loss	6 dB	2-3 dB	1-2 dB
Sidelobe Rejection	45 dB	65 dB	70 dB
Deviation from Linear Phase	±1.5°	±1.5°	±1.0°
Amplitude Ripple	0.5 dB	0.05 dB	0.05 dB
Triple-Transit Suppression	-40 dB	-50 dB	-50 dB

C. Fixed Phase-Coded Delay Lines. Tapped phase-coded delay lines for analog matched filtering can be straightforwardly implemented with SAW technology. A simple 3 chip device is shown in Figure 4. Operation in the generation or correlation mode is possible. To generate a bi-phase code, a voltage impulse is applied to the input transducer producing an acoustic wave having a spatial duration equal to the transducer length. The input transducer length is equal to the tap spacing, resulting in a uniform amplitude output signal as the acoustic wave passes beneath the output transducer. The phase of the output voltage is determined by the relative position of the taps, i.e. tap 3 is 180° out of phase with taps 1 and 2. The chip rate is fixed by the surface wave velocity and the output tap spacing. When the device is to be used as a correlator, the phase coded transducer is designed to have an impulse response equal to the time inverse of the to-be-processed signal waveform.[16] A sharp correlation peak occurs when the signal just fills the coded transducer.

Numerous applications for SAW-tapped delay lines as analogue matched filters (AMF) have been suggested. Collins and Grant[17] pointed out the utility of the SAW devices in M-ary communication systems, direct spread spectrum systems, continuous multiple access systems and passive navigation systems. Functions performed by the fixed SAW-AMF include synchronization, ranging, code generation and identification. Of these, the synchronization is perhaps the most important. Here the receiver contains a SAW-AMF coded with a known segment of the transmitted code. When the segment appears within the SAW delay line, a sharp correlation peak is generated and the desired timing information obtained. Because the operation is asynchronous, the lockup time is reduced by a factor equal to the matched filter processing gain over that of conventional serial search techniques,[18]

In continuous multiple-access systems, each subscriber is designated a specific pseudo-noise (p-n) sequence which enables the transmitter to select a given subscriber by simply preceding his message with the proper p-n sequence. The SAW-AMF is an attractive way of implementing this subscriber identification functiona[17]

A somewhat different use of SAW devices for electronic identification was recently demonstrated.[19] Each object to be identified contained a passive transponder with a SAW delay line coded with a specific 10 digit code. When the interrogating unit emitted a short burst (impulse), the interrogated unit responded by transmitting its unique code back to the interrogator for processing and identification. This general approach to identification is attractive because of its simplicity and low power requirement.

Generation of long PSK sequences with SAW devices has also been demonstrated. The SAW tapped delay line is used with two taps of the phase-coded output transducer connected to a modulo-2 adder which in turn is fed back to the input. With appropriate choice of the number of taps, n, and the feedback taps, a p-n sequence of 2^n-1 can be generated. Crisp[20] demonstrated a temperature-stable, 100-stage SAW-shift register operating at a bit rate of 20 MHz. Extension to 300 stages and 150 MHz appears feasible. This approach to code generation is attractive for relatively high speed, low-power consumption applications.

SAW phase-coded-delay lines have also been used to generate frequency hopped (FH) p-n codes.[18] Four 127 tapped delay lines, each coded with a different p-n sequence and each operating at a different center frequency were cascaded to share a common output. Individual devices were centered at 40, 50, 60 and 70 MHz, respectively; all operated at a 10 MHz chip rate. By impulsing the individual lines one-at-a time according to a p-n sequence, a FH/p-n sequence was generated.

Performance limitations of fixed-coded delay lines are summarized in Figure 5. Again division is made in three categories, production, custom and developmental. Additional problems are incurred with “long” devices i.e. high sensitivity to misorientation and temperature fluctuations. For these devices ST quartz is almost universally used.

D. Programmable Matched Filters. The devices described in the previous section can process only one fixed code. For greater flexibility SAW tapped-delay-lines have been developed in which the phase of each tap is programmable. A number of schemes to provide for a ±180° phase shift have been investigated; the most widely used is shown in

Figure 6(a).[22] Single pole double throw switches are used to connect taps to one of two summing busses. The switches are operated in pairs so that one tap per pair is grounded at any one time. The signal derived from each set of taps undergoes a 180± phase change when the d.c. bias polarity is changed. Many of the same general performance limitations noted for the nonprogrammable devices apply for the programmable devices. In addition it is necessary to connect the taps to the switching circuitry. The finite real estate to make this interconnection and excessive cross talk place limits on the achievable chip rate. Using hybrid schemes, i.e. quartz or lithium niobate with taps wire bonded to silicon switching circuitry, the chip rate is limited to 10 MHz. An integrated scheme, aluminum nitride transducers on a sapphire substrate with taps controlled by silicon-on-sapphire diodes, has been used to realize a 20 MHz chip rate.[23] With either of these schemes the total power required per tap is about 2 milliwatts.

An alternate SAW technique for carrying out PSK signal processing is shown in Figure 6(b).[24] The PSK signal, V_1, and a reference cw signal, V_2, are applied to transducers on opposite sides of a delay line. V_1 and V_2 are picked up by the phase-coded taps and mixed in the diodes, producing a signal V_3 at the sum and difference frequency of V_1 and V_2. The polarity of the bias current determines the tap polarity. As in other SAW schemes, taps are coherently summed using two busbars. This configuration has the advantage of requiring only two switching diodes per tap, which will potentially lead to simpler construction, higher reliability and higher chip rates than the configuration shown in Figure 6(a). Switching power is low, ~.1 mw/tap, and total power required per tap is again ~ 2 mw.

Many applications envisioned for the programmable devices are extensions of those discussed above for fixed-coded devices. The programmable capability is, for example, useful in PSK synchronization. There is a significant added flexibility since the taps can be programmed to an arbitrary segment of the transmitted code which is imminent but has not yet arrived. The programmability capability also results in a much more versatile code generator, i.e. generation of multitude of different p-n sequences is possible. Perhaps most importantly PSK data demodulation can now be carried out.

However, for many applications code lengths of 1000 chips and bit durations in excess of 100µseconds are needed. It is impractical to realize this capability by a straightforward utilization of SAW technology since the total insertion loss of such a device would exceed 100 dB. However, the potential advantages to be gained with SAW devices have led a number of investigators to seek ways of circumventing these limitations.

It is generally conceeded that the maximum practical length SAW programmable correlator is 100-150 chips. The most straightforward technique for realizing a long code capability is simply to cascade a number of the shorter devices, interspersed with amplifiers. A 650-

chip correlator was constructed in this manner before noise buildup and band limiting became troublesome.[24] A 1000-chip module using the modules shown in Figure 6(b) seems feasible.[25]

Another technique being developed is use of a single programmable SAW device in conjunction with a coherent summing loop or integrator.[26] Operation of such a device at a center frequency of 100 MHz and a chip rate of 5 MHz was demonstrated. Codes of up to 2047 chips were correlated but processing gain deteriorated rapidly with code lengths in excess of 250 chips. Furthermore, synchronism of the integrator and programmable correlator is quite difficult.

It is instructive to compare SAW matched filters to other widely used approaches, charge coupled devices and digital techniques. This is done in Table IV. Note that the SAW approach is useful where high data rates and low power consumption are necessary.

TABLE IV
Comparison of Key Performance Parameters for Matched Filters
(after Hartmann et a1[27])

	SAW	CCD	Digital
a) Operating Freq.	10 MHz-2 Ghz	1 KHz-10 MHz	0-10 MHz
b) Max.Processing Time	0.1msec	100msec	∞
c) Max.T - BW	10^3	10^3	∞($)
d) Dynamic Range	> 60 dB	> 60 dB	2^n:l
e) Pw'r.Consumption/Analog Bit	10^{-3} to 10^{-2} watts	10^{-5} to 10^{-4} watts	10^{-1} to 1 watt

E. Convolvers. The programmable devices described in Section D operate at a fixed chip rate, determined by the tap spacing and acoustic velocity. Correlation of a signal with arbitrary amplitude, phase and chip rate can be carried out using the SAW-convolver. There have been numerous proposed embodiments of the convolver; the simplest is shown in Figure 6(c). The signal, V_1, is applied to one transducer while an externally generated reference, V_2, is applied to the other. Elastic and piezoelectric nonlinearities mix the two signals producing V_3, a signal at the sum frequency and difference wave vector of V_1 and V_2. The usual operation is degenerate, $\omega 1 = \omega_1 = \omega$, so that a uniform electrode is used to detect V_3. It is easily shown that V_3 is the convolution of V_1 and V_2, time compressed by a factor of 2.[28]

Other configurations have been investigated to improve the efficiency of the basic SAW-convolver. Most rely upon coupling the electrical fields associated with acoustic wave propagating in piezoelectric materials to electrons in an adjacent semiconductor.[28] Improved non-linear response is achieved only at the expense of a considerable increase in fabricational complexity. The diode correlator[29] has also been effectively used as a convolution device. Essentially the same configuration shown in Figure 6(b) is employed, with the exception that a single diode is used per tap. The electronically generated reference and the signal are inserted at opposite ends of the delay line, mixed in the diodes and summed in the busbars. A comparison of the performance of the basic-acoustic convolver and diode correlator is shown in Table V. Parameters are individually optimized, not all are simultaneously realizable.

TABLE V
Predicted Short-Term Performance Limitations[30]
(Parameters shown are considered individually)

	Centre Frequency MHz	Bandwidth MHz	Duration µsec	TB	Inser. Loss dB	Dynamic Range dB	Spurious Rejection dB
Degenerate Acoustic Convolver	500	200	40	2000	75	55	50
Diode Convolver	500	50	40	500	20	80	35

Morgan[31] recently demonstrated correlation of a 1300 chip, 5 MHz chip rate signal at 130 MHz in a system which utilized the SAW convolver as the basic signal processing element. The 250 microsecond long code was correlated in 25 microsecond segments and the resultant correlation peaks summed in a recirculation loop. A 36 dB improvement in signal to noise ratio due to the correlation was reported. Again the limiting performance factor was band limiting in the recirculation loop.

In summary, it now is feasible to programmably correlate 1000 chip sequences with tapped-SAW devices or SAW convolvers. However, it remains to be established whether these devices can reliably meet rigid systems requirements without undue cost and complexity.

F. Other SAW Devices. A number of other SAW-based devices with some additional development could also prove useful in communications systems applications. One such device is the SAW oscillator, consisting of a SAW delay line-amplifier loop.[32] The amplifier gain is chosen to just overcome losses in the delay line resulting in stable oscillation. The resultant signal is very clean and can be modulated by up to a part in 100. The SAW oscillator exhibits good short term stability, 1 part in 10^9, moderate temperature stability, ~1 ppm/°C, but poor long term stability, ~2 ppm/mo. When the aging problem is solved the devices are attractive for use as cheap, low noise sources and would seem an excellent candidate for a space qualified local oscillator.[14]

A new but potentially very important SAW device is the SAW resonator. Structurally it consists of an interdigital transducer placed between two sets of distributed reflectors on a quartz or lithium niobate substrate.[33] Operation in excess of 800 MHz has been demonstrated; Q's in the 10^3 to 10^4 range have been obtained. Because the structure is planar it is much more rugged than its bulk acoustic wave counterpart. If practical problems such as minimizing temperature and aging effects and provision for frequency trimming can be solved, the SAW resonator will greatly simplify many UHF receivers and transmitters by elimination of frequency conversion steps, phase locked loops and multiplier chains.

A number of other SAW techniques are now emerging from the research stage. Particularly significant are devices for fast Fourier-transforms,[34] adaptive filtering,[35] signal storage and imaging.[36] The continuing evolution of the technology assures that SAW devices will have a significant impact on systems of the 1980's.

A related area, magnetostatic surface waves, is currently receiving attention as a means of carrying out signal processing directly at microwave frequencies.[37] Relatively low loss and variable delay capacity makes it an attractive candidate for a group delay equalizer.[14]

IV. Conclusions. Although the SAW technology can be considered a fairly mature technology, use of SAW devices in communications systems to date has been minimal. However, because SAW devices are capable of high performance in a simple, rugged, compact structure and can be designed with great accuracy, wide systems usage should be soon forthcoming. The bandpass filter will undoubtedly see the widest application. It is exceedingly simple and can already fulfill needs for which there is no other practical solution. Programmable SAW devices, although somewhat of a specialty item, should prove important in systems employing high data rates where low power consumption is essential. Finally, the continuing strong base of SAW research and development should produce a number of devices which will impact heavily on systems evolving in the next decade.

Acknowledgments. The author is indebted to K.L.Davis for his helpful comments on the manuscript and to C.Banks for preparation of the figures.

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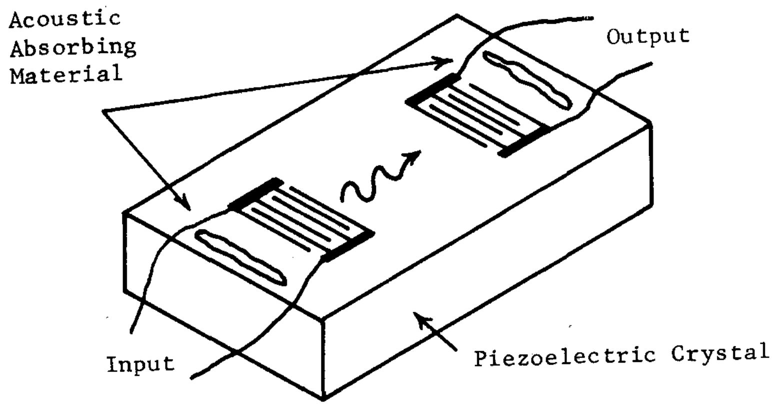

FIGURE 1. BASIC SAW DELAY LINE

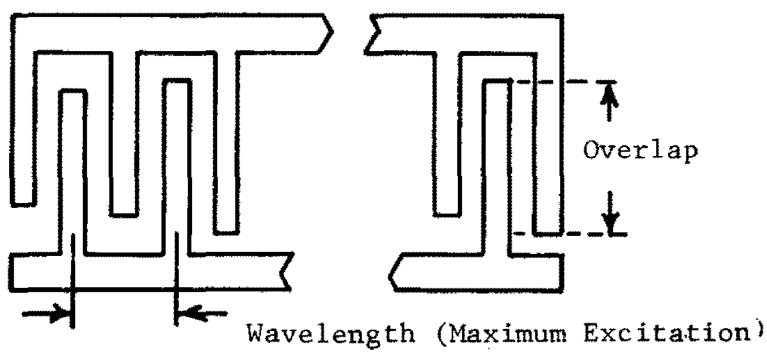

FIGURE 2. INTERDIGITAL TRANSDUCER

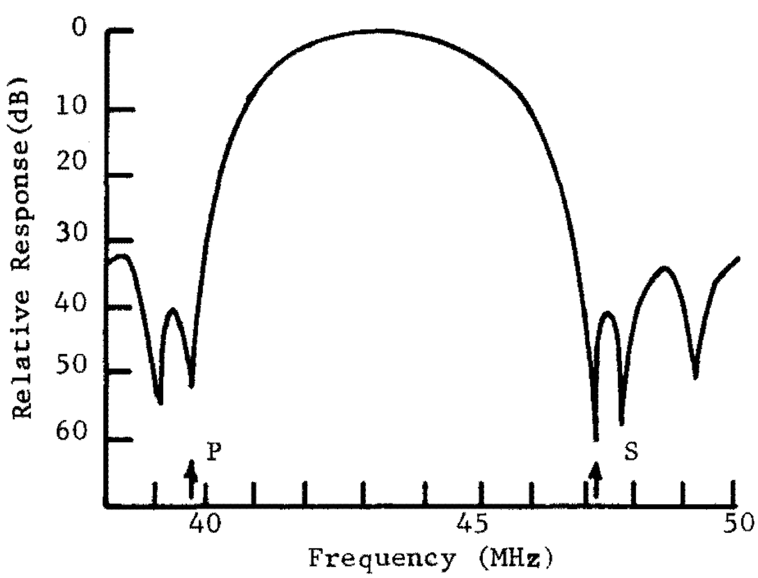

FIGURE 3. ZENITH TV FILTER RESPONSE

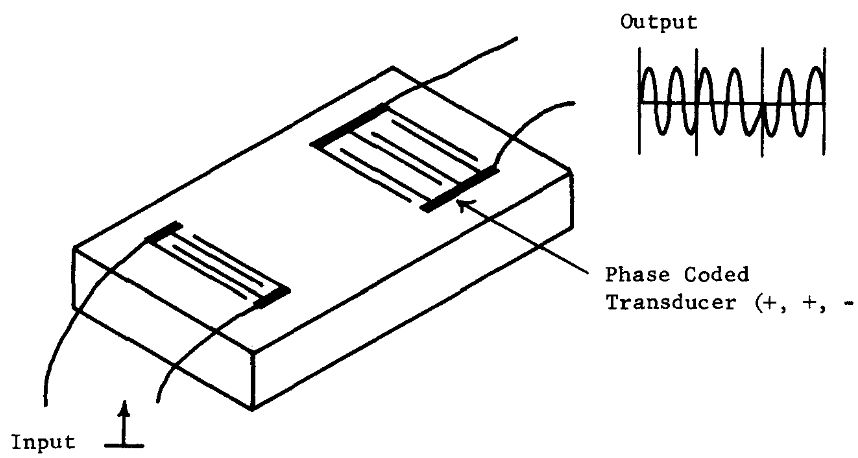

FIGURE 4. PHASE CODED DELAY LINE

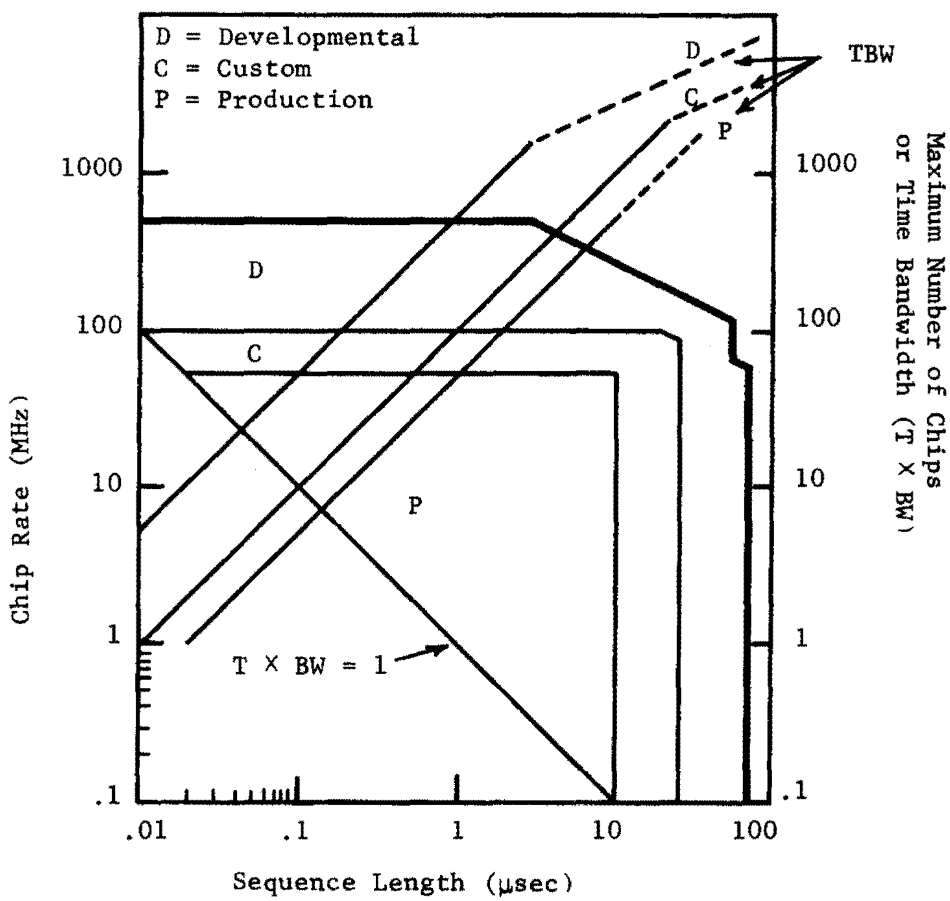

FIGURE 5. FABRICATION CAPABILITIES FOR CODED DEVICES (After Bell et al[21])

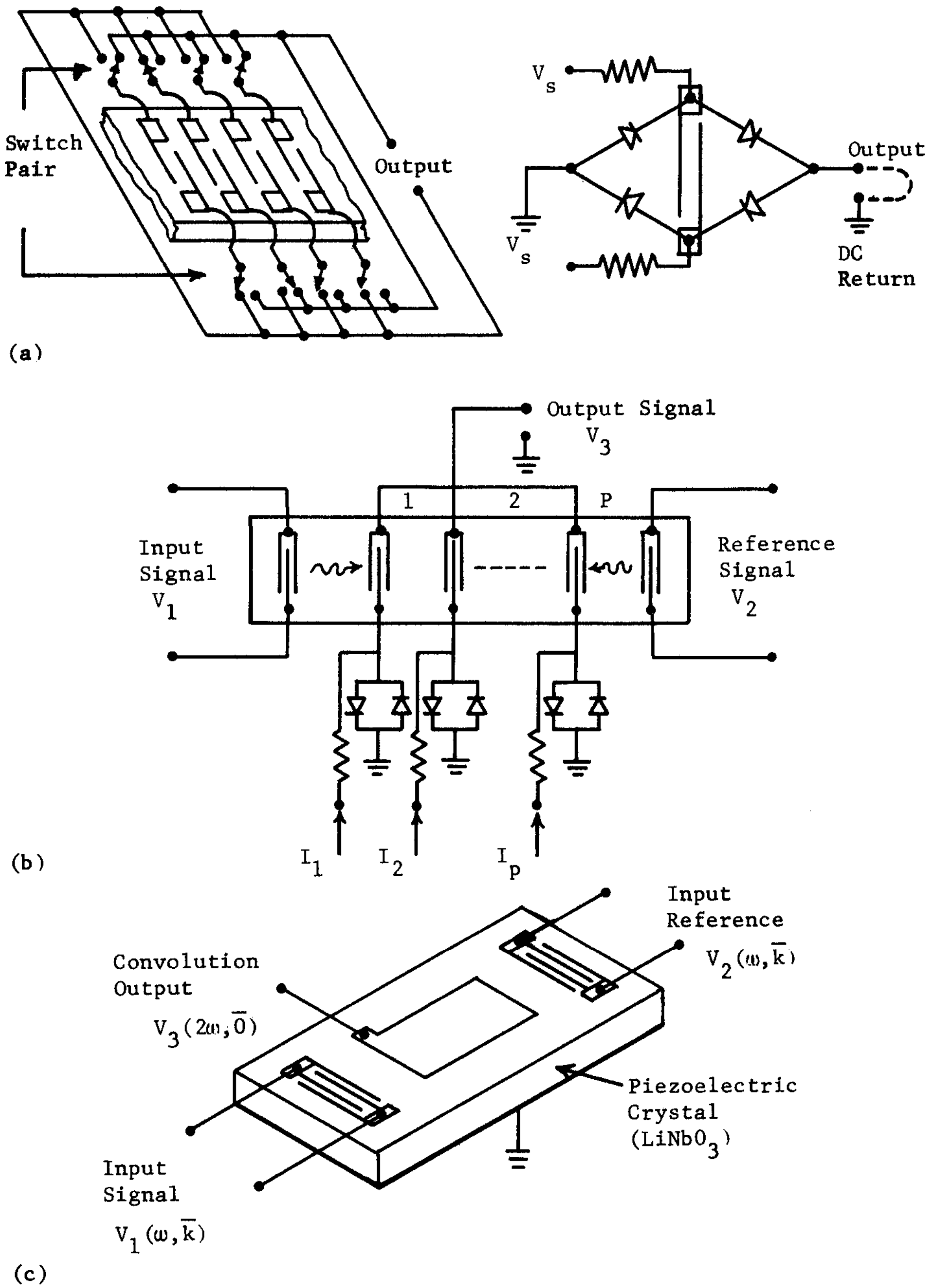

FIGURE 6. PROGRAMMABLE SAW DEVICES a) CONVENTIONAL TAPPED DELAY LINE, b) DIODE-CORRELATOR, c) CONVOLVER.