Balanced RF Duplexer with Low Interference Using Hybrid BAW Resonators for LTE Application

Jea-Shik Shin, Insang Song, Chul-Soo Kim, Moon-Chul Lee, Sang Uk Son, Duck-Hwan Kim, Ho-Soo Park, Sungwoo Hwang, and Jae-Sung Rieh

A balanced RF duplexer with low interference in an extremely narrow bandgap is proposed. The Long-Term Evolution band-7 duplexer should be designed to prevent the co-existence problem with the WiFi band, whose fractional bandgap corresponds to only 0.7%. By implementing a hybrid bulk acoustic wave (BAW) structure, the temperature coefficient of frequency (TCF) value of the duplexer is successfully reduced and the suppressed interference for the narrow bandgap is performed. To achieve an RF duplexer with balanced Rx output topology, we also propose a novel balanced BAW Rx topology and RF circuit block. The novel balanced Rx filter is designed with both lattice- and ladder-type configurations to ensure excellent attenuation. The RF circuit block, which is located between the antenna and the Rx filter, is developed to simultaneously function as a balance-to-unbalance transformer and a phase shift network. The size of the fabricated duplexer is as small as 2.0 mm × 1.6 mm. The maximum insertion loss of the duplexer is as low as 2.4 dB in the Tx band, and the minimum attenuation in the WiFi band is as high as 36.8 dB. The TCF value is considerably lowered to –16.9 ppm/ºC.

Keywords: Bulk acoustic wave, BAW, film bulk acoustic wave resonator, FBAR, RF duplexer, RF resonator.

Manuscript received May 8, 2013; revised June 17, 2013; accepted June 29, 2013.

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I. Introduction

As wireless frequency resources are limited, the bandgap between the uplink frequency and downlink frequency is getting narrower while the bandwidth is becoming wider. There has been a strong demand for a balanced RF structure for the low noise amplifier (LNA), owing to its advantage of common-mode noise rejection, which leads to a balanced topology requirement in the post-LNA filter and duplexer. Currently, most balanced duplexers and post-LNA filters use surface acoustic wave (SAW) technology due to its simple fabrication process [1]. However, SAW devices show a low Q factor (*Q*) of a few hundred and weak temperature stability, which makes it difficult to achieve such narrow bandgap duplexers as the Long-Term Evolution (LTE) band-7 duplexer (Tx: 2,500 MHz to 2,570 MHz; Rx: 2,620 MHz to 2,690 MHz), which should be designed to prevent the co-existence problem with the WiFi band (2,400 MHz to 2,483 MHz), which is a fractional bandgap of 0.7%. The thin-film bulk acoustic resonator (FBAR) or bulk acoustic wave (BAW) resonator is a promising technology that can replace conventional SAW technology, owing to its prominent advantages, including high *Q*, high power handling capability, high operating frequency, temperature stability, and the possibility of being monolithically fabricated with other integrated circuit parts [2].

Thus, there is great demand for balanced BAW devices, such as RF filters and duplexers [3]. To achieve a BAW filter with balanced output and single-ended input topology, a coupled resonator filter (CRF) was suggested [4], [5]. However, it is difficult to manufacture a CRF due to its complicated structure of dual piezoelectric layers. Herein, we propose a novel balanced BAW RF duplexer for LTE band-7 applications. To achieve low interference with WiFi, we design and fabricate hybrid BAW resonators as well as normal BAW resonators in the Tx filter. We also implement a novel BAW balanced Rx filter topology and an RF circuit block to achieve balanced Rx topology of the duplexer.

II. Design Process

1. Tx Filter Design

First, we design the BAW Tx filter for the LTE band-7 duplexer. The Tx filter is designed with a well-known ladder topology, in which individual shunt BAW resonators are designed with a hybrid structure to ensure a low temperature coefficient of frequency (TCF), allowing for low interference with the WiFi band. Individual series BAW resonators are implemented with a normal structure to achieve a wide bandwidth, as depicted in Fig. 1.

The TCF value of the BAW resonator is important for the low interference of the duplexer. The resonance frequency of the conventional BAW resonator decreases as the environment temperature increases (a negative TCF value). The negative TCF value is caused by the negative TCF constants of the materials themselves in the BAW resonator: AlN as the piezoelectric layer; Mo and Ru as electrode layers. A near zero TCF value of the BAW resonator can make it possible to reduce the gap between adjacent frequency bands in filters and can thereby prevent interference during operation under severe temperature conditions. Adding a TCF compensating layer such as SiO_2, which shows positive TCF values, reduces the TCF of the BAW resonator. Relatively thick compensating layers are required to achieve a sufficiently low TCF value. However, the thick additional layers significantly degrade the electric performances, including the resonance frequency shift, Q, and the electro-mechanical coupling coefficient (kt^2).

We develop a novel hybrid BAW structure: a pair of SiO_2 and Ru stacks (Bragg reflector) on an air cavity (air reflector), as shown in Figs. 1(c) and 1(d). The thickness of the SiO_2 stack and that of the Ru stack corresponds to an acoustic quarter-wave. The quarter-wave thickness of SiO_2 is 5,900 Å at 2.5 GHz, which is thick enough to work as an effective TCF compensation layer. However, although the hybrid BAW can effectively lower the TCF value without a resonance frequency shift, Q and kt^2 are inevitably lowered slightly. The value of Q (at resonance frequency) and kt^2 of the hybrid BAW resonator and of the normal BAW resonator is 1,600 and 5.1% and 2,000 and 6.4%, respectively, as shown in Fig. 1(e). The bandwidth performance of a filter depends on the kt^2 values of the series

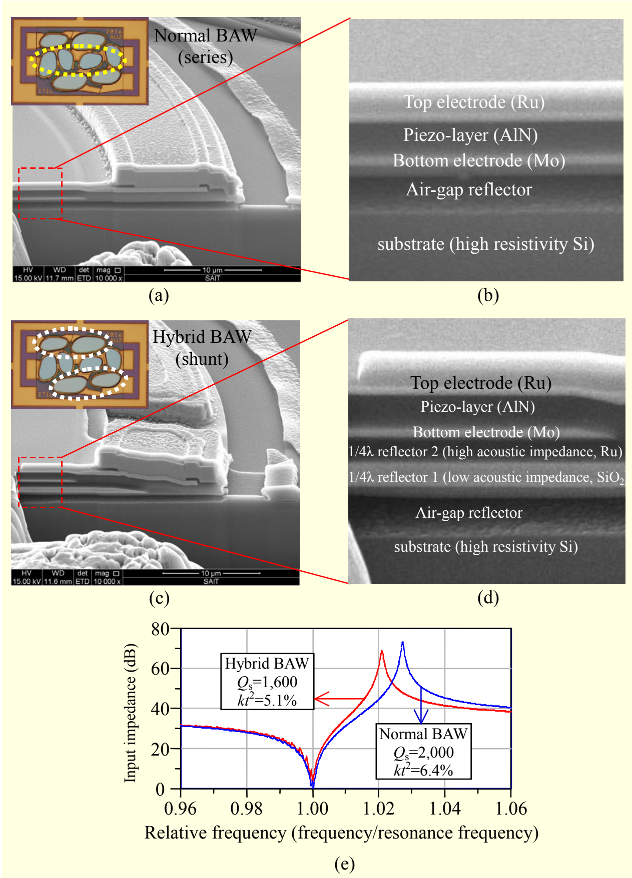

Fig. 1. Cross-sectional SEM images and measured performance of BAW resonators in Tx filter: (a)/(b) normal BAW resonator for series resonators, (c)/(d) hybrid BAW resonator for shunt resonators (prepared by focused ion beam cutting), and (e) performance comparison.

and shunt resonators consisting of the filter. To achieve a wide filter bandwidth, kt^2 must be large. Fortunately, most frequency standards require a narrow bandgap performance for either the lower side or upper side of the bandpass filter. In the LTE band-7 Tx filter, we implement the hybrid BAW structure for the shunt resonators only, which should be designed to successfully co-existence with the WiFi band.

2. Rx Filter Design

To develop BAW duplexers with balanced Rx output topology, a balanced Rx filter is used. By mixing the ladder and the lattice topologies, excellent performance with both the skirt and the attenuation can be achieved, as shown in Fig. 2.

To achieve excellent attenuation performance at the Tx band, we provide a novel design method. In a lattice part of the Rx filter, there are two series and two shunt resonators. An attenuation pole can be located in the desired position by adjusting the size ratio of the series and the shunt resonators. As

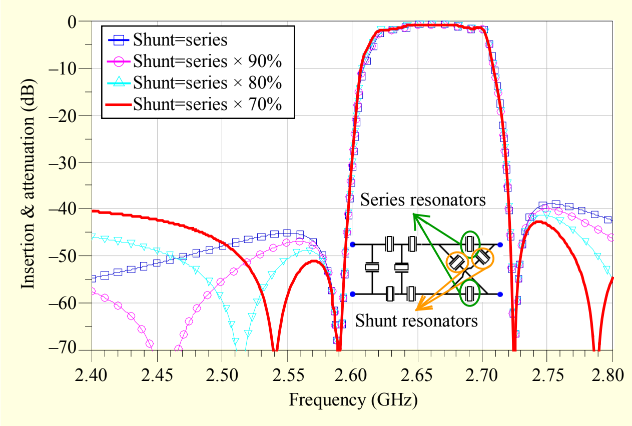

Fig. 2. Circuit simulation results: attenuation pole movement depending on size ratio of shunt to series resonators in lattice.

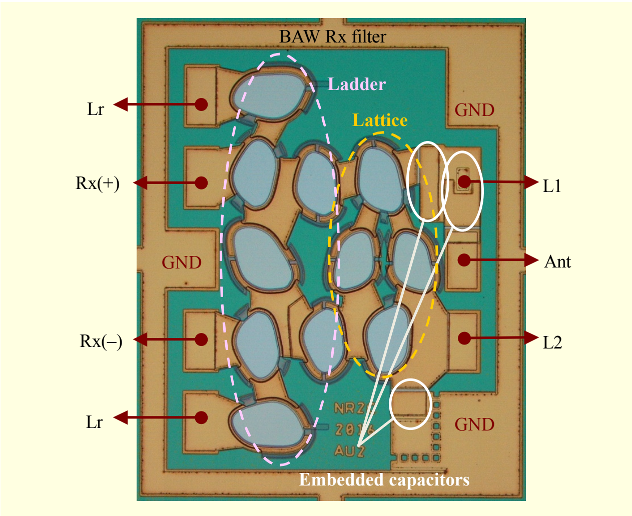

Fig. 3. Photomicrograph of fabricated Rx filter that consists of BAW resonators and embedded capacitors. Pad notations are for pins to be connected to form duplexer circuitry.

the size ratio of the shunt to the series resonators decreases, the attenuation pole moves close to the passband side. Figure 3 shows a photomicrograph of the fabricated BAW Rx filter with its pin notations to be connected during the duplexer assembly. We realize a balanced input/output Rx filter and embedded capacitors simultaneously without an additional BAW fabrication process by using passivation oxide film as a dielectric layer and Ru and Au pad layers as electrodes. Since some of the capacitors can be fabricated underneath the pad region, that area of the filter is saved effectively.

3. Duplexer Design

A phase shift network (PSN) as well as a balance-to-unbalance transformer (BALUN) should be developed to

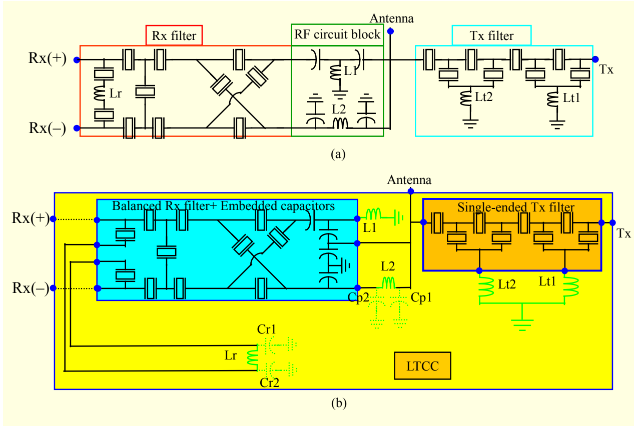

Fig. 4. Proposed circuit schematics of BAW duplexer with balanced Rx output configuration: (a) duplexer circuitry with RF circuit block between Rx filter and Tx filter and (b) reorganized circuit diagram with Rx, Tx, and LTCC.

achieve a balanced topology of a duplexer. A few inductors and capacitors are conventionally required for a PSN and for a BALUN, respectively, which complicates the duplexer design and also degrades the duplexer performance.

To overcome these problems, a novel topology is proposed herein: an RF circuit block that functions as a PSN and a BALUN simultaneously. Figure 4 shows the proposed BAW duplexer circuitry with auxiliary shunt inductors for a high attenuation performance. The green-colored components (inductors) in Fig. 4(b) are implemented in the low temperature co-fired ceramic (LTCC) substrate, and the dashed-line shunt capacitors indicate parasitic elements generated between the inductors and ground planes in the LTCC.

III. RF Measurement Results

The value of Q of the capacitors embedded in the Rx filter is measured to be over 50, which is enough for use in RF devices. Since the WiFi band is located very close to the Tx of LTE band-7, the shunt resonators in the Tx filter should have an abrupt cut-off profile and low TCF value to prevent interference during operation at various temperature conditions.

Figure 5 shows the measured RF characteristics of the fabricated duplexer. The measured maximum insertion loss of the LTE band-7 duplexer is 2.4 dB and 2.7 dB in the passband for Tx and Rx, respectively. The amplitude and the phase balances for the Rx band are measured to be within ± 0.9 dB and $180 \pm 4^{\circ}$, respectively. The isolation characteristic for the Tx band and Rx band is 54.3 dB and 50.1 dB, respectively. The attenuation of the Tx in the WiFi band, which corresponds to a fractional bandgap of only 0.7%, is as large as 36.8 dB. As the TCF value is very important for the narrow bandgap between the WiFi band and the band-7 Tx, we also measure the

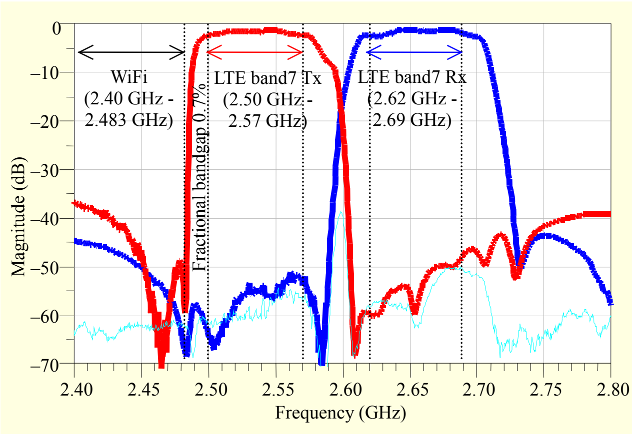

Fig. 5. RF characteristics of fabricated duplexer with notation of band standards.

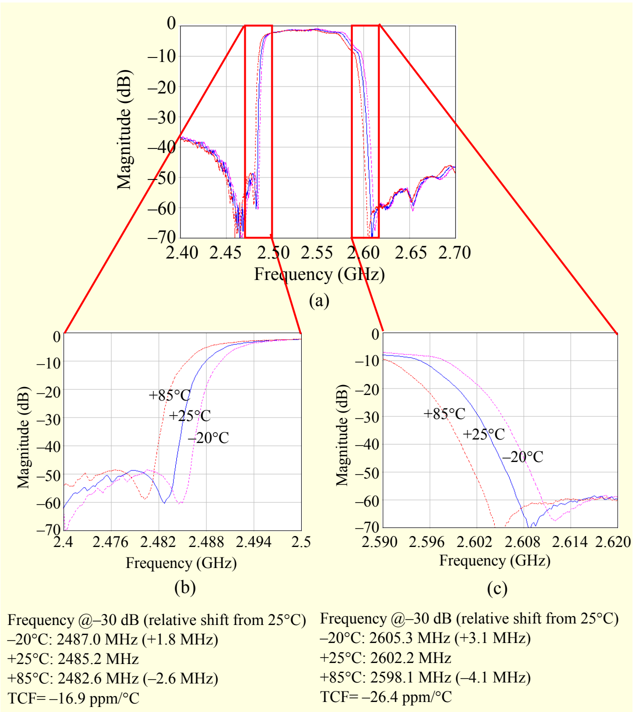

Fig. 6. (a) Experimental Tx profile of fabricated duplexer in various temperature conditions: (b) Close-up of left side in (a)-TCF value is –16.9 ppm/ºC, which corresponds to 4.4 MHz temperature drift and is mainly affected by shunt resonators implemented with hybrid BAW structure, and (c) Close-up of right side in (a).

performance of the duplexer in various temperature conditions: –20ºC, +25ºC, and +85ºC.

Figure 6 shows Tx performances of the fabricated duplexer in three temperature conditions. The TCF value of the lower side of the Tx filter is mainly affected by the TCF of the shunt resonators, whereas the upper side is affected by the series resonators of the filter. The shunt resonators of the Tx filter are implemented with a hybrid BAW structure to lower the TCF value of the lower side of the filter, whereas the series resonators of the filter are fabricated with a normal BAW structure. The measurement result clearly shows that the TCF value of the lower side (–16.9 ppm/ºC) is an improvement over that of the upper side (–26.4 ppm/ºC). We successfully achieve a temperature-stable RF duplexer for LTE band-7 to prevent interference with the WiFi band.

IV. Conclusion

In this work, we presented the design, fabrication, and measurement results of a small-sized BAW RF balanced duplexer with low interference for LTE band-7 application. For the low interference with WiFi, a hybrid BAW structure was implemented for the shunt resonators of the Tx filter. To achieve the balanced BAW duplexer, a novel topology with a balanced Rx filter and RF circuit block was also proposed. The balanced BAW filter, whose topology is a mixture of both lattice and ladder configurations, was acceptable to realize the balanced RF duplexer. As the RF circuit block was designed to simultaneously work as a phase shifter and a BALUN, simple circuitry for the duplexer was developed. Embedding all capacitors in the BAW Rx filter without additional processing made it possible to fabricate a miniaturized duplexer. The size of the fabricated duplexer was 2.0 mm × 1.6 mm. Measurement results showed a maximum insertion loss of 2.7 dB in the Rx band and 2.4 dB in the Tx band. The minimum attenuation in the WiFi band, which has a narrow fractional bandgap of 0.7%, was as high as 36.8 dB. The TCF value was lowered to –16.9 ppm/ºC, which is a 36% improvement.

References

[1] P-A. Girard and M. Solal, "High Performance Single-Balanced Duplexer," *IEEE/MTT-S Int. Microw. Symp. Dig.*, June 3-8, 2007, pp. 861-864.

[2] K.M. Lakin, "Thin Film Resonator Technology," *IEEE Int. Frequency Control Symp.*, 2003, pp. 765-778.

[3] J.-S. Shin et al., "1-Chip Balanced FBAR Filter for Wireless Handsets," *European Microw. Conf.*, Paris, France, Sept. 28-30, 2010, pp. 1257-1260.

[4] K.M. Lakin, "Bulk Acoustic Wave Coupled Resonator Filters," *IEEE Freq. Control Symp.*, 2002, pp. 8-14.

[5] S.R. Gilbert et al., "An Ultra-Miniature, Low Cost Single Ended to Differential Filter for ISM Band Applications," *IEEE/MTT-S Int. Microw, Symp. Dig.*, June 15-20, 2008, pp. 839-842.