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ECM Approach for Filter Design-Based Wavelet Transform Using SAW

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Abstract: This paper proposes a design of a bandpass filter based on the wavelet transform (WT) technique using a surface acoustic wave device (SAW). The proposed model is achieved through the impulse response model from the equivalent circuit of mason (ECM). This paper aimed to study the behaviour of a bandpass filter with a center frequency of 70MHz suitable for intermediate frequency (IF) stages of mobile phones and various communication systems. The study includes different piezoelectric materials such as ST quartz, Lithium niobate ($LiNbO_3$) and Lithium tantalate ($LiTaO_3$). Moreover, the transfer function, bandpass ripples, sidelobes power and insertion loss for input and output Inter-digital transducers are evaluated and simulated. The calculated parameters include the size of the substrate processing time and the scale of the wavelet function. The simulated results are compared with uniform aperture surface acoustic wave devices. The designed substrate dimensions of 2mm×2mm and sidelobes attenuation is up to 96.61 dB.

***Keywords*:** WTP, SAW, IF, ECM, IL.

1. INTRODUCTION

Due to its robustness of operating in time-frequency dispersive systems wavelet technology is considered an effective mathematical tool for various engineering fields, i.e. instantaneous signals, picture edge identification and signal analysis moreover, a scientific and industrial application [1-7].

Wavelet transform processors (WTPS) based surface acoustic wave device (SAW) represents an effective solution beat on the complicated algorithm of wavelet technology. Moreover, SAW devices have excellent characteristics such as a simple design, low cost, small size, etc. [8]. Bandpass SAW filters have a linear phase response which prevents the processed signal from being distorted compared to conventional linear phase passive L-C filters (have some inherent degree of phase nonlinearity related to the number of reactive components), SAW filter size is smaller (several hundred reactive components to meet exacting frequency response specifications), simple design and lower cost, the prementioned characteristics may render it more effective for many applications especially mobile or airborne ones. Consequently, the linearity of the SAW filter combined with the good localization in both the time and frequency domains by the wavelet algorithm [8] is the major motivation for the proposed design. In this work, a simple filter design of specifications 70MHz,1.873MHz-3dB bandwidth, first sidelobe attenuation of 96.24 dB and insertion loss of 24dB is implemented. The establishment of the proposed filter based on the simplified method for modelling SAW devices, the impulse response model (IRM) from the equivalent circuit of mason (ECM) [9-12], other models are used such as delta function model (DFMs) [13], green's function model [14,15], P-matrix model [16], and coupling of modes (COM) model [17-20]. Other models are mathematically complex, while the ECM model can simply calculate the same specification parameters. The paper is organized as follows a material and method section presents the main model design, parameters and material used. The results and discussion section includes the simulation results, comparing parameters according to different materials and the ability to improve the frequency response model.; Finally, the conclusion section.

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2. MATERIALS AND METHODS

To implement a filter using SAW device, two specially designed interdigital transducers (IDTs) fabricated on a piezoelectric material substrate are input IDT and output IDT. The two groups of IDTs may be uniform designed (unaopdized) or nonuniform aperture overlap(apodized) or a mix of them [8] Figure 1.

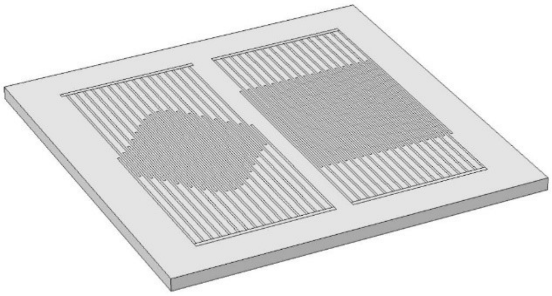

Figure 1 The Structure of the Filter Wavelet-Based

The geometric pattern of the interdigital transducer is a unique feature of saw filter design, it corresponds to a spatially sampled replica of the IDT impulse response. Accordingly, designing wavelet transform processor-based SAW device requires the design of input IDT is congruous to the envelope of Morlet wavelet function [8]. The impulse response of Morlet wavelet [21-23] is mathematically by

$$\psi(t) = \frac{1}{\sqrt{s}} e^{-\frac{1}{2}(\frac{t}{s})^2} e^{j\omega_0 t} \quad (1)$$

Where, ω_0 is the central frequency and s is the wavelet scale. The frequency domain of Equation (1) is denoted as follows

$$Y(\omega) = \frac{\psi(\omega)}{\frac{\sqrt{\pi}}{\sqrt{s}}} = e^{-\frac{1}{2}s^2(\omega-\omega_0)^2} \quad (2)$$

Then 3dB bandwidth in MHz is expressed by [8]

$$\Delta f_{-3dB} = \frac{1}{2\pi s}\sqrt{-2\,ln\left(10^{\frac{-3}{20}}\right)} = \frac{0.1323}{s} \quad (3)$$

The previous equation presents the dependance of bandwidth on the input as the output IDT is uniform and its bandwidth is much bigger. The number of interdigital transducers of uniform SAW is related to null bandwidth and central frequency by Equation (4)[9].

$$N = \left\lceil \frac{2f_0}{NBW} \right\rceil \quad (4)$$

While $f_0 = 70MHz$, $NBW = 4.3MHz$ and $\lceil \blacksquare \rceil$provides maximum integer more than a given number. The proposed filter design based on same number of input/output fingers to produce smaller size. Many previous researches have dealt with the WTP use a number of input IDT is much bigger than the output IDT producing more processing time and substrate size [24-27]. To design the input IDT's parameters as scale and 3dB bandwidth must calculated. Brain Russel et.al [21] state the following equation

$$\Delta f_{-3dB} = \frac{0.883 f_0}{k} \quad (5)$$

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Where k is the number of cycles at which the most power spectral density concentrate. Equation (4) into (5) k=N, get 1.873MHz 3dB bandwidth. The scale calculated by Equation (3) so s=0.0706, single scale WTP acts as bandpass filter so mathematical parameters are selected. Another group of parameters related to physical properties of the substrate material will apply in Table 1

Table 1 Physical Properties of Selected Materials.

Substrate material	**velocity($v_s\, m/s$)**	K^2(%)	$C_0(pf/cm)$	**Finger width ($w = \frac{v_s}{4*f_0}$)**
ST-quartz	3158	0.11	0.55	1.1279×10^{-5}
$LiNbO_3$	3992	5.3	5	$.4257 \times 10^{-5}$
$LiTaO_3$	3230	0.72	4.4	1.1536×10^{-5}

Table 1 plays a vital role in our simulation as it provides essential information about the physical characteristics of the substrates utilized. The information outlined in the table includes wave speed, as well as other critical factors such as the capacitance per unit length (C_0) and the electromechanical coupling coefficient (ECC)K^2. The importance of capacitance per unit length is emphasized when using the Mason model's equivalent circuit [9-11]. Figure 2 illustrates the complete frequency response of the filter

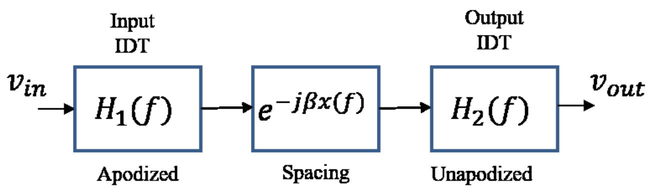

Figure 2 The Calculation Stages of a Total Frequency Response.

Where $H_1(f), H_2(f)$ is the frequency response pair of input and output IDTs and calculated as [8,9]. The total response stages figure 2 is simulated using suitable simulation tool. The spacing between input and output fingers x(f) which is a function in frequency may be reduced to a distance d when using uniform finger spacing and d is calculated as the distance between the midpoints of input and output IDTs [28].

The aperture overlap of the input IDT is calculated Equation (6)

$$L(n) = L_{max} e^{-\frac{(n-1)^2}{8s^2 {f_0}^2}} \qquad (6)$$

$$L_{max} = 1200\mu m, n = 1:34, s = 0.0706, f_0 = 70MHz$$

Figure 3 represents the positions of the fingers of input IDT.

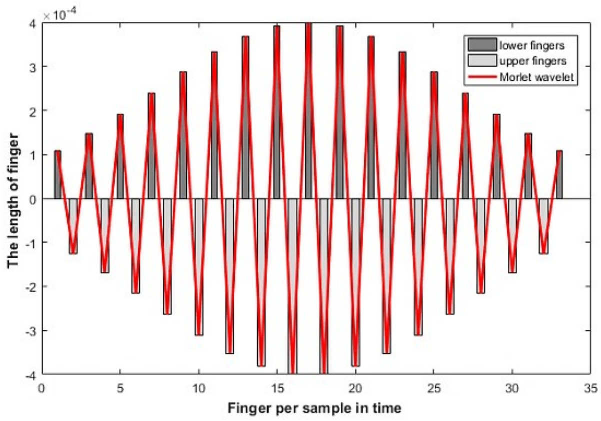

Figure 3 Positions of Fingers per Sample in Time.

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3. RESULTS AND DISCUSSIONS

In this section, the frequency response of SAW filter-based wavelet is simulated using suitable software. Comparison between wavelet apodized and unaopdized SAW is studied, moreover different window functions are applied and compared.
Figure 4 represent input /output frequency response of proposed wavelet apodized filter.

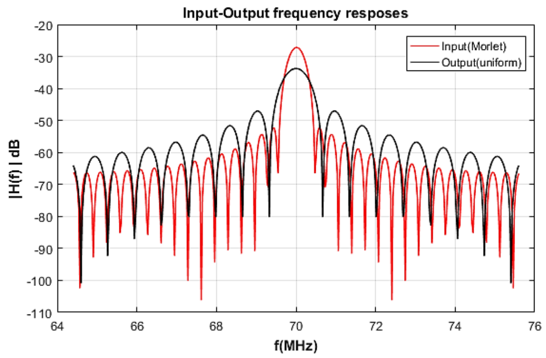

Figure 4 Input/Output Frequency Responses of Wavelet-Based SAW

Compared to the response of uniform(unapodized) input/output IDTs [9,29].

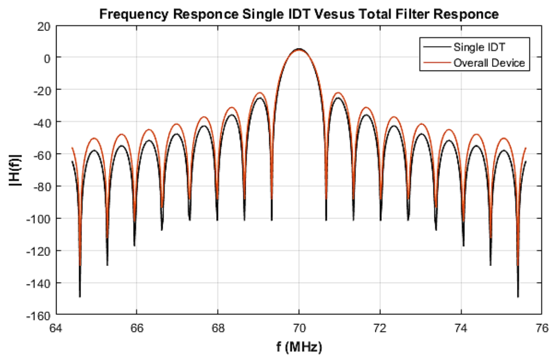

Figure 5: single IDT vs Total Response.

The simulation results for ST-quartz using both uniform and wavelet-based filters, presented in Figures 4 and 5, offer valuable insights. The results demonstrate that the wavelet bandwidth is closely linked to the input IDT and that the wavelet filter's first side lobe attenuation is 37.72dB compared to 16.78dB of the uniform filter.

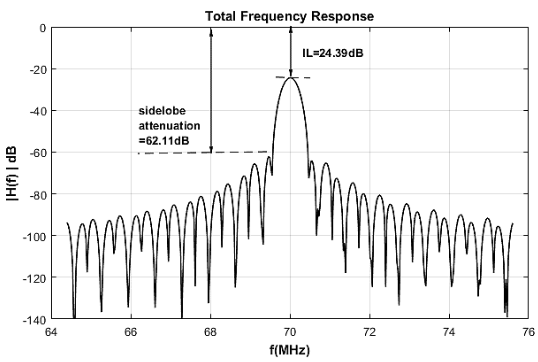

Figure 6 Total Frequency Response Wavelet-Based.

The simulation of materials in Table 1 presents the same frequency specification figure 6 except for processing time and substrate size Table 2. The processing time is the real time taken to process the

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input signal, it is calculated as the distance between the midpoint of input /out IDTS divided by the SAW velocity.

Table 2 Different Material Processing Time and Substrate Sizes.

Substrate material	Processing time (*nsec*)	Substrate size
ST-quartz	260	2mm*2mm
$LiNbO_3$	271.4	2mm*2.4mm
$LiTaO_3$	271.3	2mm*2.3mm

To improve the total frequency response of the filter Figure 6, different mathematical equations may be applied to minimize the power of sidelobes (sidelobe attenuation). To achieve an improvement in filter response, Gaussian, Kaiser, Hamming and Hanning windows were applied figures (7-10).

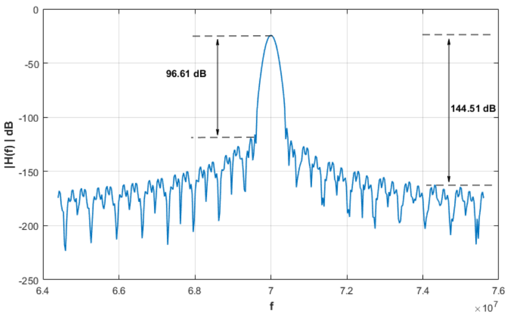

Figure 7 Gaussian Window Applied to Filter Response

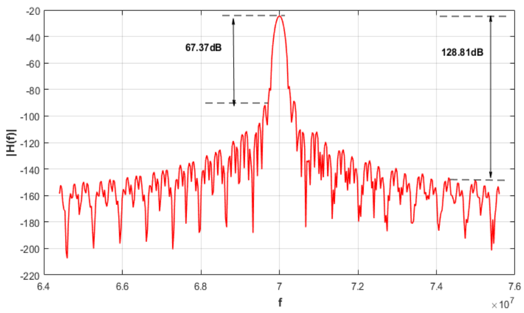

Figure 8 Hamming Window Applied to Filter Response

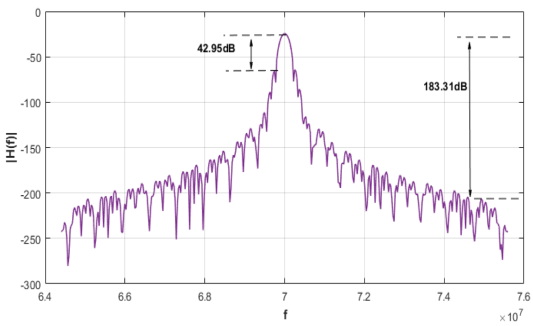

Figure 9 Hanning Window Applied to Filter Response

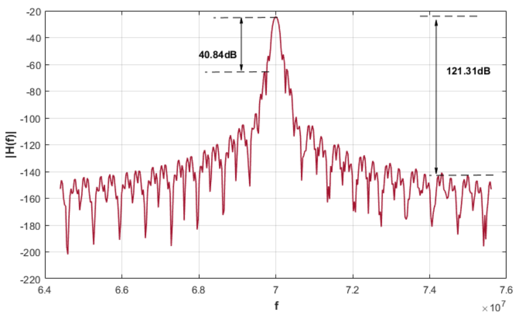

Figure 10 Kaiser Window Applied to Filter Response

Table 3 shows that different window functions produce varying levels of sidelobe attenuation and main lobe width, with the Gaussian function being the most efficient.

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Table 3 Simulated Parameters for Different Window Functions

Window Function	Insertion loss (IL)	Relative Sidelobe Attenuation		3dB Bandwidth	
		Theoretically	Simulated	Theoretically	Simulated
Gaussian	24.39dB	96.61 dB	91.1 dB	1.873MHz	1.577 MHz
Kaiser	24.39dB	40.84 dB	30.7 dB	1.873MHz	2.197 MHz
Hamming	24.39dB	67.37 dB	55.5 dB	1.873MHz	1.972MHz
Hanning	24.39dB	42.95 dB	43.2 dB	1.873MHz	1.823MHz

References [27,30], designed WTP with different scale, bandwidth and number of input /output IDTs, in addition to a practical comparison with a manufactured product [31]. A comparative analysis will be established based on the sidelobe attenuation, processing time and a size of the substrate. Table 4 represent center frequency, the number of input IDTs and output IDTs [27,30,31] for comparative analysis with our work.

Table 4 input parameters [27,30]

Reference	Scale	Max Aperture Length (µm)	Center frequency (MHz)	Number of electrode pair	
				Input	Output
[27]	0.2152	3433.5	60	117	49
[30]	0.215	3588	60	59	24
[31]	Undefined	Undefined	70	Undefined	Undefined
Proposed filter	0.0706	1200	70	34	34

Table 5 represents the results of simulation for parameters of Table 4.

Table 5 The Simulation Results

Reference	Insertion Loss	Processing Time (µsec)	Sidelobe Attenuation	Substrate Size
[27]	15.95dB	1.89	121.35 dB	8.33mm×3.84mm
[30]	20.57 dB	0.95	87.03 dB	4.23mm×4.011mm
[31]	28.5dB	Undefined	45dB	20.5mm*35.15mm
Proposed filter	24.39 dB	0.26	94.71 dB	2mm×2mm

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4. CONCLUSIONS

This research revealed a bandpass filter based on wavelet technology using SAW devices. the filter model may use equal input /output IDTs, reducing the substrate size and processing time. The model is tested using suitable software based on the ECM model. Different materials are simulated providing different times, the filter is designed on quartz substrate because of its temperature stability and its performance in narrowband filters. Other window functions are selected and simulated; the Gaussian window provides the most efficient with side lobe attenuation of 96.61 dB.

5. REFERENCES

[1] Shi, B.; Cao, M.; Wang, Z.; Ostachowicz, W. "A directional continuous wavelet transform of mode shape for line-type damage detection in plate-type structures". Mech. Syst. Signal Process 2022, 167, 108-105.

[2] Li, C.; Yu, Y.; Yang, Z.; Liu, Q.; Peng, X." ESR estimation for aluminium electrolytic capacitor of power electronic converter based on compressed sensing and wavelet transform." IEEE Trans. Ind. Electron. 2021, 69, 1948–1957.

[3] Hong, H.P.; Cui, X.Z.; Qiao, D. "Simulating nonstationary non-Gaussian vector process based on continuous wavelet transform." Mech. Syst. Signal Process 2022, 165, 108340.

[4] Psaras, V.; Tzelepis, D.; Vozikis, D.; Adam, G.P.; Burt, G." Non-unit protection for HVDC grids: An analytical approach for wavelet transform-based schemes." IEEE Trans. Power Deliv. 2020, 36, 2634–2645.

[5] Bilgili, F.; Lorente, D.B.; Ku¸skaya, S.; Ünlü, F.; Gençoˇglu, P.; Rosha, P. "The role of hydropower energy in the level of CO2 emissions: An application of continuous wavelet transform." Renew. Energy 2021, 178, 283–294.

[6] Li, X.X.; Li, D.; Ren, W.X.; Zhang, J.S." Loosening Identification of Multi-Bolt Connections Based on Wavelet Transform and ResNet-50 Convolutional Neural Network." Sensors 2022, 22, 6825.

[7] Mahmood, M.R.; Matin, M.A.; Sarigiannidis, P.; Goudos, S.K." A Comprehensive Review on Artificial Intelligence/Machine Learning Algorithms for Empowering the Future IoT Toward 6G Era". IEEE Access 2022, 10, 87535–87562.

[8] Ali, H.A., Elsherbini, M.M. and Ibrahem, M.I. "Wavelet Transform Processor Based Surface Acoustic Wave Devices." Energies,2022, 15(23), p.8986.

[9] Elsherbini, M.M.; Elkordy, M.F.; Gomaa, A.M. "Towards a Simple Model for SAW Delayline" Using CAD. Am. J. Circuits Syst. Signal Process 2015, 1, 86–92.

[10] Elkordy, M.F.; Elsherbini, M.M.; Gomaa, A.M. "Modeling and simulation of unapodized surface acoustic wave filter." Afr. J. Eng. Res. 2013, 1, 1–5.

[11] Gomaa, A.M.; Elkordy, M.F.; Elsherbini, M.M. "A computer Simulation for The Response of an Apodized SAW Filter. "J. Electr. Eng.2014, 14, 6.

[12] Elsherbini, M.M.; Elkordy, M.F.; Gomaa, A.M. "Using COMSOL to model high frequency surface acoustic wave (SAW) device." J. Electr. Electron. Eng. Res. 2016, 8, 1–8.

[13] Tancrell, R. H., and M. G. Holland. "Acoustic surface wave filters." ultrasonics,2005,11, 48-64.

[14] Milsom, R. F., Reilly, N. H. C., & Redwood, M." Analysis of generation and detection of surface and bulk acoustic waves by interdigital transducers." IEEE Transactions on Sonics Ultrasonics,1977, 24, 147.

[15] Morgan, D. P." Quasi-static analysis of generalized SAW transducers using the Green's function method." IEEE Transactions on Sonics Ultrasonics,1980, 27, 111-123.

[16] Tobolka, G." Mixed matrix representation of SAW transducers." IEEE transactions on sonics and ultrasonics, 1979,26(6), 426-427.

[17] Plessky, V., & Koskela, J. "Coupling-of-modes analysis of SAW devices." International Journal of High-Speed Electronics and Systems,2000, 10(04), 867-947.

[18] Suzuki, Y., Takeuchi, M., Nakamura, K., & Hirota, K. "Coupled- mode theory of SAW periodic structures." Electronics and Communications in Japan (Part III: Fundamental Electronic Science),1993, 76(6), 87-98.

[19] Wright, P. V. A. "new generalized modeling of SAW transducers and gratings." In Proceedings of the 43rd Annual Symposium on Frequency Control, IEEE,1989 (pp. 596-605).

Print ISSN : 2682-3993
Online ISSN : 2682-4000

[20] Hartmann, C. S., Wright, P. V., Kansy, R. J., & Garber, E. M. "An analysis of SAW interdigital transducers with internal reflections and the application to the design of single-phase unidirectional transducers." In IEEE Ultrasonics Symposium,1982, (pp. 40-45).
[21] Russell, B.; Han, J." Jean Morlet and the continuous wavelet transform." CREWES Res. 2016, 28, 115.
[22] Lee, D. T.; Yamamoto, A. "Wavelet analysis: theory and applications." Hewlett Packard journal, 1994,45.
[23] Büssow, R. "An algorithm for the continuous Morlet wavelet transform." Mechanical Systems and Signal Processing, 2007,21(8), 2970-2979.
[24] Lu, W.; Zhu, C.; Liu, Q.; Zhang,J. Implementing wavelet inverse-transform processor with surface acoustic wave device. Ultrasonics,2013, 53(2), 447-454.
[25] Liu,S.; Lu,W.; Feng,Y. "Research on three key problems of the design of the wavelet transform processor using surface acoustic wave devices." IET Circuits, Devices & Systems, 2017.
[26] Lu, W.; Zhu, C.; Liu, J.;Liu, Q."Implementing wavelet transform with SAW elements." Science in China series E: technological sciences,2003, 46(6), 627-638.
[27] Yang, B.; Lu, W.; Gao, L.; Feng, Y. "Methods of Solving Passband Ripples and Sidelobes for Wavelet Transform Processor Using Surface Acoustic Wave Device." IEEE Transactions on Industrial Electronics,2022.
[28] Campbell, C. "Surface acoustic wave devices and their signal processing applications."2012 Elsevier.
[29] Elkordy, M. F., Elsherbini, M. M., & Gomaa, A. M." Modeling and simulation of unapodized surface acoustic wave filter. "African Journal of Engineering Research,2013, 1(1), 1-5.
[30] Yang, B., Lu, W., & Gao, L."An efficient modeling approach for wavelet transform processors using surface acoustic wave devices." Measurement Science and Technology,2023, 34(8), 085119.
[31] MICROSAW," SAW 70MHz filter bandwidth1.4MHz"M063-70M1,2012.