FEM Analysis of High-Selectivity SAW Filter using SPUDT Structure

Tran Manh Ha[1,2], Do Quang Huy[1], Hoang Si Hong[1], Nguyen Thi Hue[1*]

[1] Hanoi University of Science and Technology, No. 1, Dai Co Viet, Hai Ba Trung, Hanoi, Viet Nam

[2] The Vietnam Research Institute of Electronics, Informatics and Automation, 156A Q.Thanh Str, Hanoi, Vietnam

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Abstract

Wide-band surface acoustic wave (SAW) filters using single-phase unidirectional interdigital transducer (SPUDT) showed promise to achieve low loss and high selectivity. In this paper, the SAW filters were studied via finite element method (FEM) using 2D models and utilized YZ-$LiNbO_3$ for piezoelectric substrate. With respect to the investigated center frequencies of 97 MHz and 179 MHz, the SPUDT SAW filter demonstrated low power losses (26.85 dB and 22.63 dB respectively) and high attenuation band (12.73 dB and 23.95 dB) in comparison to the bidirectional SAW filter. It was also identified that the changes in different electrode factors including the material, the thickness, and the quantity had influences on the SPUDT-type filter response.

Keywords: SAW filter, SPUDT, FEM

1. Introduction

Typical SAW filters based on bidirectional transducer structure (Bi-IDT) are affected by internal reflection among interdigital transducers (IDTs) [1, 2], which depends on the thickness and materials of electrodes [3], not only causing multiple-transit signal leading to power loss and passband ripples, but also deteriorating the passband shape and high-order resonant modes [2]. Non-symmetric transducer configuration, such as single-phase unidirectional transducers (SPUDTs), could be used in SAW filter design in order to prevent both load-dependent reflection and electrode reflectivity caused by connecting reflective transducer with finite-impedance load [2]. Therefore, this type of SAW filter achieves low insertion loss, high selectivity and almost no passband ripple [3, 4, 5]. Thus, this research utilizes this transducer geometry for designing low-loss, high-selectivity SAW filter.

To analyse SPUDTs, Hua Jiang et al. expressed the electro acoustic characteristics of IDTs via P-matrix model [6]. Also, Pyman et al. developed withdrawal weighting and apodization algorithms based on delta function model to analyze W-CDMA base station filters using SPUDT structures [7]. In addition, the stopband width and directionality dependence of SPUDTs could be evaluated using spectral theory [8]. Other studies used coupling-of-modes (COM) modeling to analyze transducer properties [1, 2, 9]. The common disadvantage of these methods is that they require the parameters that could be only determined from experimental process or numerical determination [10]. Among existing simulation methodologies, finite element method (FEA) is considered as the most accurate technique for SAW devices analysis without fabrication [5]. Elsherbini and Ionescu used FEM to simulate SAW one-port resonators and focused their applications on sensing systems [5, 11].

Accordingly, in this paper the frequency responses of SAW filter using SPUDT structures are analyzed in comparison to the responses of bidirectional IDT-based filter via FEM. After that, the influences of different transducer parameters (i.e. the material, the thickness, and the quantity) on the performance of the SAW filter would be examined. The piezoelectric substrate material is YZ-$LiNbO_3$. The center frequencies are chosen as 97 MHz and 179 MHz to satisfy the requirements of high frequency filters in practice.

2. Principles of SAW filter with SPUDT structure

The core purpose of the SPUDT structure is to obtain acceptable suppression of the multiple-transit signal by eliminating the reflection of the forward acoustic port under the circumstances of well-matching impedance of the electrical port. Consequently, it could be designed to reach low insertion loss and low reflectivity [2, 12].

[*] Corresponding author: Tel.: (+84) 986320168
Email: hue.nguyenthi@hust.edu.vn;

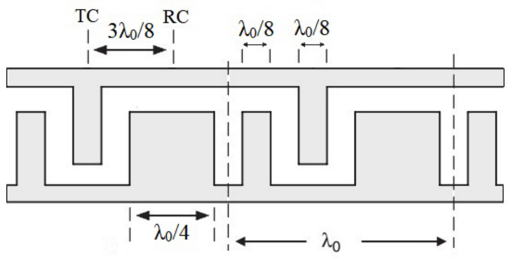

Fig. 1. Distributed acoustic reflection transducer.

The most common method to arrange IDTs for achiving the unidirectionality is using distributed acoustic reflection transducer (DART) [2]. Fig. 1 shows the particular arrangement of IDTs in the DART. Each wavelength (λ_0) period, with respect to one electrode group, contains three fingers: two with the width of $\lambda_0/8$ and one with the width of $\lambda_0/4$. To define the distance between the fingers, the transducers are considered as reflection center (RC) and transduction center (TC). The reflection center is the point at which waves incident both forward and backward have equal reflection coefficient, and the transduction center refers to the point where the forward and backward waves are in-phase and have same amplitude. The backward is reflected and then emerged with the forward. The condition for the reinforcement at the center frequency is [2]:

$$d = (2n \pm 1)\lambda_0/8 \quad (1)$$

Thus, the effective distance between the transduction and reflection centers is $3\lambda_0/8$ [2, 5, 9, 13].

3. Simulation methodology

This section describes two main simulation work in this research: 1) the comparison of SAW filter responses between the cases of SPUDT and Bi-IDT, and 2) the influences of different transducer parameters on the response of SPUDT-based SAW filter.

3.1 Comparison of SPUDT and Bi-IDT SAW filter responses

The initial approach is to utilize FEM analysis in order to compare the responses of SAW filter based on two transducer structures: SPUDT and Bi-IDT. Fig. 2a demonstrates the 2D model of the SPUDT filter, which is designed to be consistent with the DART mechanism introduced above. In the context of Bi-IDT structure, an optimal model for the Bi-IDT structure was proposed by Tran et al. [14]. Accordingly, similar Bi-IDT model and simulation tool would be applied to in this paper. The cross section of the Bi-IDT configuration is shown in Fig. 2b.

The SAW wavelengths (λ_0) could be calculated from $f_0 = v_0/\lambda_0$ [15]. In both cases, the substrate thickness and width are 1 mm and 30 mm to reduce the computational cost. The piezoelectric material for substrate is YZ-LiNbO3 because of its high electromechanical coupling factor (4.82%) compared with those factors of ST-Quartz (0.16%), ZnO/sapphire (1.1%), or XY-$LiNbO_3$ (3.58%), resulting in wideband response that is more applicable for filter realization [14, 16, 17]. The properties of YZ-$LiNbO_3$ used in simulation was demonstrated in Ref. 27 [18]. The chosen material for fingers is aluminum and the finger thickness is 2.5%.

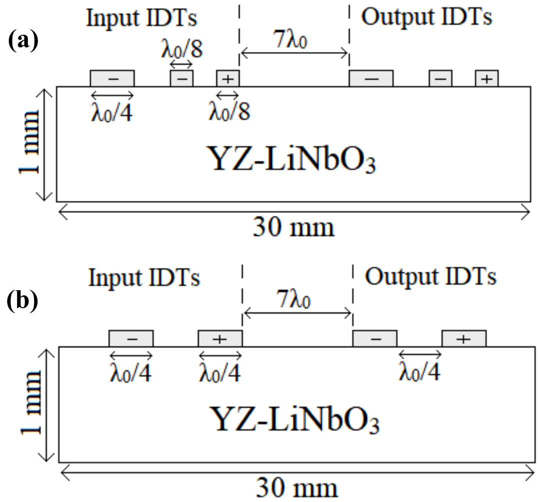

Fig. 2. 2D models of SAW filters using: (a) SPUDT and (b) Bi-IDT.

3.2 Influences of transducer parameters on the response of SPUDT-based SAW filter

The second approach was to investigate the frequency responses of SAW filter using SPUDT with respect to the changes of the material, the thickness, and the number of electrodes.

Since different materials could obtain different levels of mechanical surface wave reflection [3], the first parameter that need to be considered is electrode material properties. Although most of SAW devices commonly use aluminum for electrodes, the drawback of this material is its small density leading to over-thick film pattern for fabrication [3]. To handle this obstacle, large-mass density materials with good electrical conductivity could be used to fabricate IDTs [19]. From this point of view, Cu and Au should be good alternatives for Al. The properties of Al, Cu, and Au used in simulation are listed in Table 1. The center frequency f_0 is 179MHz, the relative thickness (h/λ_0) is 0.025, and the number of input IDT groups are 8.

After that, the effect of aluminum transducer thickness on SPUDT-based filter response is studied, in which the number of input electrode groups are kept at 8 with the center frequency of 179 MHz, and the relative electrode thickness varies from 0.025 to 0.075 with a step of 0.025.

Table 1. Properties of electrode materials [3]

	Al	Cu	Au
Mass density (x10^3 kg/m^3)	2.697	8.93	19.32
Young's modulus (GPa)	70.3	129.8	78.0
Poisson ratio	0.345	0.343	0.440
Resistivity (x10^{-8} Ωm)	3.55	2.23	2.88

Lastly, the performance of SAW devices in respect of the number of electrode groups are investigated in both cases of 97 MHz and 179 MHz wavelengths. Aluminum electrodes with the relative thickness of 0.025 are utilized.

4. Results and discussion

4.1 Comparison of SPUDT and Bi-IDT SAW filter responses

The responses of SAW filters using SPUDT and Bi-IDT structures are presented in Fig. 3. As shown in Fig. 3a with f_0 = 97 MHz, compared to the Bi-IDT filter, the SPUDT model has lower insertion loss of 26.85dB, higher attenuation band of 12.73dB, and steeper slope resulting in high-selectivity filter. In case of 179 MHz resonant frequency, the SPUDT filter also performs an attenuation band of 23.95dB, which is much higher than the attenuation band of Bi-IDT filter that is only 14.43dB as in Fig. 3b. The insertion loss and filter slope of the SPUDT filter also significantly improve.

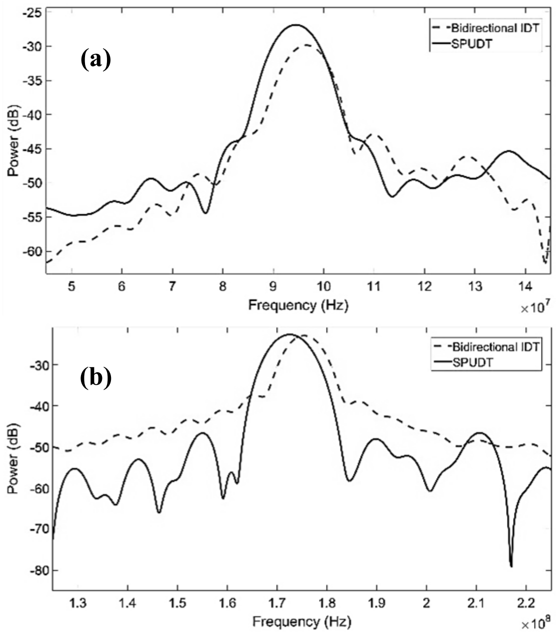

Fig. 3. Filter responses of SPUDT and Bi-IDT SAW filters: (a) f_0 = 97 MHz and (b) f_0 = 179 MHz.

In all circumstances, the reduction of phase velocity caused by IDT mass loading effect results in frequency-shifting events compared with theoretical calculations [20]. However, because the number of SPUDTs are greater than the number of Bi-IDTs in order to adjust the filter bandwidths, it is observable that the center frequencies of SPUDT-based filters are somewhat smaller than the center frequencies of Bi-IDT-based filters.

4.2 Influences of transducer parameters on the response of SPUDT-based SAW filter

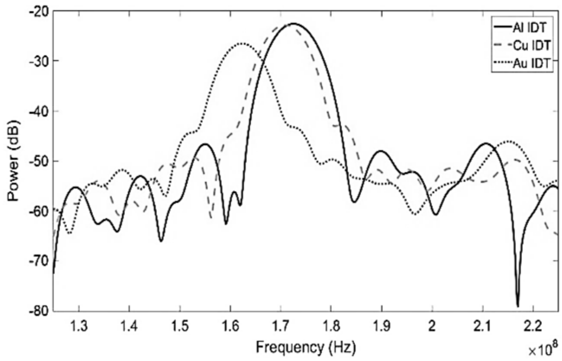

Fig. 4. Comparision of SPUDT SAW filter responses with different electrode materials.

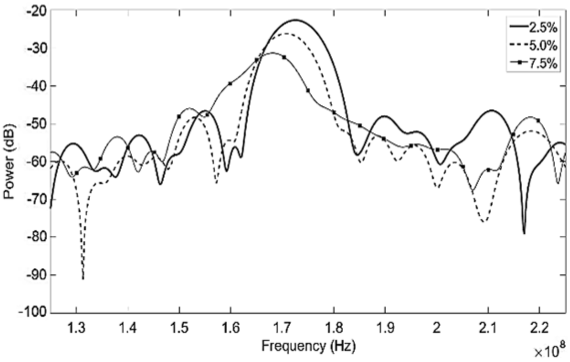

Fig. 5. Comparision of SPUDT SAW filter responses with different electrode thicknesses.

The SPUDT SAW filter responses with respect to different electrode materials are shown in Fig. 4. As can be seen in the figure, the filter using aluminum electrodes demonstrates the most significant response, particularly the lowest insertion loss (22.63 dB), highest attenuation band (23.95 dB), and steepest slope, as well as frequency correctness (6.3 MHz). The utilizations of cooper and gold deteriorate the filter response because Cu and Au have much greater mass densities than Al, but smaller stiffness coefficients, consequently leading to larger mechanical reflections and effective velocity reductions [3, 19].

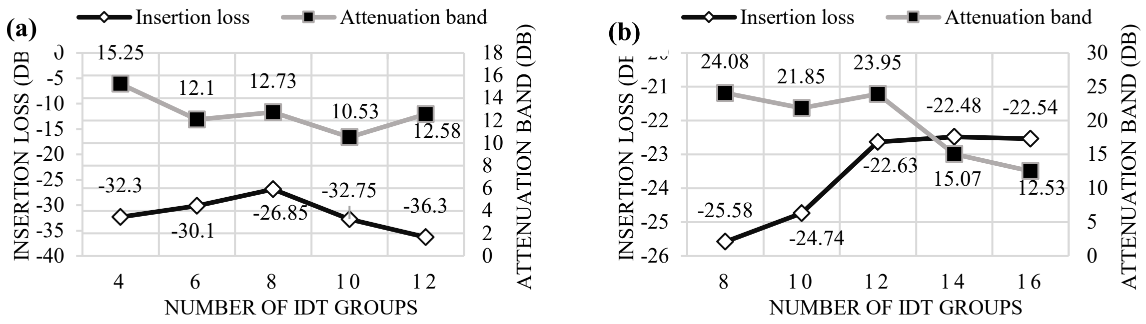

Fig. 6. Frequency responses of SAW filters with respect to different numbers of IDT groups in cases (a) f_0 = 96.9 MHz and (b) f_0 = 178.9 MHz.

Fig. 5 presents the simulation results when the thickness of aluminum electrodes varies from 2.5% to 7.5% of a wavelength. It is crystal clear that the filter responses become worse when the electrode thickness increases. Particularly, the best case is when h/λ_0 equals 0.025, in which the insertion loss is 26.85 dB, and the attenuation band is 15.73 dB. In contrast, with the relative thickness of 0.10, the insertion loss and attenuation band deteriorate to 32.76 dB and 12.01 dB. It is because the internal reflectivity in each transducer would rise with respect to the increase of electrode thickness [3]. Besides, the decrease of the center frequencies when the electrodes become thicker could be simply explained as the growth of the total mass load of IDT, which leads to the reduction of the phase velocity [20].

The relation between the loss and the attenuation of the SPUDT SAW devices and the number of IDT groups are presented in Fig. 6. It could be seen clearly that the properties of SAW filter would vary when the number of IDTs change. While the center frequency is 97 MHz (Fig. 6a), the filter achieves low insertion loss and large attenuation band when the number of electrode groups in input IDTs are 12, which might be considered as the optimal number; in other cases, the filter has to trade off amongst power loss and attenuation rejection. Similarly, as seen in Fig. 6b, the optimal geometry for 179 MHz device might contain 8 IDT groups in order to reduce power loss and obtain reasonable selectivity.

4. Conclusion

In this research, we analyzed the frequency responses of SAW filter based on SPUDT structure via 2D finite element analysis. In comparison to the Bi-IDT SAW filter, the SPUDT geometry gives better responses, in both of insertion loss and attenuation band, in order to achieve high-selectivity filters. The relations between the device performance and different electrode properties (i.e. the material, the thickness and the quantity) are also investigated. Accordingly, the simulation results firstly showed that the frequency response of SAW filter depended on the mass density and stiffness coefficient of electrode material; therefore, using aluminum electrode resulted in the greatest performance. Also, the deterioration of filter response is directly proportional with the increase of finger thickness. Finally, the SPUDT geometry was simulated in respect of different numbers of transducers, which revealed a trade-off amongst power loss, rejection, selectivity, and bandwidth as well as optimal numbers of electrodes to achieve acceptable insertion loss and attenuation band for the center frequencies of 97 MHz and 179 MHz. Further research should utilize 3D model to investigate the effects of IDT length on the filter response as well as other advanced SPUDT geometries.

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