Development of Miniature Filters for Wireless Applications

Kenneth M. Lakin, *Senior Member, IEEE*, Gerald R. Kline, and Kevin T. McCarron, *Member, IEEE*

Abstract—**Miniature filters have been under development for wireless applications from 500 MHz to over 6 GHz using thin piezoelectric films on common substrates. This paper discusses recent results in the development of miniature filters using a solidly mounted resonator (SMR) concept wherein the acoustic resonator is isolated from the substrate with a sequence of quarter wavelength thick layers that form a reflector. The SMR concept is discussed in detail and applications to filters is presented. Ladder filters have been demonstrated with insertion losses in the 3 dB range using aluminum nitride films for the piezoelectric and appropriate substrates such as silicon, sapphire, and glass. The ladder filters reported consist of interconnected series and shunt resonators forming a monolithic structure on a single die of comparable size to an integrated circuit.**

I. Introduction

WIRELESS NETWORKS are growing rapidly in the spectrum from 500 MHz to 6 GHz. These systems include pager, cellular phone, navigation, satellite communication, and various forms of data communication. Supporting these emerging or growing systems has been a significant advancement in integrated high frequency and digital control circuits. However, less attention has been paid to the development of analog frequency control technologies such as filtering.

The need for filters has become more apparent as spectrum crowding increases with the deployment of new systems. In particular there is a growing need for front-end filters that protect receivers from adjacent channel interference and output filters that limit the bandwidth of transmitter noise. Further, subsystem miniaturization may require high performance filters to occupy the same packages as high frequency integrated circuits or at least employ packages that are similar and are handled the same way in production.

Resonators for use in frequency control may consist of inductor and capacitor (LC) circuits or equivalent elements obtained from distributed effects. At microwave frequencies the low Q of LC resonators limits applications to low pass, high pass, or wider bandwidth bandpass filters. Consequently most microwave frequency resonators are composed of sections of coaxial, stripline, or other forms of transmission lines whose dimensions are dependent upon a fundamental propagation mode velocity.

Manuscript received March 2, 1995; revised July 7, 1995. This work was supported in part by the U.S. Army SBIR program, the U.S. Office of Research and Development, the U.S. Army Advanced Concepts and Technology program, DARPA SBIR program, and the U.S. Navy SBIR program.

The authors are with TFR Technologies, Inc., Redmond, OR 97756 USA.

IEEE Log Number 9415505.

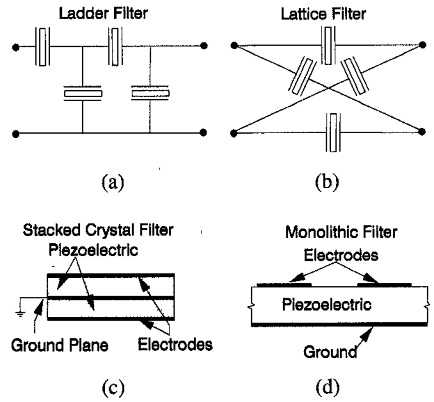


Fig. 1. Basic filter types implementable with thin film piezoelectric materials. (a) electrically connected ladder filter, (b) lattice filter for balanced networks, (c) stacked crystal filter, and (d) a plate-wave monolithic filter.

Because acoustic waves propagate approximately four to five orders of magnitude slower than electromagnetic waves, bulk and surface acoustic wave resonators are much smaller than even high permittivity based EM structures. For that reason considerable attention has been directed toward microwave acoustic filter development [1]–[4].

Filters that can be synthesized with acoustic resonators are shown in Fig. 1. In Fig. 1(a) and (b) are two classes of electrically connected resonator filters that could be composed of bulk or surface wave resonators. At low frequencies ladder filters generally use shunt capacitors to control loop currents rather than resonators. Ladder filters fabricated on a common aluminum nitride membrane supported by a silicon substrate have been reported [2].

The lattice filter is suitable for balanced circuits and was once widely used at low frequencies. Such filters could be fabricated with thin films and then used in balanced integrated circuit networks.

Two forms of acoustically coupled resonator filters are shown in Fig. 1(c) and (d). The monolithic filter is used in considerable volume at frequencies below 200 MHz while the stacked crystal filter (SCF) is most suited to higher frequencies where films can be grown to effect the proper acoustical bonds between the layers.

Variations of the SCF have been reported with operation as high as 11.6 GHz [3]. This device is suited for use in systems where the near-in skirt selectivity of the ladder filter is not needed. Inductor tuning may be used to increase the bandwidth and reduce insertion loss. However, inductor tuning greatly increases the size of the filter.

The monolithic filter requires a degree of energy trapping for proper operation. Low frequency devices employ the energy trapping properties of plate waves in AT quartz and other shear wave material cuts. Since the widths of the trapping electrodes are of the same order as the thickness of the piezoelectric plate, higher resolution fabrication is required at microwave frequencies than required by thickness mode resonators and filters.

The various forms of crystal filters and their use at intermediate frequency locations in wireless systems is well known. The use of crystal filters at system operating frequencies, and particularly close to the antenna, is relatively new because until recently crystal filters have not had the low insertion loss, bandwidth, and impedance levels necessary for these applications.

Resonators for use in electrically connected crystal filters can be of several forms including SAW grating resonators. Of interest here are those resonators fabricated with thin films supporting the bulk thickness mode resonance of either shear or longitudinal waves.

Since basic filter layouts are known, the key issues in high frequency filter development are resonator design and methods of resonator fabrication. In considering thin film bulk wave resonator fabrication techniques it is useful to define a resonator structure as one being bounded by extremes of mechanical impedance that tend to keep the waves confined within a desired volume. Conventionally, air or vacuum interfaces are used although the broad definition allows for other configurations, as will be discussed.

Resonator fabrication techniques suitable for use with piezoelectric films and microelectronics processing are shown in Fig. 2. The resonators in Fig. 2(a) and (b) have low impedance material interfaces of air or vacuum.

The configuration of Fig. 2(a) is a membrane structure supported by the edge of the substrate [5]–[6]. 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. Substrates such as silicon and gallium arsenide have been used with some success. However, strain in the film can lead to breakage, and the approach is limited in any case to substrates in which a VIA can be readily formed.

The second configuration involves fabricating an air gap under the resonator [7]. This may be accomplished by first depositing and patterning an area of temporary support film, next depositing and patterning an overlay piezoelectric resonator with electrodes, and finally using an under cutting etch to remove the temporary support. The result is a membrane supported at the edges but free from the substrate in the resonator region. Typical materials might be ZnO or SiO_2 for the temporary support and AlN or ZnO for the piezoelectric. The final membrane resonator is fragile as in the case of Fig. 2(a) but is applicable to a larger number of substrates since a VIA is not required in the substrate. However, strain

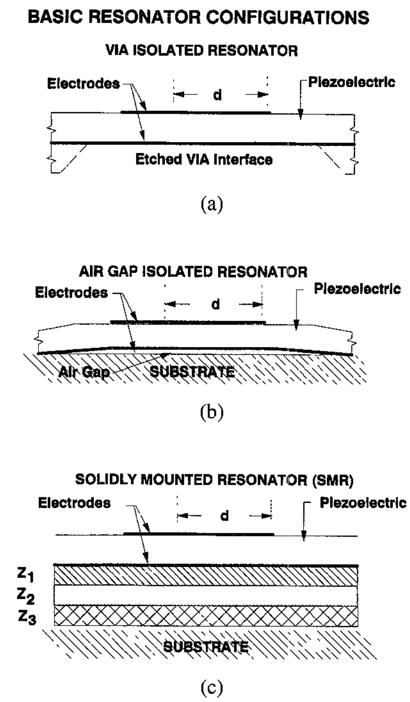


Fig. 2. Resonator types fabricated with thin films. (a) Membrane or FBAR resonator, (b) Air Gap resonator, (c) SMR resonator using quarter wavelength reflector layers.

in the deposited piezoelectric film can cause the membrane to warp and rest upon the substrate giving rise to uncertain resonator performance.

II. Solidly Mounted Resonators

In an effort to obtain a more rugged thin film resonator structure other approaches have been investigated. The solidly mounted resonator (SMR) in Fig. 2(c) is of a considerably different form than the membrane structures described above. Since the piezoelectric is solidly mounted to the substrate some means must be used to acoustically isolate the piezoelectric from the substrate if a high Q resonance is to be obtained.

In 1965 Newell [8, 9] described a method of transforming the impedance of a resonator mounting substrate to a lower value at the crystal that gave partial isolation. The technique used quarter wavelength (wavelengths are referred to the center frequency of the resonator in this paper) sections of materials having large impedance ratios that favorably transform the substrate impedance. The difficulty of the process at the time was proper bonding of layers although the use of thin films was projected as a viable technique. Nevertheless, Newell showed that both free and clamped interfaces could be obtained using quarter wavelength thick transformation layers.

The technique of Newell, and later others [10], involves a transformation of the substrate impedance, using a certain number of layers, to a relative value suitable for clamping or freeing the surface. However, in the work reported here the SMR response is conceptually and practically independent of the substrate and therefore materials with inferior acoustic properties, such as epoxies or plastics, may be used for the substrate. The operation of the reflector structure in this case is more analogous to that of the grating in a SAW resonator. Unlike the SAW resonator, the magnitude of the individual internal reflections may be large without fear of exciting spurious modes. The structural details of the bulk wave reflector are different and much fewer individual reflectors are required to make a high Q resonator.

An important effect of the reflector layers, as demonstrated by Newell, is the partial lateral stiffening of the piezoelectric plate that minimizes displacements associated with plate wave generation and consequent spurious resonances normally observed in free plates. The potential for generating surface waves at the edges of resonators has not been examined.

In the SMR configuration the top surface may have a normal air or vacuum interface while the bottom is solidly mounted through a reflector structure to the substrate. The reflector interface with the piezoelectric region may present a high or low impedance depending on the detailed configuration of the reflector. Both top and bottom interfaces can be formed by respective reflector structures although only the case of one SMR reflector interface and one air surface is considered here.

The analysis of the SMR starts from a fundamental one dimensional equation defining the electrical impedance of a bulk acoustic wave resonator [4]

$$Z = \frac{1}{j\omega C} \times \left[1 - K^2 \frac{\tan\phi}{\phi} \frac{(z_r + z_l)\cos^2\phi + j\sin 2\phi}{(z_r + z_l)\cos 2\phi + j(z_r z_l + 1)\sin 2\phi}\right] \tag{1}$$

where ϕ is the half phase across the piezoelectric plate, K^2 the piezoelectric coupling, z_l and z_r are normalized acoustic impedances at the boundaries, and C is the high frequency capacitance. If the boundaries are composed of a low impedance material (like air or vacuum) the boundary impedances are zero and the electrical impedance reduces to

$$Z = \frac{1}{j\omega C}\left[1 - K^2 \frac{\tan\phi}{\phi}\right]. \tag{2}$$

This gives the impedance versus frequency characteristics of simple acoustic resonator having thin electrodes, such as shown in Fig. 2(a) and (b). It is also the form of impedance for more complex resonators around the resonant frequencies. In which case the piezoelectric coupling is interpreted as an effective value rather than a real material constant.

The analysis of the reflector structure is most conveniently done using two fundamental equations of wave propagation. The total reflection from a material discontinuity is given by

$$\rho = \frac{z - 1}{z + 1} \tag{3}$$

where $z = Z_m/Z_i$ with Z_m the impedance of the material beyond the interface and Z_i is for the region of the incident wave. Across material sections effective impedances due to standing waves is given by the transmission line equation

$$Z_{\text{in}} = Z_0 \left[\frac{Z_t\cos\theta + jZ_0\sin\theta}{Z_0\cos\theta + jZ_t\sin\theta}\right] \tag{4}$$

where Z_{in} is the input impedance, Z_t the load impedance, Z_0 the characteristic impedance of the section, and θ the total phase across the section.

For an ideal free surface (zero force) $z = 0$ and for an ideal clamped surface (zero particle motion) z must be much larger than unity. Therefore in the SMR structure, if the total reflection is strong enough, a free ($\rho = -1$) or a clamped ($\rho = 1$) surface can be synthesized. An air or vacuum interface can accurately approximate a free surface yet no known single material can form an adequately clamped surface, for high Q resonator purposes.

For multiple layers the impedance at the reflector interface is derived from a recursion relation for quarter wavelength layers

$$Z_{iq} = Z_q^2 / Z_{i(q+1)} \tag{5}$$

where subscript i denotes the input impedance of section q. By numbering sections from the top of the reflector, the effective normalized impedance is,

$$\begin{aligned} z &= \left(\frac{Z_1}{Z_p}\right)\left(\frac{Z_1}{Z_2}\right)\left(\frac{Z_3}{Z_2}\right)\left(\frac{Z_3}{Z_4}\right)\cdots \\ &= \left(\frac{1+\rho_{p1}}{1-\rho_{p1}}\right)\left(\frac{1-\rho_{12}}{1+\rho_{12}}\right)\left(\frac{1+\rho_{23}}{1-\rho_{23}}\right)\left(\frac{1-\rho_{34}}{1+\rho_{34}}\right)\cdots \end{aligned} \tag{6}$$

where Z_p is the impedance of the piezoelectric region and the subscripted reflection coefficients are for the indicated interface. With appropriate subscript, the impedance in (6) can be used in (1) to calculate the electrical impedance of a piezoelectric plate. The first part of (6) is in a familiar circuit impedance form whereas the second part is more physical in describing the phenomenon as a composite of surface reflections at a number of interfaces. If the odd layers are of low impedance relative to the even layers then the successive reflections give rise to a low impedance and apparent free surface. If the odd layer impedances are high and the even layers low impedance then the interface appears approximately clamped. From (4) and (6) it is clear that layers are added until the desired reflection coefficient and interface impedance are obtained.

Accordingly, in the SMR approach described here, multiple reflections from a number of layers adding in phase are used to synthesize an open or clamped interface independent of the properties of the substrate. Layers are added until the total reflection is sufficiently large in magnitude to give the desired resonator response and layers need not be added in pairs.

The frequency response of the multi-layer reflector can be obtained by successive application of the full transmission line (4). The wave reflections are most pronounced at the quarter wavelength frequency, and well outside the center frequency the reflectors are less efficient. The magnitude of the apparent mechanical impedance versus frequency for a number of layers is shown in Fig. 3.

The frequency bandwidth of the high reflectivity region of the reflection determines in part the series and parallel resonant frequencies of the resonator and, therefore, the bandwidth and insertion loss of a filter made from SMR's. The number of layers and the impedance discontinuity between adjacent layers determines the magnitude of the reflection at center frequency.

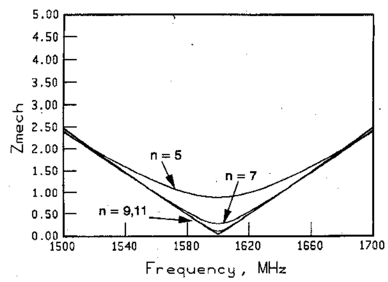


Fig. 3. Mechanical impedance versus frequency around the quarter-wave frequency for various reflector layers composed of SiO_2 and Si_3N_4. Impedance units are 10^5 gm/sec cm^2.

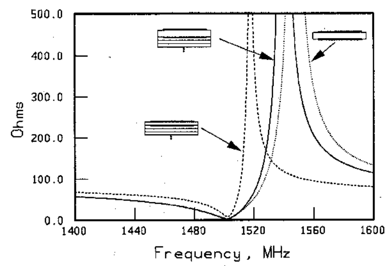


Fig. 4. Magnitude of electrical impedance versus frequency for three resonator types. The solid line is an SMR with a nominal half wavelength thick resonator, the coarse dashed line is an SMR with a quarter wavelength thick resonator, and the fine dashed line is for a membrane type resonator as illustrated by the insets. The piezoelectric material is AlN and the reflector uses W for the high impedance material and SiO_2 for the low impedance material. All resonators have the same series resonant frequency and the parallel resonant frequencies are different according to the effective coupling coefficients.

Fig. 4 shows the modeled magnitude of electrical impedance versus frequency for three resonator cases of interest. The first is an SMR having the first layer, adjacent to the piezoelectric, of low impedance then alternating between high and low for the remaining layers. In the second case the first layer is of a relatively high impedance and the others alternate between low and high. Finally, the third case is of a free plate resonator for comparison. In both SMR examples an odd numbers of layers were used, although increasing the number by one made no difference in the results. The impedances were approximately 100 and 12 (units of 10^5 gm/sec cm^2) for the high and low impedance regions respectively. AlN was used for the piezoelectric and Al for the electrodes.

The degree of free or clamped motion at the reflector interface is determined by the magnitude of the apparent impedance discontinuity. The input impedance of the reflector must be either small or large relative to the piezoelectric material itself. Using materials such as ZnO and AlN for the piezoelectric, it is easier to synthesize a relatively low impedance than a high impedance even when using materials such as W and SiO_2 in the reflector. Consequently, the effective coupling coefficient, as determined from (2), for the quarter wavelength thick resonator is much smaller than the half wavelength resonator. The piezoelectric coupling for the three cases in Fig. 4 are: 7% for the free plate, 5.7% for the half wavelength SMR, and 1.4% for the quarter wavelength thick SMR.

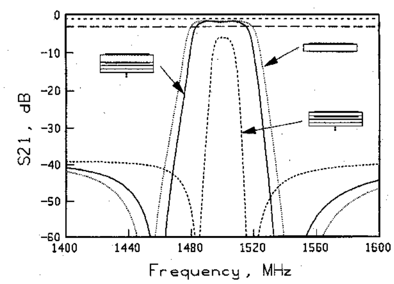


Fig. 5. Theoretical response of a ladder filter using the various resonator types described in Fig. 4.

The most significant advantage of the SMR resonator approach described here is that it can be fabricated on a wide variety of substrates and, with a sufficient number of layers, the acoustic properties of the substrate are not important. The SMR structure is extremely rugged compared to membrane devices, is in much better thermal contact with the substrate, and does not require a VIA. The rugged construction gives rise to a high device yield during manufacturing and allows the device die to be handled just as any other circuit die. Without a VIA the device die are approximately four times smaller in area than membrane die allowing four times as many die per wafer.

The absence of a VIA or any special substrate preparation shows considerable promise for direct integration onto active circuit wafers. It is necessary, in this case, to first passivate the IC's and then fabricate SMR devices, in areas provided, after all IC processing has taken place.

The fabrication of the SMR is more complex than for a membrane resonator because of multiple layers and material parameter controls required during film deposition. Any use of conductive materials in the reflector structure may require patterning to avoid parasitic effects in complex filter structures.

III. SMR Filters

Thin film resonator filters have been under development for some time [1]–[7] using the membrane approach. These filters have shown some promise but manufacturing yields with fragile membranes is low and spurious responses from plate waves has been a problem. The use of piezoelectric films on thick substrates to create overmoded resonators and filters allowed strain in the resonators without fractured membranes and showed an absence of spurious resonances [4]. In order to obtain high performance and high manufacturing yield the SMR approach is being applied to ladder and other filter configurations.

A. Ladder Filters

Filters based on the SMR concept have been under investigation here for a number of years. The impact of the SMR on a typical ladder filter is shown in Fig. 5. Here a simple filter, consisting of three series and two shunt resonators, is model for the three kinds of resonators shown in Fig. 4. As discussed earlier, the bandwidth and insertion loss of the filter is dependent on the effective piezoelectric coupling coefficient [2].

The best theoretical filter response is with the membrane resonators. However, experimental filters using membrane resonators have shown a high degree of plate mode spurious resonances [2]. The half wavelength thick SMR has approximately the same insertion loss but slightly narrower bandwidth. The filter using quarter wavelength thick resonators has a narrow bandwidth and high insertion loss as modeled.

Experimental results for a ladder filter composed of three series and two shunt SMR's is shown in Fig. 6. Fig. 6(a) is S_{21} for the near-in frequency response and shows the deep notches that increase the filter skirt selectivity. The high frequency notch is due to parallel resonance in the series resonators and the low frequency notch is due to series resonance in the shunt resonators. Fig. 6(b) is the S_{21} wide band response showing a uniform level of out-of-band rejection due to the voltage divider formed by the resonators acting as capacitors. For comparison, the response of a four pole ceramic filter is shown in Fig. 6(c). The in-band insertion loss is better than the current experimental SMR but the high frequency rejection and skirt selectivity are much poorer. The size of the ceramic filter is 8 mm × 7 mm × 33 mm and the SMR filter die is 1 mm × 1.5 mm × 0.5 mm.

One of the important features of the SMR filter is the absence of apparent spurious plate wave resonances anywhere in the filter response. The third harmonic response of the filter is suppressed as a result of resonator and filter design. The out-of-band rejection is very favorable compared with high dielectric constant filters.

Some systems, such as GPS, require front end filters with an insertion loss of less than 1.5 dB in order not to degrade the signal-to-noise ratio. Therefore, techniques to improve the insertion loss of ladder filters through improved film quality and thickness control are under investigation.

B. Duplexer Filters

Because of their potential for small size and low cost manufacturing, SMR filters for duplexer circuits used in cellular phones are now under development. The deep notches on either side of the ladder filter are an advantage in the implementation of duplexer circuits where the transmit and receive filters are close in frequency and skirt selectivity is important. In particular one design uses the parallel resonance of the series output resonator in the transmitter filter to isolate the transmitter from the receiver.

Results of a theoretical modeling of a cellular phone duplexer filter design are shown in Fig. 7. The duplexer is modeled as a three-port network with one port the output from the transmitter, the second the antenna, and the third the output to the receiver. The S_{21} response from antenna to receiver input is shown in Fig. 7(a), S_{21} from transmitter to antenna in Fig. 7(b) and the transmitter to receiver feedthrough is given in Fig. 7(c).

The size of the designed SMR duplexer filter die would be approximately 1.8 mm × 1.8 mm × 0.5 mm. A shunt inductance is required across the antenna port in this design. In contrast, the size of a ceramic duplexer is approximately 2.0 cm × 0.5 cm × 1.6 cm in surface mount form.

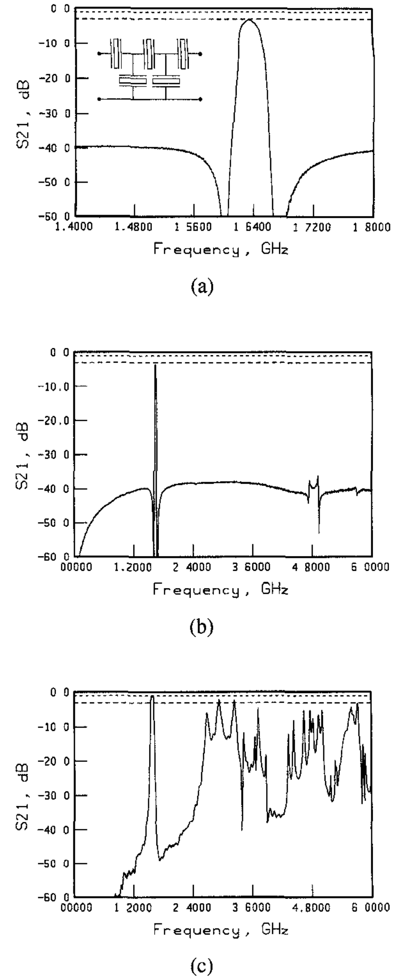


Fig. 6. Experimental results for a ladder filter fabricated on a glass substrate, (a) and (b), and ceramic filter, (c). The horizontal dashed lines are at 1 and 3 dB. (a) Near-in response, (b) wide-band response, (c) wide-band response for ceramic filter. The high impedance material is AlN and the low impedance material is SiO_2 for a total of seven layers on a glass substrate.

C. Solidly Mounted Stacked Crystal Filters

In an SCF [11]–[14] the two piezoelectric plates are separated by a ground plane as shown in Fig. 1. The structure has a number of resonant modes that can be excited by one of the driven piezoelectric plates. The lowest order mode is where the two piezoelectric layers (including electrodes) are a total of one half wavelength thick. In this case each plate is a quarter wavelength thick and therefore the coupling is less than optimum. The most efficient mode is where each plate is a half wavelength thick and the overall resonator is therefore a full wavelength thick (second harmonic). The basic problem with the SCF is that when operating on the most efficient mode the adjacent resonance are only removed in frequency by half the desired frequency, as shown in Fig. 8. Techniques to get rid of one or more of these spurious resonances have been described previously [15] but are more complicated than the technique described below.

The bandwidth of the reflector can be made sufficiently narrow that the SCF is efficient at only the center frequency. The result of using an SMR to implement a three section SCF is shown in Fig. 8 where the first and third harmonics have

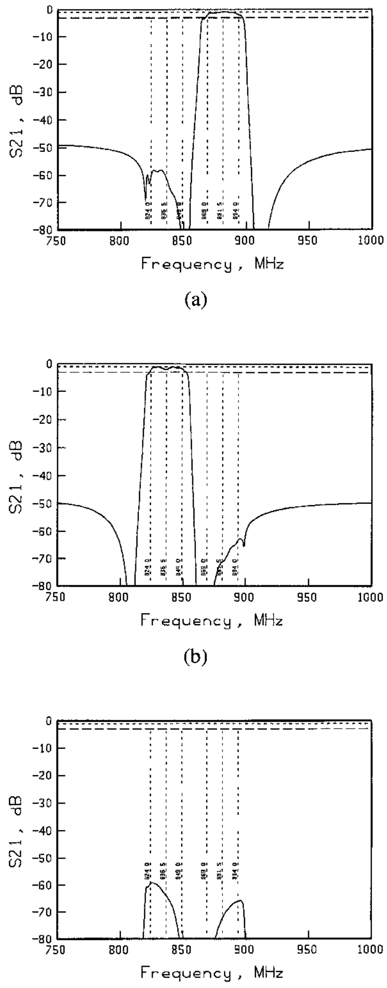


Fig. 7. Theoretical modeling of a three-port cellular phone duplexer synthesized with solidly mounted resonators and ladder filters. Responses are (a) antenna to receiver, (b) transmitter to antenna, and (c) transmitter to receiver.

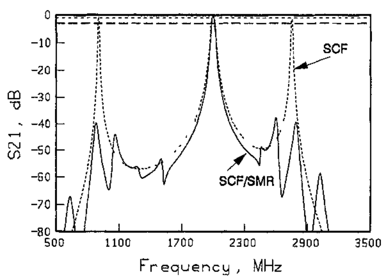


Fig. 8. Modeled response of a three section stacked crystal filter implemented with membrane, dashed lines, and solidly mounted resonators, solid lines. The narrow band response of the reflector greatly attenuates the spurious response of the filter without significantly degrading the mid-band response.

been significantly reduced to below 70 dB. For a two section SCF, not shown, the harmonics are reduced to less than 50 dB.

D. Manufacturing Considerations

Various thin film resonators and associated filters have been demonstrated in prototype form over the past fifteen years. The adoption of the technology to systems requires that performance goals are met and that devices can be manufactured in a cost effective manner. The main manufacturing issues are process survivability and frequency setability. The SMR configuration has greatly increased device yield during processing by avoiding fragile membrane structures.

Frequency setability is almost entirely dependent upon thickness control of those layers within or nearest the piezoelectric layer. The degree of frequency setability required is dependent upon the application. For example, a GPS filter can be designed with sufficient bandwidth to allow for temperature variations and film thickness nonuniformities. In contrast, duplexer filters having close transmit and receive channels will require closer fabrication tolerances or post fabrication trimming.

Shown in Fig. 9 is a uniformity map across a 100 mm diameter wafer. The filter center frequency is within ±0.7% over the full wafer and the insertion loss is generally within ±0.15% dB. The average center frequency is 1670 MHz and the average insertion loss is 2.9 dB. The uniformity is a composite of the thickness and material properties of all the layers but most sensitive to the layers nearest to or within the resonators.

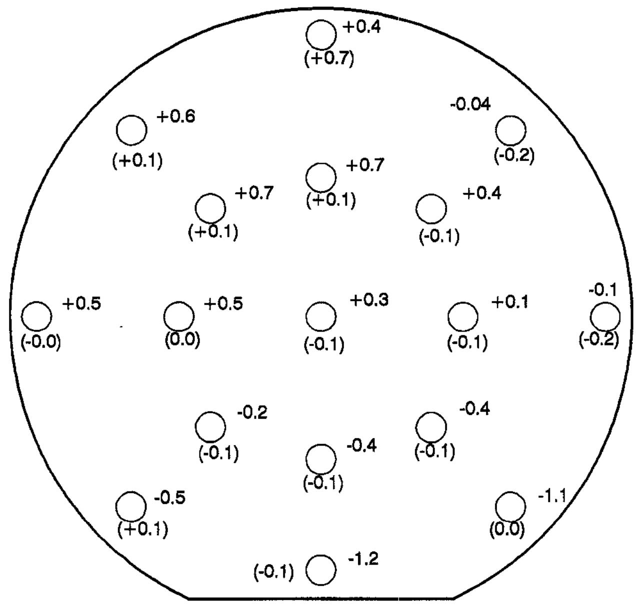


Fig. 9. Uniformity data across a 100 mm wafer for SMR filters. Center frequency is within ±0.7% and insertion loss is within (±0.1) dB approximately. The average center frequency was 1670 MHz and the nominal insertion loss was 2.9 dB. Filters were similar to the one of Fig. 6.

IV. Summary

Miniature filters have been demonstrated with insertion losses in the 3 dB range for application to wireless systems. These filters have been synthesized using solidly mounted resonators that do not require a VIA in the supporting substrate. The resonators are isolated from the substrate using a sequence of quarter-wavelength thick layers that form an efficient reflector.

New applications of the SMR concept to cellular phone duplexers and narrow bandwidth high out-of-band rejection stacked crystal filters were described.

A high degree of uniformity has been shown for fabrication in the solidly mounted resonator configuration. Efforts are now underway to improve filter insertion loss and to extend the concept to higher frequencies.

REFERENCES

[1] C. Vale, J. Rosenbaum, S. Horwitz, S. Krishnaswamy, and R. Moore, "FBAR filters at GHz frequencies," in *45th Annual Symp. Freq. Cont. Proc.*, 1991, pp. 332–336.

[2] K. M. Lakin, G. R. Kline, and K. T. McCarron, "Thin film bulk acoustic filters for GPS," in *1992 Ultrasonics Symp. Proc.*, pp. 471–476.

[3] R. B. Stokes and J. D. Crawford, "X-band thin film acoustic filters on GaAs," *IEEE Trans. Microwave Theory Tech.*, vol. 41, no. 6/7, pp. 1075–1080, Dec. 1993.

[4] ——, "High Q microwave acoustic resonators and filters," *IEEE Trans. Microwave Theory Tech.* vol. 41, no. 12, pp. 2139–2146, Dec. 1993.

[5] T. W. Grudkowski, J. F. Black, T. M. Reeder, D. E. Cullen, and R. A. Wagner, "Fundamental mode UHF/VHF miniature resonators and filters," *Appl. Phys. Lett.*, vol. 39, no. 11, pp. 993–995, Nov. 1980.

[6] K. M. Lakin and J. S. Wang, "Acoustic bulk wave composite resonators," *Appl. Phys. Lett.*, vol. 39, no. 3, pp. 125–128, Feb. 1981.

[7] H. Satoh, Y. Ebata, H. Suzuki, and C. Narahara, "An air gap type piezoelectric composite resonator," in *39th Annual Symp. Frequency Control Proc.*, 1985, pp. 361–366.

[8] W. E. Newell, "Face-mounted piezoelectric resonators," in *Proc. IEEE*, vol. 53, June 1965, pp. 575–581.

[9] ——, "Ultrasonics in integrated electronics," in *Proc. IEEE*, Oct. 1965, vol. 53, pp. 1305–1309.

[10] L. N. Dworsky and L. C. B. Mang, "Thin film resonator having stacked acoustic reflecting impedance matching layers and method," U.S. Patent 5 373 268, Dec. 13, 1994.

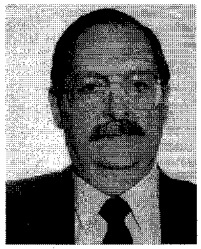
[11] A. Ballato and T. Lukaszek, "A novel frequency selective device: The stacked crystal filter," in *27th Ann. Freq. Contr. Symp. Proc.*, June 1973, pp. 262–269.

[12] K. M. Lakin, G. R. Kline, R. S. Ketcham, and J. T. Martin, "Stacked crystal filters implemented with thin films," in *43rd Ann. Freq. Contr. Symp.*, May 1989, pp. 536–543.

[13] K. M. Lakin, "Equivalent circuit modeling of stacked crystal filters," in *35th Ann. Symp. Freq. Contr. Proc.*, May 1981, pp. 257–262.

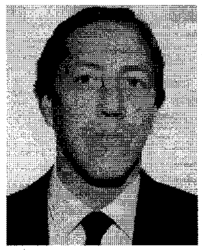
[14] G. R. Kline, R. S. Ketcham, and K. M. Lakin, "Low insertion loss filters synthesized with thin film resonators," in *IEEE Ultrasonic Symp. Proc.*, Oct. 1987, pp. 375–380.

[15] K. M. Lakin, "Modeling of thin film resonators and filters," in *Proc. IEEE MTT-S Int. Microwave Symp. Dig.*, June 1992, pp. 149–152.



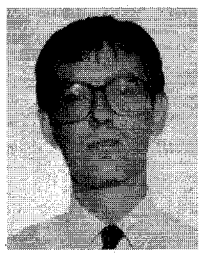
Kenneth M. Lakin (S'65-M'70-SM'79) received the B.S. degrees in electrical engineering and engineering physics in 1964, the M.S. degree in electrical engineering in 1965 from the University of Michigan, and the Ph.D. degree in applied physics from Stanford University in 1969.

He was a Faculty Member in the Electrical Engineering and Materials Science Departments at the University of Southern California from 1969 to 1980 where he conducted research on surface acoustic wave devices, thin film resonators, and piezoelectric film growth and characterization. He formed TFR Technologies in 1989 and is acting as President while conducting research on thin film resonators, piezoelectric materials, filters, and numerical analysis of electromechanical resonators for microwave frequencies. He has published over 100 technical papers in areas of acoustic signal processing device and materials research.



Gerald R. Kline received the B.A. degree in physics in 1967 from William Jewell College.

He was employed by Iowa State University from 1967 to 1989 where he did research in x-ray diffraction, neutron diffraction, solar energy materials, and microelectronic materials and processing. He was a co-founder of TFR Technologies where he was employed through June 1995 doing research and development on thin film based microwave resonators and filters and associated devices.



Kevin T. McCarron (S'88-M'90) received the B.S. degree in physics from Loras College in 1984 and the B.S. degree in electrical engineering from Iowa State University in 1991.

He was employed at Iowa State University from 1985 to 1992 where he did research on thin film deposition of piezoelectric materials. He joined TFR Technologies in 1992 as a Process Engineer and is currently developing processing techniques for fabrication of thin film piezoelectric devices.