Design and Simulation of Band 40 RF SAW Ladder-Type Filter

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Abstract—A novel bandpass ladder-type surface acoustic wave (SAW) filter design is presented in this paper. The filter allows frequencies in the range of 2300 MHz to 2400 MHz to pass through it and attenuates the out-of-band frequencies. The ladder-type filter is designed with the help of series and shunt resonators resonating at different frequencies. By optimizing the resonating frequency of the resonators, we achieve a better passband with a center frequency of 2350MHz. Due to the presence of multiple filter stages, we achieve better out-of-band rejection and better selectivity. As the SAW bandpass filter possesses sharp cut-off, high stability, high reliability, compact size, better out-of-band rejection, good power handling capacity, and wide bandwidth compared to other filter structures SAW filters are widely used in mobile phones to filter both RF and IF frequencies.

Keywords—Surface Acoustic Wave (SAW), RF filters, Butterworth-van-dyke (BVD) model, multi-stage filter design, piezoelectric, ladder-type filter, Band 40

I. INTRODUCTION

With the emergence of the fifth generation of mobile communication, IoT, Big Data, Cloud Computing, and Artificial Intelligence are all being integrated, driving the development of a digital society. RF Filters using Surface Acoustic Wave (SAW) Technology have been used in RF front end of Mobile telecommunication devices. Surface Acoustic Wave devices have become an important aspect of the implementation of Radio Frequency (RF) filters used in modern-day transceivers because of their advantages of compact size, low cost, and better compatibility with integrated circuits. In particular at the industrial, scientific, and medical (ISM) frequency of 2.5 GHz, this frequency range is employed as a carrier frequency for numerous novel wireless communication and sensor applications. It is also used as an intermediary frequency for broadband systems running at higher frequencies. SAW filters are commonly utilised in the 2.3GHz to 2.4GHz frequency range due to their filter applications in mobile communication systems. Section II gives highlight on the SAW fundamentals viz., BVD model, impedance element filter. Section III gives an idea about the methodology followed to design and a ladder-type filter. Section IV and V covers results and its analysis and conclusion respectively.

II. SURFACE ACOUSTIC WAVE FUNDAMENTALS

A. Overview

SAW filters operate based on transduction, i.e., conversion of electrical energy into acoustic energy and vice-versa. There are different types of SAW filters based on their construction viz. Inter-digitated interdigital transducer (IDT), Dual-mode SAW (DMS) filter, and Ladder-type filter structure. Insertion Loss for Ladder-type filter is 1dB to 3dB which is better compared to insertion loss for IDT (3 to 4 dB) and DMS (2 to 3 dB) type filters. The bandwidth of the ladder-type filter is much wider around 4% compared to IDT and DMS type filters. The ladder-type filter provides better insertion loss, wider bandwidth, good attenuation in out-of-band, and good high-power durability. These ladder-type filter properties are desirable when designing a high-frequency SAW filter.

The basic structure of the SAW resonator consists of Reflectors and Interdigital transducers (IDTs), as shown in Fig. 1. The waves keep bouncing between the reflectors on either side of the IDT. For the waves which are in phase, the impedance is low and the amplitude is high. The waves which are out-of-phase the impedance is high. Hence, it is also referred to as impedance changing device [13].

B. BVD equivalent model

To represent a mechanical system into its electrical equivalent system we use Butteworth-van-dyke (BVD) model, refer to Fig. 2. The BVD model consists of two parallel branches, the series resonant branch represents the mechanical system and the other represents the electrical equivalent capacitance of the IDT. \( C_m \) is the motional capacitance that represents the elasticity of the resonator, \( L_m \)
is the motional inductance that represents the mass and $R_m$ indicates the acoustic energy loss. $C_0$ indicates the clamped capacitance between two electrodes of the IDT [13], refer to (1), (2), (3).

$$C_m = \frac{C_0 K_t^2}{i^2}$$

(1)

$$L_m = \frac{1}{\omega^2 C_m}$$

(2)

$$R_m = \frac{\omega L_m}{Q}$$

(3)

C. Piezoelectric material

Each substrate possesses different properties that are suitable for a specific set of applications. The electromechanical coupling coefficient ($K_t^2$) is a measurement of the piezoelectric material's ability to produce acoustic energy. The thermal and electrical properties of the piezoelectric substrate are dominated by the cutting angle of the piezoelectric substrate. The temperature coefficient represents the shift in frequency versus the operating temperature of the SAW component [11]. Frequency response shifting is easy on a substrate with a high thermal conductivity material.

TABLE I. DIFFERENT TYPES OF SAW SUBSTRATES

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Velocity (m/s)</th>
<th>Coupling coefficient ($K_t^2$)</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>42° Lithium Tantalate</td>
<td>4200</td>
<td>0.076</td>
<td>Low loss filters</td>
</tr>
<tr>
<td>112° Lithium Tantalate</td>
<td>3300</td>
<td>0.0075</td>
<td>Mid band filters</td>
</tr>
<tr>
<td>64° Lithium Niobate</td>
<td>4790</td>
<td>0.115</td>
<td>Low loss filters</td>
</tr>
<tr>
<td>Quartz</td>
<td>3150</td>
<td>0.0012</td>
<td>Narrowband filters, short delay lines, resonators</td>
</tr>
</tbody>
</table>

$$K_t^2 = \frac{\pi^2 (f_p - f_s)}{4f_p}$$

(4)

D. Resonator Filter

The resonator filter is also termed an Impedance Element Filter (IEF). The BVD model acts as a simple resonator that has a resonant frequency and anti-resonant frequency components. It acts as a basic building block of an n-stage ladder-type filter. By connecting the resonator in series and parallel branches we can achieve the desired filter shape by varying and optimizing the resonant and anti-resonant frequency components.

The resonator designed in Fig. 3 has a resonant frequency of 2380 MHz and this corresponds to the passband's center and has an extremely low impedance, allowing signals to pass from input to output. The impedance increases dramatically as the frequency approaches the anti-resonant frequency, attenuating the signals traveling from the input to the output. The impedance decreases in magnitude as the frequency is increased beyond the anti-resonant frequency, finally approaching the static capacitance [2].

Shunt resonators, on the other hand, are built so that their anti-resonant frequency is the same as the passband. Because the impedance across these resonators is high within the passband, the signal is guided through the series elements to the filter's output port. However, as the signal frequency decreases, the signal is greatly attenuated before it reaches the output as the shunt component's resonance frequency approaches and is shunted to the ground through the low impedance.

III. METHODOLOGY

We aim to design a SAW ladder-type bandpass filter that will allow signals in the frequency range 2300-2400 MHz to pass through it and reject the out-of-band signal. The filter is designed based on certain objectives such as the simulation methods i.e., electrical equivalent model (BVD model), number of filter stages, the synthesis methods i.e., the topology of the acoustic wave filter (ladder-type), operational frequency range, piezoelectric substrate electromechanical coupling coefficient, Lithium Tantalate substrate features.

The filter design is based on passive elements viz. $R_m$, $L_m$, $C_m$, $C_0$. We tune and optimize the variable parameters such as frequency of shunt elements, Quality factor, tuning elements at the input and output ports, and the $C_0$ to adjust the impedance value. We optimize the electrical equivalent parameters until we achieve the insertion loss and return loss within specified limits. The ratio of incident power to transmitted power is known as insertion loss. Return Loss, on the other hand, is defined as the ratio of incident power to reflected power. The term "return loss" refers to how effectively devices or lines are matched. If the return loss is high, the match is good, and a large return loss is desirable.

A. Synthesis method for filter design

The Ladder-type and Lattice-type topologies are utilized to create an Acoustic Wave filter. The ladder-type structure produces a bandpass region with the combination of multiple
series and shunt resonators. The low impedance of series resonators and the high impedance of shunt resonators combine to provide a good passband. The deep nulls on either side of the passband generate great selectivity, which is an advantage of utilizing this filter. However, the bandwidth of the ladder-type filter will be constrained by the electromechanical coupling coefficient of the piezoelectric material. On the other hand, the Lattice-type produces a passband region by matching the magnitudes of the series and shunt resonators impedances while having different reactance properties. There is a trade-off in selectivity, but this method of synthesis is superior to the ladder method for wide-band filter design [2].

B. Simulation of the ladder-type filter

Here, we have used Butterworth-van-dyke model as the simulation method for designing the acoustic wave filter. The BVD model represents electrical equivalent capacitance and the mechanical system with passive elements in the two branches as shown in Fig. 2. By varying the value of gamma, we can vary the bandwidth of the resonator. Gamma decides the bandwidth depending upon the electromechanical coupling coefficient. Bandwidth is the ratio of the difference between resonant and anti-resonant frequency to the anti-resonant frequency. Bandwidth is inversely proportional to the gamma value and directly proportional to the electromechanical coupling coefficient. Multiple such resonators when connected in the ladder-type synthesis method we obtain a bandpass filter. We get a smooth passband at the center frequency when the series resonator’s resonant frequency (fr) equals the anti-resonant frequency (far) of the shunt resonator. As the order of the filter increases, there is an improvement in the slope of the passband region, and also the out-of-band rejection is improved.

C. Optimization of electrical equivalent parameters

As the number of stages increases, the number of series and shunt elements increases therefore we have more variable parameters to tune and optimize the filter design. We have used tuning elements to minimize the passband ripples and to obtain a passband region with a sharp cut-off, and high stability. The bandwidth of the optimized filter is more than the desired bandwidth to compensate for any shift in frequency after the filter is fabricated.

IV. SIMULATION RESULTS AND ANALYSIS

When a series impedance element filter and a shunt impedance element filter are coupled, the series element’s resonant frequency coincides with the shunt element’s anti-resonant frequency, yielding a bandpass filter with two deep notches on either side. The series element's resonant frequency is the same as the passband’s center frequency, allowing signals to pass from input to output. The anti-resonant frequency is the same as the passband for the shunt element [2]. Similarly, we may build a decent bandpass filter with a steeper slope of the passband and minimal passband ripples by connecting numerous such stages of series and shunt elements in a ladder-type arrangement. The out-of-band rejection and the impedance ratio of the filter improves as the order of the filter grows.

The passband becomes steeper and has more selectivity when more series and shunt elements are added. The passband of the filter consists of ripples that are not desirable. This is because the filters are designed without using the matching inductors at input and output ports. If we add matching inductors and tuning inductors, we can vary the impedance levels of the filter and tune the values to get desired passband response.

The acoustic wave bandpass filter has a 3dB bandwidth of 128MHz. The insertion loss (S21) specification is set to -1.8dB as shown in Fig. 7, and we can observe that the simulation results of the insertion loss are meeting the specified goals. Similarly, the return loss desired is -10dB and as per the simulation result, we meet the required specification, refer to Fig. 8. Ideally, the magnitude of return loss should be as high as possible and the magnitude of insertion loss should be as low as possible. The rejection below the passband is around -35dB and the out-of-band rejection above the passband goes up to -60dB. The impedance ratio is achieved as high as 120dB, refer to Fig. 6.
Lithium Tantalate substrate which possesses piezoelectric properties. Due to this type of design structure, the EM waves can travel through circuits that are sensitive to EM waves. The EM waves are converted into acoustic waves that travel at approximately 4000 m/s compared to EM waves that travel at 3 x 10^8 m/s. A surface acoustic wave bandpass filter provides sharp cut-off, linear characteristics, high stability, and is highly reliable. The fabricated filter or final product can be used in mobile handsets in RF communication due to its compact size, better out-of-hand rejection, good power handling capacity, and wide bandwidth compared to other filter structures. Due to their advantages over piezoelectric ceramic filters and monolithic crystal filters in terms of operating frequency band, form factor, and cost performance, SAW filters predominate in applications for mobile communication systems.

REFERENCES


