A Film Bulk Acoustic Resonator (FBAR) Duplexer for USPCS Handset Applications

Paul Bradley, *Senior Member, IEEE*, Richard Ruby,John D. Larson III,
Yury Oshmyansky, and Domingo Figueredo

Agilent Technologies, Newark, Ca 94560, USA

***Abstract* — We will describe the design and measured performance of a duplexer based on Film Bulk Acoustic Resonators (FBARs) for the 1900 MHz PCS cellular phone market. Typical specifications for the duplexer require the Tx filter to attenuate frequencies in the Rx band by >40 dB while maintaining a worst-case insertion loss of 3.5 dB over the Tx band. VSWR must be better than 2.2 in the pass-band (8.5 dB return loss). The Rx filter must attenuate the Tx frequencies by > 50 dB while maintaining a worst-case insertion loss of 4.2 dB in the Rx band. Again, VSWR must be better than 2.2.**

I. INTRODUCTION

The transmitter and receiver frequency bands used by PCS cell phone systems are quite close together (Tx band: 1850-1910 MHz, Rx band: 1930-1990 MHz). This places severe demands on the RF duplexer component that permits the same antenna to be used for both if we are to avoid interference and obtain low worst-case insertion loss at the same time. Ceramic resonator technology is able to meet these requirements, but with a component about the same size as a cigarette filter. Surface acoustic wave devices can reduce the size considerably, but poor electrical performance has required a split-band approach using switches to select the upper half-bands or lower half-bands. This requires control circuitry and two high-power switches with significant insertion loss that waste power, limit range, and distort the linear signals produced by the power amplifier. Receiver sensitivity is also degraded by the switch insertion loss. FBAR devices overcome both these problems[1].

II. FBAR DEVICES

The Agilent FBAR is a three-layer structure with top and bottom electrodes of molybdenum sandwiching a middle layer of oriented piezoelectric aluminum nitride. An air interface is used on both outer surfaces to provide high Q reflectors at all frequencies. When RF signals are applied near the mechanical resonant frequency (about 1.9 GHz for PCS) the piezoelectric transducer excites the fundamental bulk compression wave traveling perpendicular to the films..

As seen through the electrical terminals, the FBAR has an equivalent circuit model known as the Modified Butterworth-Van Dyke (MBVD) described in detail in an earlier publication [2] and shown below (Fig. 1). Co represents the physical plate capacitance of the FBAR. and Rs represents the physical resistance of the electrodes. The components Cm, Lm, and Rm represent the motional resonance that is coupled to the voltage across the plate capacitor by the piezoelectric effect in the AlN. Ro is a phenomenological element added to improve the quality of the least-squares fit to the measured FBAR reflection coefficient data. It includes the dielectric loss tangent of the AlN and models most of the losses associated with parasitic lateral modes in the FBAR. The ratio of Co/Cm is inversely proportional to the strength of coupling of the electric field in the piezoelectric material to the mechanical motion of the FBAR. All modeling of designs is done in terms of this capacitance ratio rather than the often-used coupling coefficient Kt**2 which is another measurement of the piezoelectric coupling strength, and hence crystal quality of the AlN.

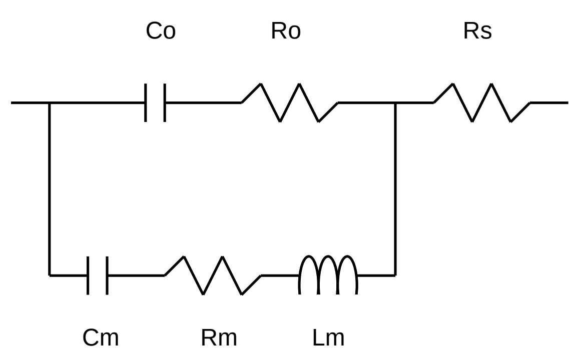

Figure 1 The modified Butterworth-VanDyke (MBVD) equivalent circuit model for FBARs

This equivalent circuit may be fitted to measured FBARs and the resonant frequencies, Q's, and impedance levels may be extracted for filter designs. The most important features of the FBAR impedance versus frequency are:

1) Far from the resonant frequencies it behaves like the plate capacitance Co in series with the two resistors Ro and Rs (because Cm has a much higher impedance).
2) At the frequency 1/{2*pi*SQRT(Lm*Cm)}, there is a series resonance with a purely real impedance, typically 1-2 ohms.
3) At 1/{2*pi*SQRT[Lm*(Cm*Co/(Cm+Co))]}, there is a parallel resonance with a purely real impedance, typically 1000-3000 ohms.
4) These two resonances are about 2.5% apart in frequency which gives us very steep filter skirts if these resonators are used in ladder filter topologies and permit bandwidths in excess of 3.5%.

III. The Duplexer Design

The duplexer consists of two FBAR ladder filters, the transmitter filter (Tx) and the receiver filter (Rx), each packaged in an ultra-low electrical parasitic hermetic 3 mm x 3 mm ceramic package, and a few small passive components as illustrated in Figure 2. One port of the Tx filter is to be connected to the transmitter section of the cell phone and the other is connected to the antenna. The antenna port is also connected to one end of a quarter-wave transmission line. The other end of the quarter-wave line connects to the Rx filter which then connects to the receiver section of the cell phone.

Each filter has resonators with only two frequencies, with the shunt FBARs frequency a few percent lower than that of the series FBARs. Off-resonance the "naked" filters appear like capacitor ladders that have a fairly flat frequency response except for a weak dependence on how well impedance matched the network is to the 50 ohm test environment. As the frequency approaches the series resonance of the shunt FBARs (the first resonance of either type of FBAR encountered), the input of the filter begins to look like a very low impedance to ground producing a deep transmission null (attenuation pole). With a slight increase in frequency, we approach the parallel resonance of the shunt elements which are then high impedance and we get very low attenuation in the filter. At slightly higher frequency, the series FBARs reach series resonance and present a very low impedance compared to the shunts and again we get very low insertion loss here. At higher frequencies still, the series elements begin to look like very high impedance and very little input arrives at the output producing another deep transmission null just above the pass-band. Above this frequency range the "naked" filter again looks like a capacitor ladder producing a fairly flat rejection.

This description is important to understand the quarter-wave transmission line connecting the two filters. In the pass-band of the Tx filter, just below the pass-band of the Rx filter, the Rx filter has a very low impedance. The quarter-wave transmission line transforms this to a very high impedance which does not then load the Tx filter. The reverse is true for the Tx filter in the Rx pass-band. Since it already has a high impedance, it is not necessary to do anything to prevent its loading the Rx filter.

In order to obtain the required 50/40 dB of rejection and isolation without sacrificing the insertion loss of the duplexer, we have found it convenient to introduce additional attenuation poles in the rejection bands of both filters which maintain high rejection as we move away from the deep nulls at the foot of the filter skirt. This is achieved by adding a small series inductance to two shunt FBARs in each filter. This not only introduces new nulls in the filter response, but it significantly shifts existing poles to produce higher rejection. It reduces the series resonant frequency by effectively adding a few percent of real inductance to the motional inductance in the series path of the FBAR. This does degrade Q, but achieves better overall response. The parallel resonant frequency is unaffected. This increased separation permits higher rejection, although at a cost of slightly slower roll-off. These external inductors may be implemented as printed circuit board traces.

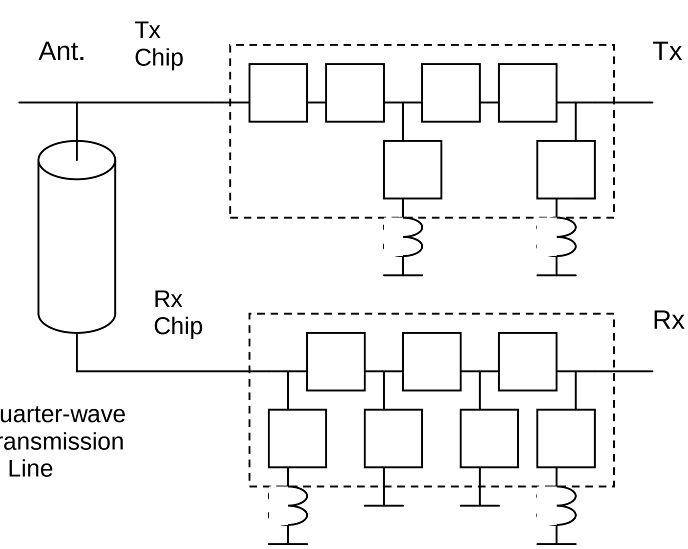

Figure 2 The PCS duplexer design (squares are FBARs) includes 1/4-wave line and two FBAR filter chips.

The FBAR ladder filters consist of 6 resonators for the Tx filter (4 series, 2 shunts) and 7 resonators for the Rx filter (3 series, 4 shunts). The external inductors are optimized with ADS [3] for best insertion loss, rejection, and return loss of the Tx and Rx response. The isolation was not explicitly optimized in simulations since it is roughly the sum of the insertion loss and rejection of the Tx and Rx responses added at a given frequency. The design strategy was to exceed the rejection requirements by a comfortable margin (3-5 dB) over the PCS bands with 5 MHz margins on either side to provide tolerance for variations and use any additional degrees of freedom to obtain the best worst-case insertion loss (over the same frequency ranges) while demanding adequate return loss. There is a trade-off between the steepness of the roll-off and the return loss in the middle of the pass-band. This trade-off has a large impact on yield since the steepness of the skirt affects the range of filter frequencies that can be used to build duplexers. Typical roll-off from pass-band to stop-band is 10 MHz. This steep roll-off is necessary to allow for shifts over temperature and manufacturing variation in the filter frequency while maintaining high yield.

Since the Tx filter must be able to tolerate up to 1 watt of incident power for long periods of time, power handling of the series FBARs was roughly quadrupled by using two FBARs in series, each with double the area (half the impedance) to replace the single FBARs used in the original ladder filter design. Although it is essential to have a well characterized package with low parasitic elements, the equivalent circuit model for the ceramic package is left out of the above schematic for clarity.

The impedance and length of the quarter-wave line is not critical and we have found it allows a smaller component footprint to use a higher than optimal impedance for this of about 70 ohms due to the narrower trace and larger inductance per unit length (compared to 50 ohms). The inductor values are all in the range of 1-4 nH and are chosen by the optimization described earlier. These are meandered around the packaged FBAR filters on a 5.6mm x 11.9 mm printed circuit board for a total thickness of 1.9 mm.

IV. MEASUREMENTS

The measured response of 200 duplexers made at our manufacturing division in Malaysia is shown (Fig. 3) in the neighborhood of the transmitter and receiver bands for USPCS (Tx band: 1850-1910 MHz, Rx band: 1930-1990 MHz). All specifications are met. The measured devices in Figure 3 were built using surface mount components. The design using all printed passive components is still in

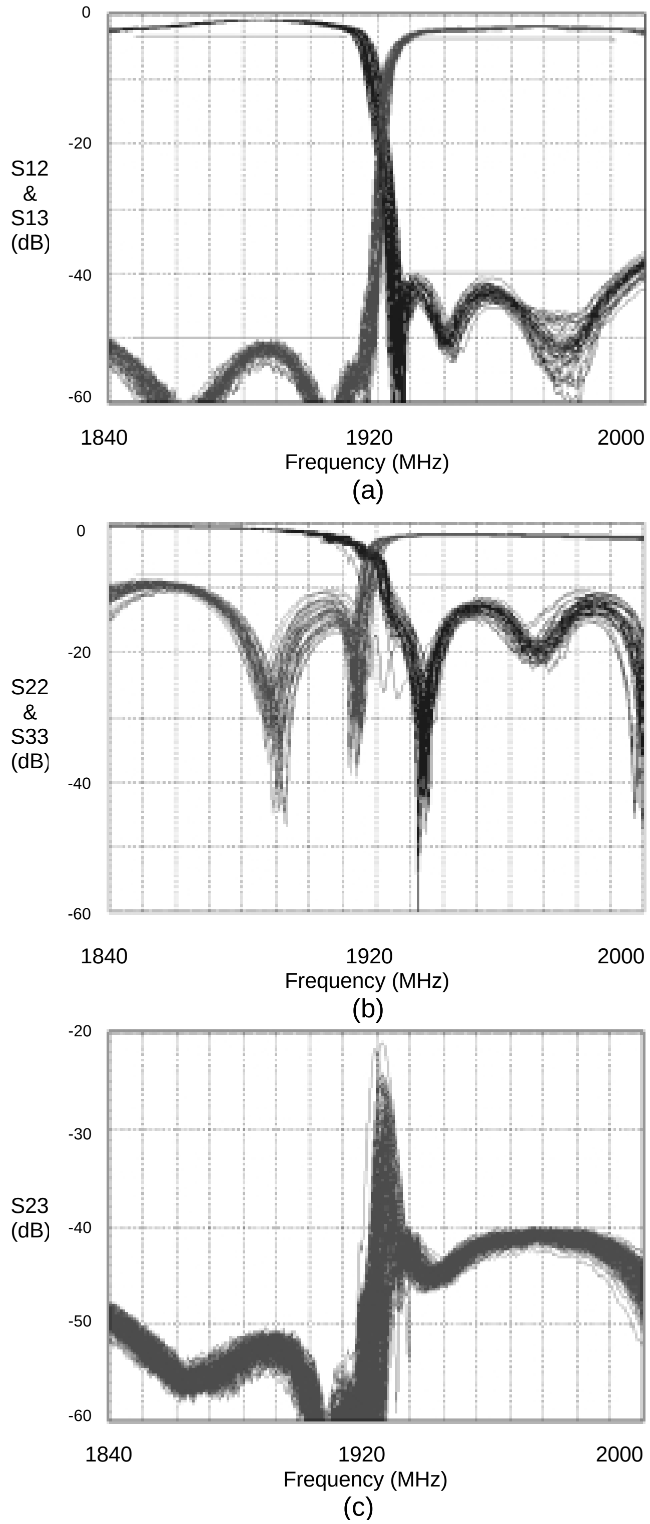

Fig. 3. S-parameters of Tx/antenna and Rx/antenna response for 50 duplexers (a), Tx return loss and Rx return loss of 50 duplexers (b) and the Tx/Rx isolation(c) for a sampling of 200 duplexers.

final development to improve specifications and yield for purposes of cost reduction.

V. Conclusion

FBARs in ladder filter topologies with small external low-Q passive elements have been successfully used to meet the required duplexer specifications for USPCS handsets. Duplexers are now in volume production using 4” wafers and a 6” wafer fabrication line is under construction. These hermetically sealed duplexers are dramatically smaller than ceramic duplexers (5.6 mm x 11.9 mm x 1.9 mm) and exhibit superior performance compared to surface acoustic wave devices primarily due to their higher Q.

Acknowledgement

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References

[1] J. Larson III, R. Ruby, P. Bradley, and Y. Oshmyansky, "A BAW Antenna Duplexer for the 1900 MHz PCS Band," *1999 IEEE Ultrasonics Symposium*, Oct. 17-19, 1999.

[2] J. Larson III, P. Bradley, S. Wartenberg, R. Ruby, and Y. Oshmyansky, "Modified Butterworth-Van Dyke Circuit for FBAR Resonators and Automated Measurement System," *paper 3H-5, presented at the IEEE International Ultrasonics Symposium in San Juan, Puerto Rico,* Oct. 22-25, 2000, Proceedings not yet in print.

[3] Advanced Design System (ADS) for RF and Microwave Circuit Design – a product of EESOF, a wholly owned subsidiary of Agilent Technologies, Inc.