SURFACE ACOUSTIC WAVE APPLICATIONS

Since the introduction of the SAW interdigital transducer in the late 1960s, SAW devices have tremendously affected a broad range of systems. The key to this technology is the ability to sense or tap a traveling electroacoustic wave on a piezoelectric substrate whose velocity is 10^5 times slower than an electromagnetic wave. The velocity and photolithographic line resolution determine the practical SAW operating frequency range from approximately 30 MHz to 3 GHz. Typical devices are manufactured in volumes from a few cubic millimeters at high frequencies to a few cubic inches at lower frequencies. Typically, the high-frequency devices have a small volume and low cost. Using various SAW components depending on the required specifications, it is possible to provide precise frequency filtering, frequency resonance, time-pulse shaping, and signal processing. The passive, solid-state SAW devices provide very high performance relative to their volume, weight, and cost which is the reason for their widespread use. The highest cost, precision devices are typically used for military and satellite systems which have the most demanding specifications, the intermediate cost devices are used in modest volume military man packs, military base stations, and commercial base stations, and the low cost devices are used in a broad range of commercial and consumer applications.

During the 1970s and early 1980s, military applications guided the development of the technology providing the ability to implement new and, up to that time, unachievable systems. A broad range of applications included dispersive devices and filter banks for radars, filters and resonators for conventional communication systems, delay lines for systems and weapons, and coded devices, encoded modulator devices, and convolvers for spread-spectrum systems requiring secure communications. These systems encouraged the development of most of the components still in use by SAW devices today. The advent of enormous commercial opportunities in mobile and wireless systems in the 1990s ushered in a renaissance in SAW technology and has spawned technological innovation in devices and systems.

In addition to device technological innovation, research and development on other propagating Rayleigh-like modes,

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

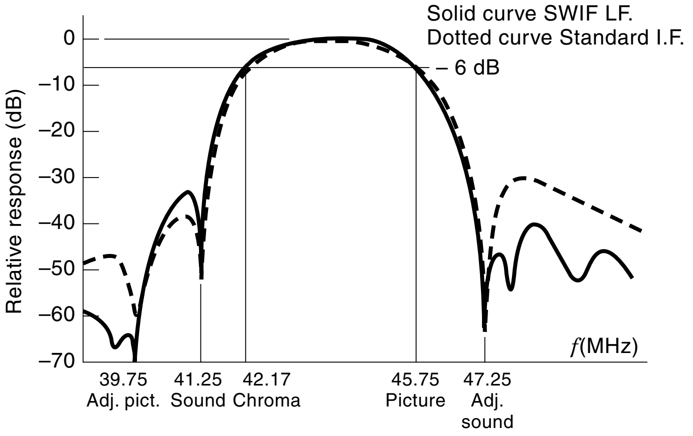


Figure 1. Early comparison of the SAW TVIF filter and the L/C equivalent circuits used in U.S. television sets. (Reproduced with permission of the IEEE, *Proceedings of the IEEE,* **64** (5): 672, 1976.)

called pseudo-SAW, and new substrate materials, such as lithium tetraborate and langasite, have provided lower loss, higher frequency, and wider bandwidth devices. These material and device enhancements allow SAW devices to compete for insertion in the RF, IF, and processing sections of modern communication systems. Commercial and consumer applications include cellular and mobile phones, car and garage door openers, VCRs, CATV, fiber optic repeaters, spread-spectrum systems, sensors, identification tags, satellite communication systems, and many more (1–4).

SAW TVIF FILTER

The SAW TVIF filter stands alone as the first significant commercial application of SAW devices for the television intermediate-frequency (TVIF) filter and deserves a highlighted discussion. Development began in the 1970s when SAW technology was just emerging. Design, analysis, fabrication, and packaging were all extremely challenging for SAW devices at that time. However, it was recognized that a significant technological advance would be achieved if a single, solid-state component could replace the bulky, mulitpole LC tank circuits in the IF which were both expensive to build and insert into the chassis. In addition, the LC sections drifted with temperature and aged with time producing a profoundly negative effect on video reception. The SAW TVIF filters were first introduced to the market in the late 1970s and demonstrated that high-volume manufacturing of the devices was feasible. Today, every TV manufactured has a SAW TVIF filter.

Figure 1 compares the SAW versus LC implementation of filtering in a TVIF section (5). The SAW TVIF filter is interesting because it demonstrates that the SAW transversal filter can meet a demanding design and cost specification. The

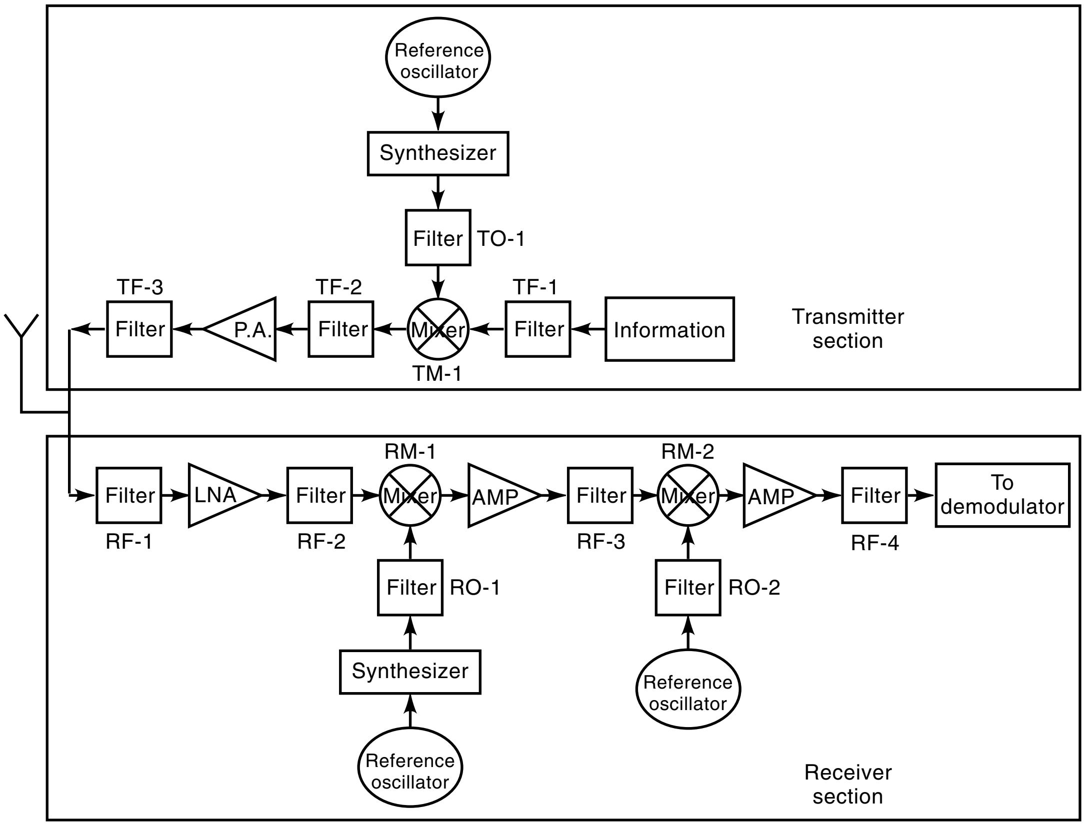


Figure 2. Schematic diagram of a generic transmitter/receiver (transceiver) system. The transceiver has a common antenna. The system can be separated into a transmitter and receiver by eliminating the common antenna. The gray blocks represent possible SAW elements witin the RF and IF transceiver sections.

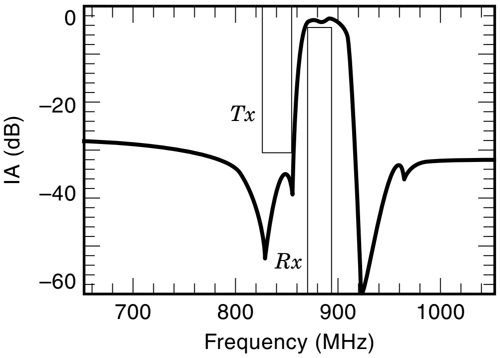


Figure 3. An 870 MHz SAW filter with a 3% fractional bandwidth and 2.0 dB insertion loss. This filter uses a multiresonator approach in a ladder-type network. This filter is used as the front end RF filter in the Advanced Mobile Phone System (AMPS). (Reproduced with permission of the IEEE, J. Machui et al., *1995 IEEE Ultrasonics Symposium Proceedings,* pp. 121–130.)

TV system requirements have been in place since TV's inception and vary by country around the world. The US system requirement is typical and is used as the example. The video and audio transmission format have remained the same for compatibility over the years and were determined from the original transmission specifications. These specifications required a nonsymmetrical template for the magnitude of the TVIF filter response and a precise dispersive group-delay response. The nonsymmetrical magnitude response sets the relative video and audio carrier levels and shapes the chroma response. The group delay must vary precisely with frequency to reproduce a sharp image and accurate colors. Early SAW TVIF filter insertion losses were greater than 20 dB which reduced the internal SAW device triple transit echo (TTE) to approximately 46 dB. A TTE greater than −40 dB produces a noticeable ghost picture which would be unacceptable to the consumer. Lower loss devices using new transducer and device embodiments reduce the loss below 20 dB while maintaining the specifications and costs required in the TV.

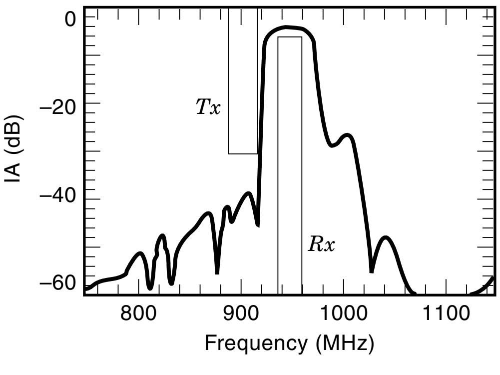


Figure 4. A 950 MHz SAW filter with an approximate 3% fractional bandwidth and 3 dB insertion loss. This filter uses a transversely coupled resonator filter which provides a two-pole response and good ultimate sidelobe rejection. This filter is used in the Global System for Mobile communication (GSM). (Reproduced with permission of the IEEE, J. Machui et al., *1995 IEEE Ultrasonics Symposium Proceedings,* pp. 121–130.)

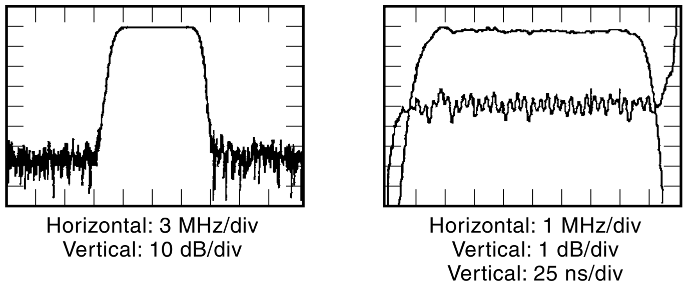


Figure 5. A typical 70 MHz IF filter having a typical insertion loss of 22 dB, 3 dB bandwidth of 8 MHz, and sidelobe rejection of greater than 55 dB. The passband has less than 0.25 dB ripple and group delay variation of approximately 40 ns. The passband ripple and group delay variation are primarily caused by the triple transit echo (TTE). The 70 MHz IF frequency is popular for military applications. (Reproduced with permission from Sawtek, Inc.)

SAW devices are manufactured by using many of the previously developed integrated circuit techniques. Multiple devices on a single crystal substrate using aluminum electrodes fabricated by conventional photolithographic techniques is very attractive. Similar to silicon technology, high-volume manufacturing provided the vehicle for advancing the technology so that costs were reduced. Costs for SAW TVIF filters dropped from several dollars per device in the 1980s to under $0.50 for current devices and are currently manufactured in volumes of millions per month. The SAW technology and device embodiments have been changed and refined to provide better performance at a lower cost (4). As the first high-volume commercial SAW application, the TVIF filter can be credited for the confidence that companies had when developing the current wide range of high-performance, low-cost commercial SAW products.

TYPICAL WIRELESS COMMUNICATION SYSTEM

There are tremendous numbers of different wireless communication systems for audio, video, and data transmission. Rather than attempting to focus on any one system which has its own specific characteristics, a more generic approach is

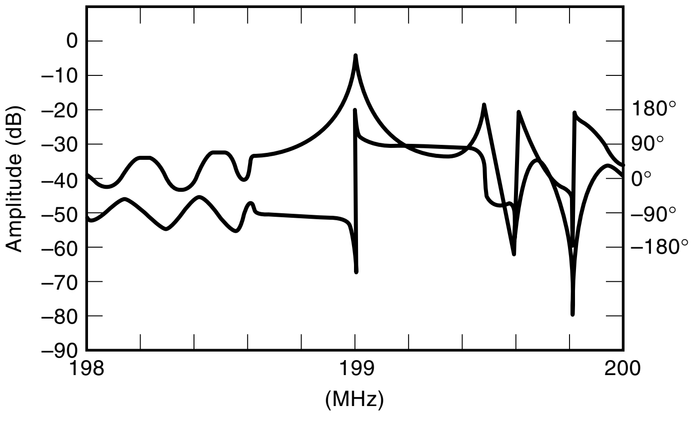


Figure 6. Magnitude and phase response of a 199 MHz, two-port, SAW resonator on quartz. (Reproduced with permission from Sawtek, Inc.)

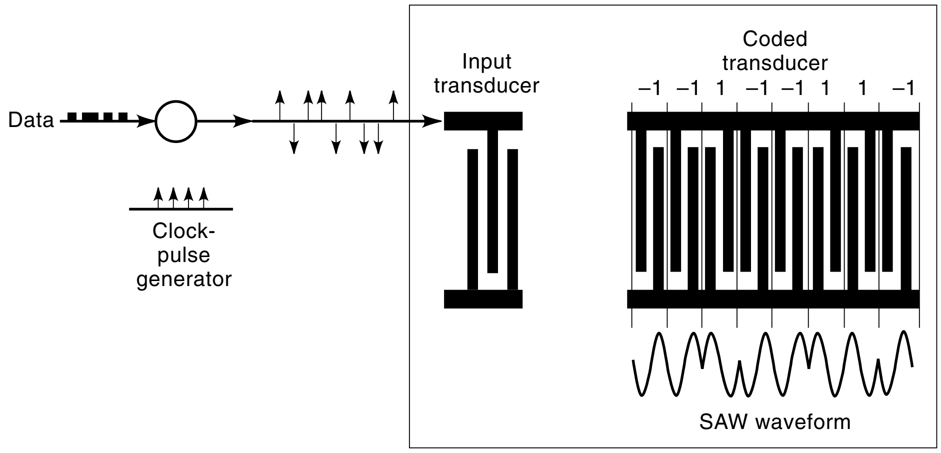


Figure 7. Schematic diagram of a typical SAW phase-shift-keyed (PSK)-type coded filter. The input data is converted into a series of phase-modulated impulses which then produce the SAW output-coded waveform.

taken. Figure 2 shows a schematic for a typical transmitter and receiver system. The radio-frequency (RF) section eliminates spurious responses and establishes the noise figure for the system, and the intermediate frequency (IF) sections provide the channel selectivity and limit the noise bandwidth. To reduce cost, the second IF section is eliminated when possible. The oscillator/synthesizer is used for channel selection and may be used as the system clock. The postprocessing of the signal may also contain SAW devices in many coded and secure communication systems. The gray blocks represent elements in which SAW devices may be inserted, depending on specifications.

RF SAW Devices

The receivers of interest operate in the frequency range between approximately 30 MHz and 3 GHz where typical SAW devices find application. The RF section center frequency and bandwidth are consistent with the channel requirements, and fractional bandwidths can be from fractions of a percent to tenths of a percent. The RF section consists of one or two RF filters and a low-noise amplifier (LNA). As an example, a typical mobile telephone system's center frequencies vary from approximately 450 MHz to more than 2 GHz with fractional bandwidths of 1% to 5%. One RF filter which has very low loss and good selectivity is desired. However, two filters may be necessary, the first with very low loss and marginal selectivity and a second filter with a higher loss and better selectivity. Any loss prior to the LNA is a direct reduction in signal-to-noise ratio. Therefore, RF filters require extremely low loss, typically between 1 dB and 3 dB. Figure 3 shows a typical SAW front-end RF filter for a mobile phone application at 870 MHz with an insertion loss of approximately 2.0 dB and a 25 MHz bandwidth (6). Typically nulls are designed at the adjacent transmit/receive frequencies for a transceiver, and sidelobe rejection depends on the design approach. The second RF filter can have a relaxed insertion loss specification but typically has greater out-of-band spurious suppression. Figure 4 shows a SAW interstage filter at 950 MHz with approximately 3 dB insertion loss implemented by using a transversely coupled resonator approach (6). SAW filter design techniques for RF filters include two-transducer low-loss designs, interdigitated interdigital transducers, single and multitrack resonant structures, and ladder/lattice impedance filters. For cellular applications, the antenna is common to both the transmitter and receiver, and it may be necessary for the RF receiver filter to accept large input power at the transmission frequencies. SAW ladder/lattice filters are currently of great interest because they handle high power and provide low loss and acceptable selectivity. Other important considerations are the temperature coefficient of frequency and the material coupling coefficient. The bandwidth must be increased to accommodate operation over the required temperature range, and the coupling coefficient determines the maximum achievable bandwidth for a given insertion loss.

IF SAW Devices

The IF filter typically has greater selectivity and higher insertion loss than the RF filter. The IF center frequency is chosen for good image rejection and adjacent channel selectivity and is lower than the transceiver operating frequency, typically from tens to hundreds of megahertz. The IF filter must have a narrow transition band and low sidelobe levels to limit the noise within the system and may also have specific traps to reduce adjacent channels, intermodulation, or other spurious carrier responses. The insertion loss is usually not as stringent a requirement as in the RF filter because the signal-to-noise ratio is set before this stage and amplification is typically low cost and available. IF stage insertion loss can range from several dB to as much as 50 dB depending on the fractional bandwidth and system requirements. Figure 5 shows a

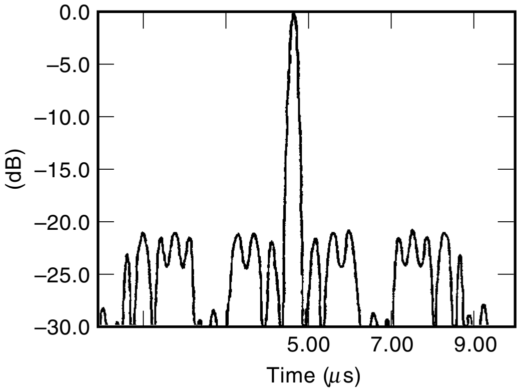


Figure 8. Measured time-domain response of a 128 chip PSK SAW correlator. (Reproduced with permission from Sawtek, Inc.)

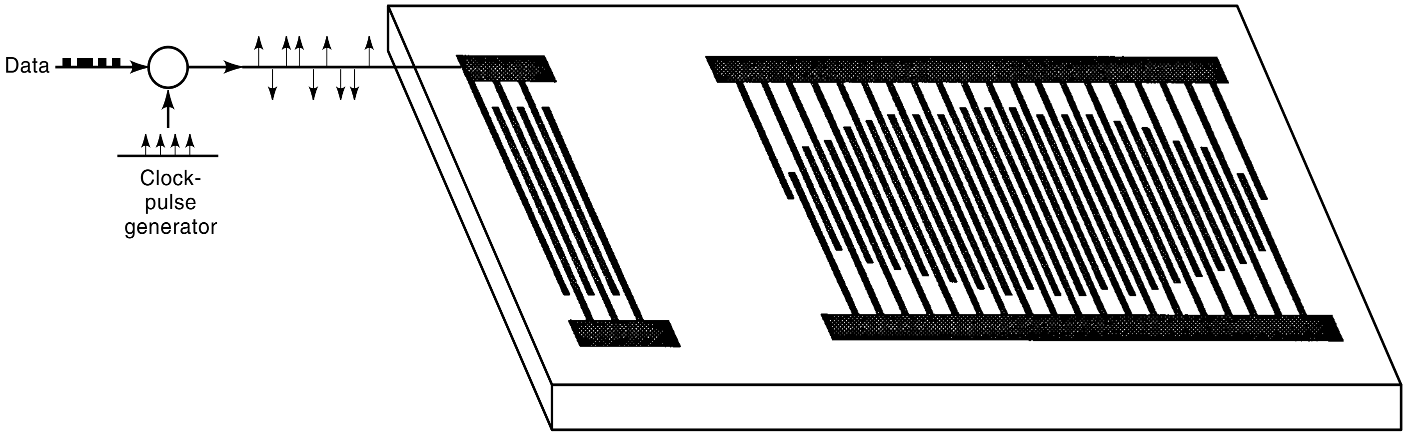


Figure 9. Schematic diagram of a typical SAW minimum-shift-keyed (MSK)-type coded filter. The input data are converted into a series of phase-modulated impulses which then produce the SAW output-coded waveform.

typical SAW IF bandpass filter at 70 MHz, insertion loss of 22 dB, 8 MHz bandwidth, and group-delay variation of approximately 40 ns. The filter is a conventional two-transducer, SAW transversal implementation which demonstrates the excellent passband shaping, extremely sharp skirts, and near constant group-delay response.

SAW Resonator Oscillator Applications

The oscillator/synthesizer often uses a SAW resonator for the frequency-control element having a center frequency such that, when mixed with the incoming carrier, it results in a signal at the IF center frequency. The oscillator frequency is chosen on the basis of a wealth of system considerations including the reception frequency, single versus double conversion, inter- and cross-modulation products, and other specifications. It is desired that the resonator be high *Q*, low loss, and have excellent temperature stability versus frequency. As an example, Fig. 6 shows a 199 MHz, quartz, two-port SAW resonator response. The peak to spurious level typically needs to be greater than 10 dB to ensure that any excessive loop gain in the oscillator does not result in oscillator instability. SAW resonator *Q*'s are typically several thousand and can be designed to tens of thousands. SAW oscillators often compete with bulk acoustic wave (BAW) devices which typically operate at much lower frequencies and use multipliers to obtain the frequencies of interest. Both SAW and BAW-based oscillators are often called crystal oscillators (XO). Oscillators have frequency drift primarily caused by the crystal temperature coefficient of frequency (TCF) and often have sophisticated electronics and temperature control to achieve long-term and short-term stabilities. Various configurations include the voltage-controlled (VCXO), temperature-controlled (TCXO), oven-controlled (OCXO), and microprocessor-controlled (MCXO) crystal oscillators.

Using a narrowband SAW resonator, it is also possible to produce a notch filter (7). Notch filters are used to eliminate a narrow carrier that is produced within a radio, such as in the oscillator, or they are used to eliminate an external signal, such as an adjacent channel carrier frequency. Various circuit configurations are used with resonators to produce a notch. The notch filter should have good temperature stability and a notch bandwidth adequate to track over the required operating temperature range. Multiple coupled resonators are used to obtain a larger notch bandwidth than the conventional single-pole resonators.

SIGNAL PROCESSING APPLICATIONS

Coded and Quadrature Modulators

PSK SAW Filter. Because each tap in a SAW device is independently controlled, it is very easy to implement simple-phase, shift-keying (PSK) biphase coding into a device. A schematic of a typical PSK-coded SAW used for coding the data in a spread-spectrum system is shown in Fig. 7. A digital data stream is converted into a series of impulses whose polarity corresponds to the sign of each data bit. The input transducer launches the wave whose phase depends on the sign of the input pulse and which is then convolved with the coded transducer. The SAW-coded transducer is composed of a series of time chips. The sign of each chip is implemented

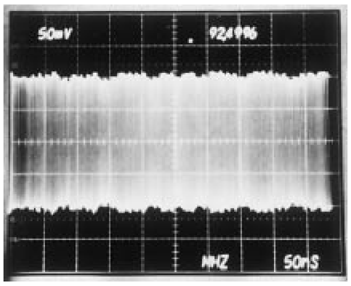


Figure 10. Predicted and measured time-domain response of a SAW MSK system at 300 MHz and a 92.5 MHz data rate. The predicted response has approximately 4% amplitude modulation compared to the 7% measured. The main cause for amplitude modulation is hardware system implementation.

by properly connecting of each electrode to the appropriate bus bar. The overall SAW impulse-response length is equal to the data bit length. The output from the SAW-coded transducer can be further modulated for transmission. A similar SAW filter can be used as the matched filter at the receiver where a compressed pulse is achieved whose phase is a function of the original data stream. The frequency bandwidth is determined by the chip impulse-response length, and the processing gain is a function of the number of chips per bit. Figure 8 shows the measured time response of a 128 chip PSK correlator which exhibits a peak-to-sidelobe ratio of approximately 21 dB, as expected.

Continuous-Phase Frequency-Modulation Devices

SAW devices are designed in both the time and frequency domains. The ability to pulse shape allows developing and implementing precise modulation schemes that are very difficult to implement with other technologies. Quadrature modulation techniques are very popular for transmission, they include quadrature-phase shift keying (QPSK), minimum shift keying (MSK) and others. The MSK waveform, along with many others, forms a class of continuous-phase frequency modulation (CPFM), encodes the information in the phase and frequency of each chip or bit, and has a uniform amplitude envelope. The phase continuity and uniform amplitude provide minimum distortion when transmitting through power amplifiers which are often nonlinear. These advantages are obtained at the expense of a wider chip null bandwidth which reduces data rates. A schematic of a simple way to implement a CPFM system is shown in Fig. 9 where the SAW device provides pulse shaping when excited by an impulse. For MSK, the pulse envelope shape is a simple one-half cycle cosine whose length is equal to the required bit length. The data bit length is one-half the MSK impulse-response length and, therefore, the device impulse response from a given data bit impulse overlaps adjacent data bits to form a nearly continuous, flat-envelope code stream. The predicted and measured SAW MSK waveforms are shown in Fig. 10.

Synchronous Optical Network

The synchronous optical network (SONET) has critical and demanding timing for data transmission. When transmitting over long distances, such as transoceanic, it is necessary to recover the clock from the actual nonreturn-to-zero (NRZ) data stream to retime the data at intermediate points along the network. One popular method is to use a SAW filter within the clock-recovery circuit, as shown in Fig. 11. Figure 12 shows a high Q, 622 MHz, quartz, SAW filter used in a SONET clock-recovery system. The device has a typical insertion loss of 16 dB, and a quartz substrate is used to minimize temperature drift effects. In addition to the clock recovery, SAW devices may be used in SONET as delay elements for timing or for data pulse shaping to minimize intersymbol interference and reduce the probability of error in data recovery.

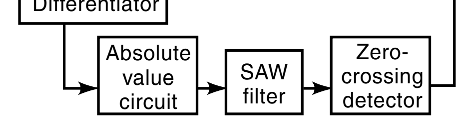
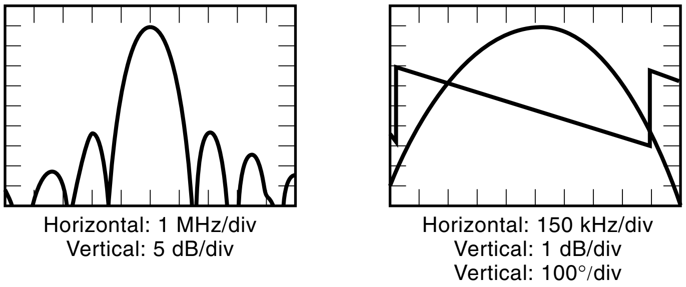


Figure 11. A simple schematic diagram of a SONET clock-recovery circuit using a SAW filter.



Horizontal: 1 MHz/div
Vertical: 5 dB/div

Horizontal: 150 kHz/div
Vertical: 1 dB/div
Vertical: 100°/div

Figure 12. Frequency response of a 622.08 MHz SAW filter used in a SONET clock-recovery circuit. The device has a typical insertion loss of 16 dB, a 3 dB bandwidth of 0.93 MHz, a delay of 700 ns, and is fabricated on quartz. (Reproduced with permission from Sawtek, Inc.)

Channelizers

In wideband communication systems which have multiple channels, it is often required to break the receiving bandwidth into adjacent channels. Sometimes these are channels that are processed independently, or there are times when multiple channels may be combined into a wider band channel. This requires a sophisticated system that has well-matched individual channels and an electronic system which provides the required switching network. SAW channelized receivers have met this demanding requirement for both military and commercial applications. A complete integrated SAW channelizer system allows dynamic, active switching in or out of one or more channels. The superimposed frequency response from a seven-channel, 330 MHz SAW filter bank is shown in Fig. 13. The uniformity of amplitude and out-of-

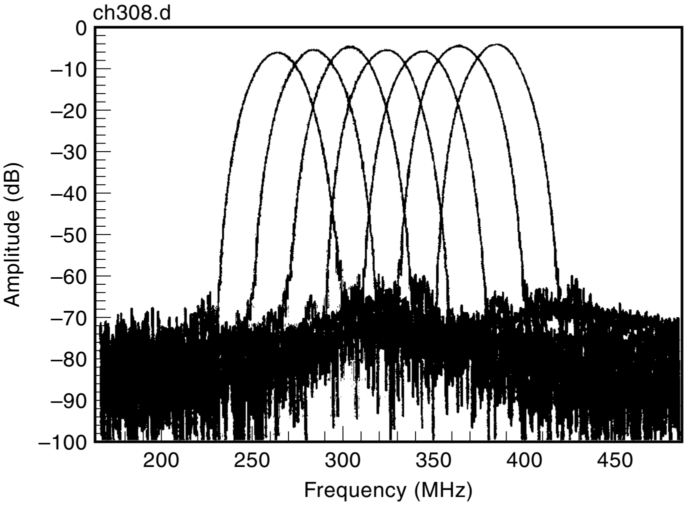


Figure 13. The superimposed frequency response of all channels of a seven-channel SAW filter bank at a center frequency of 330 MHz. (Reproduced with permission from Sawtek, Inc.)

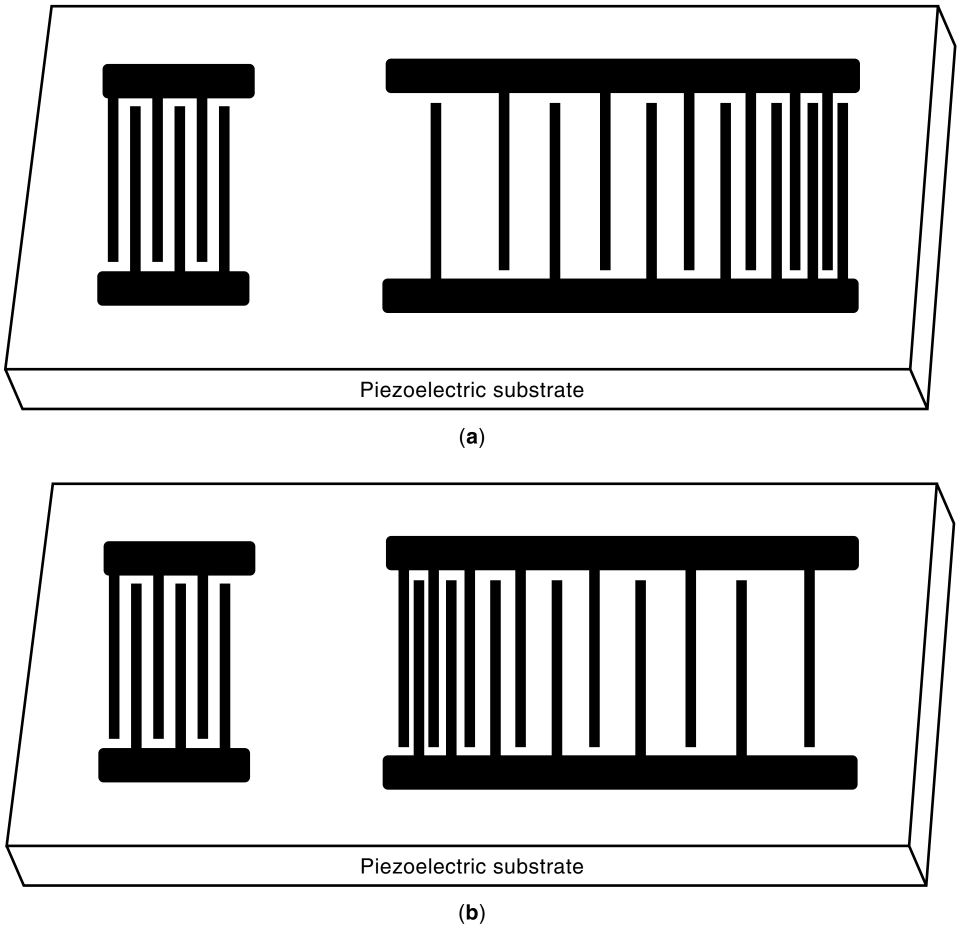


Figure 14. (a) Schematic of an up-chirp SAW filter. (b) Schematic of a down-chirp SAW filter.

band rejection (approximately 50 dB) between channels require precise filter design and system integration.

Dispersive Devices

Radar. One of the earliest and technologically important applications of SAW devices was in radar systems. The simplest radar in concept is the pulse radar. To obtain the greatest accuracy in determining an object's distance from a source, it is desirable to transmit a very narrow pulse from the source which is subsequently reflected from an object and received. The delay corresponds to the round-trip distance difference. The maximum viewing distance is limited by the path loss and the minimum detectable signal-to-noise ratio.

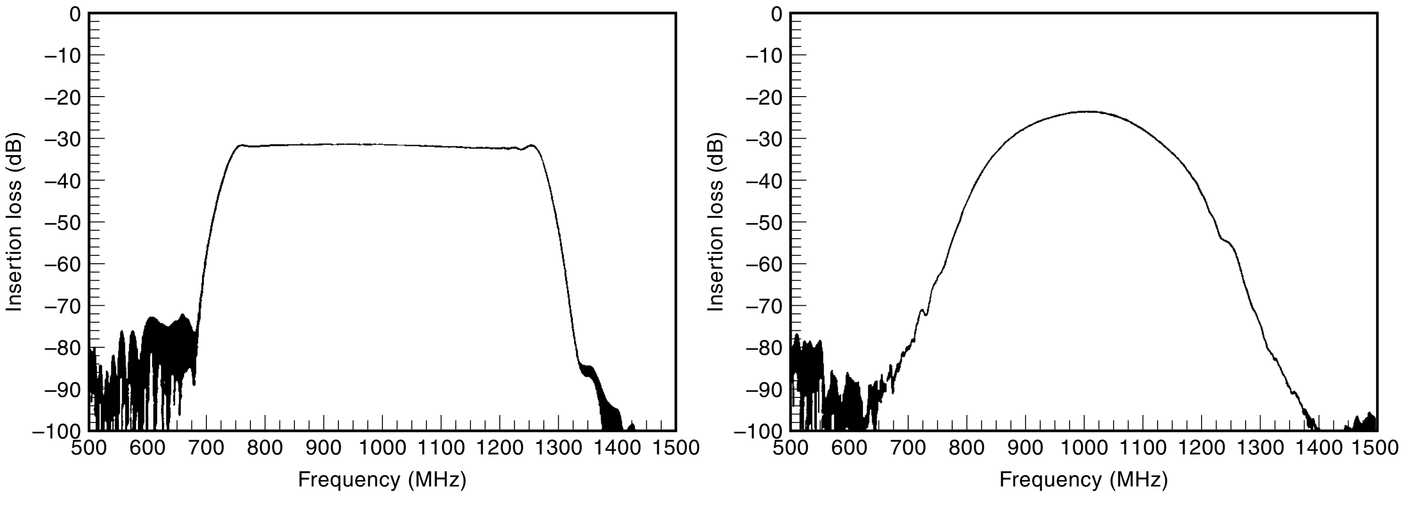


Figure 15. A dispersive SAW expander and compressor matched filter pair. The center frequency is 1.0 GHz, a 450 MHz bandwidth, 0.45 μs delay, and 1000 MHz/μs dispersion. (a) Expander and (b) weighted compressor. (Reproduced with permission from Sawtek, Inc.)

Therefore, it is desirable to transmit very narrow, high-amplitude pulses or to extend the pulse width. The former approach requires a very low duty factor and high-power transmitters whereas the latter lengthens the pulse which limits distance accuracy. The solution to these two conflicting requirements is to use a dispersive transmit pulse that changes the instantaneous carrier frequency with time. A chirp radar uses a SAW dispersive (or chirp) filter to transmit a long dispersive pulse that has significantly more energy than a simple, single-carrier frequency pulse (8). Then the return signal is sent to a matched SAW chirp filter that compresses the pulse. The SAW input/output devices are a matched set whose transmit filter is an up-chirp and receive filter is a down-chirp. Figure 14 shows a schematic representation of an up-chirp and down-chirp SAW filter. For a linear chirp, the frequency changes at a given chirp rate (Hz/s) from some minimum to some maximum value across the device. The processing gain, which is approximately given by ratio of the output compressed pulse width to the transducer impulse response length, is a direct function of the device's time–bandwidth product. Devices can be produced using simple dispersive transducers or by using long reflector structures called reflective array correlators (RAC) (8). Time–bandwidth products from several hundred to tens of thousands have been achieved. The time-domain responses of the transmitted and/or received chirps may be weighted to produce a more optimum time-domain pulse-compression response at the receiver. Figure 15 shows the frequency responses of an expander/compressor matched pair at a center frequency of 1 GHz having a bandwidth of 450 MHz, a dispersive delay of 0.45 μs, and a time-delay slope of 1000 MHz/μs. The compressed-time matched-correlator response has a compressed pulse width inversely proportional to the bandwidth (2.22 ns as compared to 2.9 ns measured) and a typical peak-to-sidelobe ratio of approximately 10 × log(time–bandwidth product) which is 23 dB.

SAW Chirp Fourier Transformer. Another application of SAW dispersive devices is in a chirp Fourier transform system that performs a real time Fourier transform of a given input signal which is confined to the system bandwidth. Given a function $f(t)$ which has a Fourier transform, $F(\omega)$, the frequency domain function is written as

$$F(2\pi\mu t) = \int_{-\infty}^{\infty} f(\tau)\, e^{-j2\pi\mu t\tau}\, d\tau$$

where $\omega = 2\pi\mu t$.

Using the identity $2t\tau = t^2 + \tau^2 - (t - \tau)^2$, the equation is rewritten as

$$F(2\pi\mu t) = e^{-j\pi\mu t^2} \int_{-\infty}^{\infty} f(\tau)\, e^{-j\pi\mu\tau^2} e^{j\pi\mu(t-\tau)^2}\, d\tau$$

This is the equation form of the chirp Fourier transform which is a time function multiplied by a complex chirp, convolved with a second chirp, and then multiplied by a third chirp. A typical SAW implementation of a multiply-convolve-multiply (MCM) chirp transform system is shown in schematic form in Fig. 16. The convolve chirp is usually twice the length of the multiply chirps. The first multiply chirp conditions the input signal by adding the dispersive delay, and then the second chirp sorts the input signal frequencies in the time domain through the convolution process, providing the amplitude-frequency response curve. The final chirp multiply is necessary only if the phase information is desired and does not affect the amplitude response. Figure 17 shows a schematic representation of the system output for an input signal composed of three different frequencies. The convolve chirp is an up-chirp which sorts the frequencies from low with the smallest delay to high with the longest delay. The output signals have a finite time length due to the limited bandwidth of the SAW chirp system. The SAW implementation of the chirp transform system is not an exact implementation of the chirp Fourier transform because it is limited in both time length and frequency bandwidth. However, it works well for bandlimited and multitone input waveforms used in radar and other military systems.

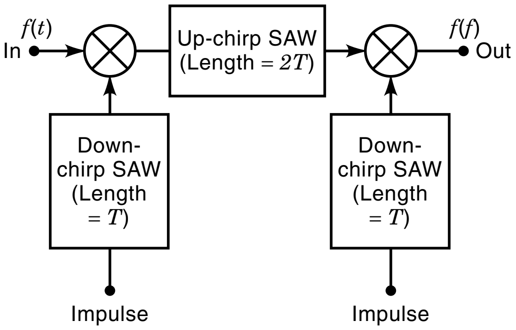


Figure 16. Schematic diagram of a SAW chirp Fourier transform system.

SAW Elastic Convolvers. Spread-spectrum systems need some type of matched filter, correlator, or convolver to extract the transmitted signal from noise and interfering sources. SAW elastic convolvers were studied in the 1970s for use in

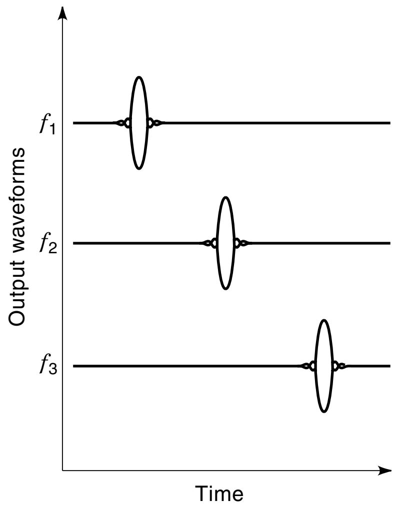


Figure 17. Schematic representation of the output waveform of a SAW chirp system given the sum of three tones having equal amplitude as the input waveform.

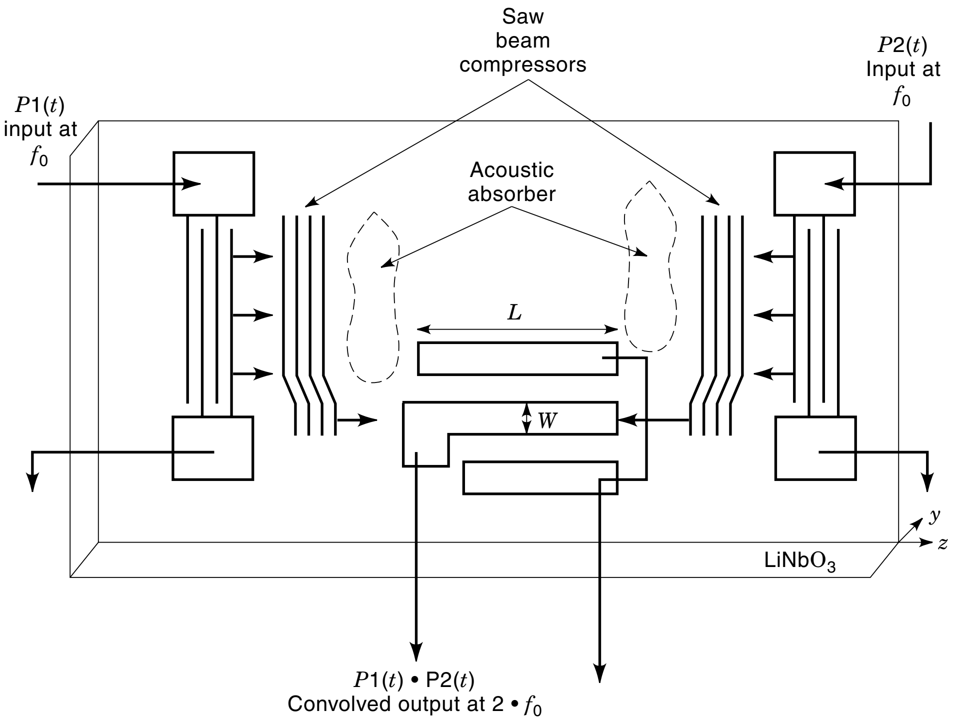


Figure 18. Schematic view of a SAW beam width compression elastic convolver.

militarily secure, spread-spectrum communication systems (8,9). The SAW convolver is a three-port device that uses the nonlinear portion of the crystal constants to perform a real-time convolution on any two arbitrary input signals within the operating bandwidth and time length of the device. The device is shown schematically in Fig. 18. The device consists of two input interdigital transducers (IDT), two beam compressors, and a long output plate between the two beam compressors. The input IDT provides the input signal from the receiver, and the reference IDT provides the known reference code signal. To enhance the nonlinear effect within the crystal, the power density is increased by compressing the SAW beam to only a few wavelengths. The beam compressors are usually either multistrip couplers, a horn-type waveguide, or self-focusing IDTs with typical compression ratios of 5 to 20. The two counterpropagating waves are compressed and then trapped under the electrode waveguide, which is only a few wavelengths wide, where they eventually slide by each other. The nonlinear crystal parameters provide point-source multiplication, and the long solid electrode provides the summing bus that is proportional to the integration time. The output signal is the convolution of the two SAW input waveforms at twice the carrier frequency of the inputs. The processing gain of the system is given by the device's time–bandwidth product. Typical devices have time lengths of several microseconds and bandwidths of tens to hundreds of megahertz. A convolver with a 10 microsecond integration length and a 100 MHz bandwidth has a processing gain of 30 dB. Typical convolver efficiency is between −50 dBm to −75 dBm which depends on the substrate material, bandwidth, integration time, and device design. Figure 19 shows the predicted and measured results of a 22 μs long, real-time SAW convolution of a coded MSK signal. The agreement between measurements and the theory of the compressed pulse are excellent.

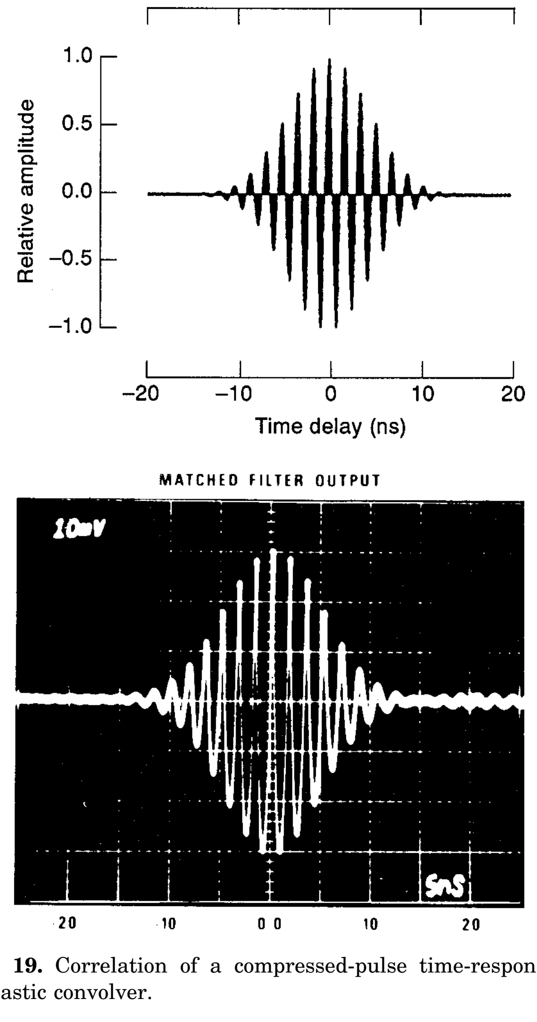


Figure 19. Correlation of a compressed-pulse time-response of a SAW elastic convolver.

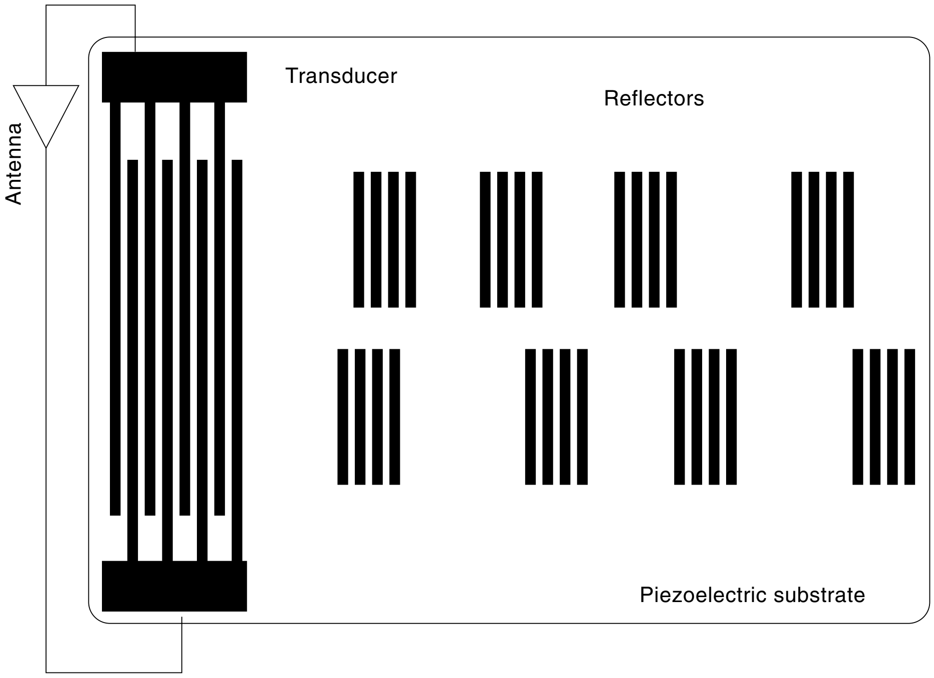


Figure 20. A schematic of pulse-excited, time-reflective type of a coded SAW tag. The device consists of a transmit/receive antenna, a dual purpose input/output transducer, and a series of reflectors which have centers of reflection corresponding to a pulse position code.

SAW REMOTE SIGNALING AND SENSORS

Identification Tags

SAW devices are used in the passive mode as identification tags or in remote sensing. A schematic of a pulse-excited, time-reflective type of a coded SAW tag is shown in Fig. 20. The tag is composed of an antenna, a transducer, and a series of partial reflectors. A remote transmitter sends an interrogation pulse that is received by the antenna and excites the SAW transducer which launches a wave. The SAW is partially reflected at each reflector and is sent back to the SAW transducer where it is retransmitted back to the interrogator. The center position of the reflector provides a series of delayed pulses that provide the unique code for identification. The device is totally passive, and the antenna and SAW chip are integrated into a single, low-cost package. Figure 21 shows the measured time-domain results for a reflective, coded, passive SAW tag. The time pulses are relatively uniform and discrete which makes demodulation of the tag information easy and accurate.

Remote Signaling

Remote signaling has become very desirable and accepted by consumers and industry. Examples include remote car door openers, car accessory operation, garage door openers, remote lights, power utility meters, and others. It makes some very simple operations even simpler and faster, increases industrial productivity, and is used in inaccessible places and environments for control and sensing. The acceptance of such systems is based on the relatively small size and cost. As an example, a transmitter for a keyless automobile entry is embedded on the actual key with minimal increase in size. A simple system used for a keyless entry system is shown in Fig. 22 (9). The system consists of two SAW filters, an amplifier, an integrated circuit for the code generator, and a battery. The two SAW filters and amplifier are placed in a single package, and a custom ASIC is designed and programmed for the specific code generator. The integrated circuit provides the code data, and the data format is simple on-off shift keying (OOSK). One SAW is used in the oscillator as the frequency-control element, and the second SAW filter is used to remove unwanted harmonics and spurious responses from the oscillator.

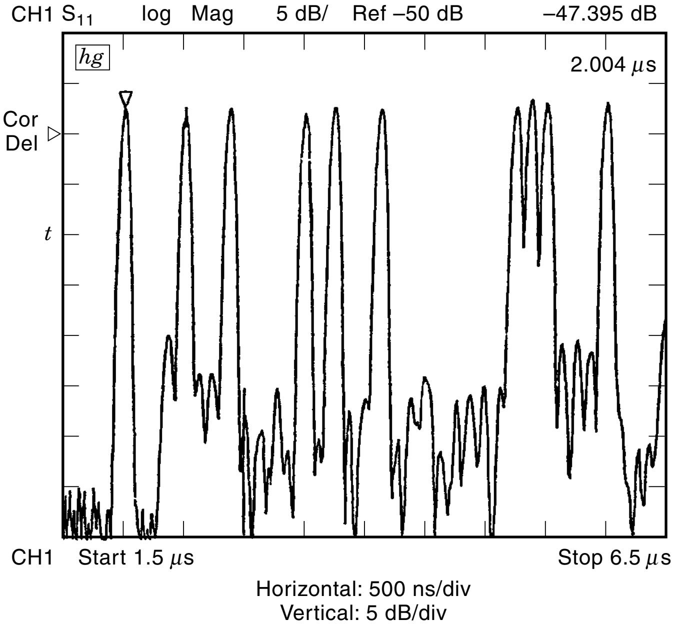


Figure 21. The measured time-domain results for a reflective coded passive SAW tag. The time pulses are relatively uniform and discrete which makes easy and accurate demodulation of the tag information. (Reproduced with permission from Sawtek, Inc.)

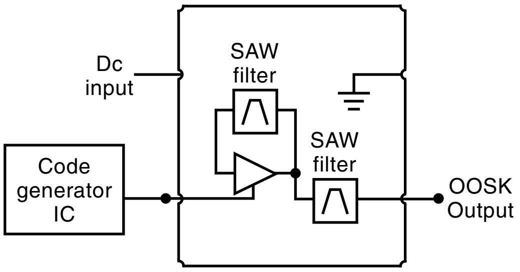


Figure 22. Schematic of a simple, low-cost SAW-based remote keyless entry system using on-off shift keying. (From RF Monolithics data sheet, HX1000)

Sensors

Sensing the external environment using SAW technology is a relatively new and growing market. The different number and types of SAW sensor devices and systems cannot be adequately presented here (10). SAW sensors are under investigation to sense gases, temperature, acceleration, pressure, and other parameters. The two critical issues are to find a sensitive sensing mechanism for the parameter of interest while eliminating or compensating for all other environmental elements; thereby isolating the measurement to only a single environmental element (gas, temperature, etc.). One popular method for measuring gases is to use a SAW delay line having a gas sensitive film in an oscillator circuit on the substrate surface. As the gas absorbs and desorbs, there is a change in the film's elastic properties that creates a change in acoustic velocity, delay, and insertion loss. This is translated into a frequency shift in the oscillator. The change in frequency versus gas absorption is often determined in parts per million for a well-calibrated system. A schematic of a simple SAW sensor is shown in Fig. 23. Sensing is developing into a very large market. Combining sensing with wireless transmission results in remote sensing applicable to a huge number of applications in transportation, medical, environmental, manufacturing, and many other fields.

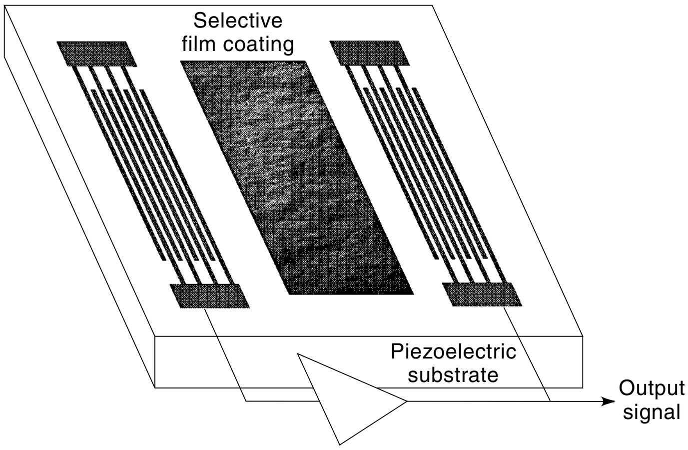


Figure 23. A schematic of a simple SAW sensor composed of a two-transducer-delay line with a selective absorbing film which changes the amplitude, phase, and/or insertion loss of the delay line.

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DONALD C. MALOCHA
University of Central Florida