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FBAR Duplexers with Minimal Shunt Inductance for Better Isolation and Packing Density

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Abstract—**Relentless pressure to reduce the size of filters, duplexers and multiplexers in mobile phone RF front end modules requires close packing of the filters and any associated PCB or SMT inductors. In these multiplexers, however, every Tx filter has to reject every Rx frequency and vice versa, while TDD bands/filters must be rejected by and reject nearly every other band -60 dB typical with -55 dB guaranteed. These seemingly contradictory requirements can both be satisfied if we reduce the magnitude of the grounding inductors of the filters to a point that their mutual inductance is not significantly degrading isolation. The Band 25 duplexer described is 1.5 mm x 1.1 mm x 0.6 mm.**

Keywords-FBAR, piezoelectric, filters, duplexers, multiplexers, handsets, elliptic filters

I. INTRODUCTION

Early Film Bulk Acoustic Resonator (FBAR) duplexers for the PCS band (Tx: 1850-1910 MHz, Rx: 1930-1990 MHz) were constructed by combining FBAR half-ladder filter chips with 4 to 7 resonators having relatively low effective coupling coefficient (K_t^2 = 3.5-5.5 %) with printed inductors on the substrate that carried the FBAR chips[1]. These inductors were several nH and required less than 5% variation about the nominal value in order to place transmission zeroes accurately in the rejection bands to improve the trade-off between insertion loss and rejection. The physical size required to guarantee high Q and tight tolerance while also minimizing the parasitic cross-coupling between these inductors sharply limited the minimum duplexer size (Fig. 1). The transmit (Tx) filter high side frequency response could be designed to roll-off sharply due to the low resonator K_t^2, while the inductors in series with the shunt resonators would stretch the low frequency band edge to cover the passband (beyond that normally available with such low coupling coefficients). This degraded the high frequency attenuation to nearly zero, especially in the Tx/Antenna response – not desirable, but manageable in narrowband Code Division Multiple Access (CDMA or “2G”) radios. More recent duplexer specifications demand better wideband rejection necessitating a different design. It must be as small as possible forcing physically smaller external inductors to be used and there are also many more out-of-band rejection requirements which are not easily met with external LC traps as could be done if more attenuation were needed at only one or two frequencies. Furthermore, the elimination of the Tx and Rx RF inter-stage filters of the radio and associated matching elements became possible with a modestly higher isolation requirement in the duplexer (-55 dB in the Tx and Rx bands). This greatly simplifies the radio design and reduces area and cost through lower component and transceiver chip pin count (transceivers also returned to single-ended Rx inputs as well). A higher-order filter approximating the equal-ripple pass band and rejection band response of elliptic filters is required. Both in-band and out-of-band attenuation can be improved through the use of more resonators to realize a higher-order filter, but at the cost of degraded insertion loss. To recover the original duplexer insertion loss in these higher-order designs, resonator quality factor must be significantly improved. Fortunately, FBARs with Q’s as high as 5000 have been demonstrated [2] and this has allowed duplexer designs with higher resonator count to have a more favorable tradeoff between insertion loss and rejection than lower-order, large inductor designs. Reducing these inductors naturally improves the wideband rejection and also eliminates the need for tight tolerance and high quality factor inductors, which allows the use of lower cost substrates without tight manufacturing control, narrower traces and spaces, and higher RF test yield through reduced performance variation. The resonances of grounding inductors with the FBAR plate capacitors are much higher frequency and no longer affect the narrowband response significantly.

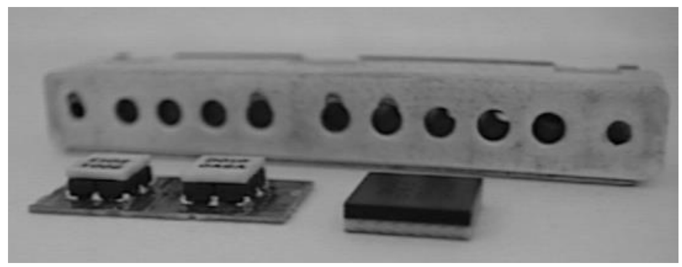


Figure 1. A ceramic duplexer the size of a cigarette butt (background) was commonly used for the PCS band in mobile handsets until the first FBAR duplexer (w/ceramic LCC ceramic packages in left foreground) became widely available. The next generation was shrunken by wafer scale packaging (black epoxy overmolded component in right foreground). The B25 duplexer described here would easily fit inside a drill-hole of the ceramic duplexer.

II. Resonator Performance and Duplexer Geometry

The Tx resonators had Rp = 7000-8000 ohms, Rs = 0.51-0.53 ohms, and K_t^2 = 7.4-7.8 %, while for the Rx resonators Rp = 5400-6200 ohms, Rs = 0.46-0.49 ohms, and K_t^2 = 7.3-7.7 %. Both transmit and receive filters are shown for scale below in Fig. 2.

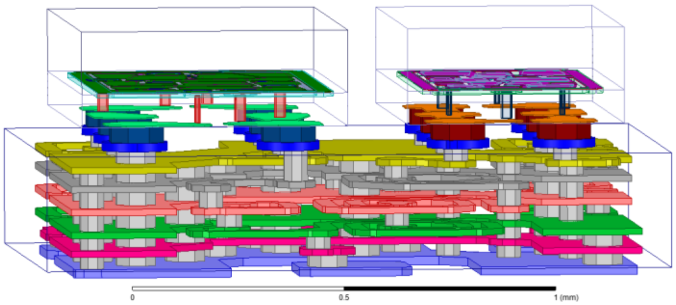
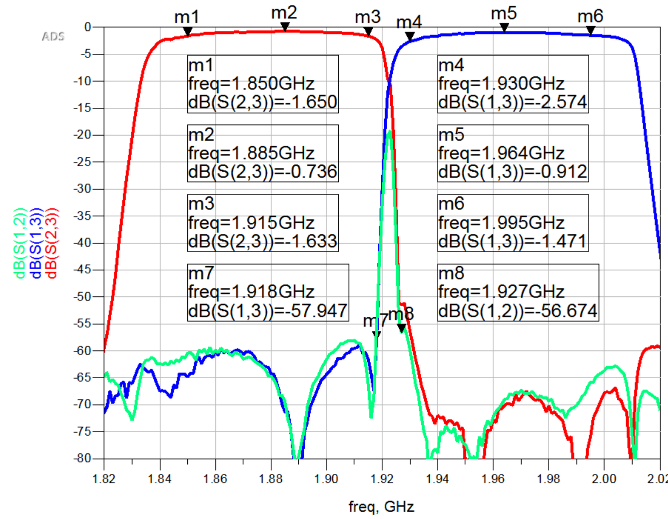


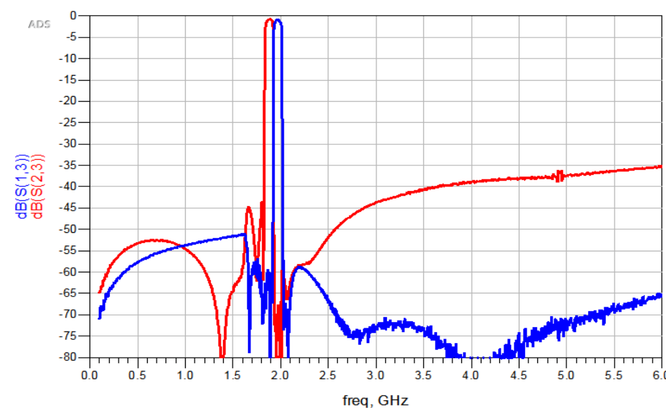
Figure 2. HFSS perspective showing Tx die on top-left, Rx die on top-right and 7-layer organic substrate on the bottom. Note the impedance matching inductors are implemented in the PCB underneath the FBAR dice with ground metal isolating them from each other. Both chips have six solder pads and some of the electrical grounds serve as thermal grounds as well. Antenna port is in center foreground, Tx and Rx ports are at the back corners.

III. Measured S-Parameters of Band25 PCS Duplexer

Measured Band 25 duplexer S-parameters are shown in Fig. 3 and 4. Marker 8 is at 1927 MHz and shows that one of the transmission zeros for the Tx filter is slightly too low in frequency causing the isolation/rejection just above here to be marginal. This is believed to be partly because of a series resonator at slightly too low a frequency. It should also be possible to shift the zeros at 1938, 1953, and 1991 MHz down by fine-tuning the grounding network of shunt resonators to equalize rejection. Note the presence of a faint replica of the pass band occurring at the third harmonic (4.9 GHz) of the resonators. Otherwise, spurious modes are weak and don't produce sharp notches in the pass band or anywhere else.



(a)



(b)

Figure 3. (a) Tx insertion loss is 1.65 dB at band edges and less than 0.75 dB in the mid-band. Rx insertion loss is less than 2.6 dB at the band edges and 1 dB in the mid-band (b) Wideband response shows higher rejection than designs with more grounding inductance and response is clear of spurious modes except the third harmonic of the resonators appearing as a faint copy of the pass band at about 4.9 GHz. This high rejection and relative freedom from spurious modes out-of-band is very helpful when multiplexing with other filters to support carrier aggregation because the filters don't load each other degrading multiplexer IL. Note the Tx rejection is 35 dB up to 6 GHz while Rx rejection is nearly 60 dB from 2.1 to 6 GHz.

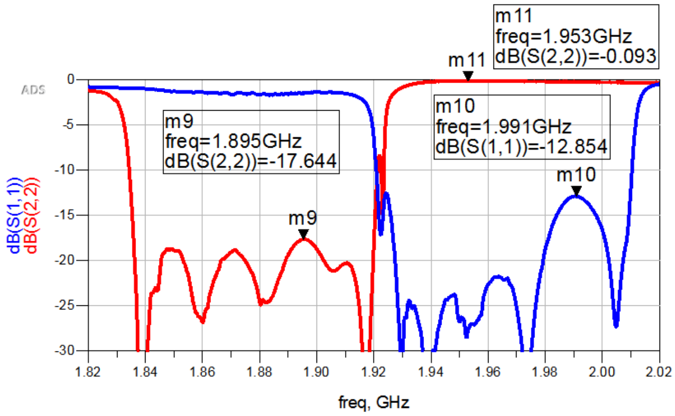


Figure 4. Worst-case Tx return loss is 17.6 dB and Rx R.L. is 12.8 dB. Rx series resonator frequencies are slightly off contributing to this large Rx R.L. Note that the R.L. for the Tx filter above band is less than 0.1 dB. This is when the Tx port series resonator is near antiresonance minimizing current flow through the series matching inductor so total dissipation in the matching inductor and the resonator is very small (compared to SAW devices). The Rx filter R.L. in the Tx band is significantly larger at 1.0-1.5 dB. It exhibits more ohmic loss and well-distributed spurious mode resonator loss at frequencies below the Rx shunt resonator fs, loading the Tx filter and degrading I.L.

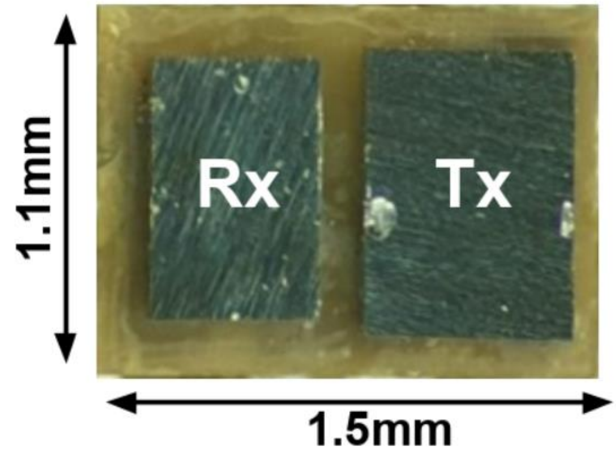


Figure 5. Band 25 (1900 MHz) duplexer. Tx die size is 0.585 sq. mm, Rx die size is 0.459 sq. mm. After-dicing size is less than 1 sq. mm total silicon area. Die thickness is about 225 microns, including FBAR wafer and hermetic lid. Separation between dice is over 100 microns and keep-out zone around perimeter is about 100 microns.

IV. Discussion of PCS Duplexer Performance

Insertion loss and rejection are good and greatly simplify the design of radios by eliminating the need for LC traps and inter-stage RF filters. Better Tx I.L. reduces the peak (and typical) current consumption in the phone significantly compared with duplexers having 3.0 to 3.5 dB worst-case Tx insertion loss. All three ports are internally matched to 50 ohms. The absence of any strongly coupled spurious modes means that the stored energy in the resonators is not much larger at spurious mode frequencies so we can expect power handling and linearity to be better than in a similar device with more severe "notches" in the pass band. Figure 4 shows the low out-of-band dissipation from these filters that produce little loading of other filters in multiplexers.

V. Physical Design

An HFSS perspective plot of the PCS duplexer is shown (with invisible over-mold epoxy) in Fig. 2. The PCB is a 7 metal layer board. The impedance matching inductors, isolation ground walls, and the small grounding inductance for the shunt resonators are all implemented on the PCB under the dice. The FBAR resonator area is a small fraction of the total die area for these chips, limited by the saw street, sealring for the lid, pads, and various spacing requirements. Tx and Rx dice are flip-chipped and connected to the PCB with solder joints. The photo shown in Fig. 5 was taken without the black over-molding epoxy which would normally under-fill and cover the dice.

VII. Conclusions

Cross-coupled FBAR 9 and 10-pole ladder filters with a grounding network using only very small inductors have been shown to yield excellent performance in a very small footprint for band 25 (PCS), giving up relatively little I.L. relative to an unconstrained design using bigger inductors. This degradation in I.L. is relatively small because dissipation in the grounding network decreases with smaller inductors, even though the poles and zeros may be less optimal in frequency. Moreover, if the impedance matching inductors can be well isolated from each other, the grounding inductors are small enough that filters and duplexers of this type design could be placed physically closer to each other without significant degradation of the required -60 dB rejection/isolation. None of the various wire-bond shielding schemes would be necessary, saving cost and area in a module. In-band and cross-band isolation would be preserved with much closer packing of FBAR filters than is typical in RF front end modules.

VIII. Acknowledgments

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