Bulk Acoustic Wave Resonators And Filters For Applications Above 2 GHz

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Abstract **Bulk acoustic wave (BAW) devices are of interest for applications at higher microwave frequencies above 2 GHz. As frequencies increase, BAW devices require thinner films which decreases processing times and makes the technology more cost effective. However, the area of resonators and associated filters also decreases and begins to impact device performance and packaging requirements. This paper will summarize the technical requirements of BAW devices in the 2 to 20 GHz frequency range and show specific results for resonators, ladder filters, and stacked crystal filters operating up to 20 GHz.**

I. INTRODUCTION

Bulk acoustic wave (BAW) devices are of interest for applications at higher microwave frequencies above 2 GHz. In the broader scope there are applications in RF instrumentation, sensors, radar systems, and optical networks. There are of course those wireless applications that cover a variety of frequency bands near and above 2 GHz such as the ISM bands at 2.4 GHz and 5.7 GHz.

In the BAW device the principal resonator is composed of thin films of piezoelectric and metal electrodes [1-4]. As frequencies increase BAW devices require thinner films that are produced by a number of deposition techniques. Thinner films decrease processing times and make the technology more cost effective in manufacturing. However, the area of resonators and associated filters also decreases and begins to impact device performance and packaging requirements. In addition, electrodes must be kept thin, in order to minimize acoustic losses, but thin electrodes increase conduction losses.

This paper will summarize experimental results obtained for BAW resonators and filters in the 2 to 20 GHz frequency range.

II. RESONATORS

Figure 1 shows the general format of single resonators and the stacked crystal filter (SCF), as further discussed in this paper. All experimental results are for resonators fabricated in the solidly mounted resonator (SMR) format with nine layers of SiO2 and AlN quarter wavelength films [5].

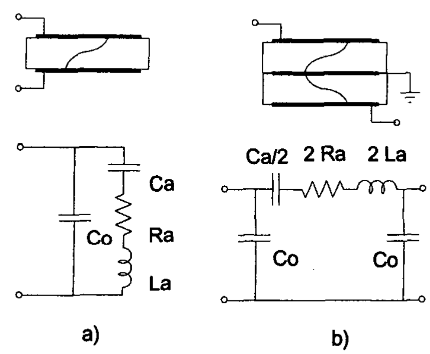
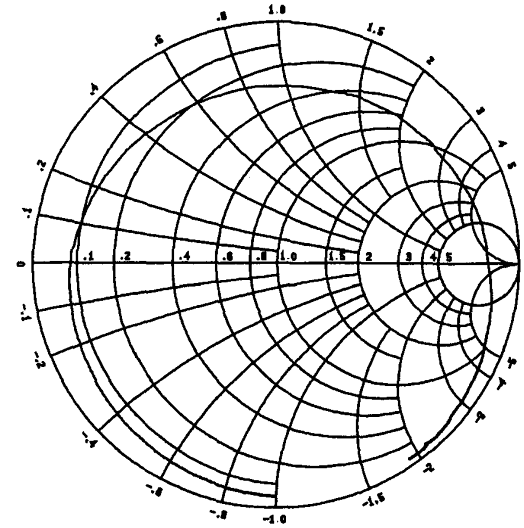


Figure 1. a) General geometry and equivalent circuit of BAW resonator. b) Geometry and equivalent circuit of stacked crystal filter (SCF). In both cases electrode conduction losses will add series resistance to the equivalent circuits.

The following figures show experimental results for resonators at 5 GHz and 20 GHz. For Figure 2 the 5 GHz resonator was fabricated with 100 nm thick aluminum electrodes and 0.9 um thick AlN piezoelectric films. The measurements are for two 90 um x 90 um area resonators connected in series and wafer probed at the die level.

The resonator in Figure 3 is of similar construction to the 5 GHz resonator except having 30 nm thick electrodes and 0.22 um thick AlN. The resonator area in this case is the equivalent of 53 micrometers square for the two larger area resonators connected electrically in series. The resonator area was originally designed for 10 GHz and accordingly the area is too large and capacitive reactance is too low for 20 GHz, making the resonator more susceptible to series inductance effects.

Resonators can be temperature compensated with the introduction of silicon dioxide, or other positive TC material, into the resonator volume to offset the negative TC of the electrodes and piezoelectric [6]. This results in a lowering of the effective coupling coefficient, K2, and a decrease in tune ability using external capacitance. When narrower bandwidth filters are desired, the lowered K2 is accompanied by increased temperature compensation.



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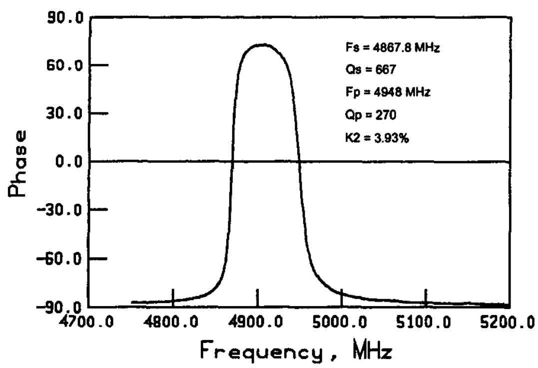

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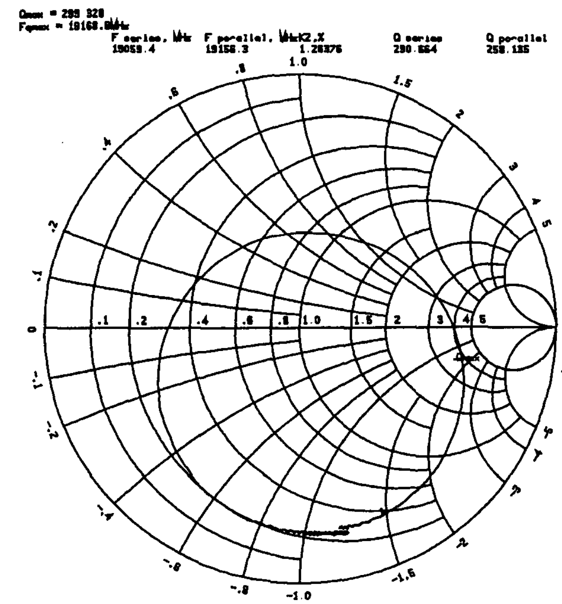
Figure 2. Experimental results for a 5 GHz resonator fabricated in the solidly mounted resonator configuration. a) Smith chart showing a clean resonance. Phase of resonator impedance with the resonant frequencies and data shown.

Higher frequency resonators are being developed. The limits of useful resonator frequencies have apparently not been reached with the experimental results obtained so far. Efforts are under way to extend the experiments towards 40 GHz.

Packaging of resonators to avoid parasitic effects is a serious problem. We have determined that commercial packages of the desired size and electrical characteristics do not exist and that custom packages must be developed similar to those described for lower frequency thin film BAW devices in the hermetic sealed format.



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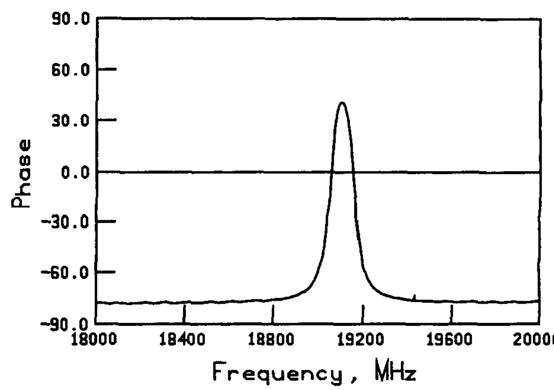

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Figure 3. Experimental results for a 20 GHz resonator. a) Smith chart response. b) Phase of impedance. Resonant frequencies and Qs are given at the top of a).

III FILTERS

At TFR, over forty different filter types have been developed and manufactured that operate above 2 GHz. These filters take the form of ladder filters or stacked crystal filters as an application requires. The SCF form is suitable for many applications at high frequencies [7-8].

Ladder filters are composed of series and shunt resonators having frequencies offset in a manner that gives a useful passband. However, the differential frequency offset from series to shunt resonators is a small fraction of the center frequency. For filter frequencies beyond about 4 GHz it becomes increasingly difficult to control the offset unless special techniques are employed [9].

Figure 4 shows the response of a ladder filter having modest out-of-band rejection. The filter consists of five series and four shunt resonators.

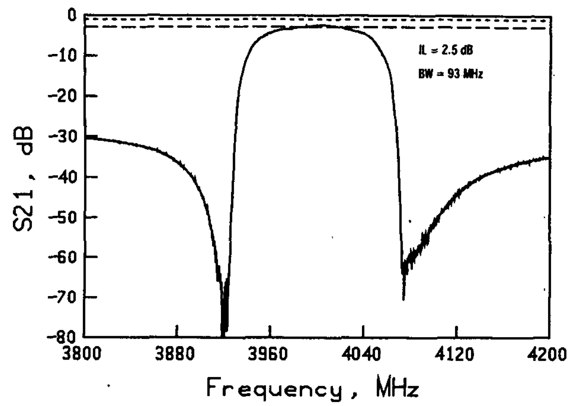


Figure 4. Experimental ladder filter using AlN piezoelectric.

In order to obtain better control of the frequency offset a method of shifting reflector layer thicknesses was adopted. Since the reflector layers have a smaller effect on resonator frequency, a larger differential thickness is required to shift the resonant frequency and accordingly better fabrication control is achieved. This method is used on narrow bandwidth filters at 3.5 GHz.

The stacked crystal filter (SCF) is finding increased applications where small size and high ultimate rejection is required. The SCF obtains high out-of-band rejection because the I/O is shielded to first order by a ground plane between piezoelectric layers. Fabrication of the SCF is more complicated than the ladder type filter because two piezoelectric layers are required instead of only one. However, the critical frequency offset associated with the ladder filter is not required in the SCF and therefore trimming of the top metal thickness is more practical during manufacturing. It is also apparent that a high degree of out-of-band rejection can be obtained in the SCF without a penalty in insertion loss.

Figure 5 shows the experimental results for a 4-pole SCF (four sections connected electrically in series on the die) using 30 nm thick aluminum electrodes and 0.6 um thick AlN for the two piezoelectric layers.

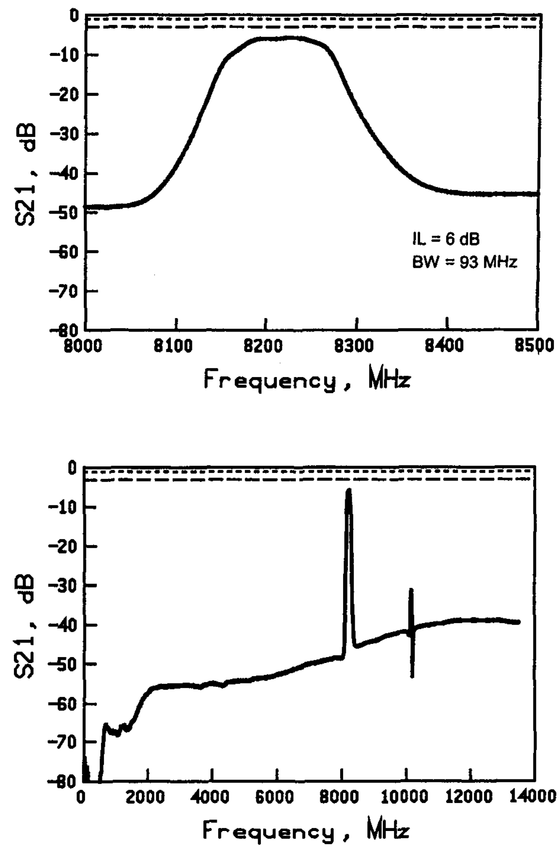
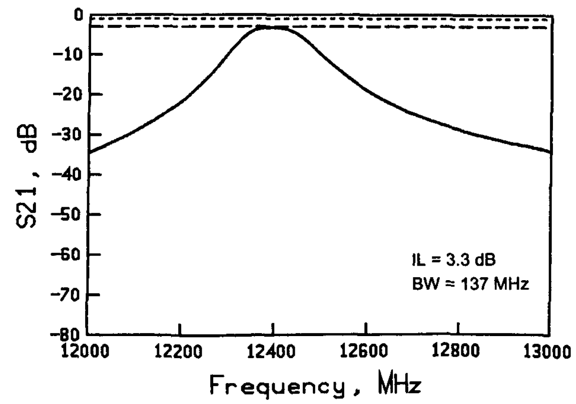


Figure 5. Experimental results for a 4-pole SCF using Al electrodes and AlN piezoelectric layers. The results are for a filter in a 1206 (3 x 1.5 mm) package. The out-of-band roll up is due to limited isolation in the package.

The active area of each SCF section is approximately 50 microns square, and the entire filter occupies only about 1% of the package area for a 3 mm x 1.5 mm package. It is apparent that that the package limits the ultimate rejection of the filter. The high frequency roll-up corresponds to the empty package response.

Experimental results for a 12 GHz nominal two-pole SCF is shown in Figure 6. The filter consists of two SCF sections connected in series electrically. The piezoelectric films are 0.26 micrometers thick and the three electrodes are approximately 50 nanometers thick. The active area of each resonator is 22 um x 44 um as shown in Figure 7. The filter was probed at the die level using a probe pitch suggested in Figure 7. The insertion loss is about 2 dB higher than a similar configuration SCF demonstrated at 1.57 GHz.



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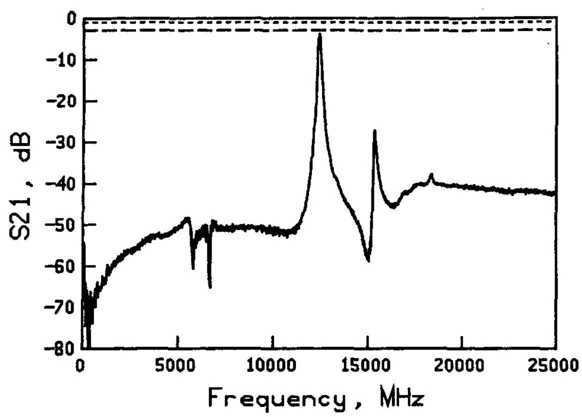

b)

Figure 6. Experimental results for a of a 12.4 GHz two-section SCF using aluminum electrodes and AlN piezoelectric. The filter die was probed at the die level. The narrow scan shows a filter bandwidth of 1.1%. The wide scan in b) shows some parasitic response at the high frequency side of the filter response.

IV SUMMARY

This paper has presented results on resonators and filters for the frequency range above 2 GHz with emphasis on devices at the higher frequency limits. Both die and packaged devices were presented. The stacked crystal filter is somewhat easier to fabricate at high frequencies and occupies a much small die area than equivalent ladder filters. The small size of filters and resonators operating at frequencies above 2 GHz suggest that they could be integrated onto IC substrates with a small effect on overall circuit size.

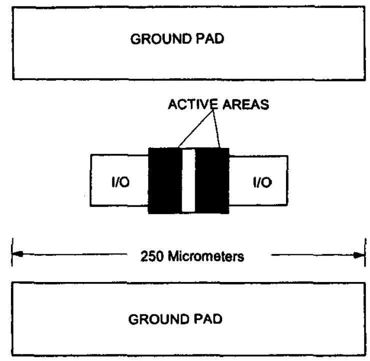

Figure 7. Approximate layout for the filter of Fig. 6. The acoustically active area is given by the shaded area. The ground and I/O pad locations and size are designed to accommodate a particular GSG wafer probe.

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