Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

Thin Film Resonator Technology

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Abstract The thin film resonator technology has been under development for over forty years in one form or another. Although the basic approach is derived from the desire to reach higher frequencies than those readily achieved by thinning bulk crystals, there have always been competing technologies or fundamental material or processing problems that have impeded the development. Finally, a point was reached in the wireless market wherein competing technologies appeared unable to meet the demands of modern wireless applications and thin film approaches began to receive some emphasis.

This paper will survey the thin film resonator technology. Every effort will be made to provide an objective analysis of the technology in relation to applications and competing technologies, and point out obstacles and promises, as known, for further technology advancement to high frequencies.

I. Introduction

Thin film piezoelectric transducers using CdS or ZnO, were first used in microwave delay lines as a means of generating the high frequency wide bandwidth time delays required by radar signal processing applications [1]. These delay lines required piezoelectric plates bonded to the delay medium (which was often sapphire) for transduction. For UHF and microwave frequencies, piezoelectric thin films were a viable approach to obtaining high frequency microwave acoustic transduction signals and held that niche application for a considerable time.

Resonators are a difficult problem due to the need for an air or vacuum interface, or equivalent boundary condition to support resonance. Considerable effort was, and still is, directed towards techniques to thin bulk crystal material to the required dimensions for high frequency operation. Advances in microelectronics processing have helped by providing lithographic patterning and advanced plasma etching and ion machining techniques. The following table gives some reference values for resonators for several materials for operation at 1 GHz.

Table: Reference numbers for thin plate resonators at 1 GHz assuming 50 Ohm nominal reactance. Tp is the plate thickness and Tm electrode thickness. Electrodes were assumed to be aluminum, unless otherwise noted, and to be 10% of the piezoelectric plate thickness. Dimensions used are: metal thicknesses in micrometers, Co and Ca in pF, La in nH, and K2 in percent. Values are for: AT Quartz, C-axis normal AlN, ZnO, and lithium niobate (LN-C), and 36 deg rotated (LN-36) lithium niobate.

Material	Tp	Tm	Co	Ca	La	K2
Quartz	1.175	0.11	3.16	0.022	1136.3	0.86
AlN-C	4.66	0.46	3.01	0.171	148.1	6.54
AlN-C	2.76	0.28W	3.0	0.18	139	7.0
AlN-C	3.52	0.34Mo	3.0	0.183	139	7.0
LN-C	2.72	0.27	3.11	0.071	355	2.75
LN-36	2.45	0.245	2.56	0.623	40.5	23
ZnO-C	2.385	0.24	2.96	0.223	113.8	8.5

The table illustrates the required plate thicknesses for 1 GHz operation at fundamental mode. The quartz plate is thinner because of its inherent lower material velocity but mostly because AT is a shear wave cut whereas the other materials listed are longitudinal.

Clearly, growing a thin piezoelectric film avoids the need to thin and then support a crystal plate. However, both approaches require some form of support mechanism for the final resonator in order to maintain the required boundary conditions. Crystal plates offer a wider variety of material properties than films because almost none of the high performance materials can be in thin film form.

In the late 60s surface acoustic wave (SAW) devices began to emerge as a promising technology that, to a great extent, eliminated the need for bulk wave resonators at VHF and UHF and avoided having to solve the formidable manufacturing problems associated with bulk wave resonators. This was not because surface acoustic waves had just been discovered, but rather because a simple means of transduction was invented that converged with significant advances in microelectronics having to do with the production of fine metal lines. Today SAW devices are a major mainstay of wireless frequency control devices.

Also in competition with thin film resonator technology are those devices that derive from dielectric electromagnetic resonators. Advances in ceramic material science have resulted in very low cost filters for many wireless applications.

Eventually, the need for microwave frequency filters and miniaturization reestablished the need for BAW thin film resonators.

II. Thin Crystal Plates

The obvious approach to reach higher frequencies with conventional resonators is to thin plates until the desired frequency is obtained. AT-cut quartz crystal plates are commercially available in thickness of less than 25 micrometers having areas of approximately 25 mm square. There are practical limits to thinning large area crystal plates, but perhaps more important is the need to support the thin-plate resonator after the fact.

The inverted mesa, shown in Figure 1, is a configuration wherein a thin resonator region is supported by a much thicker supporting substrate of the same material [2]. Chemical etching techniques have been extensively investigated along with ion milling to obtain thinner regions[3-11]. Considerable effort has been directed towards chemical etching techniques that do not leave a crystal facet roughened surface and resonators are commercially available. Ion machining imparts considerable energy to the surface and can cause undesirable heating. Reactive plasma etching requires somewhat less energy and can be used to thin quartz plates or adjust resonator frequency.

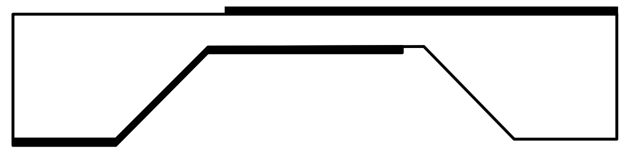


Figure 1. Inverted mesa resonator wherein the substrate crystal material is machined to form a thinner resonator region. The approach is particularly suited to quartz because of its machining capabilities.

The experimental results shown in Fig 2 were derived from an inverted mesa resonator blank purchased from XECO [12] and then patterned with electrodes.

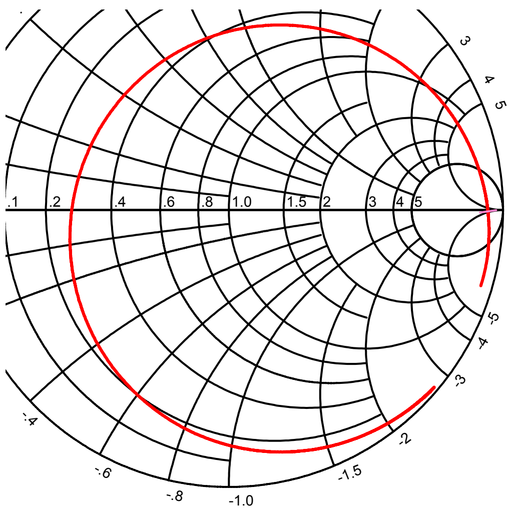
The chemical properties of quartz that allow it to be relatively easily chemically or plasma etched are generally not available in other materials of interest for resonators.

Shown in Figure 3 is an alternative crystal plate fabrication and support method [13]. The crystal plate is bonded to a substrate having an appropriate void region for the required air or vacuum resonator interfaces. Once bonded the crystal plate can be thinned to the desired amount while the peripheries of the crystal plate is supported by the substrate. A variation of this approach would be to carry out the bonding and plate thinning and subsequently open the void or via region. For manufacturing reasons this is not a very practical approach but illustrates the lengths that were pursued to obtain thin crystal plates.

III. Thin Film Composite Resonators

Rather than thin down a single crystal plate, it became apparent to researchers early on that growing the resonator material to a desired thickness might be a viable approach [14,16]. However, these ideas occurred well in advance of the materials science and technology necessary to support actual fabrication. The basic approach shown in Figure 4 will result in a resonator having a high mode number and low effective coupling coefficient.

The composite resonator suffers from low effective coupling coefficient in almost any mode because a significant portion of the energy can be outside the piezoelectric. At overtones where there is a half wavelength across the piezoelectric efficiency can improve but the multiple resonance response has limited applicability. Very high Q resonators have been reported in these composite configurations and so have limited applications in low phase noise oscillators [17-18].



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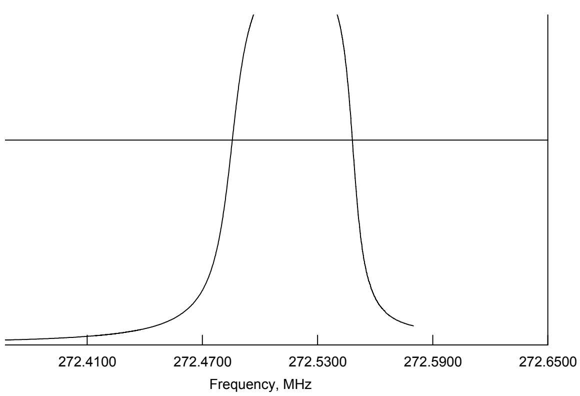
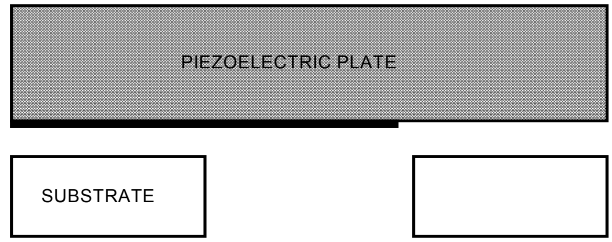


b)

Figure 2. Response of a 300 MHz quartz inverted mesa resonator. Qs = 18,000, Qp = 27,000, K2 = 0.057% .Electrodes used were Al on the bottom and Au on top. a) Smith chart, b) phase response showing clean resonance.



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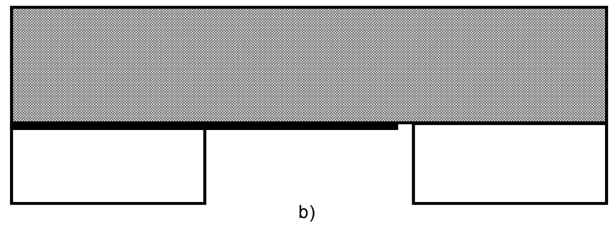

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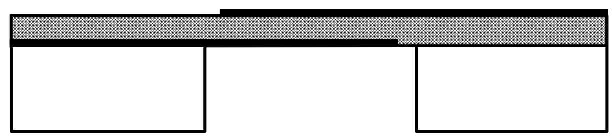


c)

Figure 3. Composite resonator formed from plates. a) Crystal plate (shaded) and substrate with hole. b) Bonded plate and substrate for thinning, c) Thinned resonator supported buy the substrate.

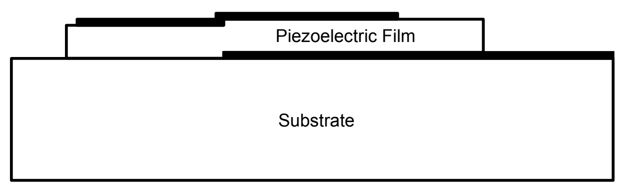


Figure 4. Composite resonator formed by a piezo-electric film transducer deposited onto a support substrate.

IV. Membrane Resonator and Filter Structures

If the composite resonator of Figure 4 is reduced in total thickness to one half acoustic wavelength, the piezoelectric is then a major fraction of the total thickness, the result is what is called here a membrane resonator. The resonator is still composite in the sense that the resonator region is composed of more than just the piezoelectric and electrodes.

The real breakthrough in composite membrane resonators occurred in the silicon microelectronics industry with the work done on silicon as a mechanical material [19]. Using microelectronics processing techniques it was possible to fabricate thin membrane structures on silicon substrates using a wafer-scale manufacturing process that resulted in composite but nevertheless fundamental mode resonators with high effective coupling coefficients necessary for filter synthesis [20-26].

Applying microelectronics processing further resulted in true thin film resonators composed only of the piezoelectric thin film "plate" and electrodes [27]. Reactive ion etching was used to remove the silicon membrane support structure to obtain both AlN and ZnO fundamental mode resonators.

Figure 5 illustrates the basic process using selective etching on silicon. A layer of p+ doped silicon is formed by diffusion followed by chemical etching to form a pocket in the substrate. The typical etches employed were sufficiently anisotropic to leave (111) crystal faces on the sidewalls and terminated on the p+ layer leaving a thin silicon membrane typically less than one micrometer thick. Alternatively, a thick oxide layer could be used to form the membrane as well. The composite resonator in Figure 4a can be converted to a higher coupling coefficient form by removing the support membrane as suggested in Figure 4b. Structures having width to thickness ratios of 200/1 have been fabricated in this manner.

One drawback of the structure in Figure 5 is the overall mechanical strength of the substrate and the substrate area required as a result of the large opening on the bottom of the die. A more suitable approach is illustrated in Figure 6. Here a temporary support is formed on a substrate followed by electrodes and piezoelectric film deposition [28-30]. After the support is removed a membrane resonator is left in place. The actual process may be somewhat complicated due to etching compatibility and other factors. A further variation is to form the membrane of Figure 6 so that the piezoelectric film is planar with the substrate. This will help avoid stress effects at the edge supports. Significant advances in microelectronics processing allow a range of resonator topologies.

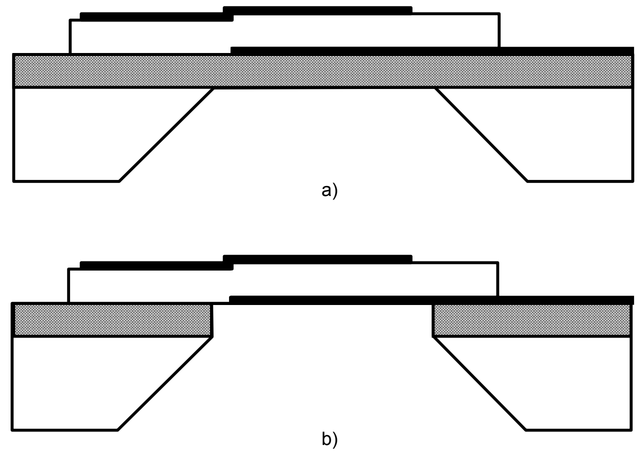


Figure 5. Early membrane structures. a) Piezoelectric film deposited on a p+ silicon membrane (shaded) or in some cases silicon dioxide films were used for support. b) Subsequent removal of the temporary support to leave a truly fundamental mode resonator.

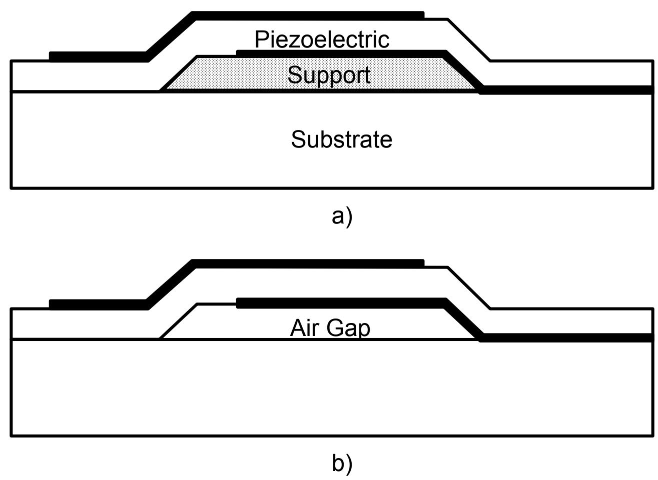


Figure 6. Membrane resonator. a) Temporary support is formed on top of a suitable substrate followed by electrode and piezoelectric layers. b) The temporary support is removed leaving a membrane resonator supported at the edges.

V. Solidly Mounted Resonator (SMR)

A more mechanically rugged resonator structure can be formed by isolating the resonator from the substrate with a reflector array that is composed of nominally quarter wavelength thick layers [31-34]. The number of layers depends on the reflection coefficient required and the mechanical impedance ratio between the successive layers. If the substrate has relatively high impedance then the first layer should be of low impedance the next high impedance etc. A suitable sequence might be SiO2 and AlN or SiO2 and W (tungsten). Because tungsten has relatively high mechanical impedance, fewer layers are required.

The bandwidth of the reflector is affected by the impedance ratio between layers with the SiO2/W sequence having a much wider bandwidth than the SiO2/AlN sequence. The various layers need not have exactly the same materials in the high/low sequence so long as the sequence alternates between high and low.

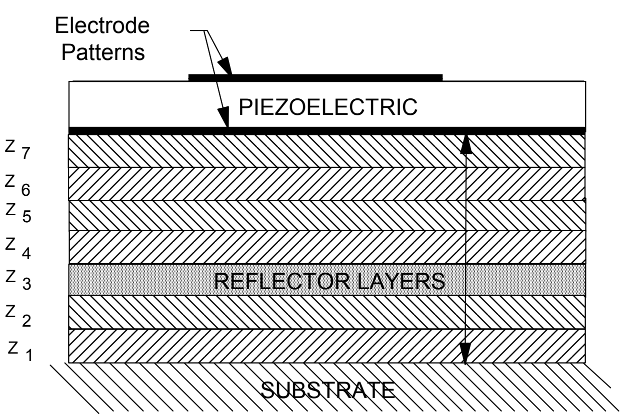


Figure 7. Solidly mounted resonator. The resonator is isolated from the substrate by a sequence of nominally quarter wavelength thick layers that form a reflector.

The SMR structure can be extended to single crystal plates. For example, a single crystal plate of lithium niobate (X-cut) was processed in the following sequence. First a 0.3 micrometer thick aluminum electrode was patterned on the wafer corresponding to the bottom electrode pattern of a resonator. Next a sequence of eight quarter wavelength thick reflector layers (1.04 um SiO2, 1.76 um AlN) was deposited on the substrate. This wafer was then carefully epoxy bonded to another lithium niobate wafer that would eventually act as the final substrate. The exposed side of the first wafer was then thinned to the desired thickness of 3 micrometers and finally a top 0.5 micrometer thick gold electrode was fabricated. The result was a wafer of SMR resonators composed of single crystal piezoelectric having properties unavailable in thin film form because of the shear wave orientation. The resonance characteristics is shown in Figure 8.

The resonance is for the third overtone and both the Smith chart and phase responses show fairly clean responses.

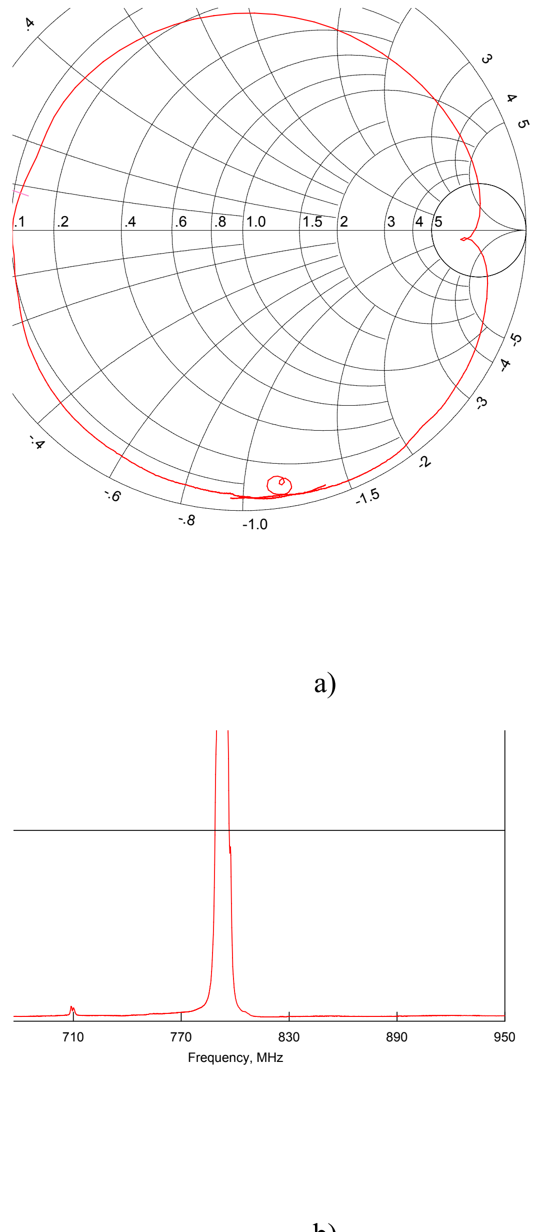


Figure 8. Results for a hybrid SMR composed of single crystal lithium niobate. Fs = 788.9 MHz, Fp = 796.8 MHz Q approx 500. a) Smith chart, b) Phase response.

VI Temperature Compensation

Temperature compensation of a resonator can be achieved by inherent material properties, as in quartz or similar materials, or through a composite arrangement of positive and negative TC materials designed so that one material's TC offsets another's to give an overall compensation. [35]

Figure 9 shows a general picture of how composite resonators can be formed to achieve a balance of temperature performance. In the SMR environment a small fraction of the acoustic energy is stored in the topmost layers of the reflector. Consequently the resonator TC is automatically partially compensated if the last reflector layer is a positive TC material such as silicon dioxide (+85 ppm per deg C). The normal –25 ppm per deg C of AlN is reduced to –15 ppm in this case.

The process to get compensation is to gradually increase the content of positive TC material and reduce the negative material to maintain the same frequency. Figure 10 shows experimental results for a nominal 2 GHz resonator. Similar resonators have been made out to 12 GHz. A large number of narrow bandwidth ladder filters are in production using TC composite resonators to both narrow the bandwidth and provide the necessary degree of compensation.

VII Resonator Tuning

Inductor tuning can be used to enhance the properties of a crystal resonator. A series inductor can be used to lower the series resonant frequency and thereby increase the inherent bandwidth of the resonator. Figure 11 shows the phase and Figure 12 the Q of a resonator with series inductor. The inductor reactance is scaled in steps of 0.1 times the reactance of Co and the inductor was assumed to have a Q of 20. It is apparent that as more inductance is applied the series resonant frequency decreases and the Q drops markedly. Parallel resonance properties do not change in this case.

The use of inductors in series and/or parallel with resonators can be used in oscillator and filter applications. Parallel inductance can be used to resonate Co to leave a single RLC branch for the resonator equivalent circuit hear series resonance. Filter applications of inductance will be described later.

Series and parallel capacitance can also be used to tune resonators but always results in a decrease in effective coupling coefficient. Series capacitance increases the series resonant frequency and parallel capacitance lowers the parallel resonant frequency.

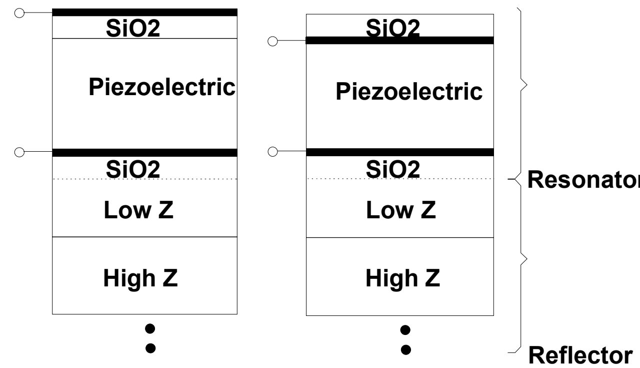


Figure 9. Conceptual schematic drawing of composite resonators. The positive and negative TC materials can be distributed in a number of ways. It is only necessary that the piezoelectric be between the electrodes.

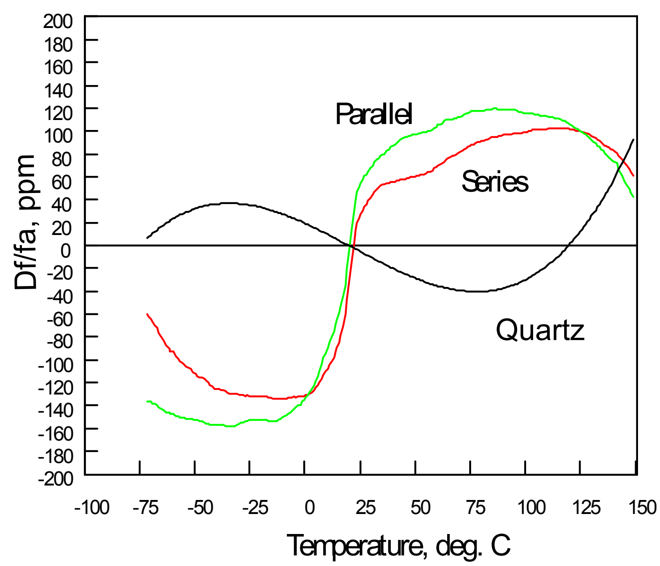


Figure 10. Measured results for a composite partially compensated resonator having AlN for the piezoelectric and SiO2 for the compensating material.

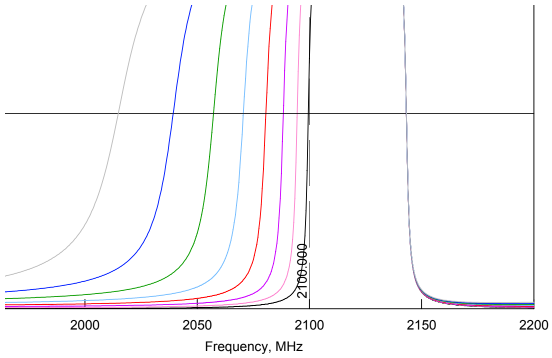


Figure 11 Calculated phase response of crystal resonator having series inductance. The family of curves is for inductive reactance steps of 0.1 times the capacitive reactance of Co. The leftmost plot is for a scaled inductive reactance value of 0.7 referenced to the original series resonant frequency.

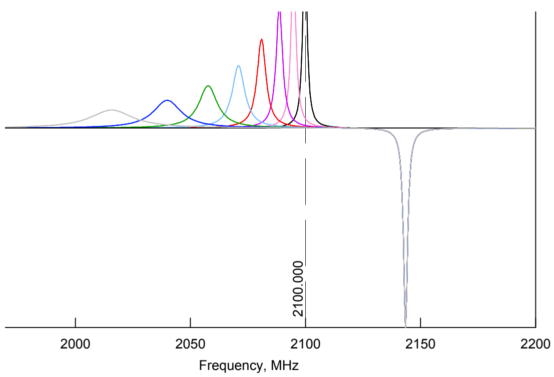


Figure 12. Calculated phase slope response of crystal resonator having series inductance. The family of curves is for inductive reactance steps of 0.1 times the capacitive reactance of Co. The peak values of phase slope correspond to the resonance Q. The series inductor Q was 20, representative of an IC inductor.

VIII. Filters

Filters can be in two basic configurations as suggested in Figure 13. Electrically connected resonators form ladder, lattice, or other similar circuits.

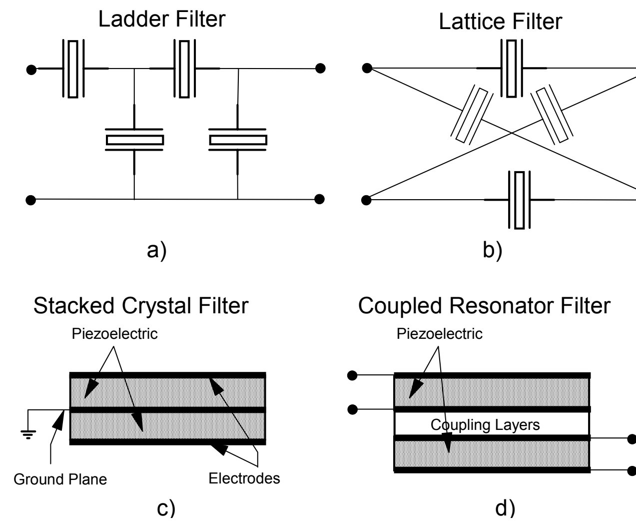


Figure 13. Filter configurations. a) Ladder filter having series and shunt resonators, b) Balanced lattice, c) Stacked crystal filter (SCF), and d) coupled resonator filter.

Ladder filters are made with resonators having different frequencies as required to synthesize the passband response [36-41]. The simplest filter has all the series resonators at the same frequency and the shunt resonators at a lower frequency so that the parallel resonance of the shunt resonator is at approximately the series resonant frequency of the series resonators. The out-of-band rejection of such a filter is controlled by the capacitive voltage divider nature of the ladder circuit when the resonators are operating as simple capacitors.

Figure 14 shows a typical response for a set of ladder filters. The filters with the greatest out-of-band rejection consist of five series resonators and four shunt resonators (5-4 configuration) whereas the filters shown having only 20 dB of ultimate rejection are in the 2-3 configuration. The narrow bandwidth filter was made with temperature compensated resonators.

Ladder filters having up to 65 dB of ultimate rejection have been made using either more sections (6-5) or with a larger ratio of shunt resonator to series resonator capacitance, Figure 15.

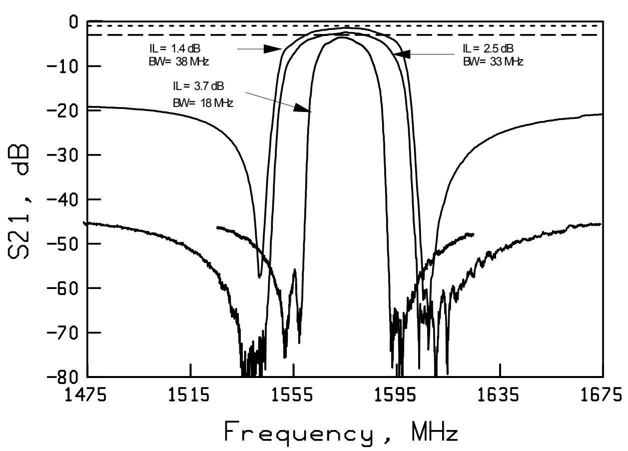


Figure 14. Typical ladder filters. There is an apparent tradeoff between in-band bandwidth and insertion loss and out-of-band rejection.

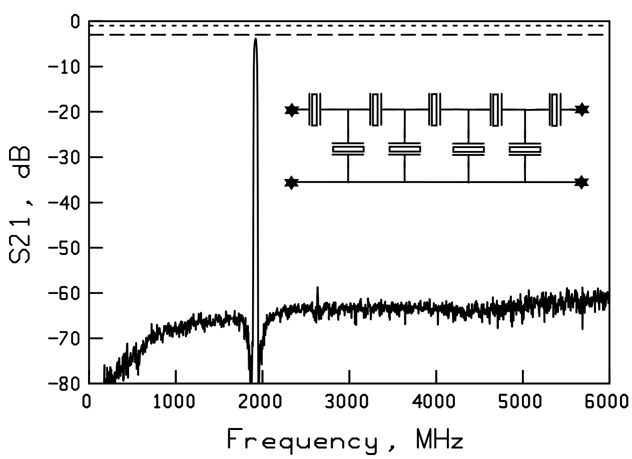


Figure 15. Ladder filter having high ultimate rejection.

Ladder filters can be made over a wide frequency range as required by systems applications. Filters are in production for us in IFs as high as 3.5 GHz and as low as 400 MHz.

Inductors can be used to tune filters in a manner other than simply increasing the resonator bandwidth. Figure 16 shows an experimental filter response wherein inductance was used to increase the near in rejection around filter center frequency. When the filter is off resonance, the shunt resonators are just capacitors and can be incorporated into an LC series resonant circuit to enhance filter rejection.

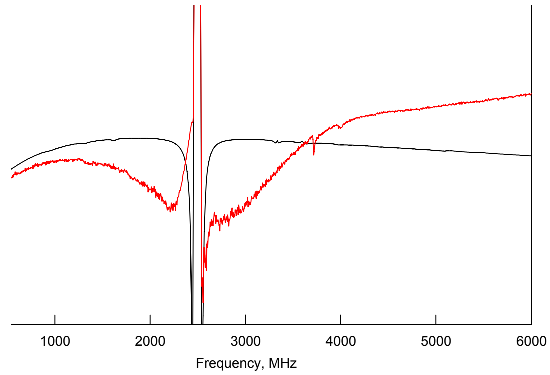


Figure 16. Filter response having enhanced hear-in rejection through inductor tuning. The experimental curve is with tuning, the smoother theoretical curve is a simulation of the filter without tuning.

The network used in the tuning is shown in Figure 17a where inductors are in each shunt resonator branch. A similar effect can occur if there is a common mode inductance from the filter package to actual circuit ground, Figure 17b. The imperfect grounding of the filter can result in tuning effects, deliberate or otherwise.

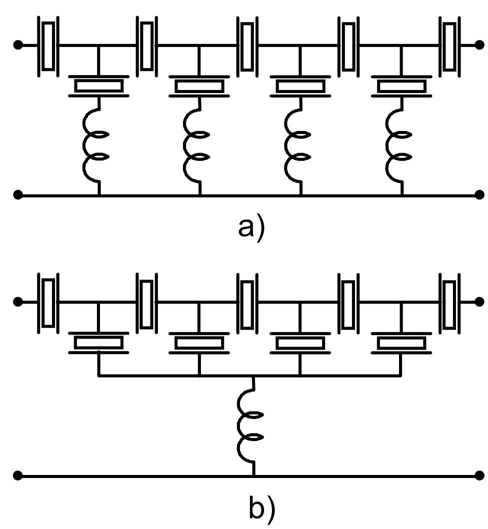


Figure 17. Tuning networks for ladder filters. a) Each shunt resonator is tuned. b) All shunt resonators have a common inductance, such as from die to ground in a package.

IX Acoustically Coupled Resonator Filters.

One of the primary thickness mode acoustically coupled resonators is the Stacked Crystal Filter (SCF). The SCF is composed of multi-layers of piezoelectric and metal layers, as shown in Fig. 18a [42-45].

The response of the SCF is improved by fabricating in the Solidly Mounted Resonator (SMR) format on a limited bandwidth reflector array. The experimental response for a two-pole GPS filter is shown in Figure 19. Similar filters have been made out to 12 GHz [46].

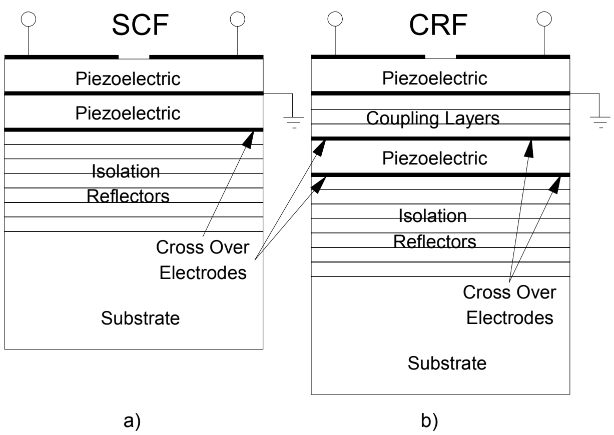


Figure 18 .Acoustically coupled resonator filters. a) A two section SCF composed of two single section SCFs electrically connected in series. A vertical pair of resonators acts as a one-pole filter, two in series, as shown, act as a two-pole filter. b) A Coupled Resonator Filter (CRF) similar to a) except that top and bottom resonators have reduced mechanical coupling. Here the vertically disposed resonators are acoustically coupled by one or more layers having limited transmission response. The overall result is a two pole response for each section and a four pole response for the pair shown.

The most fundamental limitation in achieving wide bandwidth and low insertion loss with piezoelectric devices has been the effective coupling coefficient of the native material. For thin film BAW devices there is unfortunately a limited set of materials available and the corresponding effective coupling coefficient of a simple resonator is often not adequate for straight forward filter synthesis. Accordingly, external circuit components, primarily inductors as described earlier, have been used historically to increase effective resonator coupling coefficient and to synthesize wider bandwidth filters at the expense of circuit size and simplicity. Variations in acoustic coupling techniques can also be used to increase filter bandwidth but ultimately the piezoelectric coupling coefficient is the limiting factor.

The limited bandwidth inherent to the SCF configuration can be overcome by reducing the coupling between the vertically disposed resonators in such a way that they begin to act as independent resonators rather than as a single over-moded resonator. The resulting configuration is called a Coupled Resonator Filter (CRF), Figure 18b, to distinguish it from the SCF, [47].

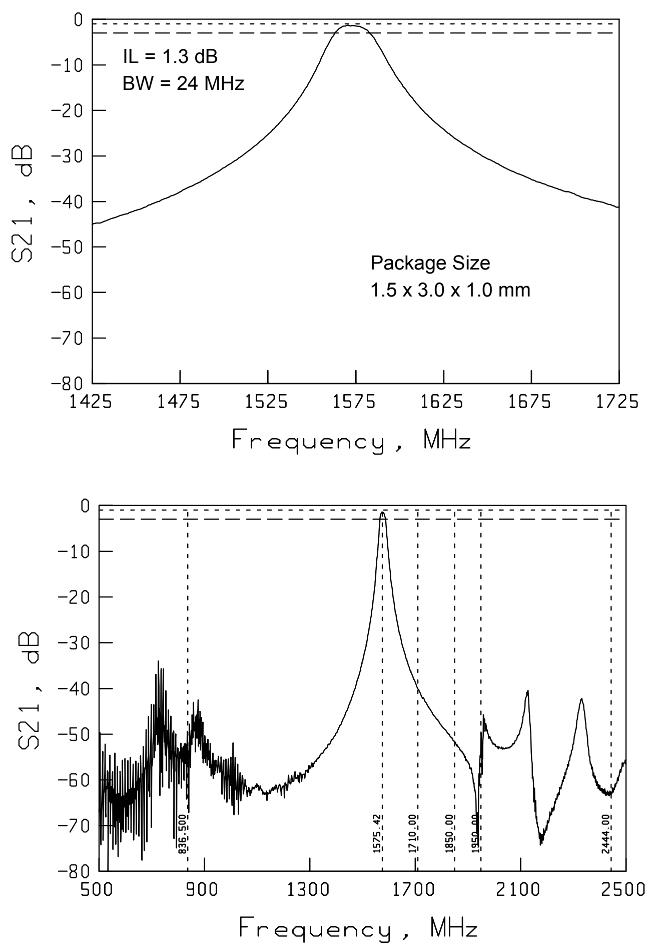


Figure 19. Experimental response of a two section SCF showing a high level of spurious response rejection at the cell phone transmit frequencies. The active area of the die is approximately 0.35 x 0.7 micrometers. Results are shown for a larger package.

In the CRF the acoustical coupling between resonators is used to control filter bandwidth. A convenient coupler uses a sequence of nominal quarter wavelength thick layers whose transmission response is designed to allow optimum resonator coupling.

Electrical interconnection of filter sections provides a way of increasing the multi-pole response and, for an even number of poles, allows the I/O electrodes to appear near or at the top of the structure for ease of fabrication. In the CRF, the cross-over electrodes for the bottom resonators are independent of the I/O electrodes, in contrast to the SCF wherein the ground electrode is shared. Having independent electrodes for the top resonators, in the CRF, allows the common I/O electrode to be split into two independent electrodes. When the I/O resonators are electrically isolated, except for stray capacitance, the filter can be operated in a full balanced mode or as a balanced to un-balanced transition.

Shown in Fig. 20 is the measured response of a CRF designed for the 1960 MHz cellular phone band. The 3 dB bandwidth of the filter is approximately 67 MHz, as designed for that particular application. The 1 dB bandwidth is wider than the 60 MHz channel and the passband flatness should be suitable for CDMA type applications. No inductors are used in this device and consequently the filter die is small.

An important factor in applications is cost. The filter in Figure 20 has a die size approximately as shown, with the active resonators effectively 200 um x 200 um in area. With some die overhead for I/O and other considerations the die size can be as small as 0.5 mm x 0.75 mm. In wafer scale manufacturing, this amounts to approximately 80,000 die per wafer and around 50,000 die for 63% yield. With sustained wafer through put this should result in low cost filters.

Figure 21 shows the results for an experimental 4-pole CRF. The resonators use W/Al electrodes to enhance bandwidth and reduce device size. A degree of plate waves and other non-ideal responses are shown. A more optimized resonator design should lead to more satisfactory results.

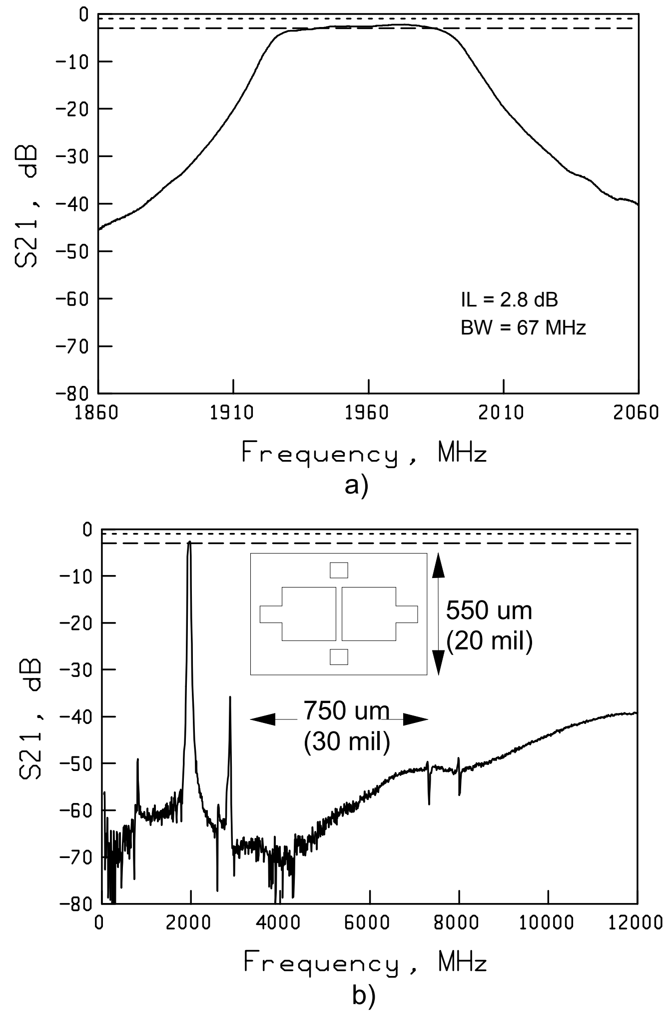
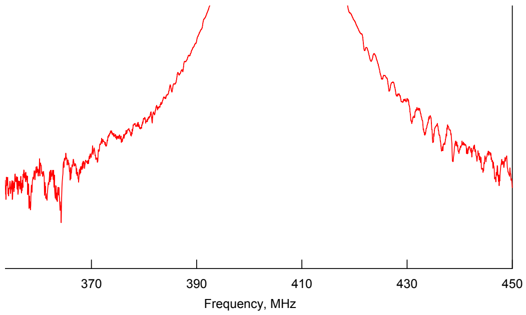


Figure 20. Experimental results for a four-pole coupled resonator filter (CRF) using AlN as the piezoelectric. The 3 dB bandwidth is 3.6%.

X. Other Filter Options.

The issues in selecting resonator and filter options generally reduce to: 1) cost, 2) performance, and 3) size. The priorities of these three is highly system and market dependent. The largest segment of the wireless market is the cell phone. Here cost is paramount but the other issues are also important. The shift to wider bandwidth signals has lead to the need for wide bandwidth filters in critical applications, such as the hand-set duplexer circuits.

The duplexer circuit has moved from large dielectric filters to SAWs and, more recently, to BAWs. Major advances in SAW filters has allowed this technology to remain competitive [50].



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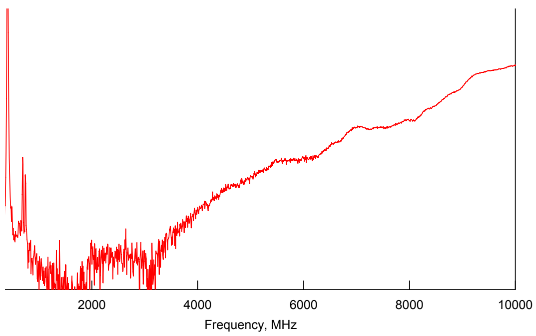

b)

Figure 21. Experimental results for a 400 MHz coupled resonator filter. The filter is in a 1015 package.

With comparable performance and size, the major issue with SAW and BAW is manufacturing cost. In SAW, high resolution lithography and expensive substrate materials are required, but the actual manufacturing process is a single lithography and generally just a single metal deposition.

For BAW devices, three or more layers of materials must be deposited with a high degree of precision and control. Since lateral resolution is not critical, lithography is inexpensive. With processing on silicon wafers, BAW devices offer most of the wafer scale processing advantages associated with IC manufacturing. It is probably safe to assume that BAW production will move from 100 mm diameter silicon wafers to 200 mm and maybe beyond. Those processes that are close to conventional IC processing will be low cost.

At low frequencies, below 2 GHz, SAW devices seem to offer a significant cost advantage. Beyond 2 GHz the cost of SAW production increases rapidly due to lithography constraints. For BAW the instant cost of manufacturing goes approximately as the inverse cube of frequency. First, the die area drops as the inverse square of frequency (for a given impedance level) and so there are more die per wafer. In wafer scale manufacturing costs are mostly on a cost per wafer basis. Second, at higher frequencies, all the BAW films are thinner and so the critical film growth steps are shorter which in turn allows more wafers to run in a unit of time. Accordingly, in that simple picture the number of die produced in a unit of time goes inversely as frequency cubed.

At around 5 GHz the BAW die size is rapidly diminishing and other costs, such as handling and packaging may limit the cost savings of high frequency. For example, the CRF of Figure 20 reduces to a die size of about 0.25 mm square but the saw kerf itself will be about 25 micrometers wide. An expected yield might be 300,000 die per wafer. Assuming a market of 200M devices per year, that assumed yield amounts to less than 700 wafer runs. That small number of wafers might not be constitute "wafer scale manufacturing" for an IC facility.

Packaging is a major consideration in filter manufacturing. Current SAW packages are considered too large to effectively package some of the smaller BAW devices, such as discussed above. Because of the need for protection of the active resonator surface, some kind of wafer scale packaging might be advantageous, but the critical processing should allow for as small die as possible if wafer scale cost effects are to be effective.

Packaging will be a significant cost driver. Currently, BAW production devices use SAW or other custom packages. Packaging is a major issue that will have to be addressed. Figure 22 shows the size considerations for BAW resonator and filter packaging.

The example die size for a 5 GHz CRF suggest that the filter might better be integrated right onto the IC chip. The active acoustic area of a 5 GHz CRF is only

75 um x 75 um and with I/O overhead the size would be about 100 um square, the size of a bonding pad. Clearly the push will be for on chip integration if the device performance is enhanced and the processing is compatible. Here BAW devices will excel because the manufacturing processes are mostly compatible with ICs.

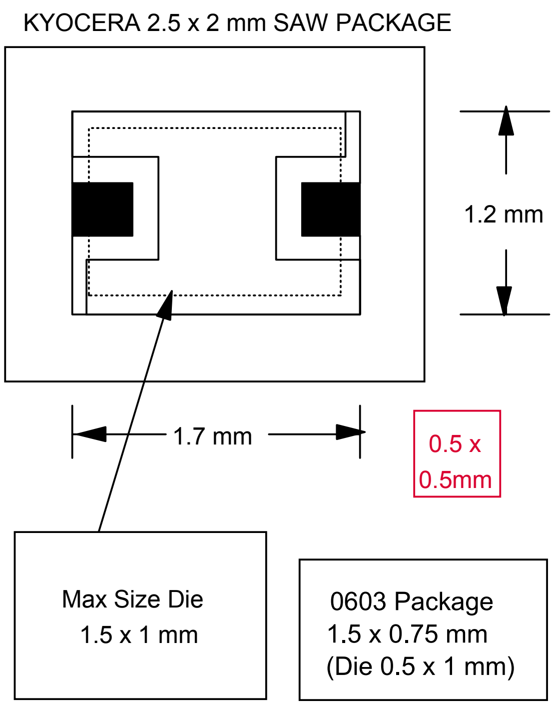

Figure 22. Package considerations for BAW devices. The 2 mm x 2.5 mm SAW package is substantially too large for many BAW devices above 2 GHz. Packages or techniques for much smaller die are required, with many BAW device die much less than 0.5 mm x 0.5 mm.

Dielectric filters are still finding applications, particularly at the higher frequencies which SAW cannot economically reach. High frequency applications or those requiring fractional bandwidths beyond about 5% will probably have to use dielectric resonator based approaches. In high volume low performance applications at 2.4 and 5.7 GHz the ceramic based dielectric resonator filters are extremely cost competitive and their large size is not always a serious drawback. Simple two-pole filters are often more than adequate for many wireless LAN systems.

XI. Summary

This paper has presented an overview of the thin film resonator technology. Efforts to reach the high frequencies demanded by bandwidth hungry evolving wireless systems has caused a rapid development of filter technology. Piezoelectric resonators have limitations on bandwidth due to the limited strength of the piezoelectric coupling. High coupling coefficient materials either are not suited for microwave frequencies or have other drawbacks such as relatively poor temperature stability or low Q.

Three forms of BAW device were described, high frequency crystal plates, and two forms of thin film piezoelectric resonator. Results were shown for conventional and new classes of BAW filters. The mainline production is in ladder filters but stacked crystal and coupled resonator filters show considerable promise for high volume wireless applications.

Costs of manufacturing is a major issue that is a moving target strongly tied to the advances and implementation of wafer scale manufacturing as practiced by the integrated circuit industry.

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