Optimum Design of MEMS-SAW Filter for Wireless System Applications

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Abstract: SAW devices have become increasingly important in implementing sensors, chemical and biological warfare agent detectors, resonators and wireless applications as a filter. These types of device can be implemented with micro-electro-mechanical systems (MEMS) to be compatible with CMOS technology. In this work we design RF SAW filter at different frequencies for wireless communication system applications. We focus on optimum design of Input/output IDTs number of electrodes, so the total frequency response of the SAW filter with required bandwidth can be achieved. The designed parameters of the piezoelectric substrate have been obtained from the experimental work for a fabricated multilayer substrate of $ZnO/SiO_2/Si$ using MEMS technology. Implementation of the optimized SAW filter in a wireless system is described. Simulation results are presented for different design of SAW filter for verification.

Key-words: SAW device, Bandpass Filters, Wireless System, Design Optimization, MEMS Technology

1 Introduction

Today's second-generation wireless communications market is very dynamic with high growth rates. Soon, third-generation systems will start operation. Moreover, wireless local-area network (LAN) systems, such as Bluetooth systems, is emerging. The key components in the microwave portion [both in the radio-frequency (RF) and intermediate-frequency (IF) sections] of the mobile terminals of these systems incorporate a part from active RF integrated circuits (RFICs) and RF modules a multitude of passive components.

The most unique passive components used in the microwave section are surface acoustic wave (SAW) filters. The component count for modern terminals is decreasing due to the progress of integration in the active part of the systems. On the other hand, the number of SAW RF filters is increasing for multiband terminals. As a consequence, passive components outnumber RFICs by far in today's systems. The market is demanding smaller and smaller terminals, thus, the size of all components has to be reduced. The size of typical SAW RF filters and SAW IF filters shrank significantly over the last years. Further reduction in component count and, therefore, size has been obtained by adding additional functionality to SAW devices. The integration of passive components and SAW devices using low-temperature ceramic technologies reduces the required printed circuit board (PCB) area further. Today, SAW modules, such as for multiband terminals, are available. Such modules include SAW RF filters for the different frequency bands [1].

Surface acoustic wave (SAW) filters have better frequency performances than other dielectric and quartz filters, including bigger free degree, better edge characteristics, and excellent phase characteristics [2]. Most importantly, SAW filters can be fabricated with a smaller size. Since SAW devices have the properties of less mass and lower loss, they are important in the high technology industry. SAW devices have become increasingly important in implementing filters, resonators and sensors. SAW devices are most typically used from 10 MHz to about 3 GHz [3].

2 Model of the SAW filter

IDTs can be represented by a parallel circuit, consisting of radiation conductance $G_a(f)$, an acoustic susceptance $B_a(f)$, and a transducer total capacitance C_t. These parameters can be obtained from the following equations as described in [4-5].

$$G_a(f)=G_a(f_o)\left[\frac{\sin x}{x}\right]^2 \tag{1}$$

$$B_a(f)=G_a(f_o)\left[\frac{\sin(2x)-2x}{2x^2}\right] \tag{2}$$

$$C_t=C_oWN_{eff} \tag{3}$$

Where:

$$x=(f-f_o)\frac{\pi N_{eff}}{f_o} \tag{4}$$

$$G_a(f_o)=8k^2f_oC_tN_{eff} \tag{5}$$

k^2 = coupling coefficient of the piezoelectric material.

f_o = center (resonance) frequency.

W = overlap between the electrodes.

N_{eff} = active number of electrode pairs.

C_o = capacitance per electrode pair per unit length (pF/m), which can be calculated from the following equation:

$$C_o=2\left(6.5\eta^2+1.08\eta+2.37\right)\left(\varepsilon_r+1\right) \tag{6}$$

$$\eta=\text{metallization ration}=\frac{\text{2*finger width}}{\text{transducer wavelength}}.$$

ε_r = relative permittivity of the piezoelectric substrate.

The radiation conductance and the acoustical susceptance can be modeled as R, L and C equivalent circuit.

Using the SAW equivalent circuit model input impedance, the series resonance model and the narrow band approximations, we can solve for the series resonance model parameters and get the SAW narrowband equivalent circuit parameters as follows:

$$R=\frac{1}{G_a(f_o)} \tag{7}$$

$$L=\frac{N_{eff}}{4f_oG_a(f_o)} \tag{8}$$

$$C=\frac{G_a(f_o)}{\left(\pi^2f_o\right)N_{eff}} \tag{9}$$

Using this model, the overall equivalent circuit (input and output IDTs) for the SAW delay line can be sketched as shown in figure 1.

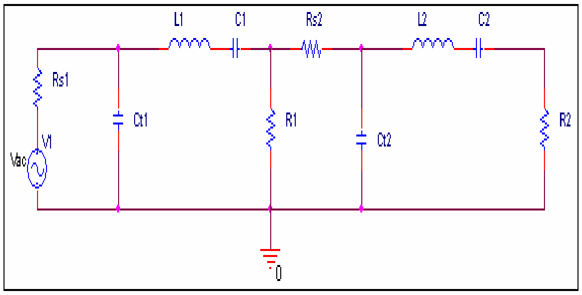

Fig. 1 SAW delay line equivalent model

3. Optimum Design of IDT Geometry

To design the IDT, the resonance frequency f_o of the filter is the first parameter considered, so that we can find the transducer wavelength λ (filter pitch) from the equation:

$$\lambda=\frac{V}{f_o} \tag{10}$$

From the previous equations, it is clear that the geometry of the single IDT depends only on the resonance frequency f_o and the velocity of the wave in the substrate.

The impulse response of the basic IDT is a rectangle. The Fourier transform of a rectangle is a sin function. For SAW filters, the bandwidth is an important factor to select only the required signal. The bandwidth of the sin function in the frequency domain is proportional to the length of the rectangular window in the space domain. As a result, narrow bandwidth requires the IDT to have a large number of fingers [7-8].

$$H(f) = H_1(f)H_2(f)e^{j\beta x(f)} \qquad (11)$$

Where H_1 and H_2 are the transfer functions for the input and output IDTs, $x(f)$ is the frequency dependant separation between those segments of IDTs that are excited at signal frequency f. For normal IDTs with uniform finger separation, $x(f)$ reduces to $x(f) = d_c$, where d_c is the distance between their effective phase centers, $\beta = 2\pi / \lambda$ is the wave propagation constant on the substrate [3].

Near the resonant frequency f_o the transfer function of an IDT may be written as:

$$H_1(f) = \sin\left[\frac{(f-f_o)\pi N_{eff}}{f_o}\right]\left[\frac{(f-f_o)\pi N_{eff}}{f_o}\right]^{-1} \qquad (12)$$

From equation (12), it is clear that a reduction in bandwidth will occur due to the multiplication of the two IDTs frequency responses (considered as two filters in cascade). Now, it is clear that choosing the optimum number of fingers for both input and output IDTs is a critical factor for the required filter bandwidth. This can be achieved easily by substituting the resonance frequency f_o and the number of fingers N_{eff} in equation (12) for both IDTs (taking into account to decrease the number of fingers in the output IDT), and multiply the frequency response for both, till we reach the required bandwidth.

4 SAW Filter Implementation

For investigation and verification, we implement the optimum SAW filter in two wireless system applications.

1- The transceiver circuit of mobile phone, the resonance frequency f_o is 902 MHz with a bandwidth of 25 MHz. If both IDTs are identical and have N_{eff} =30, a reduction in the bandwidth of SAW will occur as shown in figure 2 due to multiplication. Figure 3 shows the response of input IDT at N_{eff} =30, and response of the output IDT at N_{eff} = 6. Wide bandwidth is achieved in the output IDT (around 130 MHz). Figure 4 shows the total response of the filter after the modification, it's clear that there is no change in the bandwidth and the required total bandwidth is achieved.

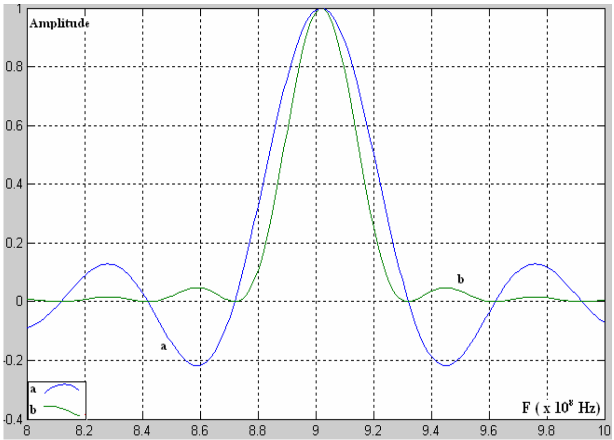

Fig 2 **:** a) Frequency response of the input IDT at N_{eff} =30 and f_o = 902 MHz

b) Frequency response of SAW at N_{eff} =30 and f_o = 902 MHz for both IDTs

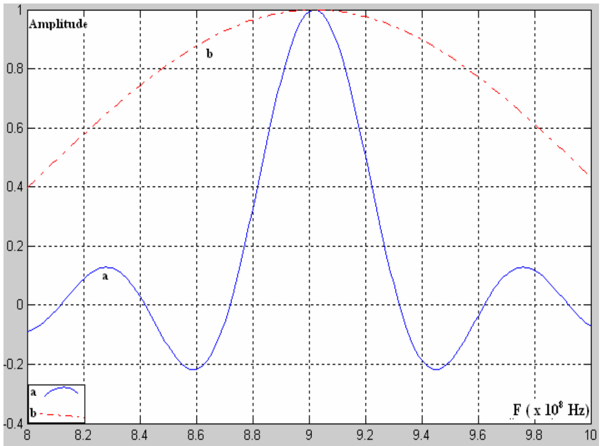

Fig 3**:** a) Frequency response of the input IDT at N_{eff} =30 and f_o = 902 MHz

b) Frequency response of the output IDT at N_{eff} = 6 and f_o = 902 MHz

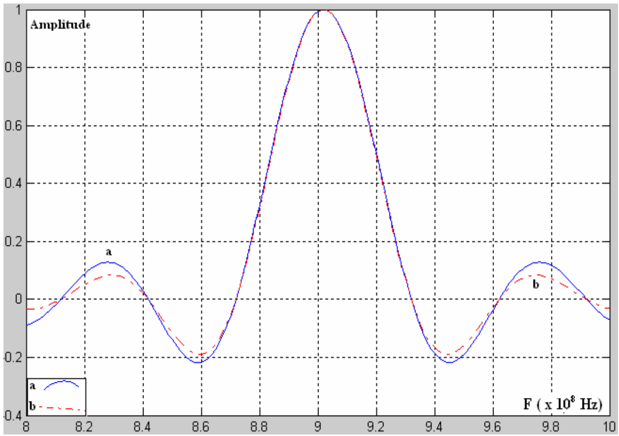

Fig 4**:** a) Frequency response of a single IDT at N_{eff} =30 and f_o = 902 MHz

b) Frequency response of SAW with input IDT of N_{eff} =30 and output IDT of N_{eff} =6, f_o = 902 MHz

2- Optimum SAW Filter in the Bluetooth Applications. For Bluetooth applications, the resonance frequency f_o is 2.44 GHz with a bandwidth of 80 MHz. Choosing N_{eff} =27, the frequency response for a single IDT will be as shown in figure 5.

If both IDTs are identical, a reduction in the bandwidth of SAW will occur as shown in figure 6 due to multiplication.

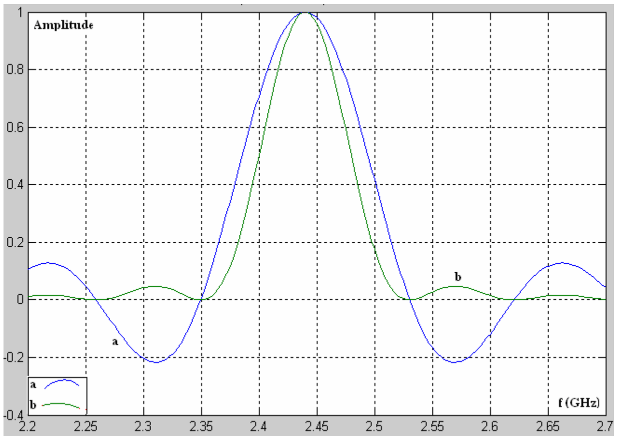

Fig 5**:** a) Frequency response of the input IDT at N_{eff} =27 and f_o = 2.44 GHz

b) Frequency response of SAW at N_{eff} =27 and f_o = 2.44 GHz for both IDTs

Figure 6 shows the response of input IDT at N_{eff} =27, and response of the output IDT at N_{eff} =2. Wide bandwidth is achieved in the output IDT (around 200 MHz).

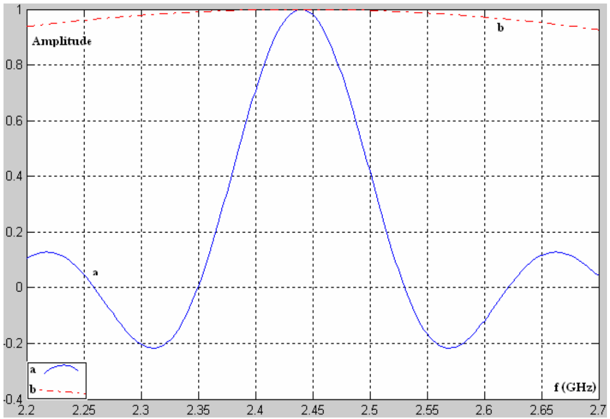

Fig 6**:** a) Frequency response of the input IDT at N_{eff} =27 and f_o = 2.44 GHz

b) Frequency response of the output IDT at N_{eff} =2 and f_o = 2.44 GHz

Figure 7 shows the total response of the filter after the modification, it's clear that there is no change in the bandwidth and the required total bandwidth is achieved.

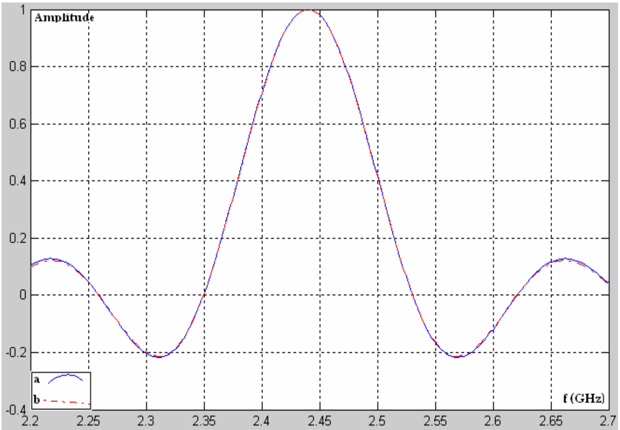

Fig 7**:** a) Frequency response of a single IDT at N_{eff} =27 and f_o = 2.44 GHz

b) Frequency response of SAW with input IDT of N_{eff} =27 and output IDT of N_{eff} =2, f_o = 2.44 GHz

5 Simulation Results

Our investigation is basically focused on the optimal design of the filter dimensions, frequency response, and bandwidth. We choose the multilayer substrate of ZnO/SiO_2/Si and $LiNbO_3$ as substrates for the SAW filter to be tested in case of mobile transceiver circuit. For case 2 of Bluetooth circuit implementation, the SAW filter have two types of substrates ZnO/Diamond/Si and $LiNbO_3$/Diamond.

The simulation results show the frequency response of the SAW filters for the previous cases. Figure 8 and 9 show the frequency response of the SAW filters with two different substrate designed with N= 30 for the input IDT and N= 6 for the output one to satisfy the required bandwidth of 25 MHz and central frequency of 902 MHz for mobile circuit.

While figures 10, and 11 show the frequency response of the SAW filter with two different substrate designed with N= 27 for the input IDT and N= 2 for the output one to satisfy the required bandwidth of 200 MHz and central frequency of 2.44 GHz for Bluetooth Circuit. Figure 12 shows the Layout of SAW device generated by MEMS Pro CAD tool.

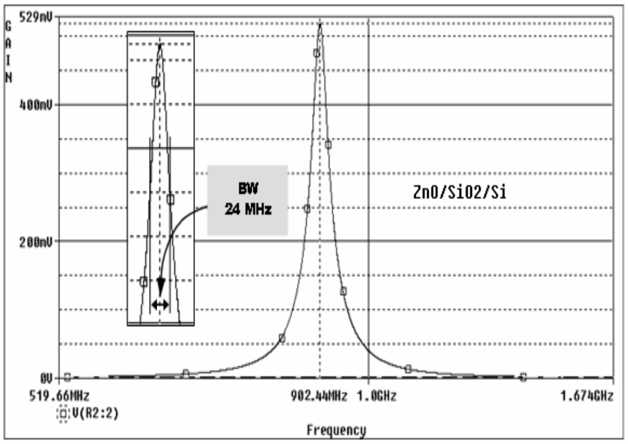

Fig. 8: Frequency response of SAW filter on ZnO/SiO_2/Si substrate

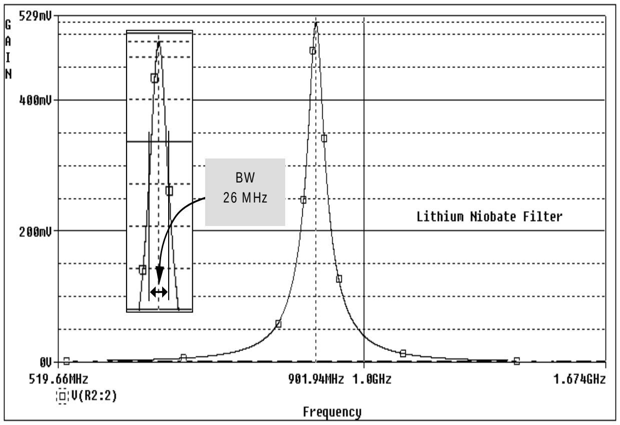

Fig 9**:** Frequency response of SAW filter on Lithium Niobate substrate

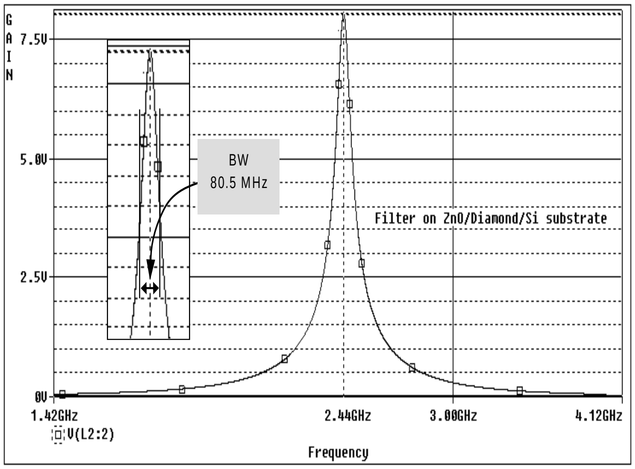

Fig 10**:** Frequency response of SAW on ZnO/Diamond/Si substrate

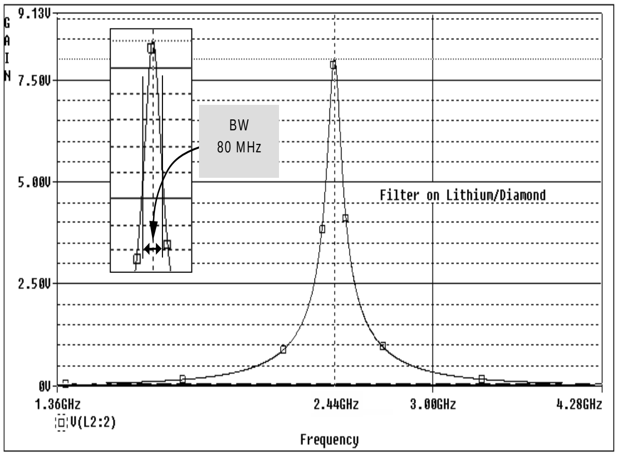

Fig 11**:** Frequency response of SAW $LiNbO_3$/Diamond Tantalate substrate

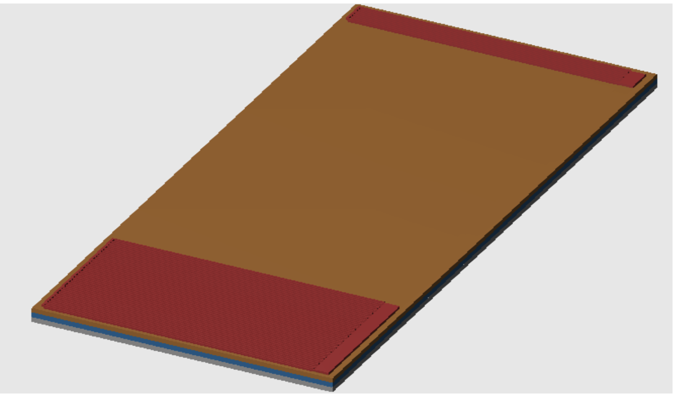

Fig. 12: layout of SAW device

6. Conclusion

In this work we focused on the design of SAW filters for wireless communication applications. On this designed we built up algorithm to obtain optimum number of fingers of input/output IDTs of the filters. A multilayer of piezoelectric substrates are used to have higher wave propagation velocity suitable for wireless application. The designed parameters of the substrate materials have been obtained from the experimental work for a fabricated piezoelectric substrate ZnO/SiO$_2$/Si using the fabrication facility of Central Electrical and Electronics Institute (CEERI), Pilani, India. Two case studies are used to test the optimized SAW filters in wireless system applications. The simulation results show that by applying this algorithm the required bandwidth of each application can be reached.

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