Microwave Acoustic Materials, Devices, and Applications

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Invited Paper

***Abstract*—This paper surveys applications of acoustic waves in microwave devices. After a general and historical introduction to bulk acoustic waves (BAWs), surface acoustic waves (SAWs), practical wave types, and acoustoelectric transducers, a review is given of technologically important materials for microwave acoustic applications. Following this, we discuss BAW and SAW microwave devices and their technologies. Specifically reviewed are thin-film resonators and filters, transversal filters, and filters for correlative analog signal processing. Finally, an overview of the most important microwave applications is given, along with manufacturing and packaging issues.**

***Index Terms*—BAW, bulk acoustic-wave devices, communications and sensor applications, SAW, signal processing, surface acoustic-wave devices.**

Nomenclature

BAW	Bulk acoustic wave.
CSSP	Chip-sized surface acoustic-wave package.
DMS	Double-mode surface acoustic-wave filter.
FBAR	Film bulk acoustic resonator.
IDT	Interdigital transducer.
PBG	Photonic-bandgap structure.
SAW	Surface acoustic wave.
SBG	Sonic-bandgap structure.
SCF	Stacked crystal filter.
SMR	Solidly mounted resonator.
SPUDT	Single-phase unidirectional transducer.
SSBW	Surface-skimming bulk wave.
STW	Surface transverse wave.
TFR	Thin-film resonator.

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II. Introduction—General and Historical

IN DESCRIBING microwave acoustic devices, this paper presents a considerable departure from the generality of microwave technology in that we are dealing with a radically different type of wave. Instead of the electromagnetic wave in free space or dielectrics, we are considering *acoustic* waves, also known as elastic waves. These involve mechanical deformations of a material and the associated internal forces, which are known as stresses [1], [2]. Tap a metal pipe, and the sound is easily heard by a listener standing a long way away, but close to the pipe. Strike a bell, and the resonance is audible for many seconds (hundreds of cycles). These observations are evidence of low-loss propagation of acoustic waves at audible frequencies. In microwave acoustics, we use acoustic propagation and resonances at much higher frequencies and, although propagation losses increase with frequency, such waves are practicable at frequencies as high as 10 GHz and above [3].

In solid materials, which are our concern here, there are two basic types of acoustic waves. For the moment, consider plane waves, with amplitude invariant over a plane wavefront. For example, the local displacement of the material, and the stresses, could all be proportional to $\cos(\omega t - kx)$, independent of the y and z coordinates (k: wavenumber). The first wave is a longitudinal wave [see Fig. 1(a)], in which the displacement is parallel to the wave vector (i.e., along the $\pm x$-direction here). This wave is similar to a sound wave in air, though the physics is rather different. The velocity depends on the material, but is typically in the range 5000 to 10 000 m/s. The second basic wave type is the shear wave, in which the displacement is in any direction normal to the wave vector, and this generally has a lower velocity of typically 3000 to 6000 m/s. The shear wave [see Fig. 1(b)] is analogous to the motion of a violin string, though the latter case involves standing waves rather than traveling waves.

There are, of course, many other configurations; for example, the waves can spread out in a cylindrical or spherical fashion. However, in all cases, the wave motion can be resolved into longitudinal and shear components. Both types of waves are nondispersive, with velocities independent of frequency. Like electromagnetic waves, acoustic waves can be reflected and refracted at boundaries.

For practical applications, attenuation is an important factor, and this depends on the choice of material. For example, in sap-

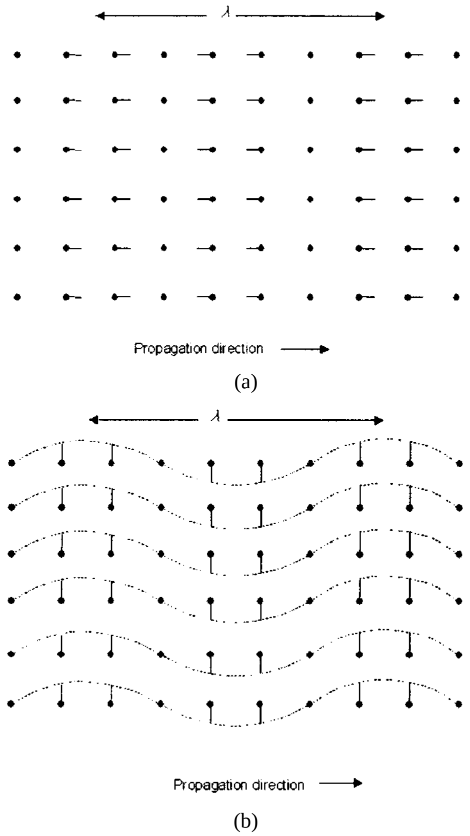


Fig. 1. (a) Schematic of an acoustic longitudinal wave in an infinite solid (λ: acoustic wavelength). (b) Schematic of acoustic shear wave in an infinite material. The dots represent particles of the material at rest, lines indicate instantaneous positions of particles when a shear wave is present (with displacements much exaggerated).

phire (crystalline alumina, Al_2O_3), the longitudinal wave has an attenuation in the region of 0.2 dB/μs of the propagation path, at 1 GHz. This figure is comparable to the performance of electromagnetic waveguides. Losses as low as this imply that devices many wavelengths long are feasible in practice.

The low velocities, some 10^5 times smaller than electromagnetic waves (in air), afford substantial miniaturization in microwave acoustic devices and suggest the use of acoustic waves for obtaining long delays in a compact space—a few microseconds for each centimeter of propagation path. In fact, one of the most common early applications was in delay lines for radars using moving target indication (MTI), where a delay equal to the pulse repetition interval (tens of microseconds) was needed. A delay line needs a propagation material, usually a solid bar, with a *transducer* at each end. The input transducer serves to generate acoustic waves in response to an applied electrical signal, while the output transducer converts incident acoustic-wave energy into an electrical output. There are many methods for generating acoustic waves, but the most common is the use of a piezoelectric material, i.e., one in which mechanical and electrical fields are coupled by interactions occurring at the atomic level. Many materials, particularly crystals, exhibit this phenomenon, though often it is too weak to be noticeable. A transducer can be simply a parallel-sided plate of piezoelectric material, firmly bonded to the propagation medium. When a voltage is applied, the plate vibrates mechanically, launching an acoustic wave. On arrival at the output a few microseconds later, the wave vibrates the output transducer and causes it to generate a corresponding electrical voltage, a delayed and attenuated version of the input voltage. Early delay lines used fused quartz, or sometimes mercury, as the propagation medium. For piezoelectric transducers, crystalline quartz can be used, though a variety of piezoelectric ceramics were also developed for this purpose.

Piezoelectricity is thus of fundamental importance to microwave acoustics. Discovered by the Curie brothers in the 1880s, it is found in many crystalline materials, and most notably in crystalline quartz. Its practical usage dates back as far as World War I, when sonar systems used quartz crystals to generate sound beams (at audio frequencies) and, thus, detected underwater objects (long before the first radars). Later, in the 1950s, piezoelectric ceramics were preferred because of their stronger piezoelectricity. However, quartz has been of primary importance right up to the present day, despite its weak piezoelectricity, because it has advantages of very low acoustic losses and good temperature stability. It finds widespread applications in the form of the quartz resonator, which can consist simply of a freely supported parallel-sided plate with an electrode on each major face. In this case, unlike the delay line, the propagation and piezoelectric functions are combined in one material. When a voltage is applied, the impedance is found to show a sharp resonance due to the excitation of acoustic waves, reflected many times between the two faces in a manner similar to an electromagnetic or optical resonator. The significance of this device as the controlling element of an oscillator is almost impossible to exaggerate. It is familiar to almost everyone, if only by name, because of its presence in clocks and watches. In addition to these consumer applications, the quartz resonator is very widely used in professional electronic equipment, wherever accurate frequency or timing information is needed.

The waves described thus far are also called BAWs, meaning that these waves propagate freely, as if in an infinite medium. Waves in quartz resonators are included in this class because reflections at the faces do not affect the basic nature of the waves. However, boundaries can, in general, have substantial effects, leading to new types of waves, often with dispersion. Many such cases were investigated by 19th Century physicists interested in topics such as mechanical behavior of engineering structures and the physics of seismic disturbances. The signals observed on a seismograph, following an earthquake, usually show contributions attributable to longitudinal and shear waves. However, there can also be a somewhat later disturbance, which Lord Rayleigh, in 1885, showed to be due to a surface wave. This wave, known as a Rayleigh wave or SAW, is guided along the free surface of a material, so that its amplitude decays rapidly with distance from the surface. The wave is nondispersive and involves longitudinal and shear components.

In the late 1960s, one of the key developments in microwave acoustics occurred. In several laboratories, it was suggested that SAWs might be of great interest for electronics because of the accessibility of the wave at the surface. Thus, in addition to the bulk wave advantages of low velocity and low loss, the surface wave might be made to interact with surface structures in many ways, such as transduction, reflection, waveguiding, and so on.

In this way, an enormous degree of flexibility could be envisaged. Moreover, the required structures, once invented, might well be realized by means of the rapidly developing lithographic technologies used for integrated semiconductor devices.

These thoughts have been borne out in a spectacular way by the subsequent development of an enormous range of SAW devices and their widespread deployment in electronic systems. The devices use crystalline piezoelectric materials such as quartz (α-SiO_2), lithium niobate ($LiNbO_3$), or lithium tantalate ($LiTaO_3$), on which the waves can be generated by applying a voltage to a set of interleaved electrodes known as an IDT. Many types of SAW devices serve as passive bandpass filters, operating in the range of 30 MHz–3 GHz, and one of the earliest applications for SAWs was an IF bandpass filter for television (TV) receivers, first developed in the 1970s. Today, all TV receivers have a SAW filter, thus, as for bulk quartz resonators, these devices are in very common everyday use. Another early application was the development of dispersive filters to extend the range of radar systems by means of pulse compression. This principle was realized in the 1940s, but became a practical reality only with the development of SAW devices 30 years later. A great variety of devices were developed for military and professional communications and radar systems. In the mid-1980s, another seismic shift occurred when SAW devices began to be applied to mobile radio systems, particularly mobile phones. This led to the development of many new types of bandpass filters and a vast expansion of production rates, now in the region near three billion devices per year.

The practitioner in microwave acoustics faces a variety of challenging topics. For example, the internal forces in a material are represented by a stress tensor with nine components, in contrast to the three components of electric field. Thus, calculations even for isotropic solids are of some complexity. However, the devices here usually have crystalline materials that are anisotropic, thus, the relevant properties vary according to the orientation of the crystal lattice. Crystalline materials are chosen because they generally offer the lowest acoustic losses, and also because piezoelectricity requires an anisotropic (usually crystalline) material. These factors complicate the subject enormously. Characterization of a material, evaluating the acoustic-wave properties for different orientations in order to identify suitable cases, is a major computational task. This is particularly so for SAWs. Wave phenomena familiar from electromagnetism—diffraction, reflection, refraction, dispersion, nonlinearity, etc., all occur in acoustics, but with complications arising from the anisotropy. Sometimes more than one material is involved, for example, the recent development of diamond substrates with high acoustic velocity, combined with a zinc–oxide film to provide piezoelectricity. These topics are of lively current interest because a variety of new materials are being developed. Analysis of devices, particularly SAW devices, can also involve deep intellectual effort, and design methods often involve sophisticated computational optimization. Another significant area is fabrication, particularly for production devices. With markets pressing for devices at high frequencies, manufacturers often need the highest quality consistent with large quantity production, involving optical lithography with linewidths down to 0.3 μm and below.

III. BAWs and SAWs

A. Practical Acoustic-Wave Types

We have seen that there are two basic types of plane waves that are important in acoustic-wave propagation in solids: the longitudinal and shear waves. Also, in general, the acoustic waves can propagate through a solid medium with combined shear and longitudinal motion. If the propagation medium is bounded, the character of the waves is substantially governed by the boundary conditions. A case of primary interest for microwave applications is the SAW wave, which can exist in a homogeneous material with a plane surface. It is guided along the surface, with its amplitude decaying exponentially with depth. The SAW wave is strongly confined, with typically 90% of the energy propagating within one wavelength of the surface. A bounded medium also supports many other types of waves depending on the boundary conditions and the nature of the solid materials that are involved. For example, in more complicated systems like plates, layered media, etc., the number of eigenmodes increases enormously, resulting in rather complex propagating modes. On the other hand, media with dimensions much larger than the wavelength can support waves with characteristics similar to those of waves in infinite media that are not bound to a surface (BAW waves).

The main types of guided waves used for todays microwave applications include various BAWs, SAWs, and pseudo-SAW waves such as classical Rayleigh waves, leaky SAWs, Bleustein–Gulyaev waves, Lamb waves, Love waves, SSBWs, STWs, etc. [4]–[6]. The nature of a specific wave type can be rather complex even if we consider linear relationships and a homogeneous piezoelectric insulator as a propagation medium (characterized by stiffness, piezoelectric, permittivity tensors, and mass density), which is normally sufficient for practical applications. A specific solution procedure including an appropriate solution ansatz relating electric potential and mechanical displacements and incorporating the mechanical and electrical boundary conditions may result in finding bound, unbound, or radiation modes usable for practical applications.

The complex propagation constant $\gamma = \alpha + j\beta$ of the wave solution, incorporating the propagation constant $\beta = 2\pi/\lambda = 2\pi f/v$ and, thus, the phase velocity v and the attenuation constant α, is one of the most important practical design parameters used in acoustic device design. The second basic design parameter is the electromechanical coupling coefficient K^2 [7], which is a measure of the efficiency in converting an applied microwave signal into mechanical energy associated with the acoustic-wave type and determines, by a given relative bandwidth, the insertion loss of the device. As is the case with γ, K^2 also depends (among others) on the piezoelectric material tensor elements of elasticity, piezoelectricity, permittivity, and mass density.

B. Practical Acoustoelectric Transducers

The key to implementing devices is acoustoelectric transduction; acoustoelectric transducers convert electrical energy into mechanical energy, and vice versa. In low-frequency applications, microphones and loudspeakers are well-known examples of such transducers. For microwave applications, piezoelectric transducers are useful both for the generation and detection of acoustic waves.

A simple configuration for a BAW delay line might be a sapphire rod with a metal film deposited on each end to form an electrode. A film of a piezoelectric material, such as zinc oxide, is deposited on each electrode by sputtering or evaporation in vacuum. Typically, this layer is chosen to be between a quarter-wavelength and half-wavelength thick. Finally, a metal film is laid down on the surface of the piezoelectric material to form a metal top electrode; this second metal electrode is normally a small fraction of a wavelength thick. We now have a transducer at either end of the rod, comprised of a metal counter electrode, piezoelectric film, and metal top electrode. At one end of the rod, a potential is applied between the two metal electrodes on either side of the piezoelectric film to excite a longitudinal acoustic wave in the delay line. After the wave has traveled through the delay line, it is detected by the transducer at the end of the rod. Another common BAW device is a crystal resonator consisting of a parallel-sided plate of crystalline quartz with electrodes on both sides. If the major dimensions are much larger than the thickness, the plate resonates at a frequency such that its thickness equals one-half the acoustic wavelength and at harmonics of this frequency. Since quartz is piezoelectric, the acoustic resonances can be excited electrically.

In the SAW arena, the invention of the IDT in 1965 [8] opened up the gateway to today's technological directions. For a piezoelectric material, a propagating SAW wave is accompanied by an electric field localized at the surface, and this enables the wave to be generated by applying a voltage to a comblike array of metallic electrodes on the surface forming the IDT. The IDT can also be used to detect SAW waves, producing an electrical output waveform, and is used today in all commercial SAW devices. Another basic SAW component is the reflector grating being periodic arrays of either metal strips or grooves. Combining IDTs and reflectors, SAW resonators and resonator filters can be constructed.

IV. Microwave Acoustic Materials

Microwave acoustic materials are characterized primarily by elastic linearity, extremely low loss, zero temperature coefficients of frequency or delay, and particularly by the presence of piezoelectricity. Piezoelectricity provides a clean efficient transduction mechanism mediating between mechanical motions and electric variables, using planar configurations available with conventional microelectronics fabrication technologies. Even compensation of stress and temperature-transient effects from elastic nonlinearities is possible with SC-cut quartz, making available high-stability BAW oscillators with stabilities better than one part in 10^9. SAW substrates provide conveniently accessible time axes for signal-processing operations like convolution.

Pride of place belongs to quartz. Its technological prominence stems from remarkable acoustoelectric properties, combined with extremely low loss. Filter bandwidth limitations due to low piezoelectric coupling led to the introduction of refractory oxides, particularly $LiNbO_3$ and $LiTaO_3$ for filters and signal processing. More recently, the gamut of available piezomaterials has been further expanded to include lithium tetraborate ($Li_2B_4O_7$), GaAs, SiC, ZnO, AlN, $KNbO_3$, lead zirconate (PZT) alloys, and polyvinylidene fluoride (PVDF) [9], [10]. One important criterion by which to measure an acoustic material is the upper frequency limit; the concept is similar to that used for assessing transistors. Maximum usable frequency $f_{\max}$ is determined jointly by K^2 and the acoustic time constant τ (quotient of viscosity by elastic stiffness). The relation is $f_{\max} = 2K^2/(\pi^3\tau)$, where $\tau = 1/(2\pi f Q)$ and Q is the measured quality factor at f, which is the nominal operating frequency [11].

The search for new materials is fed by practical demands for devices with improved characteristics, e.g., lower loss (higher Q, lower insertion loss), higher piezocoupling (increased bandwidth), better temperature stability, greater miniaturization, and higher acoustic velocity, which leads to easier fabrication of high-frequency devices, etc. Materials receiving recent attention include langasite, the *ultrahard* piezoelectrics, plus sapphire and diamond [C(d)] substrates for TFRs, as well as piezomagnetics. The langasite ($La_3Ga_5SiO_{14}$) family consists of materials such as langanite ($La_3Ga_{11/2}Nb_{1/2}O_{14}$) and langatate ($La_3Ga_{11/2}Ta_{1/2}O_{14}$) [12]. These have acoustic Q's higher than quartz, but have disordered structures. Totally ordered (Ca, Sr)$_3$ (Nb, Ta)$Ga_3Si_2O_{14}$ crystals are expected to be stiffer, have lower dielectric permittivity and higher piezocoupling. Main market possibilities are wider band (versus quartz), high-stability IF filters, high-temperature sensors, and high-Q BAW resonators [13]. Ultrahard binaries and diamond exhibit high acoustic-wave velocities up to about 18 km/s, yielding higher frequencies and greater miniaturization. Piezomagnetic acoustic materials hold considerable promise for future devices. Biased magnetostriction is equivalent to piezomagnetism. Stable biasing magnets of NdFeB alloys and rare-earth compounds (e.g., $SmCo_5$ and Sm_2Co_{17}) have recently become available. Alloy formulations now exist having minimal degradations even above 350 °C [14]. These developments make piezomagnetic acoustic devices practical for a wide range of applications, e.g., sensors, as well as nonreciprocal devices.

Periodicities at the atomic level provide anisotropy in the continuum limit. Artificial periodicities at the discrete level yield unique properties: artificial dielectrics, SAW IDTs, acoustic superlattices, PBG structures [15], and acoustic bandgap or SBG structures [16]. Currently, PBG materials are optically isotropic, and it is upon these that man-made periodicities are imposed. As scale lengths diminish, and sophistication increases with time, we can project the increasing use of materials and substrates, for both PBG and SBG purposes, that are anisotropic. It is natural to suppose that high-frequency SBGs will increasingly take advantage of microelectronic fabrication techniques and methods appropriate to semiconductors. However, whereas cubic semiconductors are isotropic optically in the continuum approximation (PBG applications), they are far from isotropic elastically. Moreover, hexagonal semiconductors are both optically uniaxial, and are quite anisotropic acoustically. By use of combinations of both intrinsic anisotropy and artificially imposed discontinuities (either periodic, or *chirped*, as in SAW devices)

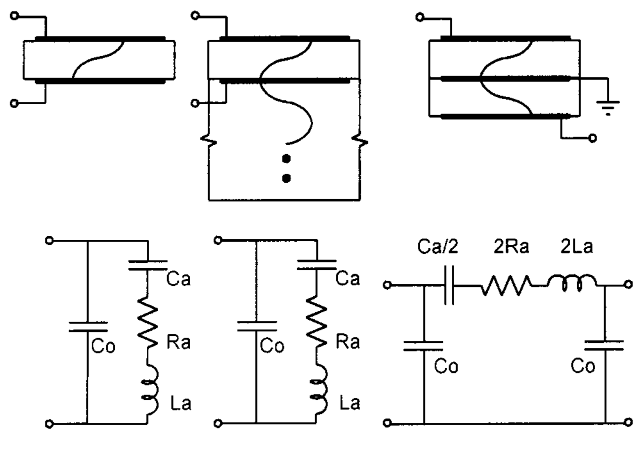


Fig. 2. BAW device basic configurations with equivalent circuits. (a) A simple crystal plate transducer with electrodes and air or vacuum interfaces forming a crystal resonator. A half-wavelength of vibration is shown across the transducer/resonator The equivalent inductor has a very high Q. (b) Thin-film transducer attached to a half-space of material. R_a is the radiation resistance. (c) A SCF formed by two bonded plates or thin films, analogous to a microwave cavity having two coupling loops.

in various directions, new PGB and SBG components with enhanced properties may be fashioned.

The microelectronics revolution is due to the electronic properties of semiconductors. Cost and packing density drivers can be impacted by providing both increased functionality and integration using the fact that the III–V and II–VI binary semiconductors are piezoelectric, and many can be fashioned to have areas with high resistivity. One may thus integrate, on one substrate, all the *smarts* associated with the usual microelectronics/nanoelectronics circuitry, along with high-Q acoustomechanical devices [17]. Resonant membranes etched in binary semiconductor chips can provide stable frequencies directly in the gigahertz range. Semiconductors additionally furnish convenient substrates for SMRs and SCFs. Devices merging acoustoelectronics, semiconductor-optics, and quantum acoustics will continue the trend toward integration. The future will see an exciting mixture of photonic/sonic/electronic interactions.

V. Microwave BAW Devices and Technology

Shown in Fig. 2(a) is a piezoelectric plate having electrodes on parallel or slightly contoured surfaces that form a transducer. When air or vacuum is the interface, the waves generated by the transduction process stay confined to the material volume. Because energy is confined in this manner, the device operates as a resonator having resonances at frequencies corresponding to odd multiples of a half acoustic wavelength across the plate thickness. Although the distinction between transducer and resonator might seem as a bit of a fine point, it does help explain the operation of a wide variety of devices that can be implemented by BAW technology. Current flow in a resonator is composed of two components. First is the normal displacement current associated with the structure as if it were a simple capacitor, represented by C_0 in the equivalent circuit. The second component is due to the interaction between the driving signal and the generated acoustic wave. The result is an equivalent circuit with a series *RLC* circuit branch having C_a much smaller than C_0, loss element R_a, and an inductance L_a. The equivalent inductance forms a series resonance with C_a and at a slightly higher frequency a parallel resonance with C_0. These extremes of impedance are very useful in implementing filters and controlling oscillator frequency.

Resonators, as described above, have mostly been implemented at low frequencies using quartz as the material. These are commonly referred to as quartz crystals or just *crystals* because of their origin from quartz in crystalline form. Since they have a similar behavior to quartz crystal resonators, the same terminology will apply to microwave frequency thin-film BAW resonators although fabricated by a markedly different process. Resonators can reach higher frequencies for a given plate thickness by operation on overtones. Here, the resonant frequency is such that the plate thickness is an odd multiple of a half-wavelength. While this approach works well enough for oscillators at low frequencies, the use of overtones is generally not suitable for filters. When coupled to another material volume, as suggested in Fig. 2(b), the driven piezoelectric plate acts as a transducer in the real sense that waves actually leave the piezoelectric region. Pairs of transducers are used to form a delay line, wherein the delay material, such as sapphire, is chosen to have low acoustic propagation loss and the thickness of the transducer is designed for the frequency of interest.

Since resonator frequency is inversely proportional to plate thickness, the push to higher frequency improvements in crystal plate thinning has allowed fundamental frequencies to approach and go beyond 300 MHz, but device operation above 1 GHz has been mostly elusive. Another high-frequency BAW approach is to obtain a specified plate thickness by thin-film deposition techniques. There is considerable breadth to the TFR technology, both in device types and applicable frequency spectrum. Much of this is due to the fact that the technology is based upon thin films that can be fabricated, by various means, on a variety of substrates through integrated-circuit-type wafer scale processing.

A. TFRs

The thin-film approach is illustrated in Fig. 3 [18], which shows three possible device configurations. The configuration of Fig. 3(a) is a membrane structure supported by the edge of the substrate [19]–[23]. Typical fabrication involves deposition of a piezoelectric film on a supporting substrate followed by removal of a portion of the substrate to form the membrane and thereby define the resonator. The configuration is similar to that used in inverted mesa quartz crystals, where a thin piezoelectric membrane is surrounded by a more rigid supporting structure [24]. The difference is in the details of how the membranes are formed and the fact that the support substrate is not of the same material as the piezoelectric, leading to the use of composite structures. This approach is limited to substrates in which the cavity is readily formed and has its roots in silicon micromachining. The second configuration [see Fig. 3(b)] involves fabricating an air gap under the resonator [25], [26]. This may be accomplished by first depositing and patterning an area of temporary support material, next depositing and patterning an

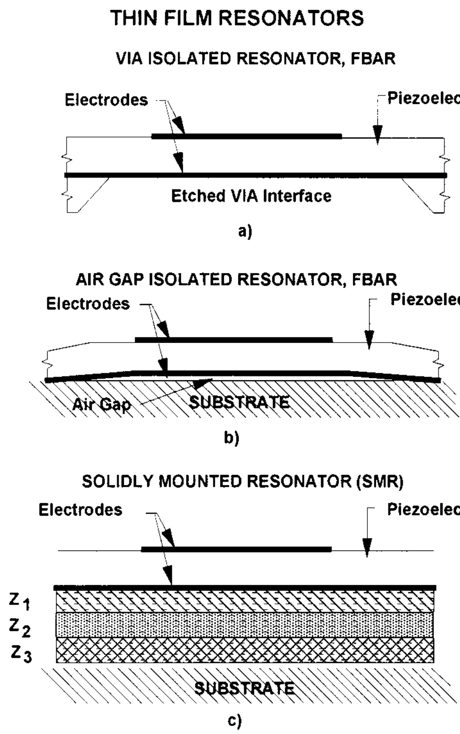


Fig. 3. Resonator configurations suitable for implementation with thin films. (a) Membrane formed by etching a via in the substrate. (b) Air gap isolated resonator. (c) SMR using a reflector array to isolate the resonator from the substrate.

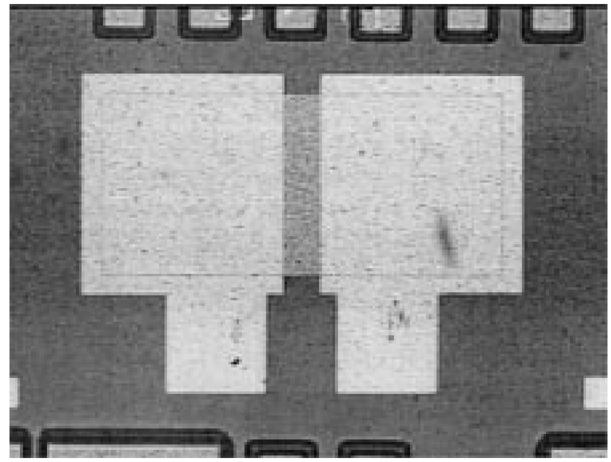


Fig. 4. Two SMR resonators integrated on an SiGe IC substrate. The resonators operate near 1700 MHz and are each approximately 200 μm on a side in the overlap area. The two lower squares are for test probing. The series connected resonators had a Q greater than 500 in this test structure.

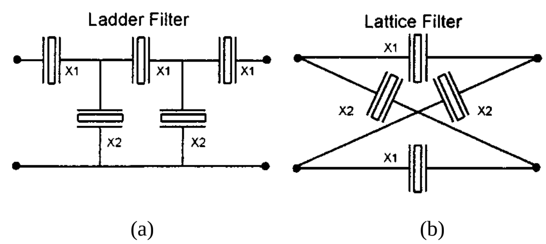


Fig. 5. Basic filter configurations. (a) Ladder filter using series and shunt crystal resonators. $X2$ is generally fabricated to be parallel resonant and $X1$ series resonant at passband center. (b) Lattice filter allowing balanced I/O.

overlay piezoelectric resonator with electrodes, and finally removing the temporary support. The approach in Fig. 3(a) has seen greater development of the two membrane configurations having been first demonstrated in 1980. The terminology FBAR was introduced in 1990 [27] and very recently applied to a similar configuration for cell phone applications [28].

The SMR in Fig. 3(c) is of a considerably different form than the membrane structures [29], [30]. Since the piezoelectric *plate* is solidly mounted to the substrate, suggesting a transducer, some means must be used to acoustically isolate the transducer from the substrate if a high-Q resonance is to be obtained. There is a method of attaching a resonator to a substrate so that the resonator is substantially acoustically isolated from the substrate [31]. The technique uses adjacent quarter-wavelength sections of materials, having large effective transmission-line impedance ratios, to form a reflector between the resonator and substrate. The result is a practical isolation of the transducer from the substrate to effect a high-Q resonator rather than a low-Q transducer. The SMR approach requires that the substrate be smooth and able to withstand modest microelectronic processing environments during the fabrication of reflectors, electrodes, and piezoelectric film. The absence of a via or any special substrate preparation for the SMR shows considerable promise for direct integration onto active circuit wafers. Sapphire, alumina, glass, and silicon wafers have been used as substrates. Fig. 4 shows a pair of resonators fabricated on a previously passivated SiGe IC substrate using the SMR approach. Fabrication of SMRs has extended over a frequency range of 300 MHz–20 GHz. Limitations on frequency are primarily driven by the ability to fabricate thin films for the reflectors and the piezoelectric transducer. At low frequencies, the main difficulty is in obtaining films of the required thickness in a finite period of time such that the process is economical. At high frequencies, the films can be grown quickly, but accordingly require a higher degree of absolute film thickness control. Nevertheless, resonators and filters, operating at frequencies in the range of 600 MHz–12 GHz, are in production for use in military and commercial wireless systems.

B. TFR Filters

TFR filters using thin-film piezoelectrics can take two general forms. First, individual resonators can be electrically interconnected to form classic filters of the ladder and lattice type, as in Fig. 5. Second, resonators can be acoustically coupled to form filters analogous to microwave cavity-coupled resonator filters. The stacked crystal configuration is shown in Fig. 2(c) along with an approximate equivalent circuit.

Ladder filters offer some flexibility in filter characteristics. The number of resonators determines the steepness of the skirt selectivity and, to a certain extent, filter bandwidth, and ratio of capacitance of shunt to series resonator determines the out-of-band rejection for a given number of resonators. The main features of the ladder filter are illustrated in Fig. 6 for three production GPS filters. The filter with the lowest insertion loss has the widest bandwidth, least rejection level, and is composed of three series resonators and two shunt resonators. This filter is typically used between the antenna and low-noise amplifier in GPS receivers. The post-selection filters, used

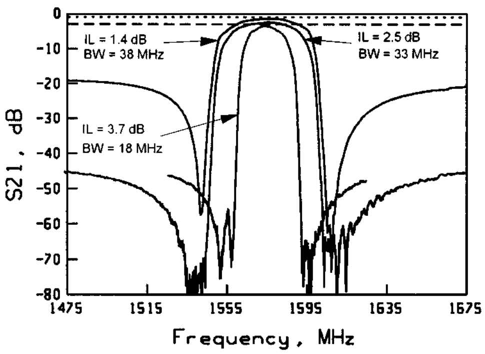
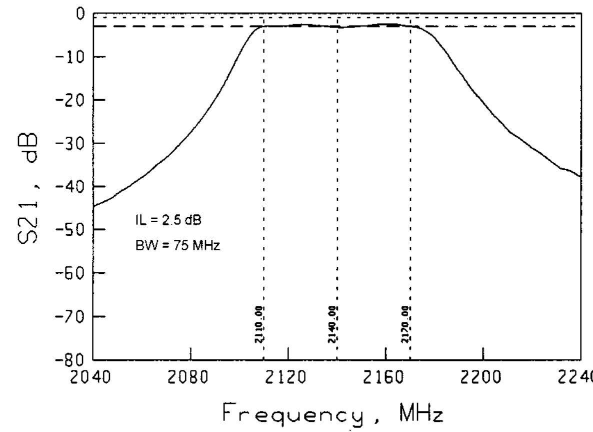
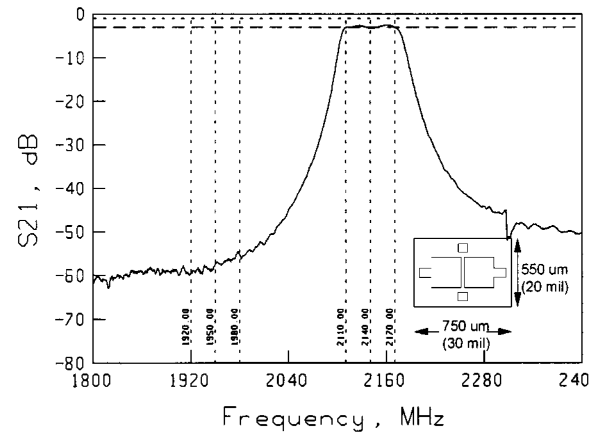


Fig. 6. Response data for three GPS filters. The lowest insertion loss data is for a ladder filter having three series resonators and two shunt resonators. The two filters having higher out-of-band rejection are post-selection filters to be used after the low-noise amplifier. These have two different bandwidths to accommodate different designs.



(a)



(b)

Fig. 7. SCF in a four-pole format. The fractional bandwidth is about 3.6% as designed for the 3G cell phone application. The experimental results are shown for an unpackaged die of the approximate size shown. Similar filters have been demonstrated with bandwidths up to 4.5%.

after the low-noise amplifier, have a much greater rejection level, narrower bandwidths, and higher insertion loss. The narrowest bandwidth filter is built with partially temperature compensated resonators, but with the same rejection level as the wider post-selection filter. Other ladder filters, including those developed for cellular phone applications, have been made at various frequencies over the frequency range from 300 MHz to 4 GHz [27], [30]. Production filters typically come in small packages such as 1.5×3 mm^2.

The stacked crystal is a useful filter configuration when low insertion loss is desired and the near-in skirt selectivity requirement is not as high as that produced by ladder filters. The SCF is analogous to a microwave cavity having two coupling loops. In membrane form, these filters have been fabricated on GaAs substrates integrated with active devices [32]. Shown in Fig. 7 are experimental results for a four-pole SCF that was designed for third-generation cell phone applications. This filter has a 3-dB bandwidth of 3.6% using aluminum nitride as the piezoelectric. Similar filters have exhibited bandwidths up to 4.5%.

C. Manufacturing Issues and Packaging

The frequency of a TFR is most dependent upon the thickness of the piezoelectric film and, to a lesser extent, other layer thicknesses. In most integrated circuit (IC) manufacturing, lateral feature geometries are critical and film thickness is less important. In TFR manufacturing, lateral features are not so important, but film thickness primarily determines the resonant frequency. In the SMR process, up to 12 or more layer depositions may be required to fabricate a device, and that has to be done in such a way that manufacturing is economical. Fortunately, the wafer scale processing allows many devices to be fabricated on a wafer at the same time with die counts ranging from 250 to 5000 for 100-mm-diameter wafers. All but the piezoelectric film deposition are common processes in IC manufacturing. Resonator frequency can be adjusted by thickness trimming, which could potentially lead to an effective yield of nearly 100%. Accordingly, high-performance filters are now being ion milled in production. One group of filters have critical cutoff characteristics requiring at least 10 dB of attenuation change over a span of less than 3 MHz at 1610 MHz. Another production filter is centered around 3.5 GHz with 0.7% bandwidth. In most cases, filters can be designed to have sufficient bandwidth to tolerate small changes in manufacturing set-on frequency, when the variation is a fraction of the total bandwidth, and to compensate temperature effects [33].

High-performance resonators and filters require a package that does not degrade device performance. Due to the small size of the device within the substrate die, a high degree of input-to-output isolation is difficult to realize and low lead inductance is required if the filter is to realize the desired rejection levels, particularly for those filters having in excess of 40-dB isolation. However, because these are acoustic devices, with potentially at least one exposed vibrating surface, some form of hermetic packaging is desirable just as with SAW devices. When membrane structures are used, a higher level of protection is required. Fragile bridge-type structures might not even survive wafer sawing and handling prior to packaging. SMR-based devices have similar packaging constraints as SAW devices and, accordingly, can use the same type of low-cost package now used in high-volume SAW manufacturing.

VI. Microwave SAW Devices and Technology

SAWs can be efficiently excited and detected by an IDT and reflected by a metallic grating placed on a piezoelectric sub-

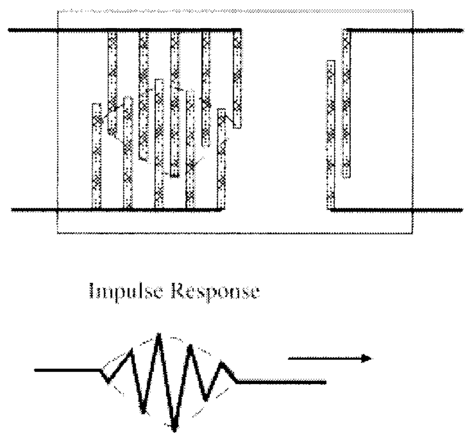


Fig. 8. Basic configuration of SAW transversal filter.

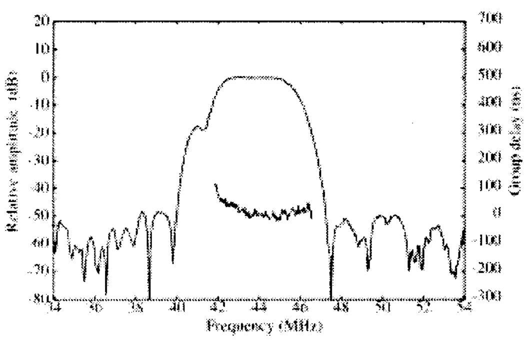


Fig. 9. Frequency response of the present TV-IF filter for the U.S. NTSC system (courtesy of Toshiba DDC).

strate. Since precise and fine IDT patterns can be generated by the use of photolithography, this mid-1960s invention stimulated worldwide research toward the development of various SAW-based signal-processing devices operating in VHF/UHF ranges [34]–[36].

A. Transversal Filters

The representative configuration is the so-called SAW transversal filter shown in Fig. 8. When an impulse signal is applied to an IDT, SAWs are excited through piezoelectricity, and are detected by the second IDT as induced charge after propagation. Since the delay time is simply determined by the propagation distance, spatial distribution of the excited SAW amplitude determines the impulse response of the device output. The arbitrary impulse responses can then be synthesized by designing the IDT pattern because the distribution is controlled by the finger overlap lengths. The frequency response is given by the Fourier transform of the impulse response. It should be noted that not only overlap lengths, but also distances between IDT fingers, are not necessary to be uniform. The dispersive delay line employs this feature skillfully. The transversal filter is known to be flexible for designing both the amplitude and phase responses, and it has been widely used for IF filtering in various communication systems.

Fig. 9 shows, as an example, the frequency response of a TV IF filter for the NTSC television system (Toshiba FO72TPL). It is seen that a very complex amplitude response is realized where moderate insertion loss of 12 dB, out-of-band rejection of 50 dB,

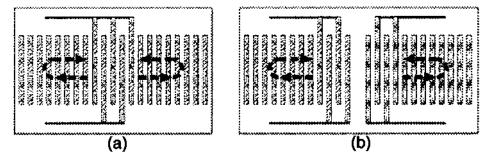


Fig. 10. Basic configurations of SAW resonator. (a) One-port SAW resonator. (b) Two-port SAW resonator.

and small group-delay deviation of typically 25 ns are simultaneously obtained. It is interesting to note that introduction of SAW filters made TV IF circuits simple, cheap, and robust [37].

B. Resonator Filters

SAW resonators are realized by the configuration shown in Fig. 10, where an IDT is bounded by grating reflectors [38]. Although multiple resonance modes may exist due to relatively long acoustic paths, the number of possible resonant modes is limited by the frequency selectivity of the grating reflectors. It is clear that the two-port SAW resonator shown in Fig. 10(b) acts as an acoustically coupled resonator filter. Flat passband shape, high out-of-band rejection, and sharp skirt characteristics are simultaneously achievable by resonator filters where two resonance peaks are adjusted to partially overlap each other in the frequency domain. These filters are often called DMS filters [39]. When quartz is used as a substrate, high-Q and good temperature stability are attainable in VHF/UHF ranges. SAW resonators have then been employed in frequency-control units for oscillators and narrow-band filters [40]. On the other hand, when highly piezoelectric substrates such as $LiNbO_3$ and $LiTaO_3$ are employed, low-loss and relatively wide-band filters are realizable by the use of the DMS configuration [41]. Wide-band DMS filters are widely used as a cleanup filter in mobile communication systems.

As is the case with BAW technology, ladder filters can also be accomplished in SAW technology. Here, instead of BAW resonators, SAW resonators are used as a circuit element [42]. This type of filter offers low insertion loss and high power durability, compared with acoustically coupled resonator filters. From these reasons, SAW ladder filters are widely used in the front-end section for communication systems [43]. Fig. 11 shows, as an example, a recent ladder-type SAW filter for W-CDMA receiver applications. It is seen that, in addition to a good signal rejection of 36 dB in the transmitter band (1920–1980 MHz), a very low insertion loss of 2.4 dB is achieved over the receiver band (2110–2170 MHz). It should be noted that the attained minimum insertion loss is only 1.4 dB.

C. Advanced Transversal Filters

There are two significant drawbacks in the SAW transversal filters with the configuration shown in Fig. 8. One is the relatively long physical length, which is related to the fact that the impulse response length is determined by the IDT length. Although the resonator filters offer smaller device size with lower insertion loss, their phase linearity is worse for certain applications. The other is the relatively large insertion loss due to the bidirectionality of the IDTs. Unidirectionality can be implemented into IDTs by the skillful use of the reflectivity of IDT fingers [44]. These IDTs are called SPUDTs. Although SPUDTs

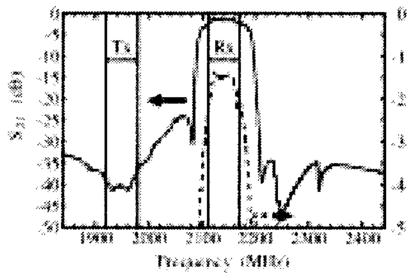


Fig. 11. Frequency response of ladder-type filter for W-CDMA Rx channel (courtesy of Fujitsu Media Device Ltd.).

are effective to reduce the device insertion loss, it was expected to be hard to reduce the physical device length. In recent years, however, it has been successfully demonstrated that when the directivity is partially reversed within each SPUDT pattern, it will cause a weak resonance due to the internal multiple reflection, which results in an extension of the impulse response length [45]. Hence, when both excitation and reflection profiles are designed properly, miniature and low-loss transversal filters can be realized. This configuration is called a resonant SPUDT. Various miniature IF filters have been developed based on the use of resonant SPUDTs.

D. SAW Filters for Correlative Analog Signal Processing

Correlative analog signal processing has been among the first applications of SAW technology. For chirp or direct sequence (DS) coded waveforms matched filtering has been achieved by SAW chirp delay lines [46], SAW coded delay lines, which are tapped corresponding to the DS code [47], and SAW convolvers [48]. All these techniques are feasible not only for military, but also for commercial applications in broad-band CDMA mobile communication systems. Compared to digital signal processors (DSPs) SAW-based processors exhibit lower power consumption and can easily perform real-time correlation of signals with bandwidths of up to a few 100 MHz.

E. Manufacturing Issues and Packaging

The SAW manufacturing has been developed from the technology of ICs. A major issue is the minimum linewidth obtainable since it determines the maximum operation frequency. Very fine lines can be obtained by X-ray or electron beam exposure; however, up to now, this is not a useful commercial variant. Usually the SAW companies apply optical exposure by which submicrometer patterning is already achievable. Today's SAW processes allow typically for highly stable linewidths of less than 0.3 μm. Wafer discs with diameters of up to 100 mm are processed. The required pattern is repeated many times on the mask so that many SAW devices can be fabricated simultaneously at a high yield. For larger SAW devices, such as long delay lines, tapped delay lines, chirp filters, and convolvers, the process is more specialized. The SAW chips are hermetically sealed in an inert atmosphere or vacuum using standard packages such as ceramic SMD packages. Thus, a very good stability of the SAW devices is achieved.

A key technology for further size reduction and passive integration might be the CSSP technique [49]. Fig. 12 shows the basic construction of a CSSP package. The SAW chip is

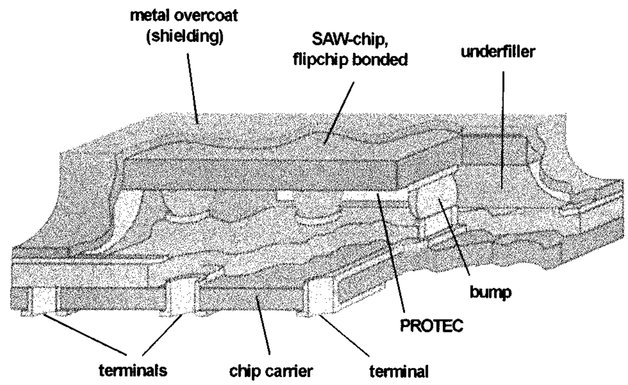


Fig. 12. CSSP package technology.

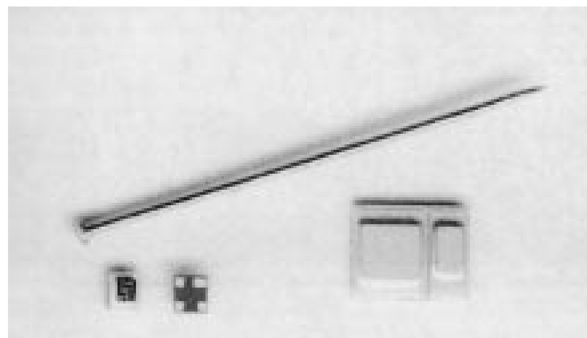


Fig. 13. EPCOS 2 × 2 × 0.8mm^3 SAW filter almost fits on a pinhead (left-hand side), prototype SAW module (right-hand side).

flip-chip mounted onto a chip carrier serving as bottom of the package. The electrical connections to the chip are realized with solder bumps. An underfiller attaches the SAW chip solidly to the chip carrier such that the backside of the chip can already serve as part of the package. While this mounting technology is quite straightforward for silicon chips, it only became attainable for SAW filters by a special chip passivation, leaving a cavity on the surface of the chip for undisturbed propagation of the acoustic waves. This technology allows for a further miniaturization of SAW filters beyond 1 mm^2 landing area. A very small SAW filter realized in a 2 × 2 × 0.8 mm^3 CSSP package is shown on the left-hand side of Fig. 13. Today, SAW filters of this size are available for PCN, PCS, and UMTS applications. The CSSP technology also allows for a higher complexity in passive integration. One chip carrier can carry a multitude of different chips. In addition, the chip carrier itself can contain a multitude of functionalities using planar integration, like diplexers, low-pass filters, matching components, and delay lines. The right-hand side of Fig. 13 gives an impression of what such a SAW module might look like. The module on display is a prototype of an integrated SAW duplexer including receiver filter, transmitter filter, and antenna matching network.

F. SAW-Based Wireless Sensors

SAW devices can be turned into wireless identification and sensor elements (transponders) for wirelessly measuring physical, chemical, and biological quantities such as temperature, pressure, torque, acceleration, humidity, etc. that do not need any power supply. The SAW transponder principle

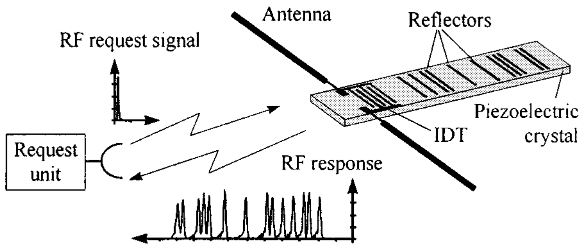


Fig. 14. Radio-link system incorporating radar transceiver and SAW transponder.

that is mostly used in practical applications is as follows (see Fig. 14) [50]: an RF burst impulse transmitted by a local radar transceiver is received by the receive/transmit antenna of a passive one-port SAW device the RF response of which is retransmitted to the receiver part of the local transceiver. Amplitude, frequency, phase, and time of arrival of this RF response signal carry information about the SAW reflection and propagation mechanisms, which, in many cases, can be directly attributed to the sensor effect for a certain measurand and/or a specific SAW device identification number (ID tag). Due to the high delay time in the order of a few microseconds, which the signal experiences in the SAW transponder, usually no intersymbol interference due to electromagnetic multipath propagation effects occur when the system operates in typical VHF/UHF indoor/outdoor radio channel environments. Passive SAW transponders do not require any power supply (i.e., they do not require batteries). Using the SAW transponder principle, it is even possible to also wirelessly read out signals of arbitrary sensors, i.e., non-SAW sensors, as long as these sensors operate as impedance sensors. In this case, a second IDT deposited on the SAW transponder substrate can be loaded by the external sensor that changes the IDT's acoustic reflectivity. Using this technique, a SAW-based tire-pressure measurement system designed for commercial vehicular applications has been demonstrated recently [51].

VII. Microwave Acoustic Device Applications

Before 1980, a vast amount of effort was invested in the research and development of microwave acoustic devices for military and communication uses, such as delay lines and pulse compression filters for radar and highly stable resonators for clock generation. The rapid growth of digital technologies, represented by the microcomputer, meant that the importance of acoustic-wave devices for military decreased year by year. On the other hand, from 1980 on, both BAW and SAW device development has focused on resonators and filters for consumer, automotive, and communication applications. Today, applications of microwave acoustic devices include [3], [52] wireless transceivers for voice, data, multimedia; spread-spectrum communications for wireless local area networks (WLANs) including WLAN robot, timing, and security applications; components in mobile communications system handsets, such as duplexers and voltage-controlled oscillators (VCOs); CDMA filters and timing; nonvolatile memories, and microelectromechanical (MEMS)/microoptomechanical (MOMS) devices. Specific SAW applications are analog signal processing (convolvers, duplexers, delay lines, and filters) for the mobile telecommunications, multimedia, and industrial–scientific–medical (ISM) bands; wireless passive identification tags, sensors, transponders, and microbalances. BAW applications include resonators in precision clock oscillators; front-end GPS filters, thin-film SMRs, and SCFs formed as SMRs for integration with microwave heterojunction bipolar transistor voltage-controlled oscillator VCOs.[1] In this arena, the telecommunications industry is clearly the largest user of microwave acoustic devices, consuming approximately three billion acoustic-wave filters annually, primarily for mobile cell phones and base-stations. These devices are typically SAW filters for the RF and IF sections of the transceiver electronics. SAW filters also address the high-volume market of television IF filters. There are several emerging applications for acoustic-wave devices as sensors that may eventually equal the demand of the telecommunications market. These include automotive applications (torque and tire-pressure sensors), medical applications (biosensors), and industrial and commercial applications (vapor, humidity, temperature, and mass sensors). It is worth noting that acoustic waves find a role in many areas other than microwaves, including film thickness monitoring, nondestructive evaluation (NDE), ultrasonic cleaning, medical scanning, and acoustic microscopes.

VIII. Conclusion

The rapid revolution in microelectronics has been the driver in the recent evolution of microwave acoustics. What has evolved in both BAW and SAW microwave acoustics is a fascinating interdisciplinary blend of the intricacies of acoustic-wave device physics with materials physics, field theory, microwave network and signal concepts, wafer scale IC manufacturing, and in particular, wireless communication applications. Design and modeling of microwave acoustic devices involve some complications. First, the devices are acoustic in nature, but are measured and used in an electronics environment. Second, models of an analytical form might not fit the usual circuit design software programs. Third, the models may not be sufficient and not comprehensive to model all the phenomena that can occur in inherently three-dimensional devices incorporating at least acoustic, electric, piezoelectric, and electromagnetic effects. Although BAW and SAW technologies have developed their own grammar and language through the many different disciplines involved in their development, the most pertinent issues to be addressed can be understood in terms of microwave theory and techniques. In the upcoming decade, microwave acoustics is facing new challenges not only because of its technology trends (new materials, (mixed-effect) devices, manufacturing techniques, packaging techniques (modules), applications), but also because of the dynamical developments in its professional business that are currently characterized by, among others, a lack of microwave acoustic engineers, an unsatisfactory exchange and cross licensing of intellectual property rights, and an increasing shift of research efforts from industry to research institutes.

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