Design of RF Bulk Acoustic Wave Duplexer for UMTS-1 Band

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Abstract: The performance of RF resonant circuit is improved by adding inductor in the circuit. Firstly, according to the equivalent circuit of a single lossless film bulk acoustic resonator (FBAR), the resonant frequency and anti-resonant frequency formulas of the resonator are derived. According to the expressions, the principle of improving circuit performance by series parallel inductors is studied. Secondly, considering that too large inductor will bring great challenges to the subsequent process, the inductor size is optimized through Π-T transformation principle. Based on this research, another mobile duplexer is designed for umts-1 band (transmitting band: 1920-1980mhz, receiving band: 2110-2170MHz). The insertion loss of transmitting filter and receiving filter is better than 2dB, and the isolation of transmitting filter and receiving filter is greater than 58db and 77db respectively.

1. Introduction

With the rapid development of mobile communication technology, mobile communication terminal products have been given more and more uses [1]. At present, smart phones and tablet computers not only provide basic voice communication functions, but also have image acquisition, positioning systems, Bluetooth communication, and data transmission and other functions [2]. With the development of the times, the communication frequency is getting higher and higher, the frequency band is divided more densely, and the guard band is narrower. RF bandpass filters and duplexers are required to have smaller size, lighter weight and higher performance [3]. However, traditional ceramic filters and SAW filters have great defects in chip integration, power processing and frequency-temperature stability, and the operating frequency of SAW devices is usually around 1GHz [4]. The combination of the development of Micro-Electro-Mechanic System (MEMS) technology and piezoelectric materials with high electromechanical coupling coefficient and high quality factor (Q value) gave birth to a new thin film bulk acoustic resonator (Fbar, thin film bulk acoustic resonator) technology. Compared with other technologies, Fbar technology has significant advantages such as reduced equipment volume, small in-band insertion loss, high out-of-band suppression, high Q value, good temperature stability, high power capacity, and strong resistance to electrostatic shock. Therefore, the FBAR technology is of great significance to the manufacture of small-sized and small-sized RF filters or duplexers. At the same time, FBAR devices have great advantages in insertion loss and power handling capabilities, and can be fully integrated with other CMOS/RF IC circuits to implement single-chip radios or transceivers [5]. The FBAR duplexer is used to isolate the communication that enters the mobile phone from the communication that is sent out to achieve two-way voice and data transmission. The duplexer plays a very important role in mobile phones [6]. They also achieve a high degree of isolation, high sensitivity and high reliability for the transceiver [7]. When designing FBAR devices, it is often necessary to introduce inductors to improve circuit performance. This article mainly explores the improvement principle of series and parallel inductance to the circuit, and carries out equivalent circuit transformation to the inductance with too large value. Based on this research, Fbar technology is used and Mason model is used to design a duplexer with low insertion loss and high out-of-band rejection that can be used in the 5G frequency band.

2. Theory

2.1. The Basic Principle of Resonators

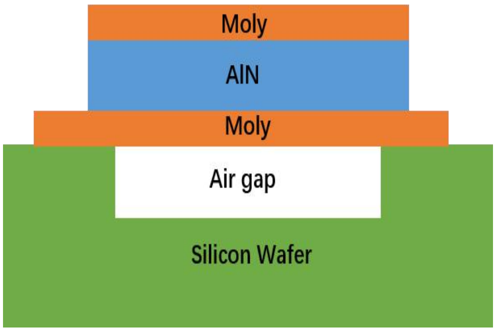


Figure 1: Cross section of FBAR.

The duplexer is composed of a transmitting filter (Tx filter) and a receiving filter (Rx filter), and the basic unit of the filter is a resonator. Figure 1 is a cross-sectional schematic diagram of FBAR, with Mo as the top and bottom electrode materials, AlN as the piezoelectric film, and Si as the substrate. The simplest resonator model is a sandwich structure of upper electrode-piezoelectric layer-lower electrode. Air interface at top electrodes and bottom electrodes can provide an acoustic impedance mismatch for the resonator, confining most of the acoustic energy in the sandwich stack structure. During the manufacturing process, a passivation layer is added top electrode the bottom electrode to ensure that the C-axis preferred orientation of the piezoelectric film is better. A seed layer will be added above the top electrode to prevent the metal electrode exposed in the Mo electrode from being oxidized [8]. At the same time, the corresponding circuit model Mason model will also add a seed layer and a passivation layer in addition to the basic three-layer structure. Generally, the two layers are made of AlN. The performance characteristics of FBAR devices are closely related to the thickness and quality of electrodes and piezoelectric materials. The factors that affect the performance of piezoelectric materials also include the dielectric constant (if too low, the resonator will become too large; if too high, the area of the resonator will become smaller, which will cause the Q value to decrease), the intrinsic Q value of the material, and the compatibility of the material in mass production, it has better silicon compatibility, higher phase velocity, higher resistivity and lower weight density than ZnO, so AlN is often selected as the electrode material. Mo has the characteristics of low resistivity, high acoustic impedance, low density, and low thermal expansion coefficient, so it is often used as an electrode material [9].

2.2. The Principle of Fbar Filter

The connection of a series FBAR resonator and a parallel FBAR resonator constitutes a basic FBAR band-pass filter. The connection method is shown in the Figure 2,3. It can be seen that the parallel resonance frequency of the series FBAR and the series resonance frequency of the parallel FBAR determine the bandwidth of the FBAR filter. The series resonance frequency of the series FBAR and the parallel resonance frequency of the parallel FBAR correspond to the center frequency fc of the filter [10].

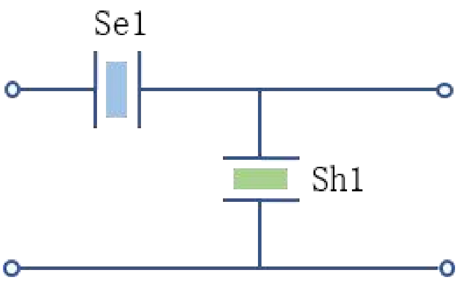


Figure 2: Filter structure diagram.

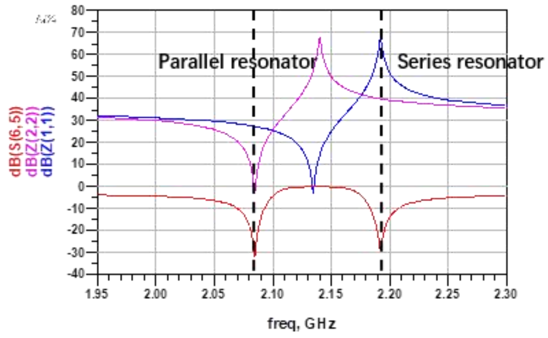


Figure 3: Principle of FBAR filter.

2.3. The Influence of Series and Parallel Inductance on Circuit Performance

The basic component of an acoustic filter is a resonator with two electrical nodes. In order to explore the influence of series parallel inductors on the performance of FBAR, the FBAR is roughly regarded as a piezoelectric transducer neglecting the loss, and its equivalent circuit model is BVD model. As shown in the Figure 4, the simplified model can quickly predict the effect of series or parallel inductors of resonators on circuit performance [11]. The electrical response of the device with better conductivity is called the resonant frequency, and the electrical response with lower conductivity is the anti-resonant frequency. According to the equivalent circuit, the expressions of and can be written as:

$$f_r = \frac{1}{2\Pi\sqrt{L_D C_D}} \tag{1}$$

$$f_s = \frac{1}{2\Pi\sqrt{L_D\left(\frac{C0 * C_D}{C0 + C_D}\right)}} \qquad (2)$$

Where the frequency of f_a is always higher than f_r.When the inductance Ls is connected in series in the circuit (as shown in the Figure 5), according to the formula, the total inductance in the circuit increases, so f_r decreases (moves to the left) to get f_{r1}; In addition, Ls and C0 are connected in series to get a new f_{r2}. The larger the Ls in series, the larger the left offset of f_{r1} and the smaller the right offset of f_{r2}. When the inductance Lp is paralleled in the circuit (as shown in the Figure 6), according to the formula, the total inductance in the circuit decreases and f_a increases (shifts to the right) to get f_{a1} ;When Lp is paralleled with ((C0 * cm) / (C0 + Cm)), a new anti-resonant frequency f_{a2} is generated. The larger the Lp in parallel, the larger the left offset of f_{a2} and the smaller the right offset of f_{a1}.

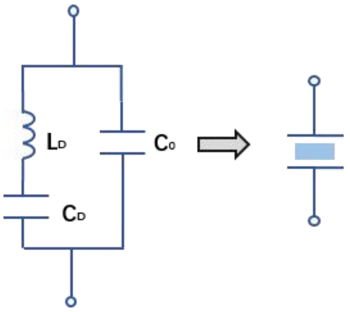


Figure 4: BVD model and equivalent symbol.

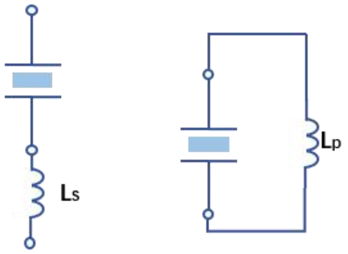


Figure 5: Schematic diagram of series and parallel inductance.

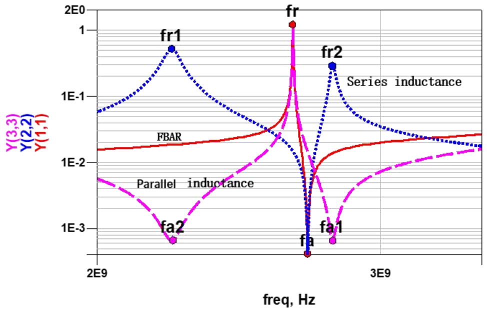


Figure 6: Schematic diagram of resonant frequency offset after series and parallel inductors.

2.4. Π-T Transformation of Inductance

The equivalent transformation of T-type circuit and Π-type circuit is one of the feasible methods to simplify the circuit. Similarly, T-type inductor and Π-type inductor can achieve equivalent transformation, and when Π-type inductor is transformed into T-type inductor, the inductance value will decrease, that is, smaller inductance value can achieve the same circuit improvement effect [12]. The transformation relationship is shown in the Figure, and the equivalent expression between them is as follows:

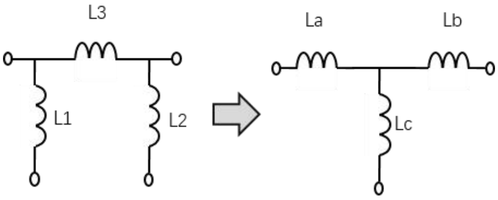


Figure 7: Principle of equivalent transformation.

$$L_1 = \frac{L_a * L_b + L_b * L_c + L_c * La}{L_a}$$

$$L_2 = \frac{L_a * L_b + L_b * L_c + L_c * L_a}{L_b} \tag{3}$$

$$L_3 = \frac{L_a * L_b + L_b * L_c + L_c * L_a}{L_c}$$

The influence of series and parallel inductors on resonant frequency and the equivalent circuit transformation principle can be used to optimize the filter's out of band suppression and reduce the inductance value in the circuit, which provides theoretical support for the subsequent diplexer design.

3. Design Flow of Duplexer

Table 1: Design index of B1 band duplexer.

Parameter	Tx filter	Rx filter
Passband	1920-1980MHz	2110-2170MHz
Insertion loss	>-2dB	>-2dB
Out of band suppression	<-30dB @10 – 1574 MHz <-50dB @2110 – 2170 MHz <-28dB @2400 – 2484MHz <-30dB @3840 – 5940 MHz	<-35dB @10-1920MHz <-50dB @1920-1980MHz <-30dB @2400 – 2483.5 MHz <-35dB @2484 – 3000 MHz

The function of duplexer is to separate the wireless receiving and transmitting signals at the antenna end [13]. For the full duplex system, the signal is received and sent in different frequency bands, so each filter has its own technical specifications. Secondly, the diplexer has high requirements for the isolation between filters. In recent years, duplexer for mobile phone has developed rapidly. In the early years, the duplexer used in mobile phone was ceramic, but compared with the SAW duplexer introduced in 2001, the SAW duplexer has a significant advantage in volume[14]. The FBAR duplexer first adopted by Agilent company is superior to the traditional saw and ceramic duplexer in many aspects by reliable manufacturing process and integrated technology. The design of FBAR duplexer is more complex than that of single filter. Duplexer is usually composed of two filters, TX filter and Rx filter. The basic connection principle is shown in the Figure. Next, we will take the B1 band duplexer as an example to show the design process of an FBAR duplexer. The main technical specifications of duplexer are as follows.

3.1. Design of Resonator

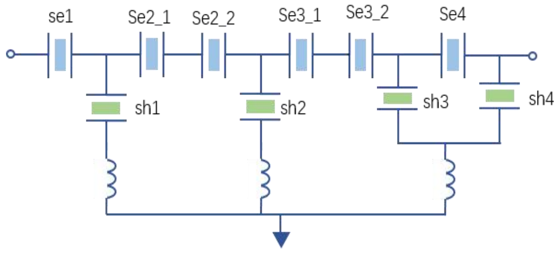
Whether it is the design of filter, duplexer or other FBAR devices, the first step should focus on the resonator, and the parameters of the resonator have a great influence on the subsequent design work[15]. The circuit model used in this design is Mason model. The first is to determine the Q value of the design objective. According to the (4) (where is the acoustic attenuation coefficient, ω is the angular resonance frequency, and is the wave velocity)

$$freq * Q = \frac{\omega}{2\alpha_{(\omega)} V_{\alpha}} \tag{4}$$

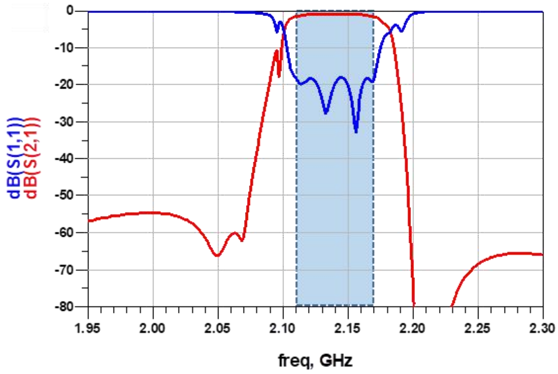
The value of Q is related to frequency, and under certain conditions, the right side of the equation can be regarded as a constant [16], where Q is inversely proportional to freq. Secondly, by adjusting the film thickness of the resonator, the center frequency of the resonator can meet the design requirements. According to the design index, the center frequency of TX filter is 1950mhz, and that of Rx filter is 2140MHz.

3.2. Design of Filter

According to the previous paper, the filter is composed of series resonators and parallel resonators. The difference between the series resonant frequency and the parallel resonant frequency is called the bandwidth of the resonator. The bandwidth of TX filter and Rx filter is 60M.The front-end circuit needs to deal with multiple bands, and the RF filter must also provide high frequency selectivity to minimize the interference of each band. The out of band suppression can be improved by adjusting the cascade order of the filter; The insertion loss of the filter can be improved by using series parallel inductors in the proper position of the circuit. Finally, the fourth-order RX filter and the fifth order TX filter are designed, and their topological structure is shown in the Figure 8. According to the simulation results of the filter, in the current circuit structure, the TX filter with insertion loss less than 1.7db and return loss greater than 16dB, the RX filter with insertion loss less than 1.6db and return loss greater than 18db are obtained.



(a)



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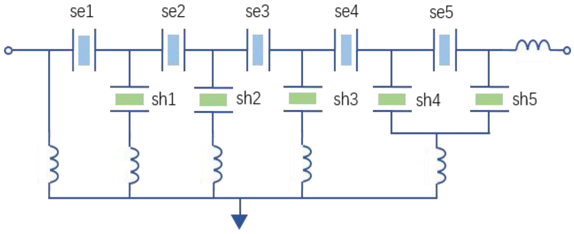

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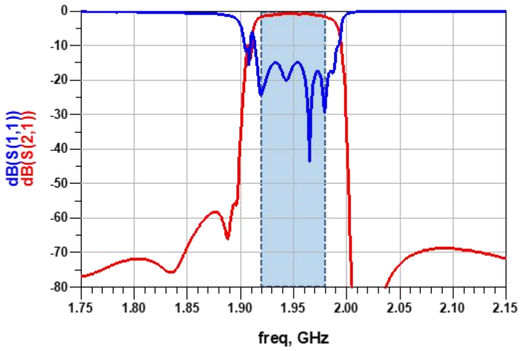
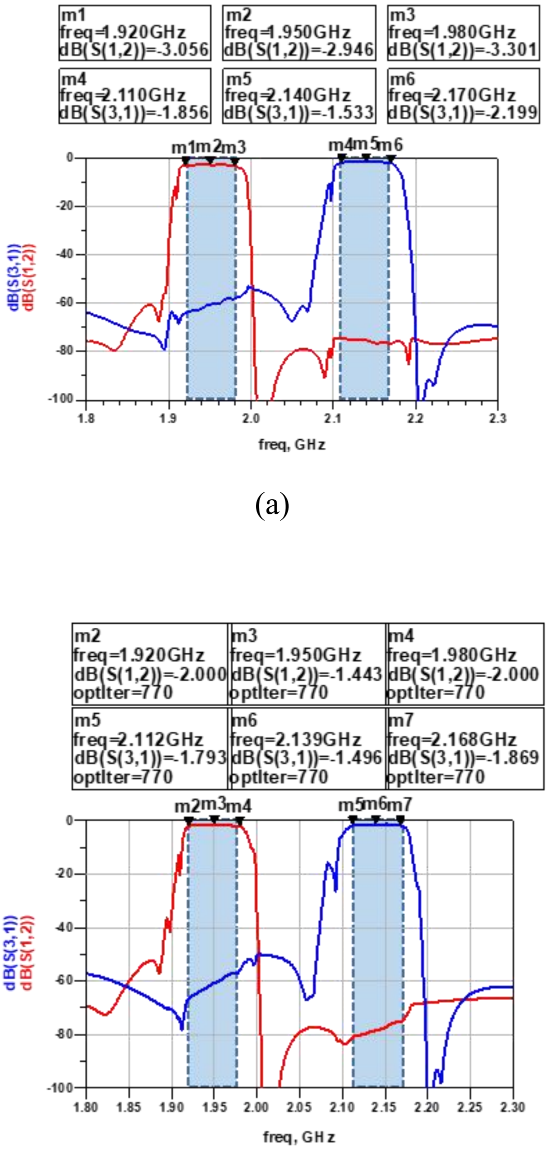


(d)

Figure 8: Connection topology and simulation results of duplexer.
(a)Topology of Rx filter (b) Simulation results of Rx filter
(c) Topology of Tx filter (d) Simulation results of Tx filter.

3.3. Design of Duplexer

According to the connection principle of the diplexer shown in the Figure 9, after combining the TX filter and the RX filter, the simulation result diagram of the diplexer as shown in the Figure is obtained. When the TX filter and the RX filter are connected in parallel at the antenna end, the RX filter will form a load effect on the TX filter [17], which will degrade the insertion loss and ripple in the passband of the TX filter. According to the data in Fig.9 (a), the band insertion loss of Tx filter and Rx filter in this duplexer is-3.3db and-2.199db respectively. Increasing the size of series resonant cavity can improve insertion loss, and decreasing the size of parallel resonant cavity can improve attenuation. In order to realize the FBAR band-pass filter with low IL and high attenuation characteristics, it is necessary to optimize the series parallel resonators of various sizes. The simulation results of the optimized duplexer are shown in the Figure. Compared with before optimization, the performance of the diplexer is greatly improved.



(a)

(b)

Figure 9: Before and after the optimization of the duplexer simulation and comparison.

4. Conclusions

In this paper, a duplexer for B1 band is designed by using FBAR technology and based on Mason model. The influence of series and parallel inductors on RF circuit is analyzed, and the inductance value in the circuit is optimized according to Π-t principle. In order to solve the load effect of TX on Rx, the diplexer circuit is optimized twice, and the technical specifications of the diplexer in this frequency band are obtained. The final design result is that the insertion loss of TX filter is less than 2dB, the suppression of Rx band is more than 65dB, the insertion loss of Rx filter is less than 1.9db, and the suppression of TX band is more than 55dB. Through the summary of the circuit design of B1 duplexer, it provides a feasible design process for the design of other frequency band FBAR equipment, verifies the superiority of FBAR technology in the field of high frequency communication, and provides the basis for the subsequent design.

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