Analysis of the influence of inductance and capacitance on film bulk acoustic wave filter

C R Peng¹², G Liu¹, H Zhong¹² and Y Shi¹²
¹ Science and Technology on Electronic Information Control Laboratory, Chengdu, 610036, China
² School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, China
E-mail: huizhong@uestc.edu.cn

Abstract. Film bulk acoustic wave (BAW) filter is a kind of new type filter based on MEMS technology. And it has the advantages of high working frequency, simple manufacturing process, small size, integrating and has become a research hotspot in recent years. Compared with surface acoustic wave filter and ceramic dielectric filter, it has higher operating frequency and Q value. In this paper, the working principle of film bulk acoustic wave filter is briefly analysed, and ADS simulation software is used to further explore the influence of inductance and capacitance on its S parameter.

1. Introduction
Film bulk acoustic wave filter is composed of multiple film bulk acoustic wave resonators (FBAR) by cascading, which realized the miniaturization by micro-electro-mechanical system (MEMS) technology. And it has a large market share in the mobile phone communication industry at the present [1]-[5]. With the advent of 5G era, the market demand of surface acoustic wave (SAW), bulk acoustic wave (BAW) and other RF filters is also increasing significantly. The majority of BAW filter market share is occupied by Avago and Qorvo [6]-[10]. At present, the CETC 55th and 26th Institute 26 and Wuxi Haoda in domestic have broken through the bottleneck of BAW filter technology in mobile phone applications. In order to realize the application of BAW filter in 5G communication sub6G band, the research on high frequency BAW filter has been intensified. In 2018, Akoustis and Qorvo developed BAW filter products with operating frequency up to 5.25 GHz respectively.

There are mainly two kinds of acoustic filters used by mobile communication terminals, surface acoustic wave filters and film bulk acoustic wave filters [11]-[12]. The SAW filter works by using the principle of acoustic wave propagating on the surface of piezoelectric crystal, and realizes frequency selection by using the interdigital transducer. Its working frequency is determined by the speed of sound and the period of the interdigital transducer [13]-[15]. The BAW filter works on the principle of acoustic wave propagating inside piezoelectric crystal. The working frequency of BAW filter is mainly determined by the sound velocity of bulk acoustic wave and the material thickness [16]-[18].

Many technical problems in traditional ceramic dielectric and SAW filters limit their further development. SAW filter has been widely applied in the current filter market, but its technical difficulty is how to further reduce the width of interdigital electrode to improve its working frequency.
The SAW filters with a low frequency, are generally only suitable for applications below 1.5 GHz, and are easily affected by temperature changes. The BAW filter with small size, higher working frequency and higher power capacity is currently the only one that can be compatible with CMOS process and has broad market prospects. At present, the monopoly pattern of several international manufacturers has been formed. The main suppliers of SAW filter are Several Japanese manufacturers such as Murata, TDK and Solar Induced, while BAW filter is Avago and Qorvo, which occupy more than 95% share in the world. In the next few years, Yole and Skyworks both predict that the filter market will grow rapidly as the 5G era which begins to demand more and more spectrum. According to the report, BAW filters grew the most rapidly. By 2022, the global filter market size will exceed $15 billion.

2. The operating principle of film bulk acoustic wave filter

The film acoustic wave filter is a kind of RF filters which be composed by multiple single film acoustic wave resonators with a specific resonant frequency according to a certain circuit structure. Therefore, the BAW resonator is the basic unit of the filter. The structure of cavity thin-film bulk acoustic resonator (FBAR) is shown in Figure 1. The film bulk acoustic resonator (FBAR) is a kind of device with a sandwich structure at the top electrode of a piezoelectric layer formed at the bottom electrode on the substrate material [23]-[25]. Its principle can be briefly described as follows: using the piezoelectric property of piezoelectric materials, the electrical energy input at both ends of the electrode is converted into mechanical energy (sound energy). When the sound wave resonates in the upper and lower interface, the impedance shows the minimum value. According to the transmission line theory, total reflection of sound waves occurs at the boundary of high and low acoustic impedance layers, and standing wave oscillation is generated in the piezoelectric layer, which can greatly reduce the loss of sound waves. Then, the reverse piezoelectric effect transforms the mechanical energy into electrical energy, and the resonator only allows waves of specific frequencies to pass through. Each thin film body resonator has a series resonance point and a parallel resonance point.

![Figure 1. Structural schematic diagram of cavity bulk acoustic resonator](image)

There are two common filter structures: ladder type and grid type. The circuit structures of ladder type and grid type of BAW filter are shown in Figure 2 and Figure 3 respectively.

![Figure 2. Circuit of structure of ladder type.](image)

![Figure 3. Circuit of structure of grid type.](image)

The ladder type shown in Figure 2 is composed of series and parallel resonators. The white and black parts are represented series and parallel resonators respectively. The condition for forming a
bandpass filter is to ensure that the serial resonance frequency of the serial resonator is equal to that of the parallel resonance frequency of the parallel resonator, and the bandwidth of the bandpass filter is the difference between the both. However, the bandwidth of filter satisfying such condition often fails to reach to the required index. In actual design, the two frequencies often artificially separated to meet the requirements of bandwidth, but it will cause large insertion loss.

Figure 4. Operating principle of ladder type.

The parallel resonance frequency of the parallel resonator in the Figure 4 is approximately identical to the serial resonance frequency of the serial resonator. When the operating frequency of the ladder type is at point a, it is at the minimum impedance point of the parallel resonator. The input signal is imported into the ground by the parallel resonator, and the output port has no signal output. When the operating frequency is at point c, it is at the maximum impedance point of the serial resonator, the input signal cannot pass through the serial resonator, and the output signal is also zero. When the operating frequency is at point b, it is at the minimum impedance point of the serial resonator, the input signal can be passed through the serial resonator nondestructively.

Ladder type has the advantages of fast rolling and falling down and good rectangular coefficient, which is often used in engineering design. The working principle of grid type is similar to that of ladder type. In the design, adding inductance or capacitance in the circuit structure of BAW filter will increase the bandwidth. Therefore, it is vital to study its mechanism for future design.

3. ADS software simulation verification

The influence of series inductance and parallel capacitance on the performance of the bandpass filter is investigated by using ADS simulation software. Firstly, the Mason model of FBAR is established in ADS simulation software. However, Mason model is not convenient to directly analyse the influence of inductance and capacitance on resonant frequency, MBVD model with loss consideration is also established to analyse the simulation results more intuitively [26]-[28].

The circuit structure is shown in the Figure 5 in where \( R_m \) is the mechanical losses, \( L_m \) is the dynamic inductance, \( C_m \) is the dynamic capacity, \( C_0 \) is the static capacity and \( R_S \) is electrode and wire losses. And then the serial resonator and the parallel resonator are connected according to the circuit structure of ladder type, as shown in Figure 6 The S parameter curve of the first-order filter of ladder type is shown in Figure 7.

Figure 5 Basic circuit structure of MBVD model

The transmission characteristics of the bandpass filter are shown in Figure 8 through external serial inductance on the parallel resonator branch of the first-order filter with change of inductance value between 0nH and 4nH. With the increase value of inductance in series on the parallel resonator,
the left transmission zero of the bandpass filter moves to the left continuously and right transmission zero keeps constant. Therefore, the total bandwidth is increased.

**Figure. 6** Circuit structure of the first-order filter.  
**Figure. 7** S21 parameter of the first-order filter.

**Figure. 8** Transmission characteristic curve with serial inductance.

The MBVD model can be equivalent to the parallel FBAR, and its equivalent circuit is shown in Figure 9. Its impedance equation can be written as follows:

\[ Z_{total}(\omega) = j\omega L_m - \frac{j}{\omega C_0 + \omega^2 C_m} \]

(1)

where, \( R_m \) is so small that can be ignored, \( L_s \) is the external inductance and \( \omega \) is the operating frequency. And \( \omega_s = 1/\sqrt{L_m C_m} \), where \( L_m \) is the dynamic inductance.

**Figure. 9** MBVD equivalent circuit of parallel FBAR.

When the parallel resonator is operated at serial resonance frequency, \( Z_{total} \) is equal to zero. The value of the external inductance can be expressed as:
It is not difficult to find that when the value of the serial inductance increases, the serial resonance frequency of the parallel resonator will decrease, leading to the left transmission zero move to the left and the bandwidth increase.

Similarly, the external parallel capacitance on the serial resonator branch of the first-order filter changes of capacitance value between 0pF and 4pF. And the transmission characteristics of the bandpass filter are shown in Figure 10. With the increase value of capacitance in parallel on the serial resonator, the right transmission zero of the bandpass filter moves to the left continuously and left transmission zero keeps constant. Therefore, the total bandwidth is decreased.

\[
L_s = \frac{1}{\omega^2 C_0 + \frac{\omega^2 C_m}{1 - \left(\frac{\omega}{\omega_b}\right)^2}}
\]  

(2)

\[
Z = \frac{1}{j\omega(C_0 + C_m)} \frac{1 - \omega^2 L_m C_m}{1 - \omega^2 L_m \frac{C_mC_0}{C_m + C_0}}
\]  

(3)

As \(Z\) tends to infinity, the parallel resonant frequency can be expressed as:
\[ f_p = \frac{1}{2\pi \sqrt{L_m \frac{C_m C_0}{C_m + C_0}}} = \frac{1}{2\pi \sqrt{L_m \frac{C_m}{C_m + 1}}} \] (4)

According to the above equation, when the external capacitance is connected in parallel at both ends of the series resonator, the parallel resonance frequency will decrease, leading to the left shift of the right transmission zero and the decrease of the bandwidth. The influence of inductance and capacitance on the passband characteristics of the filter is clarified by the combination of simulation calculation and theoretical calculation.

4. Conclusion
In the design of BAW filters, the insertion loss and the bandwidth in the passband are often mutually dependent. In order to widen the working bandwidth, the series resonant point of the series resonator and the parallel resonant point of the parallel resonator can not be equal, but this often leads to too large insertion loss in the passband and energy transmission will be lost largely in the passband. In this paper, under the condition that the insertion loss in the passband is basically constant, we can change the bandwidth through the external inductance or capacitance to realize the broadband design of the filter.

Acknowledgments
This research was jointly supported by Science and Technology on Electronic Information Control Laboratory under Grant No. JS20190600088 and Key Research and Development Project of Science and Technology Bureau, Sichuan Province which are Grant No. 2020YFG0042 and No. 2020YFG0041.

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