fibers may some day find a place; the biggest questions are probably economic rather than technologic, although research is needed to clarify which of the alternative pathways to attaining high capacity is to be preferred.

Fiberguide might also be used to provide control and communication for electrical power companies, where the insulating properties and noninductive nature of fiberguide would be great assets (36).

Although the United States has held a leading position in this technology, much research into the use of fibers for telecommunications is being conducted in Japan, where the service to power companies has received great emphasis (36). There is also considerable interest in the art in England, Germany, and France.

The Future

The pace of activity is feverish, expectations are high, and economics continues to regulate the ultimate usage of glass fibers in telecommunications. With so many fiberguide potentialities and so much effort to find economically viable applications, photons in fibers seem certain to flourish.

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New Technologies for Signal Processing

Charge-transfer and surface acoustic-wave phenomena are used in advanced signal processing devices.

Robert W. Brodersen and Richard M. White

The signal processors discussed here—the charge-transfer device (CTD) and the surface acoustic-wave (SAW) device—are based on new electronic design principles. Charge-transfer and SAW devices use an analog representation of information which moves along a path on a planar surface: in the CTD charge packets move in a semiconductor, and in the SAW device elastic wave energy propagates. Short-term storage of charge is possible in the CTD, and the speed of motion of charge through the device can be controlled externally, providing the opportunity to accept information at one rate and output it at another. In both the CTD and the SAW, simple means exist for sensing the moving charge or wave frequently along its path; with either technology this permits one to realize new types of signal processors based on the concept of the transversal filter, which is discussed below.

Charge-transfer and SAW devices are in similar stages of evolution. Their development until recently has been primarily in research laboratories which were perfecting the technologies. Both technologies are now sufficiently well understood that designers are beginning to incorporate them in complex electronic systems. A few of these new system applications and the advantages obtained by using either a CTD or an SAW are presented in this article. We expect that an accelerating use of these devices will be seen as system designers become more familiar with them and the devices themselves become more readily available.

Charge-Transfer Device Delay Lines

A CTD is an array of closely spaced capacitors fabricated by using metal oxide semiconductor (MOS) technology. Its operation involves the movement of a charge packet which is stored on one

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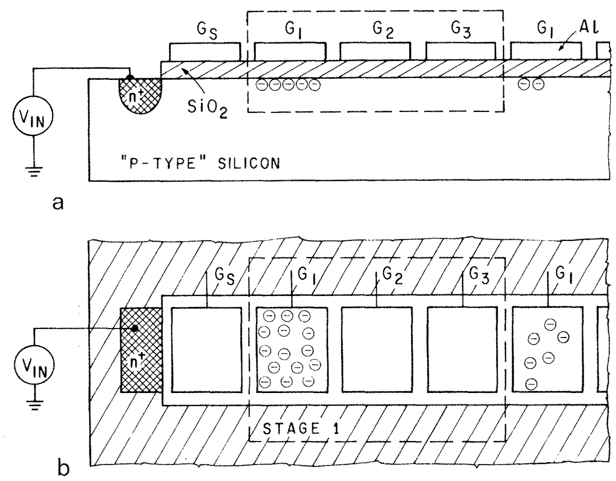


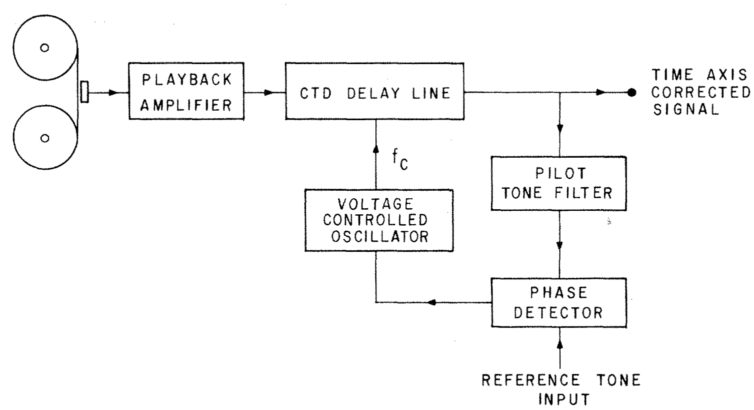


Fig. 1 (left). (a) Cross section of a portion of a CTD with an input composed of an n^+ diode and sampling gate G_s which isolates the signal charge packet. The first stage of the device is enclosed by dashed lines. (b) Top view corresponding to (a). Fig. 2 (right). Timing error correction system for tape recorders, using the variable delay capabilities of a CTD.

capacitor to an adjacent capacitor in the array. In addition to signal processing, CTD's are finding important use as digital memories as well as solid-state imagers (*1*). The simplest application of a CTD is as an electronically variable analog time delay. In this section we briefly discuss the basic operation of a CTD (*2*) delay line and two applications that are made possible by this unique CTD capability.

A cross section of a typical CTD structure is shown in Fig. 1a. The device is composed of a silicon dioxide insulating layer 1000 angstroms thick sandwiched between a metal layer (typically aluminum) and a semiconducting (silicon) substrate, which for CTD's is generally doped to be p-type. A CTD is formed by selective etching of the metal (see Fig. 1b), localized oxidations, and diffusion of elements such as boron and phosphorus into the silicon. Its features can be extremely small (on the order of micrometers), and photographic techniques are used to define the circuit patterns.

Application of a positive voltage to one of the metal gates depletes the p-type silicon underneath that gate of holes, which are its major charge carriers. However, this voltage attracts the minority carrier electrons, because it produces an energy minimum (potential well) for electrons at the interface between the silicon and the insulator. It is these potential wells that are used for storing and transferring the signal charge.

The potential wells can fill up with electrons much as a container can fill up with fluid. There are two sources of these electrons: a controlled number of electrons (a signal charge packet) can be introduced into a well formed under the first gate G_1 by means of an external input voltage, $V_{in}(t)$, or electrons can be randomly introduced throughout the CTD by thermal generation from within the silicon. The CTD's are therefore dynamic devices in which the desired signal charge can be stored only for intervals that are short enough so that the thermal generation is sufficiently small. This time is typically of the order of seconds at room temperature.

To transfer the charge from one MOS gate to another, appropriate clocking pulses (typically 10 to 15 volts) are applied to the metal gates. To transfer the charge from gate G_1 to the adjacent gate G_2, a positive voltage is applied to G_2 (creating a potential well beneath it) while the well under G_1 is collapsed by reducing the G_1 voltage. The electrons that were stored in the G_1 potential well will now transfer along the semiconductor-insulator interface to the new well under G_2. A similar transfer moves the charge from G_2 to G_3 and then from G_3 to the next G_1 gate outside the dashed lines in Fig. 1.

The three gates enclosed by the dashed lines in Fig. 1 are called a stage; one complete clock cycle of T_c seconds is required to move the charge packet one stage to the right. When the charge packet transfers into the second stage it is sufficiently isolated that another packet can be introduced into the first stage without causing mixing of the two packets. In this way N charge packets, which are analog representations of N time samples of $V_{in}(t)$ (one sample every T_c seconds), can be stored simultaneously in an N-stage CTD. Since the delay through one stage is T_c seconds, N stages yield a delay of NT_c seconds. Therefore to change the time delay it is only necessary to change the period, T_c, of the external clocking waveforms. It is important to note that even though the input signal is sampled in time (as in the case of digital processing) the amplitude of the signal is retained in analog form. This makes it possible for the CTD to have the stability and convenience of operating under clocked timing while retaining the computational efficiency of an analog approach (an advantage that will be shown later).

To sense the delayed input signal, it is necessary to convert the charge packet back to either a voltage or a current. A voltage can be generated by transferring the charge packet onto an output capacitance, which has a buffer amplifier attached to it.

An important characteristic of CTD circuits is their high density, which stems from the use of the MOS technology as well as their extremely simple repetitive structure. A single stage of a CTD designed for signal processing typically measures 25 by 250 micrometers, which means that a 100-stage device is only 0.25 by 0.025 centimeter. Since a typical MOS integrated circuit measures 0.5 by 0.5 cm, this CTD requires only about 2 percent of the total available circuit area. It is therefore desirable in systems applications to integrate other system functions onto the same integrated circuit (IC) as the CTD. This capability of system integration is expected to provide much of the impetus for future developments in CTD signal processing.

Two applications of the CTD delay line that make use of the ability to vary the transfer rate of the charge packets (by varying the clocking period T_c) are transient data recording (*3*) and the correction of timing errors in tape recorders (*4*).

Many physical phenomena occur so quickly that it is very difficult to analyze the data from a single event as it happens. It is therefore desirable to store the data and then perform the analysis at a more moderate rate. Unfortunately, most conventional storage techniques require that the data be converted first into a digital representation with a high-speed analog-to-digital converter, which can become extremely expensive for short sampling intervals. A CTD provides a very inexpensive and convenient means of sampling and storing a data transient in analog form. Since the CTD sample period can be varied, after a number of samples have been taken at sufficiently short sample intervals (that is, a high enough clock rate $1/T_c$), the clock rate is reduced and the data are read out at a slower rate for analysis. Devices that can store 1000 samples taken at time intervals as short as 50 nanoseconds (a clock rate of 20 megahertz) are commercially available, and clock rates as high as 130 Mhz have been achieved with special CTD designs (*5*).

Because the clock rate of a CTD is variable, it is also possible to have an electronically variable time delay, since the total delay time through an N-stage delay line is NT_c. This ability is very useful for correcting small, rapidly varying timing errors such as those which arise in video tape recorders because of an out-of-round capstan, fluctuations in the drive motor speed, and tape stretching. (Long-term timing errors can be corrected by the slower conventional motor speed control techniques.) Figure 2 shows a CTD timing error correction system (*4*) in which a steady pilot tone is recorded on the tape along with the desired signal. During playback the signal and pilot tone are delayed by a CTD delay line. The delayed pilot tone is then compared to a reference tone of the same

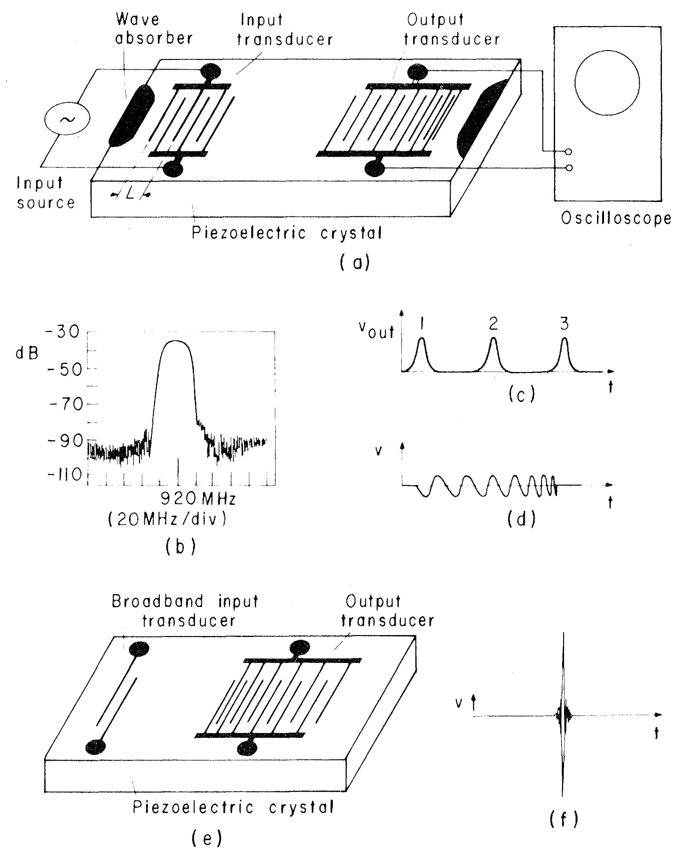
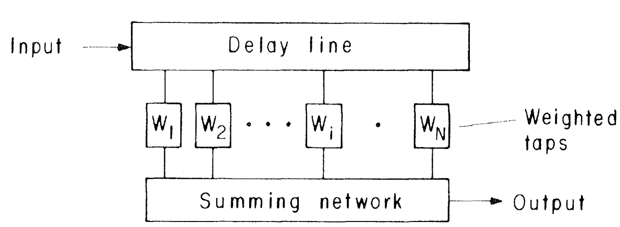


Fig. 3 (left). Operation of SAW electrode transducers. (a) Schematic of a typical SAW device, showing the voltage source connected to the input transducer producing surface waves that propagate to the output transducer, which has nonuniformly spaced fingers. The output voltage might be displayed on an oscilloscope as shown. The strongest wave excitation by the input transducer occurs if the distance L equals one SAW wavelength at the input source frequency. (b) Bandpass filter characteristic (insertion loss versus frequency) resulting from frequency-dependent excitation and reception by transducers in an actual SAW filter (*21*). (c) Frequency analyzer application showing the output voltage V plotted against time delay t in a device like that in (a) when low, medium, and high frequencies are input (outputs 1, 2, and 3, respectively). (d) Chirp output that would be obtained from the device in (a) if a voltage pulse of very short duration were applied to a broadband input transducer consisting of a single pair of electrodes. (e) Sketch of an SAW device having a broadband input transducer and an output transducer identical with the device in (a) but reversed right to left. (f) Sketch of the output when the expanded chirp pulse (d) is applied to the input of the device in (e). [The voltage and time scales are the same as in (d).] Note that the pulse has been compressed in time and increased in amplitude, permitting detection and precise timing in a noisy environment.



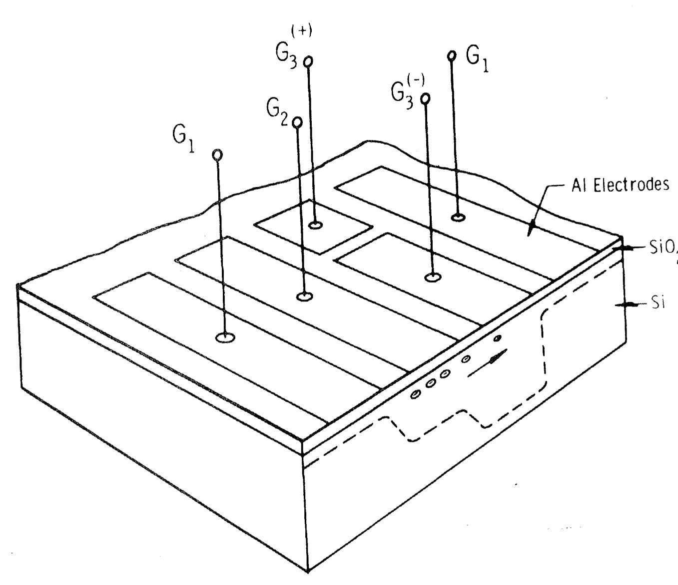


Fig. 4 (above). Schematic of the transversal filter, which is the basis for the design of many CTD and SAW devices. Fig. 5 (right). Portion of a CTD transversal filter, showing the split in one electrode (G_3) that determines the weighting coefficient.

frequency, and timing variations can be detected as a phase change between the recorded pilot tone and the reference tone. The phase detector shown in Fig. 2 will produce a voltage proportional to this phase difference which is used to control the frequency of an oscillator in a standard voltage-controlled oscillator circuit. This frequency determines the clock rate (and thus the delay) through the CTD in such a way as to eliminate the timing error that was detected. The advantage of such a system is that it could be integrated on a single IC and thus could provide a very inexpensive technique for improving recorder performance.

There are many other applications of analog time delay (*6*), including echo generation for electronic music, ghost cancellation in television, and filtering. Also, by the addition of input (or output) structures at each stage of delay, time division multiplexers (or demultiplexers) for radar and communication systems can be implemented (*7*).

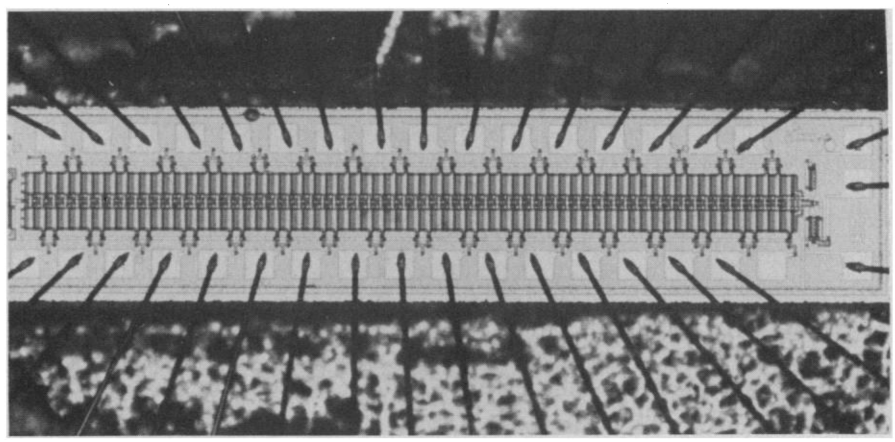


Fig. 6. Photomicrograph of a 32-stage CTD that has an output (nondestructive) at each stage of delay. The total device size including the rectangular bond pads for connecting the 32 output leads is 0.1 by 0.5 cm. The CTD itself is the long rectangular structure between the rows of bond pads. [Courtesy of G. Weckler, Reticon Corporation]

Surface Acoustic-Wave Principles

In SAW devices information is represented by ultrasonic acoustic waves propagating freely along the surface of a planar solid, rather than by charge packets moved along by an external energy source as in the CTD. These waves, whose intensity is greatest at the surface, involve exceedingly minute motions of the particles of the solid on which they propagate: in typical SAW devices the particle displacements are at most a few angstroms (*8*).

The wave velocity depends on the materials comprising the path of propagation and on the structure employed. The surface wave velocity is independent of frequency for a uniform solid, but propagation on a layered solid is dispersive (frequency-dependent). A typical velocity for surface acoustic waves is 3×10^3 meters per second, which is 100,000 times lower than the velocity of electromagnetic waves in a vacuum; hence, at a given frequency an SAW wavelength (wavelength = velocity/frequency) is about 100,000 times smaller than an electromagnetic wavelength. (For example, a 300-Mhz signal in an SAW device would have a wavelength of only about 10 μm.) The lowest frequency at which SAW devices are useful is limited to about 5 Mhz by the dimensions of available crystals and the increase in wavelength as frequency decreases, while wave attenuation and fabrication difficulties set an upper limit of a few gigahertz for room-temperature devices. Thus the CTD and SAW devices typically operate in complementary frequency ranges, and the data rates of SAW devices may be very high.

It is easy to convert electrical signals to surface acoustic waves (and vice versa) by use of transducers based on the piezoelectric effect. If a surface wave propagates on a piezoelectric crystal (such as crystalline quartz) or on a nonpiezoelectric crystal coated with a piezoelectric layer (such as a silicon wafer coated with piezoelectric zinc oxide), a traveling electric field accompanies the propagating acoustic wave. In effect, the displacements of the atoms of the medium produce local electric fields inside and just outside the solid. One can couple external sources or detectors to these electric fields by means of conducting electrodes evaporated onto the surface and shaped by photolithographic techniques like those used in making integrated circuits.

Figure 3a shows an SAW device on a piezoelectric insulator. The signal source creates electric fields between the evenly spaced fingers of the input electrode transducer on the left side in Fig. 3a, producing surface waves that propagate toward the output electrode transducer (on the right), where they produce an output voltage that might be displayed on an oscilloscope. (Waves launched to the left by the input transducer are absorbed by the absorbing material on the left end of the crystal.) Each finger of the input transducer acts as a source of waves; the frequency of the strongest wave excitation by the input transducer will be that for which the spacing between alternate fingers equals one SAW wavelength, because for this frequency the contributions from the individual electrodes will add in phase. Thus, using the earlier example of 300-Mhz waves and a phase velocity of 3×10^3 m/sec, the center-to-center distance, L, of alternate electrodes should be one wavelength or 10 μm.

If the transducer on the right in Fig. 3a were identical with that on the left, this device would function as a simple delay line, delaying signals by about 3.3 μsec for each centimeter separating the two transducers. The device would operate well only in a band of frequencies near the design center frequency (300 Mhz) because at frequencies far removed from that the waves produced by individual electrode fingers would tend to interfere destructively, causing decreased output. Such frequency-selective transmission has been used to make miniature SAW bandpass filters for operation in television sets and other electronic equipment (Fig. 3b).

Considering again the output transducer as it is actually shown in Fig. 3a, we note that the placement of fingers varies along the transducer, from larger spacings on the left side to smaller ones on the right. This variable spacing causes the left end of that transducer to respond most strongly to lower-frequency waves (larger wavelengths) and the right end to higher-frequency waves. Thus if a brief input signal composed of many frequency components is applied to the input transducer, the low-frequency components produce a voltage at the output transducer sooner than the high-frequency components do because they arrive earlier at the portion of the output transducer that is responsive to them. Thus one can make a frequency analyzer with this simple structure, in which frequency differences in an impulse excitation are converted to differences in arrival time which can be measured on an oscilloscope (Fig. 3c).

Let us consider two other uses of this device, in pulse expansion and pulse compression. If we apply a voltage of very short duration to an input transducer consisting of just one pair of electrode fingers at the left of the device of Fig. 3a, a surface wave having many frequency components is produced, and when this wave passes under the output transducer shown, the output voltage is a waveform with a frequency that varies from low to high (Fig. 3d). Such a waveform is called onomatopoeically a chirp. Chirp waveforms have applications in radar, sonar, medical ultrasonics, and other signal-processing fields. In radar, for example, a reflected signal from a very distant target may be lost in noise because of the limited amount of peak power one can generate and transmit from an antenna; in medical ultrasonics, the instantaneous intensity that can be safely transmitted into the body is limited to avoid tissue damage. One can alleviate these problems by amplifying and transmitting a chirp waveform generated as described above (*9*), receiving the echo (also a chirp that starts at a low frequency and rises to a high frequency), and applying the received echo to the broadband input transducer of an SAW device like that of Fig. 3a but with its output transducer reversed (that is, with its closely spaced electrode fingers nearer to the input transducer than the widely spaced fingers, as shown in Fig. 3e). In this second SAW device the low-frequency components are detected after the high-frequency ones, and the long-duration low-amplitude received signal is compressed into a much shorter pulse of higher amplitude (Fig. 3f). Thus the travel time to a reflecting target could be determined with precision in spite of interfering noise.

These examples show how very simple patterns of electrodes on the surfaces of piezoelectric crystals are used to make SAW devices for such varied operations as signal delay, filtering, frequency analysis, and pulse expansion and compression.

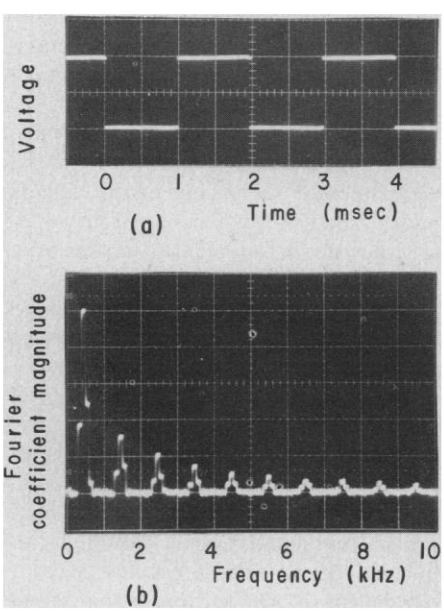


Fig. 7. CTD spectrum analysis: (a) 500-hertz square-wave input, and (b) CTD spectrum analyzer output showing the magnitudes of the lowest-frequency spectral components. The magnitude of the *n*th harmonic is proportional to $1/n$ as expected.

Transversal Filtering

Filters are circuits that are generally used to pass or reject different frequency components, which is probably the most common function performed in electronic systems. It is difficult to conceive of any moderately complex electronic system that does not employ some type of filter (*10*).

One approach to filtering is to use a transversal filter, which is shown in block diagram form in Fig. 4. The output of a transversal filter is a weighted sum of delayed replicas of the input signal. Any desired frequency response can be obtained (*11*) by properly choosing the weighting coefficients W_i (within constraints determined by the allowable amount of delay).

Surface acoustic waves provided the first practical and convenient way to make high-performance, compact transversal filters which can operate at data rates of hundreds of megahertz. Charge-transfer devices have also been used extensively to perform transversal filtering, but at lower frequencies (100 hertz to 5 megahertz). The conventional approach to filtering (inductance-capacitance and active filters) in this frequency range requires the use of circuit components (for example, inductors and precision resistors) that cannot be integrated onto a single IC. This can severely limit the complexity of the system that can be integrated, since a relatively large amount of circuit area is required to interface the IC with the external components. In addition, the use of external components can significantly increase the cost and degrade the reliability compared to those of a fully integrated system.

In the next two sections we give examples of the use of CTD and SAW devices to demonstrate their advantages.

CTD Transversal Filters

There are several methods for implementing transversal filters based on CTD's. The highest performance is obtained with the split electrode approach (*12*), in which some of the metal gates used in transferring the charge are split into two sections, as shown in Fig. 5. The charge that flows into each part of the split gate is proportional to the product of the channel voltage and the gate capacitance. The channel voltage is equal to a delayed value of the input voltage. The capacitance of each side of the gate is determined by the placement of the gaps (Fig. 5), which are located to yield the weighting coefficients W_i. It is therefore only necessary to sense the differential value of the displacement charge between the two sides of the *i*th split gate G_3 in order to obtain multiplication of the delayed input signal by W_i. By summing the charge on the two bus lines that connect the split gates, the sum indicated in Fig. 4 can be obtained.

This approach has the advantage of high density [800-stage transversal filters have been made (*13*)] as well as high performance [10-bit accuracy of the coefficients W_i is possible and filter dynamic ranges in excess of 80 decibels have been achieved (*14*)]. The major disadvantage of this approach is that since the weighting coefficients are fixed once

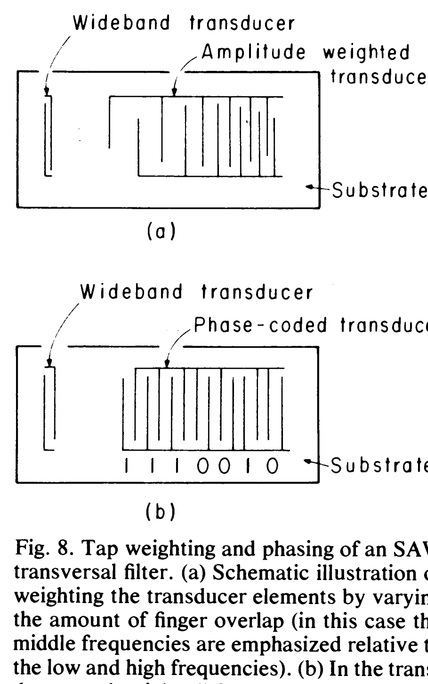


Fig. 8. Tap weighting and phasing of an SAW transversal filter. (a) Schematic illustration of weighting the transducer elements by varying the amount of finger overlap (in this case the middle frequencies are emphasized relative to the low and high frequencies). (b) In the transducer on the right all fingers overlap the same amount but the phasing of pairs of fingers varies because of changes in bus bar connections. A binary sequence represented by transducer phasing is indicated below the output transducer.

the photolithographic mask has been made, it is not possible to vary the filter response after the device is fabricated or to perform adaptive filtering functions. This type of device is limited to applications that require a large number of filters having the same response in order to amortize the cost of mask making over many units.

For lower-volume application a programmable device would be more desirable because it could be tailored by the user. One way to obtain this capability is to sense nondestructively the delayed value of the input at each stage of a delay line, bring this off the IC, and then perform the multiplications and summation externally. A photomicrograph of a commercially available 32-stage tapped analog delay line is shown in Fig. 6. External resistors and amplifiers can be used to perform the multiplications and summation, providing a complete transversal filter whose characteristics (tap weights) can be altered.

It is informative to compare the amount of computation that can be performed by a CTD transversal filter with the capabilities of a general-purpose computer such as an IBM 360 or a CDC 6400. These computers can perform about 10^7 multiplications and sums in 1 second (*15*). A CTD filter of 10^3 stages can perform 10^3 multiplications and 10^3 additions (2×10^3 operations) in parallel during each clock period. Since a filter can be operated as fast as 5 Mhz, this means that a CTD filter can achieve a processing rate of $(2 \times 10^3) \times (5 \times 10^6) = 10^{10}$ operations per second. Thus the CTD filter, which might cost as little as $1 or $2, can perform three orders of magnitude more computation per second than the large, general-purpose computers. Of course these computers are not limited to special-purpose operation like the CTD filters, but because of the parallel architecture of the CTD processor and the efficiency of analog computation, the CTD approach retains enormous processing advantages for special applications.

Spectral or Fourier analysis (the decomposition of a time waveform into its frequency components) could be performed by a bank of CTD band-pass transversal filters. This is very wasteful, however, compared with an approach that makes use of the chirp z-transform algorithm (*16*). With this algorithm, an N-point Fourier transform could be implemented on a few IC's using only four N-stage CTD transversal filters (*17*).

The first 100 coefficients from the output of a 500-point CTD Fourier-spectrum analyzer are shown in Fig. 7b. The input signal was a 500-hertz square wave (Fig. 7a). The harmonics of the square-wave spectrum are clearly evident at 1.5, 2.5, . . . khz. A CTD spectrum analyzer realizes the advantages expected from the use of the parallel analog processing of the CTD transversal filters. It can calculate a spectrum many times faster than the fastest special-purpose digital computer. In addition, because it can be integrated onto a few IC's, substantial savings can also be made in cost, size, weight, and power (*18*).

Spectral analysis by use of the CTD chirp z-transform is expected to be very important in image processing, speech recognition, radar Doppler processing, sonar spectral analysis, video bandwidth compression, and other applications requiring low-cost spectral analysis.

Processing Signals with SAW Devices

Surface-wave devices are useful in part because the SAW electrode transducers themselves are transversal filters: delay results from propagation of the wave along the substrate under the electrodes, which tap off a portion of the wave energy, and summing of currents from individual taps occurs in the broad bus bars connecting the fingers. Tap weighting and phasing is easily accomplished by (i) tailoring the amount of overlap of adjacent fingers (the output from each pair of fingers is roughly proportional to the amount of overlap) and (ii) connecting corresponding fingers of each pair to one bus bar or the other for proper phasing (Fig. 8).

Most of the SAW devices (*19*) used to date have been bandpass filters (*20*) based on the transversal filter concept. Illustrative are SAW filters used in connection with television receivers, both in the intermediate-frequency sections of commercial receivers (*21*) and in some electronic television games where they confine the output transmission to the selected channel (channel 3 or 4). Such SAW filters are smaller than conventional filters made with inductors and capacitors, they can be reproduced precisely once the photolithographic master has been designed and made, and they do not require adjustment after manufacture. Another example is the SAW inverse filter (*22*), whose frequency response is ap-

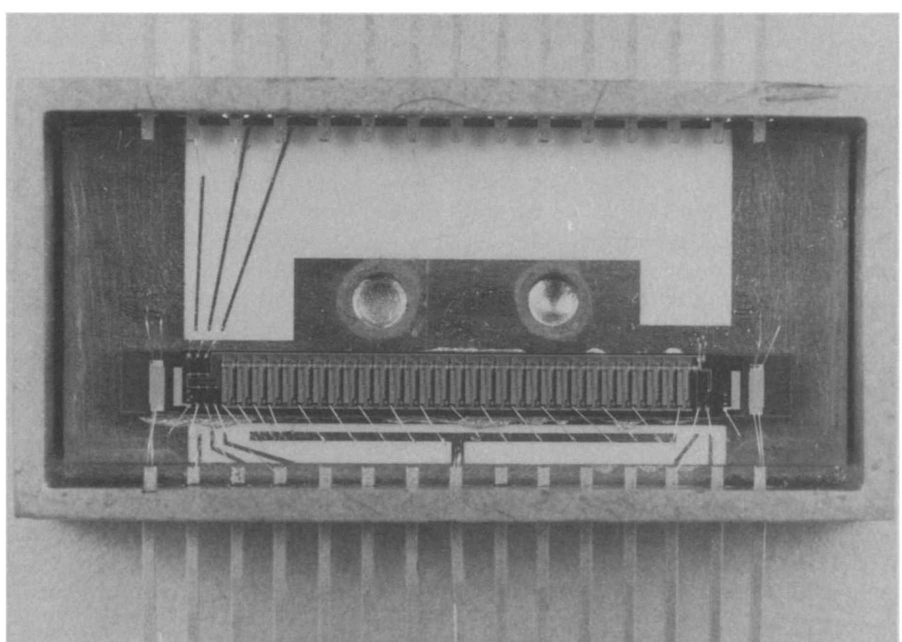


Fig. 9. Electronically programmable SAW matched filter mounted in a conventional flatpack. Thirty-one taps are visible on the ¾-inch-long silicon substrate that extends across the lower portion of the package. Gold wires carry currents from the taps to the summing electrode on the white insulating circuit board below the silicon device. Piezoelectric zinc oxide sputtered onto the silicon after fabrication of the circuit is the light rectangle at the far left side of the wafer; the 100-Mhz SAW input transducer is located there. Tap phasings are set by read-only memory located above the line of taps. The signal to select the desired filter characteristic reaches the device through one of the six angled conductors crossing the white circuit board at the left end of photograph. The device can be used to generate the waveform to which it is matched if the SAW transducer at the right side of the silicon wafer is used. [Courtesy of F. Hickernell, Motorola Corporation]

proximately reciprocal to that of the sensor whose output is filtered. For example, partial correction for the limited frequency response of the source and receiver in a nondestructive tesing or medical ultrasonic system can be achieved with such a real-time filter. The matched filter is another useful device that can be made with the SAW (or CTD) technology. The impulse response, $h(t)$, of a matched filter is the time reverse of the signal, $s(t)$, to which the filter is matched; thus $h(t) = s(-t)$. The matched filter (*23*) has a much larger output for the desired signal $s(t)$ than it does for other input signals because the outputs from all the electrode fingers (taps) add in phase when the desired signal is midway in its passage through the filter. An example of such a matched filter was shown in Fig. 3e; the chirp output from the first SAW device was compressed by the second device because of the reversal of the transducer on the right (*24*). Matched filters can also be used in digital transmission systems for source-receiver synchronization, and in secure communications systems.

Changing the responses of these filters is sometimes of interest; for example, one might want to change the codes to which a receiving filter was matched in a secure communications system. Surface acoustic wave devices that can be programmed electronically in a few microseconds have been realized in several ways by combining piezoelectric and semiconductor materials. One practical approach has been to change the phasings of the taps on SAW filters by providing semiconductor diode switches for each tap to determine which bus bar it is connected to at a particular time (*25*). Field-effect transistors employing the piezoresistive effect have also been used as taps in a matched filter (*26*) constructed in a silicon wafer onto which zinc oxide is sputtered; a programmable read-only memory on the silicon wafer determines the proper phase for each tap when the filter is set to match a particular code (Fig. 9). Another powerful approach to programmability employs nonlinear effects: the input signal and a propagating or stored signal representing the waveform being sought mix in the nonlinear device to produce an output at the sum frequency; the output is maximum when the desired signal is present in the input. Such nonlinear SAW devices can also be used to perform the complex operations of convolution and correlation of high-frequency signals (*27*).

Some idea of the variety of applications to electronics that have been demonstrated can perhaps be obtained from these final examples: SAW's can be used for modulating and deflecting light in integrated optics (*28*); in an undersea pressure sensor where changes in wave travel time between transducers are measured (*29*); for temperature-compensated signal storage and delay in small disk-shaped quartz wafers (*30*); and, through partial reflection of waves at grooves or electrodes, to make high-quality resonators and very selective radio-frequency filters (*31*).

Conclusions

In charge-transfer and SAW devices new electronic principles provide efficient low-cost solutions to existing signal-processing problems. The combination of analog computation with a discrete time signal representation, which is available with CTD signal-processing devices, is found to have considerable advantages in reducing the cost, power, size, and weight of signal-processing systems. An important factor in obtaining these reductions is the compatibility of the CTD technology with standard MOS circuits, which allows integration of additional non-CTD functions and allows the design of integrated circuits that are complete subsystems in themselves. In addition, the ability to vary externally the transfer rate of the charge packet is the basis of many unique CTD applications.

In SAW devices the analog signals are represented by waves moving at a speed that cannot be varied, but the technology permits one to make sophisticated signal processors that operate at very high data rates with signal frequencies up to gigahertz. Taken together, the CTD and SAW technologies permit one to realize signal-processing functions that a few years ago would have seemed impossible.

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