Advances in Microwave Acoustic Frequency Sources

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Abstract —This paper reviews the principal advances with microwave frequency sources that use mechanical vibrations and waves in their frequency-controlling elements. Specifically, the review discusses the direction microwave acoustic technology has taken in the utilization of bulk acoustic-wave (BAW), surface acoustic-wave (SAW), shallow bulk acoustic-wave (SBAW), thin-film membrane, and composite structures to generate stable microwave frequency sources in the range from 100 MHz to 1 GHz and above.

I. Introduction

OPTIMAL OPERATION of coherent communication systems, as well as certain radar and electronic warfare systems, depends on stable reference sources. With the evolution of new equipment capable of operating in the microwave region and the trend to push their operation into the millimeter-wave regime, the demand for new and unique reference frequency sources, at the highest frequency possible, is apparent. The standard and most common signal generation technique presently used is the HF bulk acoustic-wave (BAW) crystal ($\leqslant 30$ MHz) in an oscillator circuit whose output is then multiplied to the desired frequency of operation. To achieve operation above 1 GHz, this approach leads to degradation in performance due to the resulting multiplication noise and accompanying complicated mode spectrum. For example, in going from a 5-MHz reference oscillator frequency to 5 GHz, a 10^3 multiplication must be performed and this results in a phase noise degradation of 60 dB. This follows from the well-known relationship $(P_{sb}/P_c)_{\text{dBc}} = 20 \log N$, where P_{sb} is the sideband power, P_c the carrier power, and N the multiplication ratio. In terms of hardware, the additional components required add up to increased size, weight, cost, and power dissipation. Fig. 1 shows the typical conventional hardware for a 30-MHz BAW source multiplied to 300 MHz. For a higher output frequency, the multiplication ratio would be greater, thus requiring even more hardware.

Recent years have seen outstanding accomplishments in the realization of direct fundamental and/or low-order harmonic mode operation of UHF acoustic devices. The technological bases for these devices are bulk acoustic waves in ultrathin films, surface acoustic waves (SAW's), and shallow bulk acoustic waves (SBAW's). The last are sometimes called surface-skimming bulk waves (SSBW's). All these devices make use of either piezoelectric crystals alone or of nonpiezoelectric solids with piezoelectric transducers. BAW's are excited by electrodes located on both sides of the piezoelectric material, SAW's and SBAW's by interdigital transducers (IDT's) plated on one side of the piezoelectric substrate.

Both resonator-type and delay-line-type operation have been reported in a very large number of papers. The publications referred to in this paper are presented to give the reader an indication of the overall progress and of the direction the field is most likely to take in the future. The frequency progression with time for various acoustic technologies is provided in Fig. 2. Here, we see the advancement to higher frequencies at the rate of approximately one decade for each decade in time. Fig. 3 shows the range of frequencies available using the various technologies and makes comparison to select operational frequency requirements of systems. Special note should be made that frequency coverage from 1 MHz through more than 10 GHz can be achieved by employing the BAW, SAW, SBAW, dielectric resonator oscillator (DRO) and magnetostatic wave oscillator (MSW) devices as shown. Thin-film membrane and composite structures are special cases of bulk-wave devices and will be discussed separately. Some band range overlap is thus apparent, and the optimum device to be chosen for a particular application will not in general be dictated by frequency alone. The report, therefore, is divided into sections that deal with the various types of mechanical vibrations and waves used in microwave oscillators; in addition, two sections discuss the general problem of stability as a function of environmental influences, and a comparison of the parameters of the various microwave acoustic sources is given.

Survey papers that predate the mid-1980's and cover not only microwave devices but also the field of BAW and SAW concepts in general are provided in [1]–[5]. Three special issues of the Transactions on Microwave Theory and Techniques are also available. One deals with SAW device applications in general [6], whereas the other two treat microwave acoustics and acoustic signal processing [7], [8]. A special issue of the journal *Ferroelectrics* devoted to the centennial of the Curie brothers, the discoverers of piezoelectricity, is a source of papers cover-

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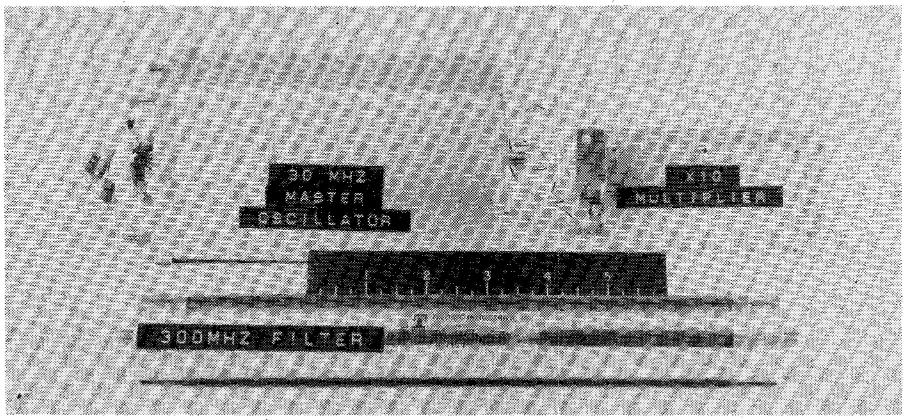

Fig. 1. Hardware for a conventional 300-MHz bulk-wave-derived source. The ovenized BAW 30-MHz master oscillator is followed by a times-ten multiplier. A 300-MHz bandpass filter is required to remove the multiplier harmonics and mixer products.

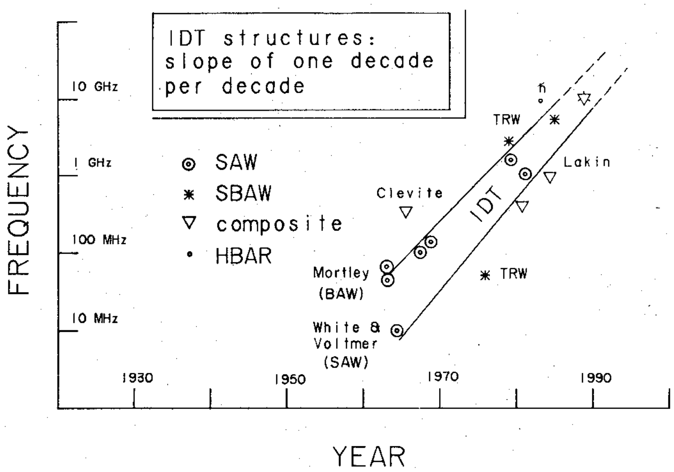

Fig. 2. Increase in acoustic-wave device frequency performance with year. Surface acoustic-wave and shallow bulk acoustic-wave devices employ interdigital transducers introduced by Mortley [125] and White and Voltmer [126]. IDT upper frequency limits have increased tenfold each decade of time. Composite resonators produced by Clevite [27], Westinghouse (HBAR) [36]–[38], Lakin [45]–[46], and TRW [74] are also shown; these are bulk-wave devices.

ing SAW materials and devices [9], as is a special issue of the *IEE Proceedings* [10]. In addition, two books which describe the fundamentals of acoustic surface waves, the properties of materials which affect device performance, and several important devices and structures are listed in [11] and [12]. Finally, the entire field of acoustic resonators, devices, and oscillators, including microwave applications, is covered in the book *Precision Frequency Control* [13].

II. VHF and UHF Single-Crystal BAW Resonators and Oscillators

The fundamental frequency of VHF and UHF BAW resonators is inversely proportional to their thickness. Using standard lapping and polishing methods, an upper frequency limit for the traditional fundamental thickness mode of AT plates is considered to be approximately 50 MHz. This corresponds to a plate thickness of about 30 μm, a thickness at which the plates become too fragile to handle. Two techniques are currently under intensive investigation to extend the use of single-crystal BAW resonators to higher VHF and UHF frequencies by further reducing the thickness of the vibrating plate. In the first, a chemical etching and polishing method is employed. Frequencies of 372 MHz (fundamental mode) and 1.12 GHz (3rd overtone) with Q's of 15 000 and 5000, respectively, have been reached using ultrathin SC-cut quartz resonators [14]. AT-cut resonators that operate as high as 1.2 GHz on the fundamental mode have also been reported [15]. An alternative method uses ion beam milling and (reactive) ion etching to reduce thickness [16], [17]. Q's of 29 000 for fundamental AT's at 120 MHz and 12 000 for 3rd overtone AT's at 852 MHz have been obtained [16]. Fig. 4 shows the plate configuration that is typically employed when either thinning process is employed [18]. A thin membrane (1.6 μm to achieve 1 GHz) is produced in the center of a wafer with an outer ring thickness of $\geqslant 50$ μm to provide mechanical strength. The electrodes are then deposited directly on this membrane to achieve the desired electrical characteristics. The Q's of these resonators are about 1.5 times larger than those of SAW devices in vacuum.

To date, various cuts of quartz (AT, BT, SC) and $LiTaO_3$ have been investigated, and frequencies up to 1 GHz with a $Q \cdot f$ product $>10^{12}$ have been realized [19]. The phase noise floor of oscillators employing such devices was measured to be -150 to -170 dBc/Hz [20], [21]. A recent technique of observing acoustic-wave reflection by a holographically produced grating within a crystal points to yet another type of BAW resonator for future application [22]. Hand in hand with the development of resonators and oscillators for the VHF and UHF range have been advances in the area of measurement methods. The transmission method is employed for the characterization of devices up to 200 MHz [23], [24]. According to this method, the crystal to be measured is located in the series arm of a π-network, and the voltage transfer ratio is measured with equal-frequency separation in the vicinity of the resonance

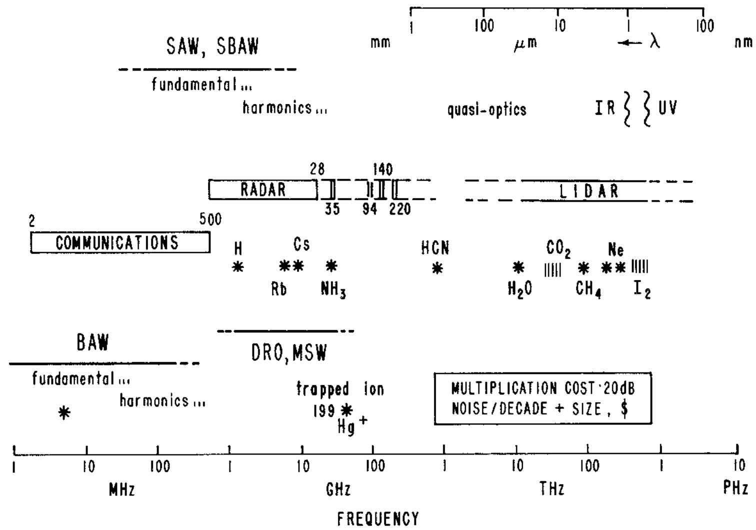

Fig. 3. Frequency ranges of sources and system operation bands. The communications band (2–500 MHz) is largely covered by BAW sources, of which the 5-MHz oscillator (starred) has the greatest stability. Overlapping the communications and radar (0.5–28 GHz) bands are the SAW and SBAW sources. Dielectric resonator oscillators [13] and magnetostatic wave oscillators cover the radar band. Extending from the microwave into the millimeter and optical regimes are the resonances, shown starred, based on molecular, atomic, and electronic transitions [13]. Present-day frequency standards based on these lines are hydrogen, rubidium, and cesium; international time and frequency are defined in terms of the cesium resonance. Laser and trapped-ion lines for future standards are also marked [13].

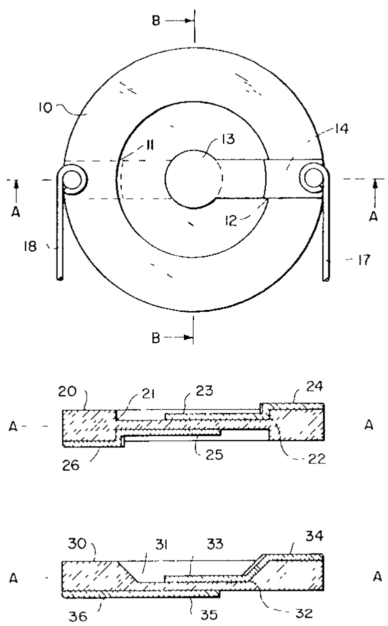

Fig. 4. Ultrathin UHF bulk acoustic-wave device; figure taken from [18]. The piezoelectric material 10 is thinned in the central region to form an outer annulus 20 for mounting, monolithic with the central, piezoelectrically resonant membrane driven by electrodes 23, 25. At resonance, the membrane thickness is a integer multiple of one-half the acoustic wavelength.

frequency. After a correction for the residual susceptance in the load circuit has been made, the values of the crystal parameters can be determined. A second method permits computation of the complete admittance (Y) matrix from direct measurements of the four scattering (S) parameters of the resonator at frequencies between 200 MHz and 2 GHz [25]. The second method permits a determination of the series arm parameters from the matrix even where crystals do not show a zero phase response. This is frequently the case above 200 MHz.

III. BAW Resonators and Oscillators with Piezoelectric and Nonpiezoelectric Substrates; Composite and Thin-Film Structures

In the foregoing, we have discussed briefly BAW resonators with self-piezoelectric coupling materials. It is advantageous in certain applications to use a separate frequency-determining body with an electroacoustical coupling medium, such as a cadmium sulfide (CdS) layer to form a thin-film transducer on a quartz crystal wafer [26], [27]. This is a modern approach to composite resonators [28]. Fundamental-mode oscillators operating up to 4 GHz have been realized employing thin films sputtered onto a silicon membrane [29]–[35]. Fig. 5 provides a sectional view of such a resonator [31].

Composite resonators offer the advantage that a high-overtone resonance can be used and the resonator need not be extremely thin and fragile. Also, one is not restricted to the use of piezoelectric materials as the frequency-stabilizing medium. A group of researchers [36]–[41] investigated and described various types of resonators consisting of substrates of sapphire, ruby, spinel, silicon, $LiTaO_3$, and $LiNbO_3$, with ZnO transducers, in the range from 1 to 10 GHz. The operation of a high-overtone resonator is depicted in Fig. 6 [36]. If opposite surfaces of a high-Q substrate are parallel, a resonance response will occur at all frequencies for which the distance of the surfaces is an

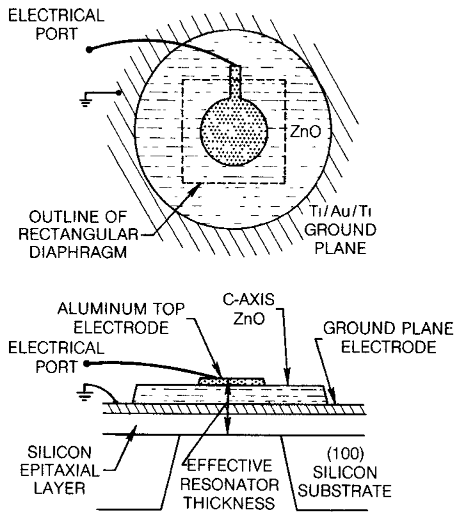

Fig. 5. Thin-film acoustic-wave composite resonator device [31]. The nonpiezoelectric silicon epitaxial membrane is driven into mechanical resonance by the strongly piezoelectric ZnO film; frequency is determined by the effective resonator thickness shown. The silicon membrane is formed by back-etching the substrate to expose the doped epilayer.

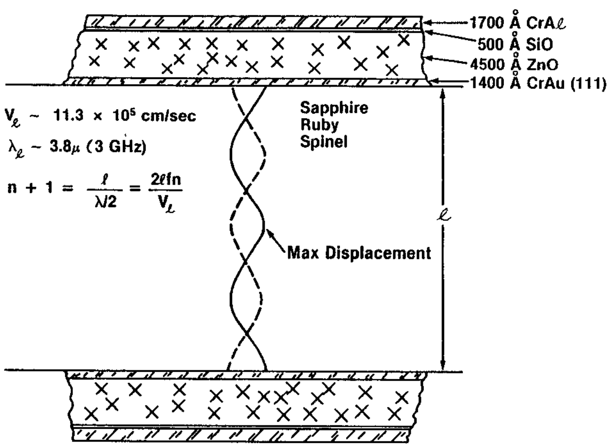

Fig. 6. Composite harmonic bulk acoustic resonator device [36]. A high-Q substrate supports a piezoelectric driving layer and electrodes (see Fig. 5). The drive structure may be placed on one or both substrate surfaces, and operated in the manner of either a one- or two-port SAW resonator.

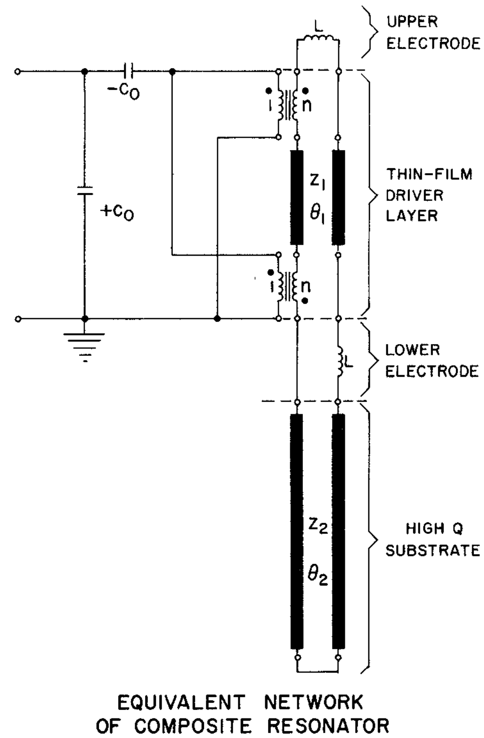

Fig. 7. Equivalent electrical network of a one-port composite BAW resonator [55]. Piezo-transformers couple energy between the electrical port and the mechanical transmission lines supporting the acoustic waves. Line acoustic impedances are Z_1 and Z_2, and θ_1 and θ_2 are the line angular lengths.

integral number of half wavelengths. Frequency-tuning techniques have also been explored [42]. The $Q \cdot f$ values are larger than those of quartz and are limited in part by the aperture of the resonator, by the parallelism of the surfaces, and by diffraction, the last being influenced by the anisotropy of the medium [36], [37]. A VCO containing the composite BAW resonator was found to have a phase noise comparable to that of a low-frequency standard crystal oscillator multiplied to the same frequency but with a 10:1 reduction in hardware [39].

Another interesting approach to BAW thin-film resonators is described in [43]–[46]. Here, GaAs is used as the resonator material directly or with AlN for the transducers employing wafer top planar processing. The fact that this fabrication method is compatible with integrated-circuit technology makes this approach very attractive. The frequency range from 850MHz to 1.3 GHz was investigated and Q's up to 2500 were measured. Mesa-shaping by etching the ZnO film of ZnO/Si resonators in the region surrounding the top electrode proved to reduce the spurious mode spectrum [47]. Magnetron sputtering proved to be an attractive and rapid method of deposition of thin films of ZnO, AlN, and potassium lithium niobate (KLN) on a variety of SAW substrates [48]. ZnO/Si and AlN/Si composite structures have been fabricated [49], [50] with temperature coefficients of frequency less than 1 ppm/°C around room temperature and better than AT quartz over the range $-20°$ to 120°C. UHF oscillators controlled by AlN/Si resonators have been constructed using computer-aided-design procedures [51]. It has been shown that the parasitic capacitance–resistance branch of a ZnO/SiO_2 bulk-wave resonator can be eliminated, a measure that increases the effective coupling factor [52]. Methods for modeling the characteristics of composite resonators have also been developed [53], [54]. In general, excellent agreement exists between predicted resonance spectra and experimental data [53]. The standard equivalent circuit consisting of lumped circuit elements is not suitable for an accurate electrical characterization of a composite resonator. The transmission-line network shown in Fig. 7 is the appropriate representation for the composite resonator [55].

IV. SAW/SBAW Devices for UHF/Microwave Frequency Sources

To date, SAW devices have made their most significant impact at frequencies above the traditional frequency of operation of BAW devices (> 40 MHz) and below the start of the microwave regime (<1 GHz). Thus, SAW devices, representing a relatively mature technology in this frequency band, presently fill a gap in which no other acoustic structures have yet to assert themselves. The photolithographic fabrication techniques employed with SAW's to produce the transducer geometries required at these frequencies are achievable by standard, single-stage photographic methods and lend themselves to mass production. The result is an easily reproduced device, providing wide device design flexibility, in a rugged planar construction suitable for microelectronic integration. Coupled with the ease of a planar fabrication method is the desirable property that SAW devices have Q factors as high as 10 000 and conveniently slow velocities of approximately 3 km/s. Consequently, a number of diverse functions, such as delay lines, bandpass filters, matched filters, resonators, and convolvers, have been demonstrated using SAW devices [2], [3], and these are finding ever-increasing use in communications, electronic warfare, and radar systems. The literature on SAW devices and their applications is extensive; some representative papers are given in [56]–[58]. In addition, the reader is referred to the recent issues of IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, (formerly TRANSACTIONS ON SONICS AND ULTRASONICS), *Proceedings of the IEEE Ultrasonics Symposium*, and *Proceedings of the Annual Frequency Control Symposium* (*AFCS*).

One area which deserves special attention, however, is the application of GHz-frequency SAW devices [59]–[63], harmonic operation of SAW devices [64], [65], and the relatively new SBAW [66]–[70] devices to provide high-frequency, high-stability oscillators [71], [72]. In general, the SAW or SBAW device is employed in an oscillator circuit in one of two configurations. One depends on using the element as a delay line and the other employs it as a resonator structure. Both the delay line and the resonator structure can be modeled as a device that provides a delay in the feedback loop of an amplifier, with the conditions for oscillation being simply that the loop gain exceed unity and the total phase loop shift equal $2\pi n$, where n is an integer. Fig. 8 shows the general block diagram for an acoustic-based oscillator. The delay-line approach has the advantage in that it can provide a relatively wide tuning range, respectable FM capability, and high power handling capability. The resonator-controlled oscillator, on the other hand, provides an inherently higher Q; thus, the above properties are in a sense traded off to obtain good short-term frequency stability.

In an attempt to provide frequency generation beyond 1 GHz, the stringent geometry requirements of the SAW device at these frequencies have led to more emphasis being placed on investigations with SBAW oscillators [73]–[78]. In contrast to SAW, SBAW penetrates into the body of the substrate, but can be designed to travel nearly parallel to the surface. Fig. 8 shows, in cross section, the launching and reception of SAW and SBAW [67]. The SBAW devices referred to in this paper also include a device called surface skimming bulk wave, which describes

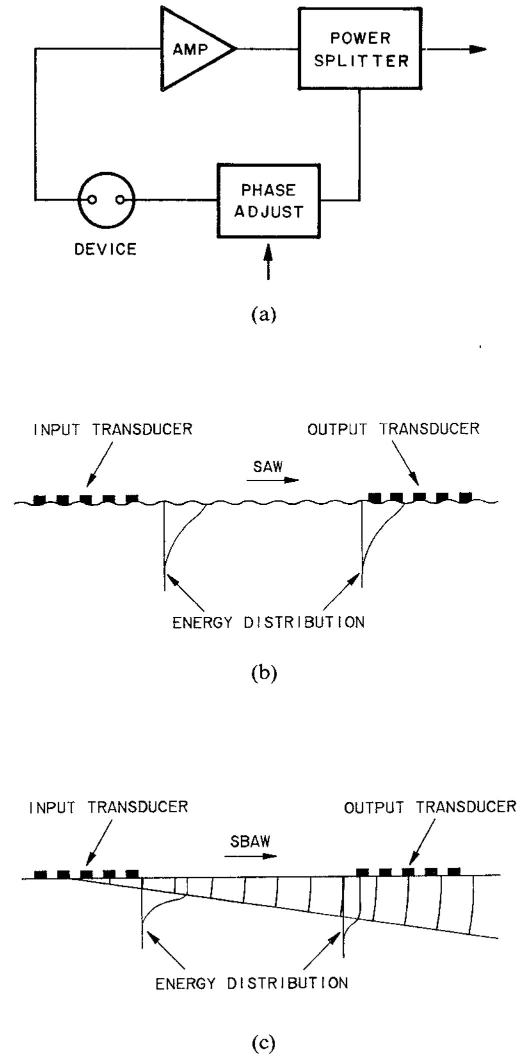

Fig. 8. (a) Block diagram of SAW-based oscillator. "Device" refers to either a SAW delay line or two-port resonator. Frequency fine-tuning is accomplished by adjusting the phase shifter (b) Cross-sectional distribution for surface acoustic waves propagating between IDT arrays. Wavenumbers are imaginary into the substrate, leading to a trapping of the energy within a few wavelengths of the surface. (c) Cross-sectional energy distribution for shallow bulk acoustic waves propagating between IDT arrays. Real wavenumbers in the depth direction lead to a fan-shaped beam resembling the pattern of an end-fire antenna array.

TABLE I
KEY FEATURES OF SAW AND SBAW

INTERDIGITAL TRANSDUCTION
Ultra-High Frequency Operation
Response Shaping by Photolithographic Processes
Large Design Flexibility; Spatial Fourier Transforms
PLANAR STRUCTURE
Semiconductor Fabrication Techniques
Microelectronic Components/IC-Compatibility
Mechanically Rugged
Simple Tuning Operations Possible
Significantly Reduced Size and Weight
PERFORMANCE POTENTIAL
Cubic Temperature Behavior (SBAW only)
Clean Mode Spectrum
Surface Contamination/Defects Insensitivity (SBAW only)
Superb Phase Noise Floor

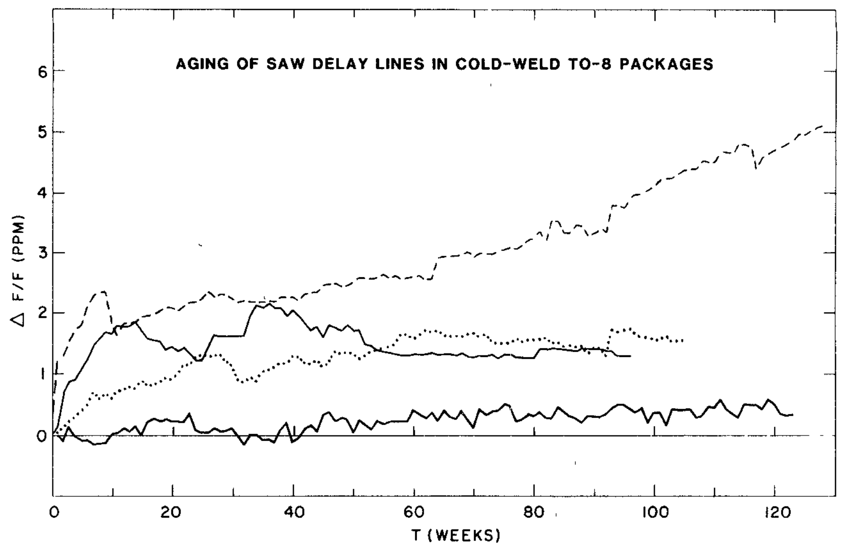

Fig. 9. Aging performance of SAW delay lines [91]. Low long-term aging is achieved by careful attention to cleaning and high-vacuum sealing techniques.

the same acoustic-wave type [73]. The primary advantage of SBAW or SSBW is that the frequency, for a given interdigital transducer geometry, is about 1.6 times higher than the corresponding SAW frequency for ST cuts, all other considerations being equal [67]. In addition, crystal cuts with SBAW propagation are available that can provide cubic f–T characteristics similar to the BAW AT cut [74] and improved parabolic behavior [79] for applications where temperature stability is the driving factor. Experimental results with devices have been reported at fundamental frequencies to 3.0 GHz and harmonic operation at 4.2 GHz [77]. A simple frequency doubler demonstrated the operation of the 4.2-GHz device at 8.4 GHz, thereby providing stable frequency operation at *X*-band with only a low order of multiplication. Papers giving a good survey of the accomplishments of SBAW devices are given in [66]–[79]. Information on singly and doubly rotated cuts (close to AT, BT, and SC) and curves of frequency constant, piezoelectric coupling, and temperature coefficient for doubly rotated cuts are included in [80]–[82]. The phase noise of the SBAW oscillator at offsets greater than 10 kHz proved to be less than the noise of a 10-MHz BAW crystal oscillator plus multiplier [76]. The value of the noise floor was between -140 and -160 dBc, measured at 1 MHz offset from the carrier. Table I summarizes the key features of surface acoustic-wave and shallow bulk acoustic-wave devices.

V. Multifrequency Sources

The future trend will be to employ these devices in architectures which will provide rapid-hopping, multifrequency microwave sources. This will occur because of the projected need for frequency agility in future space communications and radar systems. Various schemes have been proposed whereby a small number of oscillators are combined with mix-and-divide circuits to provide a large number of output frequencies. In the so-called direct synthesis approach, frequency hopping has been demonstrated to occur at switching times of <100 ns. Obviously, each system will have its own performance requirements, but the synthesizer parameters of output waveform, frequency band, step size, resolution, spectral purity, etc., that have been demonstrated can be found in [83]–[85].

VI. Stability of Oscillators as a Function of Time, Temperature, Force, Pressure, and Acceleration

Regardless of the acoustic device configuration, the stability of a microwave acoustic oscillator as a function of time and, specifically, the long-term drift or aging have been the concern of a number of investigators. In the case of the ST-cut substrate for the SAW delay lines or resonators, the following results are pertinent.

1) The transducer metallization is, to a large extent, responsible for aging, possibly due to a stress relaxation. Aluminum doped with copper is a beneficial combination for the electrode material [86]–[91].

2) The types of holders and packaging of delay lines and resonators also influence aging. The following measures decrease the long-term drift: vacuum baking and cold-weld hermetic seals [87], [89], [92]–[95] and the use of specific enclosures, such as TO-8, HC-28, all-quartz packages [89], [91], [92]–[99], without organics for mounting the substrate [87].

3) Under optimum conditions, the systematic drift rate per year becomes smaller than 2 ppm [89], [91], [92], [98], [100], [101]. Most of the drift measurements were made between 160 and 600 MHz on delay lines and resonator oscillators. Recently, it has been found that random frequency fluctuations with periods up to months and years are superimposed on the systematic drift [91], [97]. This noise is less for resonators than for delay lines, but its source is not yet known. Typical aging data from four 400-MHz delay-line oscillators sealed in cold-weld TO-8 packages are shown in Fig. 9. The random frequency

TABLE II
COMPARISON OF ACOUSTIC MICROWAVE SOURCES

TECHNOLOGY	FREQUENCY	Q·f	Short term f drift	Long term f drift	SSB Phase Noise Floor, 10 kHz - 1 MHz Offset Freq.	Advantages	Disadvantages
Single Crystal BAW resonator oscillators Quartz, $LiTaO_3$	100 MHz - 1.5 GHz (Lab effort)	$1\cdot10^{12}$ to $3.8\cdot10^{13}$ (Quartz) $0.07\cdot10^{12}$ to 1.10^{12} ($LiTaO_3$)	$5\cdot10^{-9}$ to $5\cdot10^{-11}$ per sec	$5\cdot10^{-6}$ to $< 5\cdot10^{-7}$ per year	-135 to -140 dBc/Hz normalized to 1 GHz region	Q about 1.5 times larger than SAW resonators	Resonator very fragile
Composite BAW resonators Substrate: Sapphire, ruby spinel, GaAs. Si, $LiTaO_3$, $LiNbO_3$ Transducer: ZnO, AlN	1 - 10 GHz	$> 10^{13}$, Potential Q 10 times that of Quartz, GaAs: $< 2.5\cdot10^{12}$	1 ppm per °C Better than AT for Si substrate		-135 to -165 dBc/Hz @ 1-2 GHz W/HBAR tracking filter	Not restricted to piezoelectric material. Crystals with very high Q can be selected	Multi-resonances very close together
SAW resonators & resonator oscillators, ST-cut Quartz	100-1000 MHz	$3.7\cdot10^{12}$ to $8\cdot10^{12}$		$< 2\cdot10^{-6}$ per year	-145 to -160 dBc/Hz @ 1 GHz	Random fluctuations less than for delay lines	Limited to less than 1.5 GHz
SAW delay lines oscillators, Quartz ST-cut	100 MHz - 1.4 GHz	$0.6\cdot10^{12}$ to $2.8\cdot10^{12}$	$1\cdot10^{-9}$ per sec 0.01 ppm per g	$< 2\cdot10^{-6}$ per year	-130 to -155 dBc/Hz @ 1-1.5 GHz	Respectable FM capability Higher power handling capability	Random freq. fluctuations larger than for resonator [91]
SBAW (SSBW) Oscillators, AT, BT, SC quartz	100 MHz - 5 GHz	2.10^{12} to 11.10^{12}	TC similar to bulk modes (AT, BT, cuts)	2-10 ppm per month	-100 to -160 dBc/Hz @ 2-3.5 GHz	Higher frequencies than with SAW can be attained. Smaller sensitivity to surface defects	Higher Insertion Loss

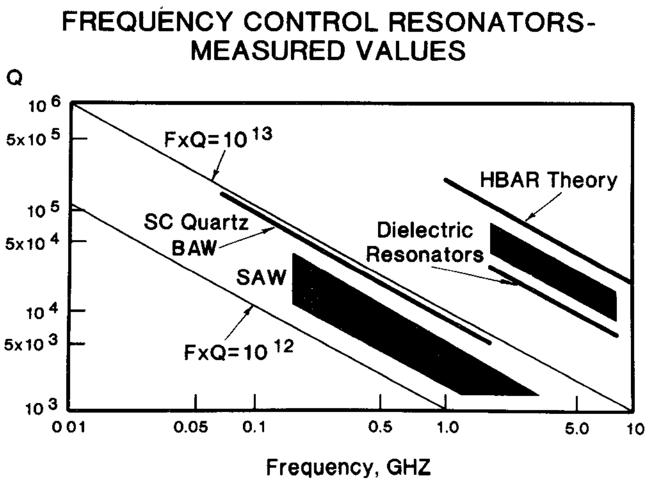

Fig. 10. Mechanical quality factor Q as a function of frequency f; constant Q times f product implies a constant acoustic material viscous loss. Shown are values for the stress-compensated SC quartz BAW cut, the ranges of observed device Q for SAW and HBAR devices, and measured Q values of dielectric resonators for DRO applications [37], [39].

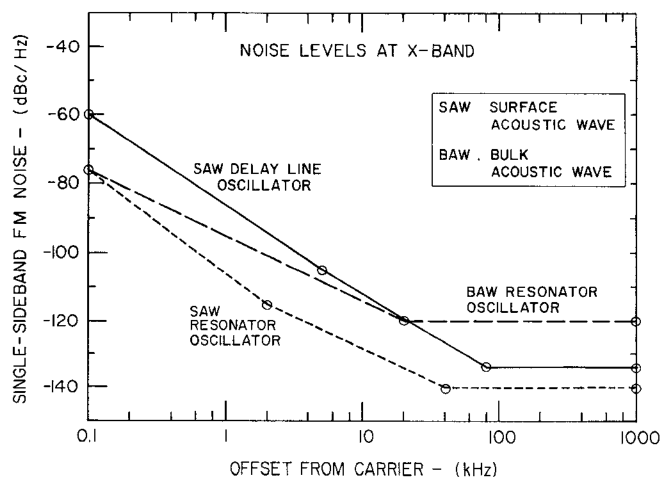

Fig. 11. Phase noise performance of typical BAW and SAW oscillators multiplied to 10 GHz [94]–[98]. Plotted is the ratio of single-sideband noise power in a 1-Hz bandwidth to carrier power level; this ratio is often called script-L. The abscissa is Fourier frequency, the offset from the carrier, in kilohertz. SAW oscillators excel in the white phase noise (flat) region at large offsets.

fluctuations can clearly be seen in this graph [91]. Recent results show that aging and random frequncy fluctuations can be improved by using an all-quartz package [102].

4) The drive level applied to the device has been found to be an important aging mechanism. This type of aging is caused by an acoustically induced migration of Al metallization. This effect can be slowed down by adding a small amount of Cu to the metallization [86], [88]. Also, an increase in propagation loss can result in up or down frequency aging. This depends upon the ratio of the oscillator frequency to the delay-line synchronous frequency [103].

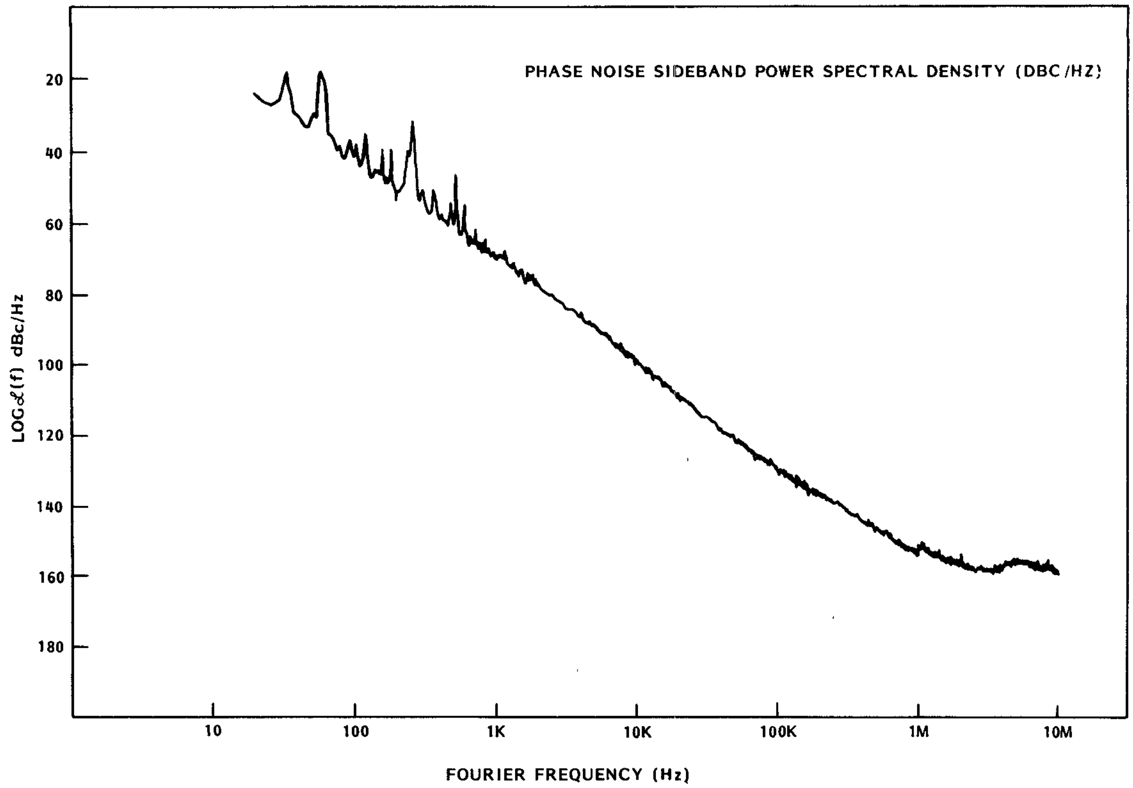

Fig. 12. Phase noise sideband power spectral density function script-L, as a function of Fourier frequency, in hertz, for an SBAW oscillator at 3.05 GHz [76].

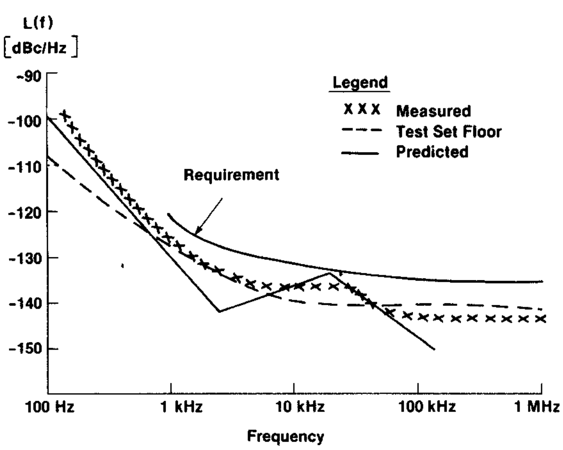

Fig. 13. Measured L-band phase noise performance of an HBAR oscillator (1.5–2 GHz). Script-L is plotted against Fourier offset frequency [39]. A typical system requirement is shown.

5) SBAW devices have long been expected to age better than SAW devices because the wave is not confined to the region close to the surface. However, this has not been borne out by measurements. Both SAW and SBAW oscillators in the gigahertz range age at approximately the same rate [104].

Much less effort has been devoted over the past years to other environmental influences on the frequency of acoustic microwave oscillators. The power flow angle and pressure dependence of SAW propagation characteristics in quartz were investigated [106], as well as the acceleration sensitivity of 1.65-GHz BAW thin-film composite resonators with a yttrium aluminum garnet (YAG) substrate and ZnO transducer [107]. Its value of about 2.2×10^{-11}/g is smaller than that of a 5-MHz resonator by two orders of magnitude. Phase noise degradation was found on a 300-MHz SAW oscillator during low-frequency random and sinusoidal vibration [108]. Thermal compensation of quartz SAW oscillators through electronic control of a phase shift element in the feedback loop has been demonstrated as a promising technique to obtain improvement over the usual ST-cut stability [109]. A unique digital circuit approach to temperature compensation of a delay-line oscillator was also investigated [110]. In this method, a second delay path with a high temperature sensitivity acts as a temperature-sensing device. Temperature compensation of SAW's can also be obtained by dimensioning and shaping of the surface grating [111], [112]. This technique applies also to horizontally polarized (transverse-type) SAW's [111] as well as to the conventional, vertically polarized (Rayleigh-type) SAW's that are treated in this paper.

Plots of wave slowness, temperature coefficient of delay, and power flow angle of a bulk resonator of sapphire or YAG with ZnO transducer provide the information necessary to effect temperature compensation in microwave oscillators [114]. Five-hundred-MHz SAW resonators were exposed to RF power, temperature, and radiation stresses, as well as shock and vibration as required for a satellite environment, and no life-degrading effects or permanent damage were found [115]. Two recent papers deal with the

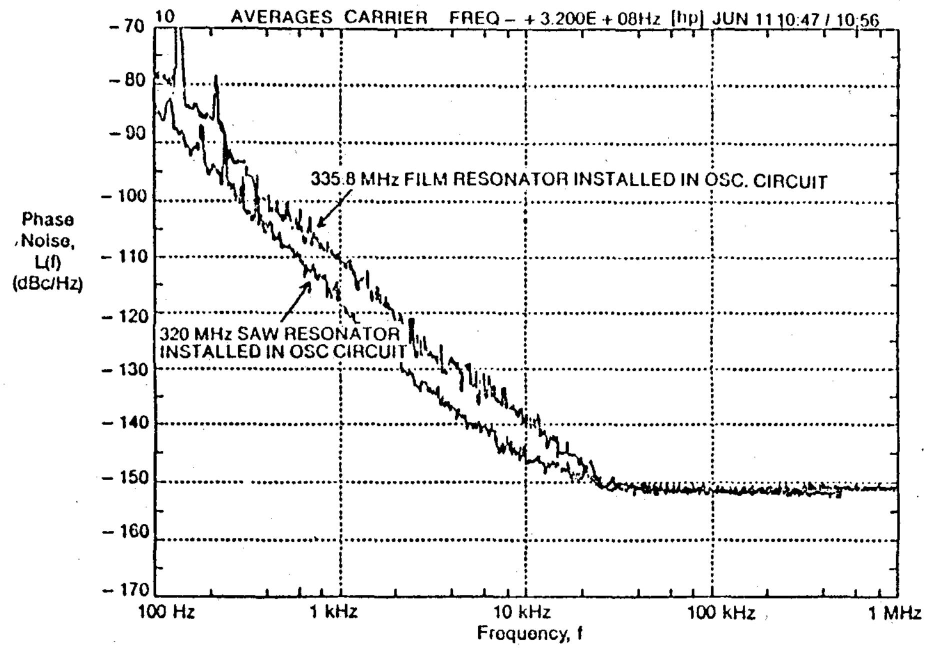

Fig. 14. Measured phase noise performance of thin-film resonator oscillators at 320- and 335.8-MHz fundamental. Script-L versus Fourier offset frequency [36]–[42].

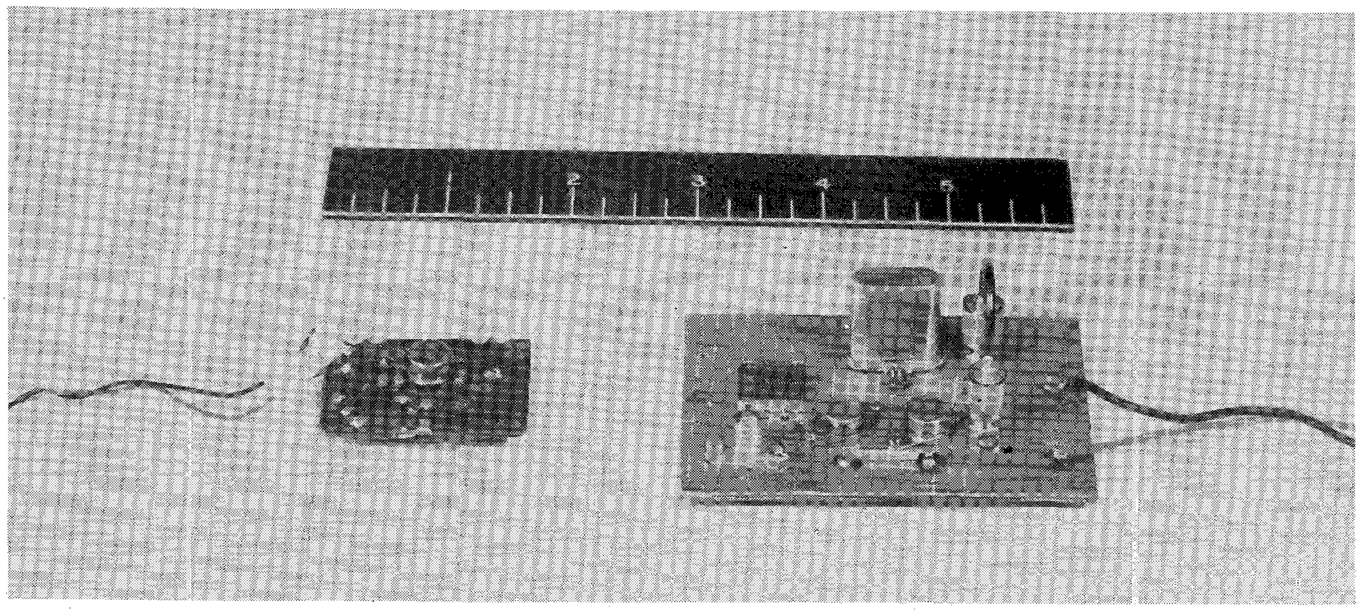

Fig. 15. Representative SAW technology UHF hardware implementations.

analysis and measurement of dynamic (transient) thermal effects in SAW devices [116], [117]. The interactions of straight-crested surface waves with temperature gradients parallel as well as normal to the propagation direction are the two major causes of transient frequency excursions in SAW resonators. Normalized frequency shift $\Delta f/f$ due to a temperature transient is proportional to $(\tilde{a}\Delta T dT/dt)$, where ΔT is the size of the temperature step, and dT/dt is the rate. The constant $\tilde{a}$ depends on cut of resonator, mounting, and manufacturing details, and the sensitivities were calculated to be of the order of 10^{-7} s/K^2.

VII. Comparison of Acoustic Microwave Sources

Table II shows select results reported to date. These data provide a very cursory overview inasmuch as there are always specific cases which will differ and the entire field of microwave acoustics is still very much in a progressive

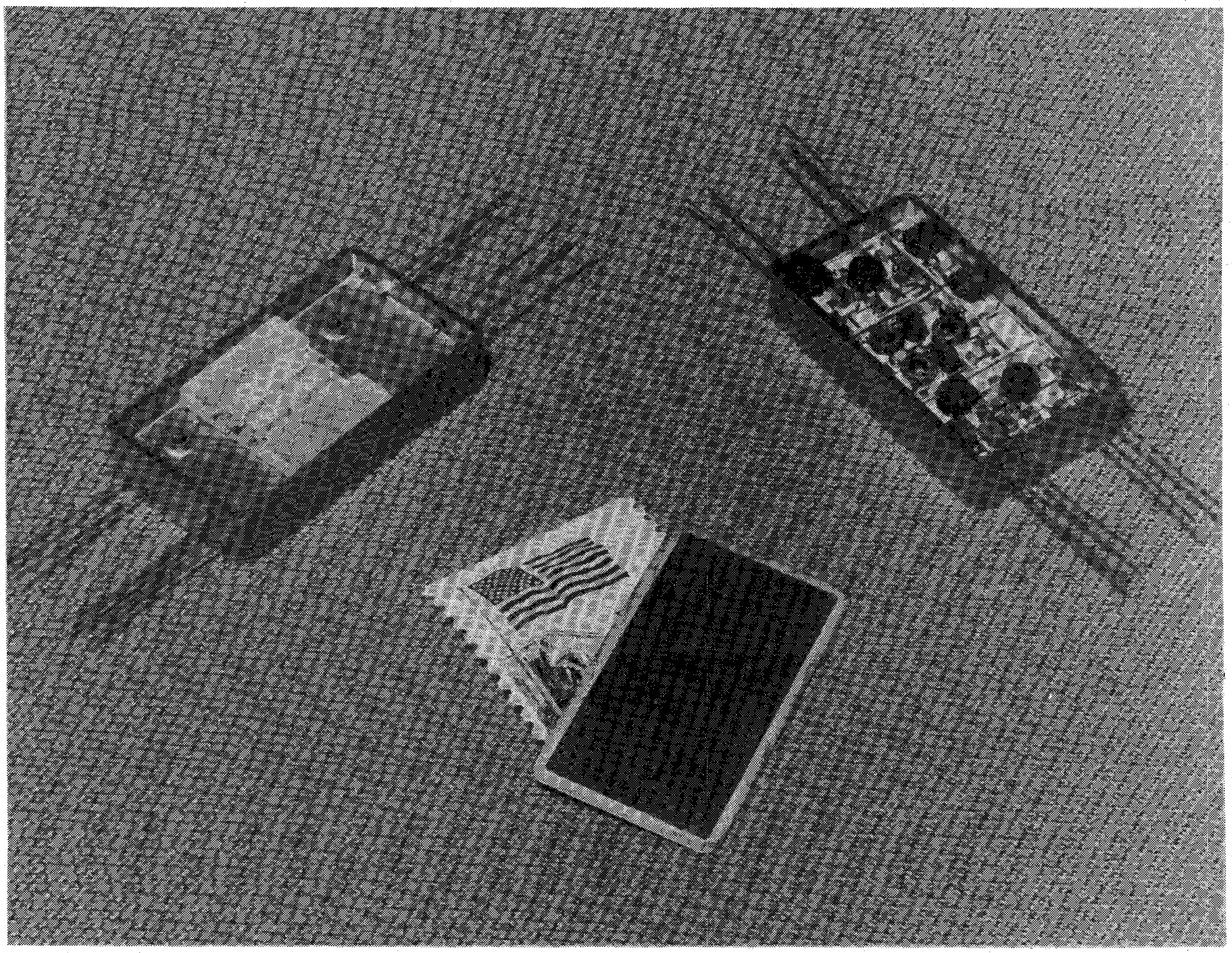

Fig. 16. Representative hardware of oscillator for *L*-band operation. The SAW delay line is fashioned from an all-quartz package (left) for low aging [98].

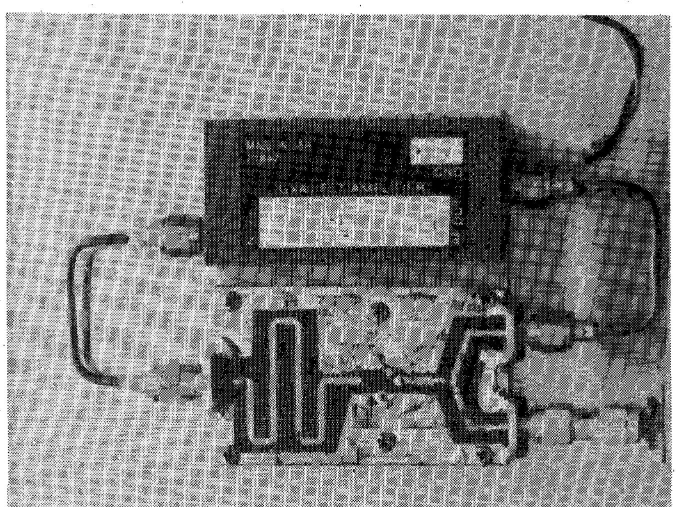

Fig. 17. Photograph of 3-GHz fundamental-mode SBAW oscillator [77].

state. The highest and lowest values for the various quantities found in the literature are entered in the table. The $Q \cdot f$ values represent in most cases the unloaded Q of the resonators or delay lines, whereas the values for drift and noise obviously pertain to the entire oscillator.

The relationships of the Q's of various BAW, SAW, and dielectric resonators are shown in Fig. 10 [37], [39]. The sloping lines in this figure are of constant $Q \cdot f$ product. The high-overtone bulk acoustic resonators (HBAR's) achieve remarkable $Q \cdot f$ values above 2 GHz. Representative single-sideband FM noise spectra for several of these technologies are shown for comparison in Figs. 11–14. The accompanying device/oscillator hardware is shown in Figs. 15–18.

VIII. Conclusions

In reviewing the present state of the art in microwave acoustic frequency sources, the authors feel that one of the

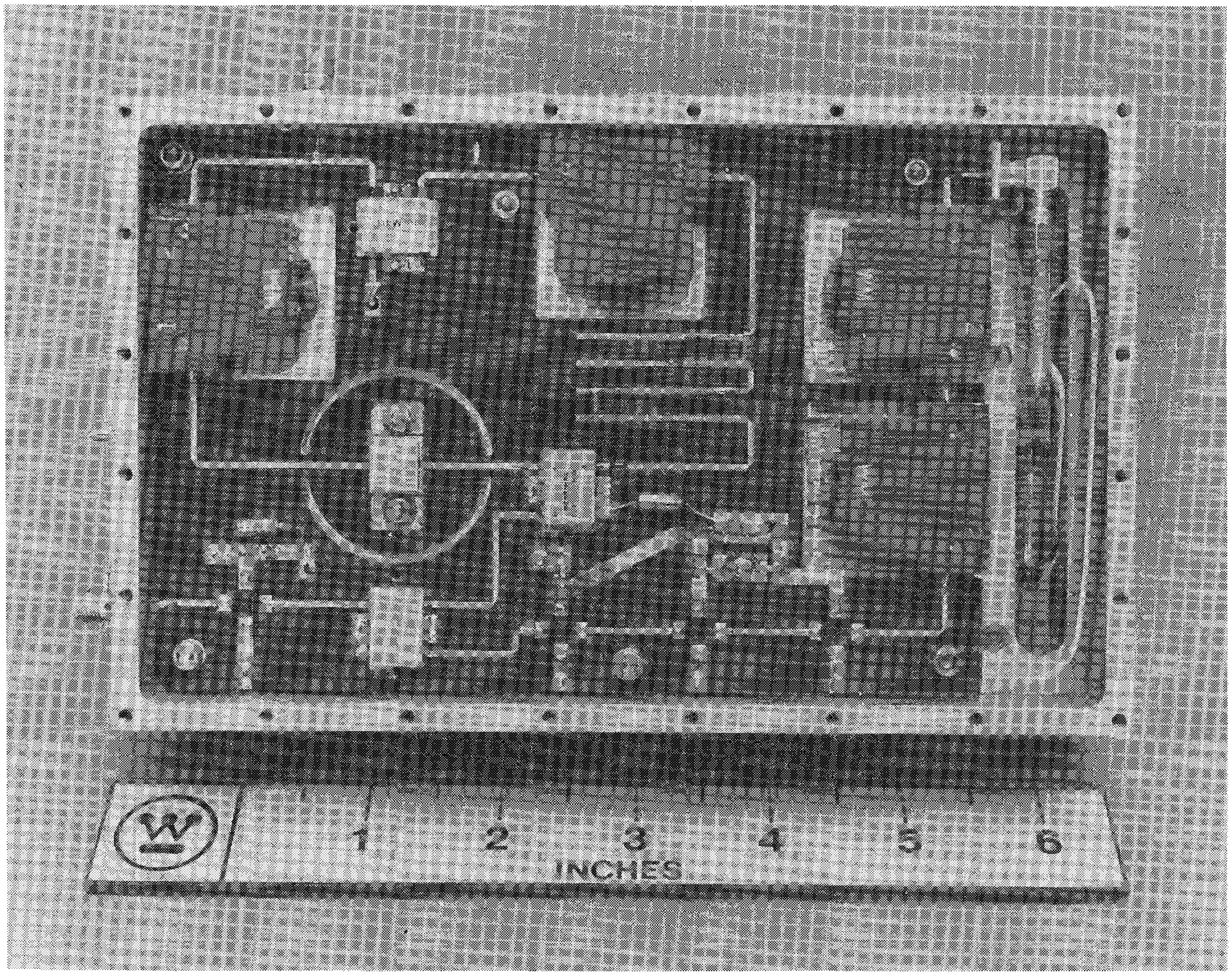

Fig. 18. Represenative hardware of an HBAR oscillator [36]–[42].

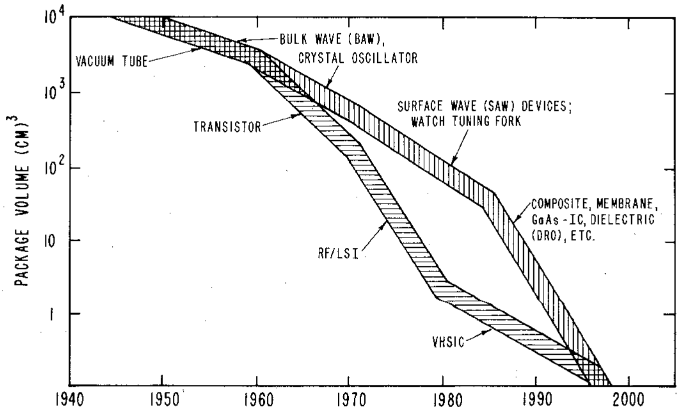

Fig. 19. Size comparisons of active circuitry and acoustic devices, showing the miniaturization of each technology with year. The trend to smaller sizes that began with the transistor accelerated with radio-frequency/large-scale integration (RF/LSI); this trend has continued with the development of very high-speed integrated circuits (VHSIC). Acoustic device size reduction was spurred by development of SAW components and by invention of the photolithographically produced quartz wrist watch tuning fork. The acoustic/active size ratio reached about 100 in the early 1980's. Newer resonant devices may shrink this gap considerably in the future.

most promising approaches to achieve frequencies as high as 10 GHz directly will be the composite resonator vibrating in overtone modes, particularly as additional work will make it more compatible with integrated-circuit technology. However, the reader is cautioned that equipment requirements will ultimately dictate the acoustic device type to be employed because of the widely variable performance achievable in phase noise, aging, temperature behavior, etc. Great strides have been made by the industry to explain and control the various phenomena that contribute to improved performance. The hope is that, following the lead of low-frequency bulk-wave device developments [105], even better solutions to these complex and vexing problems will be forthcoming in the not-too-distant future. In any event, it is apparent from the information provided here that the acoustic-wave community has successfully broken through the previous 1-GHz upper frequency limit with devices whose sizes are now comparable to microelectronic circuits, as depicted in Fig. 19 [118].

Looking to future applications, another area where acoustic devices promise to impact significantly is in their application to sensor technology. Current research suggests the use of acoustics for sensing in robotics, acceleration, flow, optical scanning, vapor, force, temperature, coding, humidity, chemical, biological, etc. [113], [119]. The most recent sensor applications proposed include a touch-sensing display panel [120] and a remote recognition system using encoded transponder tags [121].

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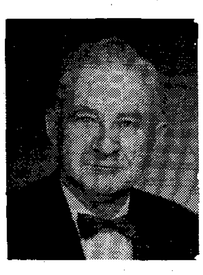
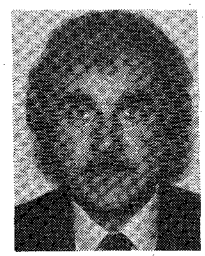


Eduard A. Gerber (A'50–SM'56–F'58–LF'80) was born in Fuerth, Bavaria, Germany, on April 3, 1907. He received the M.S. and Ph.D. degrees in physics from the Institute of Technology in Munich, Germany, in 1930 and 1934, respectively.

In 1935, he joined the scientific staff of the Carl Zeiss Works, Jena, Germany, and was in charge of research and development in piezoelectric crystals. From the time of his arrival in the United States, in 1947, until 1954, he was crystal research consultant to the Signal Corps Engineering Laboratories at Fort Monmouth, NJ. From 1954 to 1961, he served as Director of the Frequency Control Division, U.S. Army Signal Research and Development Laboratory; from 1961 to 1963, he was Director of the Solid State and Frequency Control Division, U.S. Army Electronics Laboratories; and since March 1963, he had been Director of the Electronics Components Laboratory, U.S. Army Electronics Command, all at Fort Monmouth. Since his retirement from the federal civil service, in 1970, he was a consultant to the U.S. Army Electronics Command (now U.S. Army LABCOM).

Dr. Gerber was a Life Fellow of the IEEE, cited for his contributions to piezoelectricity and frequency control. He was also a Fellow in the American Association for the Advancement of Science, a member of Commission I, U.S. National Committee of the International Scientific Radio Union, the American Physical Society, and the New York Academy of Sciences. He held eight U.S. patents and three German patents and published 38 professional papers and contributions to books. He was also coeditor of the two-volume monograph *Precision Frequency Control*.

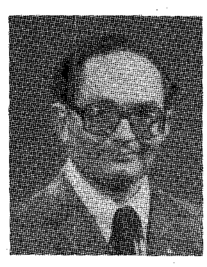
Dr. Gerber received the Department of the Army Decoration for Meritorious Civilian Service in December 1965 and July 1970 and the C. B. Sawyer Memorial Award in 1981. He died August 8, 1986.



Ted Lukaszek (S'61–M'62–SM'81) received the B.S. degree in physics from Monmouth College, West Long Branch, NJ, in 1960, the M.S. degree in solid-state physics from Fairleigh Dickinson University, Rutherford, NJ, in 1966, and did postgraduate work at the Polytechnic Institute of Brooklyn, NY, from 1967 to 1970.

Currently, he is leader of the UHF/Microwave Frequency Sources Team in the U.S. Army Electronics Technology and Devices Laboratory at Ft. Monmouth, NJ. He has done extensive work with both bulk acoustic-wave (BAW) and surface acoustic-wave (SAW) devices and has authored and coauthored a number of papers in this area. More recently, he has investigated the properties of shallow bulk acoustic waves (SBAW) and is presently applying the results of these investigations to the development of components and subsystems that serve as frequency selective and stable frequency sources in communications, radar, and electronic warfare systems.

Mr. Lukaszek is a member of the NATO Working Group AC 302(SG/1) (STG/8) Frequency Control Devices, the IEEE Standards Committee on Surface Acoustic Wave Devices, and the Technical Program Committees for the U.S. Army/IEEE Frequency Control Symposium, the IEEE Microwave Theory and Techniques (Acoustics) Symposium, and the IEEE Ultrasonics Symposium.



Arthur Ballato (S'55–M'59–SM'71–F'81) received the S.B. degree in electrical engineering from the Massachusetts Institute of Technology, Cambridge, in 1958, the M.S. degree in electrical engineering from Rutgers University, New Brunswick, NJ, in 1962, and the Ph.D degree in electrophysics from the Polytechnic Institute of New York, in 1972.

In 1958, he joined what was the Army Signal Corps R&D Labs, and is now the U.S. Army Laboratory Command, Fort Monmouth, NJ. Since that time, he has worked on analytical and experimental aspects of frequency control and selection. Specific areas of interest include evaluation of material constants of quartz and other piezoelectric substances, development of equivalent networks for bulk and SAW resonators, filter crystal and crystal filter design, measurement of circuit parameters of signal-processing devices and precision resonators, development of crystal parameter measurement equipment, and growth of high-purity quartz. Most recently, he has investigated the properties of stress and thermal transient-compensated resonators and high-frequency stable sources. These results have been presented at the Ultrasonics, Frequency Control, Microwave, Circuits and Systems, and other symposia, and published in over 100 articles and patents.

Dr. Ballato is a member of the American Physical Society and Sigma Xi, and is a Chartered Engineer of the Institution of Electrical Engineers (London). He was recipient of the 1978 C. B. Sawyer Memorial Award "for contributions in the field of piezoelectric crystals such as: stacked filters, electric circuit analogs and stress effects in doubly rotated plates," and received the U.S. Army Research & Development Achievement Award for 1980. This is the highest R&D award bestowed by the U.S. Army, and was given "in recognition of major contributions to the state-of-the-art of high precision frequency control." He serves on the Technical Program Committee of the Annual Frequency Control Symposium, and was chairman in 1982. Dr. Ballato is a member of the Administrative Committee of the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society as its Standards Committee Chairman. He was the Society's Distinguished Lecturer during 1984–1985 on the topic "Frequency & Time Sources." He is a member of the Technical Advisory Group TC-49 (Piezoelectric Crystals) of the U.S. National Committee of the International Electrotechnical Commission.