A Systematic Design Method for Band-Pass Filters Composed of Film Bulk Acoustic Resonators

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Abstract — We propose a systematic method to design band-pass filters composed of film bulk acoustic resonators (FBARs), for wireless communication. FBARs have demonstrated excellent performance due to their compact size, low loss, power endurance and IC compatibility. Modifying the traditional Butterworth theory, the ladder-type band-pass filters can be composed of FBARs to satisfy various filter specifications including impedance, center frequency and bandwidth. The filter design parameters are considered using the thickness and area of the composed FBARs, which are used to replace the conventional series and parallel LC resonators. This design philosophy can also be applied to other kinds of band-pass filters. An FBAR's filter is designed and manufactured to demonstrate our approach.

INTRODUCTION

The tremendous growth of wireless communication systems has fueled the demand for cellular phones. Recently, there has been a great demand for RF band pass filters of smaller size, lighter weight, and higher performance for advanced mobile communications. The RF filters and oscillators often turn out to be bottlenecks in the integrated CMOS/RF IC circuitry. The FBARs have become one of the most promising components due to the potential to integrate with Monolithic Microwave Integrated Circuits (MMICs). The FBAR device has a series resonance frequency f_s and a parallel resonance frequency f_p. The difference between the series and parallel resonance frequency is called as the bandwidth of FBAR resonators, and utilized to determine the effective mechanical coupling coefficient, K^2 effective. It is an important factor to determine the bandwidth of the FBAR filter. Several laboratory studies have been conducted on the FBAR bandpass filter design technique. The two port network theory is used to design the FBAR filters, which has the identical building blocks.[1] However, the adjustment building blocks may improve the filter performance. In another study, they proposed a genetic algorithm (GA) method that produces the optimal dimension of each FBAR for the desired filter response.[2] Although the genetic algorithm method can produce better response, the FBAR filter device need various piezoelectric thickness that increase process complexity. In this paper, we will illustrate how to design a bandpass filter constructed by FBARs with different building blocks and two piezoelectric thickness. The use of conventional band pass filters has a long history, and their theory has been well developed. We might modify the existing theory to suit new devices.

The conventional design of a ladder type BPF is schematically shown in Fig. 1 comprising some series and parallel resonators[3].

Typically, a resonator has inductance and capacitance and the product of inductance and capacitance can be determined by the center frequency of a filter. The remainder inductance (or capacitance) value can determine the impedance, bandwidth and the shape of the resonator. We illustrate the maximally flat (Butterworth) frequency response. For example, the definition of inductance and capacitance is

\[ R_0 = \frac{Z_0}{g_0}, \quad R_s = \begin{cases} \frac{Z_0}{g_{n+1}}, & n = \text{odd} \\ \frac{Z_0 g_{n+1}}{g_n}, & n = \text{even} \end{cases} \]

\[ L_i = \frac{Z_0}{\Delta \omega} g_i, \quad C_i = \frac{1}{\omega^2_0 L_i} \quad n = \text{odd} \]

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Where

\[ g_0 = 1, \quad g_{n+1} = 1 \]

\[ g_i = 2 \sin \left( \frac{2i \pi}{2n} \right), \quad i = 1 \cdots n \]
FBAR impedance can be modeled as Eq (2) : [4] 

\[ \frac{V_z}{I_z} = Z(\omega) = \frac{1 - \frac{\omega^2}{\omega_s^2}}{j\omega C_T} \frac{1 - \frac{\omega^2}{\omega_p^2}}{\omega^2} \]  

(2) 

where \( C_T \) is the equivalent capacitor, \( \omega_s \) is the angular series resonant frequency and \( \omega_p \) is the angular parallel resonant frequency, can be calculated for thin film piezoelectric materials and geometry parameters due to real device.

The BPF is mainly composed of series and parallel resonators in microwave circuit design, as we have discussed above. The frame structure and characteristic of a series resonator is showed in Fig. 2 If we want to apply a series resonator, the resonator needs the following characteristics in Eq. (3)

\[ \begin{align*} 
Z(\omega_0) &= Z_S(\omega_0) = 0 \\
\frac{d}{d\omega} Z(\omega_0) &= \frac{d}{d\omega} Z_S(\omega_0) = j2L = \frac{j2}{\omega_0^2} C 
\end{align*} \]  

(3) 

That is to say, we use the impedance of center frequency and his slope to define the resonator. With the substitution of Eq (1) into Eq (5) we can derive the geometry parameters in Eq (6)

\[ \begin{align*} 
\omega_p &= \omega_0 \\
C_T &= \frac{\omega_0^2}{\omega_p^2} - 1 \end{align*} \]  

(6) 

The above equation can be used to design the area and thickness of FBAR to replace the parallel resonator.

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\[ \begin{align*} 
Y(\omega_0) &= Y_p(\omega_0) = 0 \\
\frac{d}{d\omega} Y(\omega_0) &= \frac{d}{d\omega} Y_p(\omega_0) = j2C = \frac{j2}{\omega_0^2} L 
\end{align*} \]  

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This can be used to apply FBAR to series and parallel resonators of conventional BPF. But, the zero frequency of series resonators and the pole frequency of parallel resonators must overlap in BPF applications. In reality, we can tune the thickness of the piezoelectric layers and electrodes to meet this goal.

EXPERIMENT AND RESULT

In order to validate the proposed approach. Filter were fabricated on 4” Si wafer. An AlN FBAR is located on SiNx membrane above silicon wafer. Transmission line is used as feeds. Al is chosen as electrode material. The piezoelectric layer consisted of C-axis oriented AlN, which was deposed by pulsed reactor DC magnetron sputtering. Fig. 3 show the structure, and its dimension.
Fig. 3 (a) Top view of FBARs configured within transmission lines, the area $A_1 = A_2 = 2209 \mu m^2$, $A_3 = 5929 \mu m^2$ (b) Cross section B-B' of FBARs

The bottom electrode thickness is 0.13um, the top electrode thickness is 0.12um, the SiNx thickness is 0.15um and the nominal thickness of the whole AlN is 0.57um. Air terminal confine the acoustic wave between both side. The silicon substrate has resistivity $10^{-6}$-cm and the thickness 525um. The FBAR filters are characterized with HP8510C network analyzer. Samples are wafer probed using Cascade Microtech’s standard Air Coplanar G-S-G 150 pitch probe tips. Fig. 4 show the simulation and measured parameters for the FBAR

The measured parameters is compared with the simulation result in which an artificial damping is include. In all cases, the agreement is good. Cascading long CPW transmission line will cause inductance effect, so the actual bandwidth is wider than simulation result.

CONCLUSIONS

We propose a systematic method of FBAR band pass filter design using conventional series and parallel resonators. Band pass filter impedance, frequency, bandwidth, etc. can be specified according to the design of the device area and thickness. This method can also be used with other filter design theories using film bulk acoustic resonators.

REFERENCES