Temperature Stable Bulk Acoustic Wave Filters Enabling Integration of a Mobile Television Function in UMTS System

Hao Zhang, Qingrui Yang, Wei Pang, Jian-Guo Ma, and Hongyu Yu

***Abstract*—Multi-mode mobile equipment requires efficient radio-frequency (RF) filtering solutions to solve interference problems in an UMTS system integrated with a mobile television function. A RF filtering solution comprising a band-pass filter and a band-stop filter based on temperature-stable bulk acoustic wave resonator (BAW) technology is proposed in this letter. Both filters measurably demonstrate low insertion loss (~ 3 dB), high rejections (35–40 dB), and fast roll-off (~ 10 MHz from pass band to stop band). A temperature coefficient of frequency (TCF) as low as -4 ppm/°C in the filters is achieved, which is five times lower than that of a conventional BAW filter. The low TCF is of critical importance, particularly in the sharp skirts, because trivial frequency changes associated with temperature variation could lead to failure against filter specifications at the skirt corners. The proposed filtering solution can be applied to minimize interference present in similar systems, such as mobile phones integrated with satellite radio or GPS navigation.**

***Index Terms*—Acoustic resonator, bulk acoustic wave resonator (BAW) filter, TD-CDMA mobile television (TDtv), UMTS.**

I. Introduction

The wiresless standards 3G, WiMax, LTE and others are quickly consuming the radio-frequency communication spectrum [1]. Mobile media applications such as mobile television and satellite radio must therefore use the interspaces between two allocated frequency bands, or the frequency spectrums adjoining allocated frequency bands. For instance, TD-CDMA mobile television (TDtv), one of the mobile television technologies developed in Europe, seeks the frequency band of 1900–1910 MHz, which is 10 MHz below the 3G UMTS transmitter (Tx) band (1920–1980 MHz), to broadcast television data to mobile handsets [2]. To allow TDtv and UMTS to harmonically coexist in a wireless system, wireless signal interferences must be resolved.

In this letter, a pair of filters comprising a band-pass filter and a band-stop filter is proposed to achieve reduction of interferences. The basic element of the filters is a bulk acoustic wave (BAW) resonator with low temperature coefficient of frequency (TCF) [3]. High quality factors (Q) of the BAW resonators ensure the implemented filters have low pass band insertion loss and rapid transitions from pass band to stop band. The thermal stability characteristics of the resonators assure little frequency change of the filters with temperature variation, which is extremely critical because the guard band is merely 10 MHz, and a trivial frequency change would lead to failure in complying with the technical specifications of the filters.

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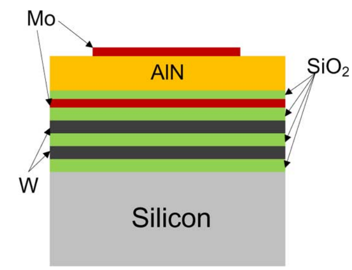

Fig. 1. Cross-sectional view of a temperature compensated BAW resonator.

II. Low TCF BAW Resonator

The BAW resonator used to build the filters is composed of a resonant body and an acoustic mirror [4] with alternating high and low acoustic impedance layers (Tungsten (W) and Silicon Dioxide (SiO_2)) that acoustically isolate the resonant body and the substrate (Fig. 1). The resonant body is an aluminum nitride (AlN) and silicon dioxide composite layer sandwiched between two molybdenum (Mo) electrodes. SiO_2 is a unique material that has a positive temperature coefficient of stiffness [5]; this coefficient is negative in most other materials. Because of this property, SiO_2 is frequently used as a temperature compensation material to reduce resonant frequency change with temperature variation in BAW resonators.

The temperature compensating SiO_2 layer is usually arranged on the topmost layer of a BAW resonator, playing a dual role of reducing resonant frequency variation with temperature and passivating the resonator to protect it from moisture or contamination in the surrounding environment. To achieve low TCF, a relatively thick SiO_2 layer must be used. This considerably degrades the Q of the resonator, because amorphous SiO_2 material causes higher acoustic attenuation than the highly crystalline AlN and Mo materials. The low acoustic impedance property of SiO_2 layer also substantially increases the frequency mass sensitivity of the resonator, making it very challenging to trim frequency to a desirable target for high product yield.

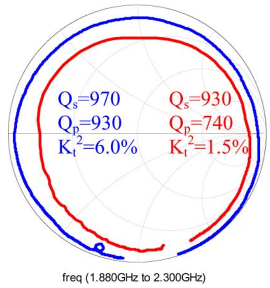

Fig. 2. Measured impedances of a conventional BAW resonator (blue) and temperature compensated BAW resonator (red).

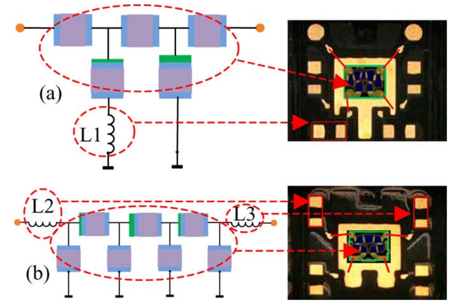

Fig. 3. (a) TDtv band-pass filter topology and assembly diagram; (b) UMTS band-stop filter topology and assembly diagram.

To obtain a low frequency trimming sensitivity and an efficient improvement in Q and TCF, a thin SiO_2 layer is placed between the AlN film and lower Mo electrode of the resonator. Depositing SiO_2 between these two layers was ever utilized in an acoustic resonator for temperature stable oscillator application [6]. Since a considerable portion of electrical field between the two electrodes falls on the non-piezoelectric SiO_2 layer, electromechanical coupling coefficient (K_t^2) of the resonator becomes smaller. For narrow band applications such as the pair of filters reported in this letter in which the fractional bandwidth is about 0.5%, K_t^2 of the low TCF resonators should be around 1–2%. To achieve a desirable K_t^2 as well as a low TCF, the thicknesses of the resonator layers must be fully optimized. The Mason model has been revised to incorporate the added SiO_2 layer. Temperature coefficients of the properties of the materials in the resonator are introduced in the model to simulate the TCF of the resonator. The thicknesses of the piezoelectric AlN film and temperature compensating SiO_2 layer are the dominant factors influencing K_t^2 and the TCF of the resonator.

Measured impedance of a conventional BAW resonator is plotted in a Smith Chart in Fig. 2. The K_t^2 is calculated from the measured impedance to be about 6.0%. The measured Q_s (Q at series resonance) and Q_p (Q at parallel resonance) of the resonator are 970 and 930, respectively. In the same figure, measured impedance of the designed low TCF resonator is plotted with K_t^2 calculated to be 1.5%. The measured Q_s and Q_p are 930 and 740, respectively. The TCF test is performed in the filters, which will be discussed later.

III. TDtv and UMTS Filters

Both the band-pass and band-stop filter were designed with a well known ladder topology, in which individual BAW resonators are electrically connected in a ladder configuration. In the TDtv filter architecture shown in Fig. 3(a), shunt resonators are applied with additional mass layers to shift their resonant frequencies down. A pass band from 1900 MHz to 1910 MHz is formed in the filter. Sufficient rejection is achieved in the UMTS band of 1920–1980 MHz by an inductor connected in series to a shunt resonator to produce a transmission notch. The transmission notch is formed by the inductor resonating with the parallel plate capacitor of the BAW resonator. It is interesting to note that the two shunt resonators present slightly different resonant frequencies. The shunt resonator connected to inductor L1 is applied with a thinner mass load layer (thus higher resonant frequency) than the other shunt resonator to maintain the pass band of the filter. The variation of L1 inductance influences both insertion loss and rejection of the filter.

The UMTS filter allows UMTS signal (1920–1980 MHz) to pass through, whereas it blocks the transmission of TDtv signals. The band-stop configuration of the filter is displayed in Fig. 3(b), which consists of three series and four shunt resonators. The mass load layers are applied on the series resonators instead of the shunt resonators. The parallel resonance of the series resonators is approximately aligned with the series resonance of the shunt resonators. A notch is created in the transmission spectrum, where the input signal encounters very high impedance in the series path and very low impedance in the shunt path. The current from the input branches out multiple times, and little power arrives at the output. The two inductors at the input and output ports L2 and L3 resonate with the parallel plate capacitors to create a through path in the UMTS band.

The layouts of both TDtv and UMTS filters fit onto a 1.0 mm × 0.8 mm silicon chip, respectively. The fabricated dies are assembled on multi-chip-module (MCM) laminates (3 mm× 3 mm) with surface mounted inductors connected to the chips with bonding wires.

The simulated and measured $|S_{21}|$ of the TDtv filter and UMTS filter are plotted in Fig. 4. The simulation and measurement match well. The TDtv filter demonstrates an in-band insertion loss of 3 dB, and an excellent out-of-band rejection—better than 40 dB in the UMTS band. The transition from pass band to stop band is rapidly completed within 10 MHz, thanks to the high Q of the BAW resonators in the filter. The UMTS filter shows an excellent rejection of more than 40 dB in the TDtv band and a low insertion loss of 2.6 dB in the UMTS band. The transition from pass band to stop band is fast, thanks again to the superior Q of the BAW resonators used in the filter.

The filter characteristic with regard to temperature is essentially determined by the TCF property of the enclosed resonators. The TDtv band-pass and UMTS band-stop filters have been tested at elevated temperatures. When the temperature increases from $-20^\circ\mathrm{C}$ to $80^\circ\mathrm{C}$, it is observed that both filters move downwards by approximately 1 MHz, corresponding to a TCF of $-4\ \mathrm{ppm}/^\circ\mathrm{C}$ (Fig. 5). A conventional BAW filter is known to have a TCF of $-20\text{–}-30\ \mathrm{ppm}/^\circ\mathrm{C}$ [7]. Because of the temperature compensating SiO_2 layer placed in the resonators, a five fold reduction on TCF of the filters has been achieved. The improved temperature stability of the filters increases the margin against the technical specifications by

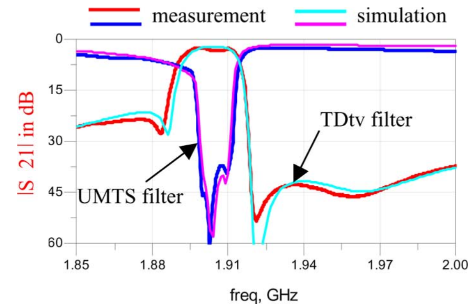

Fig. 4. Measured results of TDtv band-pass filter and UMTS band-stop filter.

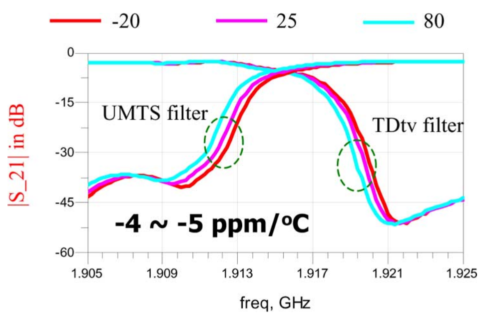

Fig. 5. Measured temperature coefficient of frequency of both filters.

minimizing the frequency change with temperature variation, which greatly releases the burden of frequency trimming and tremendously improves final product yield.

IV. Conclusion

Testing demonstrates that the fabricated temperature- compensated bulk acoustic wave band-pass and band-stop filter pair work to prevent wireless interferences and ensure a harmonic existence of a mobile TDtv system in a wireless UMTS handset. Both filters demonstrate excellent in-band insertion loss, superior attenuation in stop band, as well as rapid transition from pass band to stop band. A very low frequency shift has been measured with temperature change in the filters, and this greatly enhances the trimming effectiveness and improves product yield. The proposed filtering solution could be potentially applied to other systems, including mobile phones integrated with satellite radio or GPS navigation.

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