Application of Film Bulk Acoustic Resonators

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Abstract

Multi-pole film bulk acoustic resonators (FBAR) bandpass filters are being designed and fabricated on various substrates, including silicon and GaAs. Capable performance has been demonstrated for the large number of system insertions within the low microwave (1-3 GHz) range. Progress in applying FBAR to microwave system applications is reviewed.

Background

Over the past several decades, the development of silicon and GaAs circuitry has made great strides in size reduction. Yet, achieving the full benefit of this size reduction in both military and consumer products at microwave frequencies has been limited by realization of suitable filters. Figure 1 compares the progress in size reduction of active devices with filters at UHF to low microwave frequencies.[1] Shown are the comparative size of dielectric cavity, lumped element, and FBAR filters.

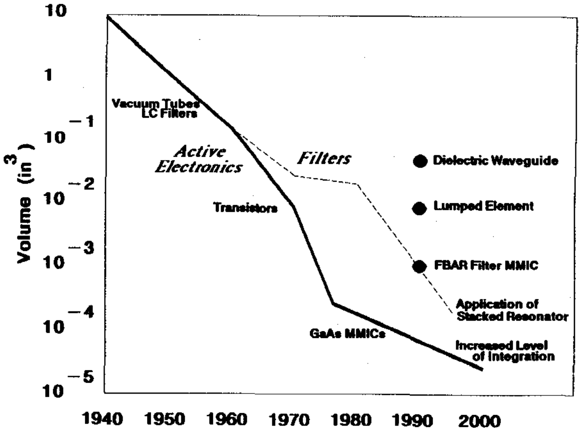
Acoustic devices[2] have played a key role in RF applications. A key reason is that acoustic waves are about 5 orders of magnitude shorter than electromagnetic waves, resulting in significantly reduced device sizes. In comparison to SAW devices, FBAR provides much lower insertion loss and smaller realization.

FBAR filters are being applied to receivers and synthesizers to significantly reduce size, weight, and cost. FBAR is the only known means for monolithic implementation of low loss, high Q filters. Moreover, its small size allows multifunction MMICs to include these capable filters - resulting in the capacity to make tuned monolithic subsystems. In parallel with work to address producibility of FBARs, investigations are being performed to insert FBAR filters into receivers and direct synthesizers. The design and fabrication of a two-pole FBAR MMIC was previously described.[3] Subsequent work has focused on the design of hybrid and monolithic multi-pole FBAR filters. These filter designs include bandpass, band reject, and switched bandpass filter banks.

Applications Summary

A significant need exists for small, low cost, high performance receivers. For radar systems, there is a clear trend toward multiple-channel receivers. Missiles similarly demand multiple receive channels with even more extreme size, weight, and cost objectives. EW systems require large quantities of parallel resources - particularly tuned narrowband receivers and channelizers. Both military and commercial communications applications require advancing capability while reducing size and cost. Similar highly integrated, low cost capability is essential for T/R modules used in active phased arrays. These requirements point to highly integrated monolithic (MMIC) technology.

Figure 1 Comparison in Size Reduction



The implementation of capable receivers requires a diversity of circuit functions. The necessary amplifiers, switches, and variable attenuators are currently available as MMICs. The high Q tuning elements needed for filters are presently lacking in monolithic processes. The development of FBAR technology is driven by this need for small, high Q filters that can be implemented in monolithic form. The ability to combine FBARs and other circuit functions onto multifunction MMICs provides significant capability to reduce both size and cost. FBAR is also a viable approach as stand-alone miniature, low profile filter.

To date, FBAR has shown the greatest promise for operation at low microwave frequencies. As shown in Table 1, a significant number of RF and IF receivers utilize the 0.5 to 3 GHz RF range. To be noted is that a vast majority of radar sensors (including high volume active and semi-active missiles) regardless of their operating frequency utilize an L- or S-Band first IF. A variety of DOD and civil RF applications use the same frequency range. The possibility exists for applying FBAR at higher frequencies, but results to date indicate significantly greater insertion loss.[4] Further research in piezoelectric materials, processing techniques, and FBAR structure may produce improved high frequency devices.

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Table 1 Partial Listing of 0.5 - 3 GHz RF Applications Suitable For FBAR Insertion

UHF (0.5-1 GHz)
land mobile communications cellular communications spread spectrum communications military communication and navigation
L-Band (1-2 GHz)
LEO satellite communications radar and EW IF Receivers beacon and IFF Transponders GPS Sensors military communication and navigation
S-Band (2-3 GHz)
radar and EW IF Receivers W-Band missile IF Receivers spread spectrum communications satellite digital audio broadcast

Application Examples

Missile seekers require high performance in a small volume. FBAR filters are being developed for insertion at the first IF, as illustrated in figure 2. The use in combination of FBAR filters and multifunction MMICs is projected to result in a 6:1 volume reduction, making the use of multi-channel receivers feasible for small diameter missiles.

Capable receivers require front end filters to provide both out of band signal and image rejection. The example to be considered is a receiver for GPS reception. The 1575 MHz input signal is assumed to be converted to a VHF intermediate frequency (IF). Filtering must reject strong terrestrial signals to prevent the desired signal from being overcome by resulting intermodulation products. Derivation of requirements is somewhat subjective, dependant upon intended RF environment and antenna characteristics. A typical requirement for civil, non-stressing signal environments is given in table 2. A second front end filter application is to provide image rejection image including the image noise contribution of the preamplifier. FBAR filter designs capable of performing both passband and image rejection functions will be presented.

Table 2 Filter Specifications For GPS Receiver

Passband Center	1575 +/- 5 MHz
Bandwidth (3 dB)	50 MHz max.
Loss At Passband Center	1 dB max.
Rejection (150 MHz from passband center)*	30 dB min.

* may degrade further away from passband depending on antenna out-of-band response

An additional application for FBAR is switched filter banks for direct frequency synthesis. Using the divide-and-mix approach illustrated in figure 3, switched filter banks are required to produce a signal output with low spurious content. These generally drive the size of the direct synthesizer. While direct synthesis provides the advantage of fast tuning speed, the associated size and cost is prohibitive for many applications. FBAR meets this need by providing a means of making small, low cost switched filter banks. The availability of this technology in the 0.5 to 3 GHz range gives synthesizer designers great flexibility.

Figure 2 Missile IF Receiver

FBAR in combination with multifunction MMICs will yield significant size reduction.

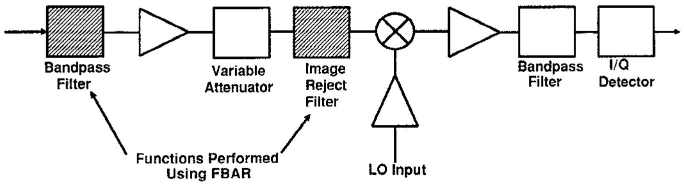
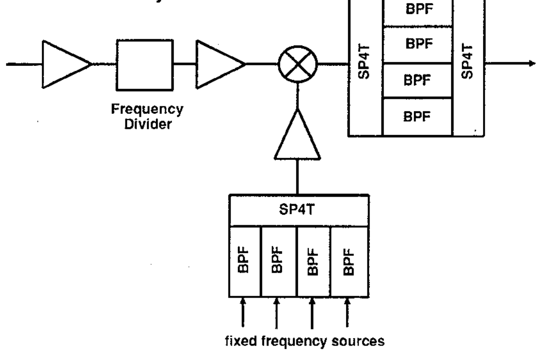


Figure 3 Direct Synthesizer Cascadable Stage

FBAR filterbanks are key to miniature direct synthesizers.



Filter Design Considerations

The FBAR structure has several unique properties which make it extremely useful for certain types of filter designs. These are:

1. **Size:** The majority of the filter volume is taken up by the inductors, capacitors, and I/O connections. Thus, the design of a filter involves minimizing the size and effect of these elements. A filter bank assembly takes advantage of this fact, since the small resonator size the eliminates the necessity of elaborate corrections for interconnecting lines.
2. **Monolithic Implementation:** The fabrication process required for an FBAR has been proven to be compatible to many semiconductor fabrication processes, opening the way for large scale integration of MMIC devices.
3. **High-Q Performance:** FBARs have been fabricated using a variety of materials, many of which have yielded Q's in excess of 1000. This is more than adequate for the applications listed here.
4. **Series and Parallel Resonance:** The series resonance is generally used for band-pass filters, by providing a transmission pole. The presence of a parallel resonance often gives the designer another degree of freedom, by providing a selectable transmission zero. This can be used to improve the selectivity of a filter.

The equivalent circuit of an FBAR resonator is shown in figure 4. Values of the various circuit elements are controlled by the physical design of the FBAR. Typical resonator parameters are given which are used in the examples to follow. This circuit is accurate only in the region of resonance, degenerating to a capacitor as the frequency as raised or lowered. The primary factor that makes this type of device preferable over a lumped element design is the existence of the physically small, high value, high-Q inductance.

In the region of interest, there is both a series and a parallel resonance. The series resonance is controlled by the physical construction of the FBAR. The parallel resonance, caused by the presence of the parasitic capacitance, can be controlled by external elements. By taking advantage of this, certain types of filter responses can be generated with a minimum of external circuit elements.

The first and most obvious response is that of a band-stop filter. The circuit here need consist only of a number of FBARs in shunt, with a series inductor between each of them. In this case, standard filter design procedures can be used, with the parasitic capacitance being designed into the filter. Thus the size of the filter is almost totally controlled by the size of the inductors.

Band pass filters can be designed with standard techniques also, but the presence of the parasitic electrode capacitance Co increases the difficulty. By placing a external parallel inductance across the FBAR, this capacitance is neutralized in the vicinity of resonance. This inductor now controls the parallel resonance, and in fact, creates a second parallel resonance. The net result of this is seen as two attenuation zeros or nulls in the loss pattern, one on each side of the passband. The selectivity of a single FBAR resonator is therefore enhanced by some amount dependant on the relative equivalent circuit values.

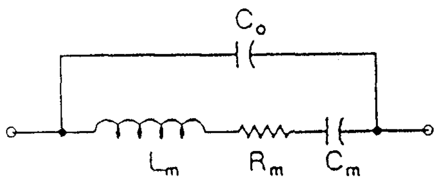
A novel application for FBAR filters is the image reject filter, where the specific requirement is for both a pass band and a stop band. By judicious selection of FBAR parameters and the parallel inductor, it is possible to place the parallel resonance of the FBAR at the rejection frequency. This typically can yield an extra 20 dB per resonator over that predicted by normal Chebychev or Butterworth design, while maintaining a good pass band response.

Filter Design Examples

Two examples illustrate the usage of FBARs in filter design. The circuit for an image reject filter and its response are shown in figure 5. In this case, the key requirement is for a narrow passband with signal rejection over an image band (spaced at twice the IF below passband center). The simple filter employs series FBARs at passband resonance and shunt FBARs at the stopband resonance. As a result, rejection of image spurious signals and noise is attainable with a minimum number of components in a small area. The undesirable lowpass response, results from the inductors which shunt the FBAR to cancel its interelectrode capacitance.

The circuit for bandpass filter with wide stopbands and its response are shown in figure 6. This filter is implemented using a combination of two FBAR poles with two lumped element poles. The result is that the FBARs contribute steep passband skirts and the lumped elements resonators provide rejection of the lowpass response.

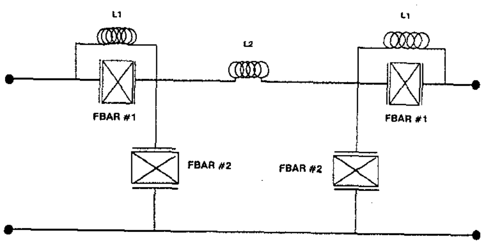
Figure 4 FBAR Equivalent Circuit Model



Parameter	FBAR1	FBAR2
Lm	117 nH	160 nH
Cm	0.103 pF	0.124 pF
Rm	3.8 ohms	3.8 ohms
Co	2.37 pF	2.83 pF

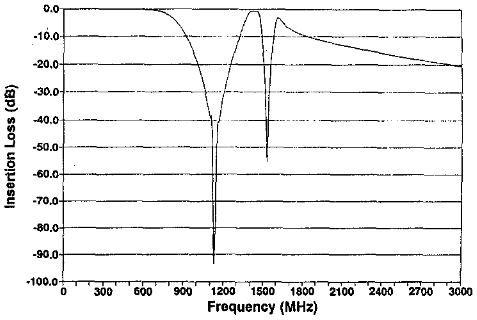
Figure 5 Image Reject Filter Example

filter schematic



L_1 = 7.4 nH L_2 = 6.0 nH

filter response (predicted)



Conclusion

Diverse applications and design guidelines have been presented for FBAR filters. Refinements in processing of critical piezoelectric films on semiconductor substrates has allowed filter development for specific products to begin. Key trade-offs involve substrate choice and level of monolithic integration to meet performance and yield requirements.

Acknowledgments

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References

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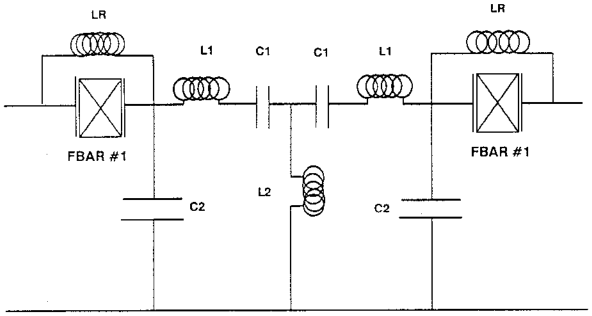
4. See companion papers by S. Krishnawamy et. al. and R. Stokes and J. Crawford for results at higher frequencies.

Figure 6 Bandpass Filter Example

filter schematic



L_R = 7.4 nH L_1 = 9.7 nH C_1 = 1.3 pF
L_2 = 1.0 nH C_2 = 5.8 pF

filter response (predicted)