Design of IF Two-Track Filters Using IDT/(100) AlN/Diamond Structure

Ruyen Ro, *senior member*, *IEEE*, Ruyue Lee
Department of Electrical Engineering
I-Shou University
Kaohsiung, Taiwan, R. O. C.
ryro@isu.edu.tw

Chia-Chi Sung, Yuan-Feng Chiang
Department of Engineering Science and Ocean Engineering
National Taiwan University
Taipei, Taiwan, R. O. C.

Sean Wu, *member*, *IEEE*
Department of Electronics Engineering and Computer Science
Tung-Fang Institute of Technology
Kaohsiung, Taiwan, R. O. C.

Abstract—**Propagation characteristics of surface acoustic waves (SAWs) in IDT/(100) AlN/diamond structures are analyzed in this study using the finite element method (FEM). The extracted coupling-of-mode (COM) parameters are employed to calculate the frequency responses of two-track SAW filters using the transmission matrix method. To enhance the sideband suppression, Chebyshev function is adopted to modify the reflectivity distributions of reflectors, which can be realized using width-modulated reflectors. The copper electrode is used to retain a sufficiently high reflectivity. Simulation results show that a two-track SAW filter applicable for the CDMA system can be tailored using IDT/(100) AlN/diamond structures.**

Keywords-surface acoustic wave; AlN; diamond; filter; finite element method

I. INTRODUCTION

Communication devices with designed specifications for various applications such as duplexers, IF and RF filters are widely used in daily situations. There are several major requirements of high-quality IF filter and RF filters as follows. First, low insertion loss is required to retain a good signal-to-noise ratio. Second, shape factor and sidelobe level have to be maximally optimized to against the interference from spurious signals. Third, the proper frequency control of filters is important to prevent overlapping between adjacent channels. Furthermore, the group delay has to be constant at the passband to avoid phase distortion. In addition, communication components with miniature size, high integration, rugged structure, and ease of mass production are feasible and can be fitted into the state-of-the-art wireless communication systems. Surface acoustic wave devices (SAWs) are one of several suitable candidates to design IF and RF filters for wireless applications [1–4].

Code division multiple access (CDMA) system uses spread spectrum technology to wider the transmit band, hence, a flatly broad passband is ensured signal against distortion. Moreover, passband with steep skirt is required to minimally the undesired loss. The specifications of a current CDMA IF filter including the following: 5dB bandwidth of at least 1.25 MHz, an attenuation of more than 30 dB out of 1.8 MHz, and the maximum insertion loss of less than 15 dB. In this study, two-track SAW filters are proposed for CDMA IF filters due to its no triple-transit influence (TTI) properties. The detailed information about the two-track SAW filters was presented in elsewhere [5]. In the two-track SAW filters, the input interdigital transducers (IDTs) are out of phase while output IDTs are in phase therefore the forward signals will eliminate; in other words, the TTI effect can be diminished. This implies that the frequency responses of such special configurations are mainly dominated by the performances of the reflectors. For a uniform reflector, its reflection characteristics, 5dB bandwidth and sidelobe suppression cannot meet the specifications for the CMDA IF filter. To overcome this problem, some researchers employed different window functions to modify the reflectivity or line width distributions of reflectors to design IF filters [5–7].

Recently, surface acoustic wave (SAW) devices using layered structures had been proven to be the mainstream for super high frequency applications. SAW operating in the second mode in the (100) AlN/diamond structure exhibits high phase velocity 10780 m/s and relatively large electromechanical coupling coefficient (K^2) 2.4% [8]. The increase of phase velocity diminishes the line width limitation and, hence, improves the feasibility of SAW devices with width-modulated reflectors such as double mode SAW (DMS) filters, two-track SAW filters, and ladder filters [9-11].

In this study, width-modulated reflectors with Chebyshev distributions in the (100) AlN/diamond structure are employed to design the two-track SAW filter applicable to the CDMA system. Copper (Cu) IDT is chosen due to its reflectivity is two times larger than aluminum (Al) IDT. The finite element method (FEM) model is established to calculate the mutual-coupling coefficients and effective phase velocities of each electrode region with various metallization ratios (MRs) and different electrode thicknesses. The transmission matrix method is then applied to evaluate the frequency responses of two-track SAW filters [5].

II. METHODOLOGY

The schematic of a two-track SAW filter on the layered piezoelectric structure which consists of an AlN film of thickness h_F and a diamond substrate is presented in Fig. 1. In Fig. 1, input IDTs in both track are identical but out of phase while identical output IDTs are in phase, which indicates that if there is no reflector in each track, the transmission coefficients will vanish and hence the TTI effect can be diminished. This implies that the frequency responses of a two-track SAW filter are mainly dominated by reflectors.

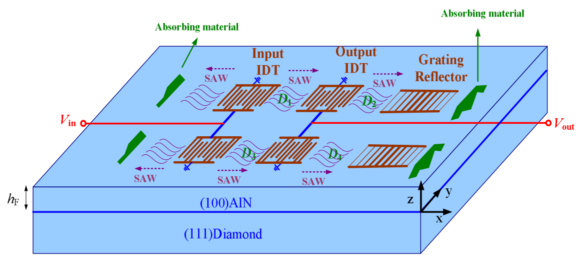


Figure 1. Schematic of a two-track SAW filter with weighted reflectors.

In this study, the FEM is employed to compute the effective phase velocity, V_{eff}, and mutual-coupling coefficient, k, of each electrode region with various MRs and different electrode thicknesses, h_E. The FEM model of the layered piezoelectric structure is presented in Fig. 2. Two vibration modes of surface acoustic waves (SAWs), a symmetric mode and an asymmetric mode, as shown in Fig. 3, can be observed in the corresponding frequency ranges [12]. The resonance frequencies of these two modes are employed to evaluate k and V_{eff} as given by [2]

$$V_{eff} = p(f_{sym} + f_{asym}), \tag{1}$$

$$k = \frac{\pi(f_{asym} - f_{sym})}{p(f_{asym} + f_{sym})}, \tag{2}$$

where p is the electrode pitch and f_{sym} and f_{asym} are the resonance frequencies of the symmetric and asymmetric modes, respectively. For a free or metalized surface, both modes have the same resonance frequency; i.e., $f_{sym} = f_{asym}$. In addition to V_{eff} and k, the constructed FEM model can also be used to calculate the rest coupling-of-mode (COM) parameters such as K^2 and static capacitance, C_0, of the layered sturcture.

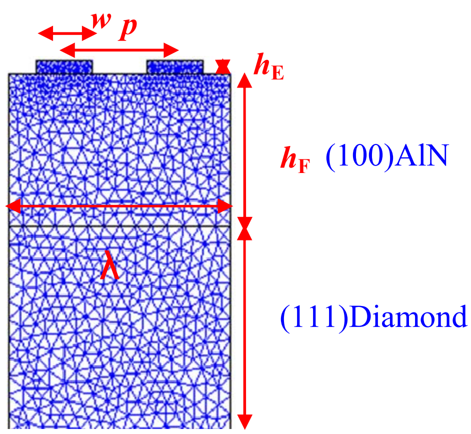
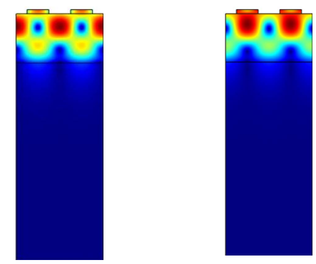


Figure 2. FEM model of the layered piezoelectric structure.



(a) (b)

Figure 3. Two vibration modes of SAWs: (a) asymmetric mode (b) symmetric mode.

The extracted COM parameters are then applied to evaluate the frequency responses of reflectors and two-track SAW filters using the transmission matrix method. Detailed discussion of the transmission matrix method can be found in reference 5. Through some manipulation, the admittance matrix of the two-track SAW filter can be given by

$$\begin{bmatrix} I_{in} \\ I_{out} \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V_{in} \\ V_{out} \end{bmatrix}, \tag{3}$$

where I_{in} and I_{out} are the currents at the input and output IDTs and V_{in} and V_{out} are the voltages at the input and output ports. The corresponding S-parameter for the two-track filter can be easily obtained from (3).

III. Simulation Result And Discussion

In this study, Cu IDT/(100) AlN/diamond structure was adopted to design the two-track SAW filters applicable for the CDMA system. The material properties of AlN and diamond used in the FEM model can be found in references 13 and 14. The extracted parameters and geometrical configurations of the input and output IDTs are given as follows: coupling coefficient K^2 = 1.71% at the thickness ratio of the AlN film h_F/λ = 0.3, static capacitance C_0 = 1.08 pF/cm, delay lines D_1 = D_3 and $D_4 - D_2$ = 0.25 λ, center frequency f = 100MHz, and the wavelength at center frequency λ = 106.28μm. The number of electrode pairs for both input and output IDTs with 100 λ overlap were 15 and 10, respectively. Both source and load impedances were 50Ω for system matching.

Because the sidelobe suppression level of reflectors with uniform width can't meet the requirements for CDMA system, width-modulated reflectors are employed to modify their reflection characteristics. The effective phase velocity and reflectivity of an electrode with different electrode thicknesses calculated using the FEM are presented in Fig. 4. As the electrode thickness increases, the maximum value of the reflectivity increases while the effective phase velocity decreases. For the 0.2, 0.6, 0.8, and 1.5% curves, the maximum reflectivity values are 0.0129, 0.0152, 0.0177, and 0.0391 with MRs being equal to 0.2, 0.325, 0.4, and 0.6, respectively.

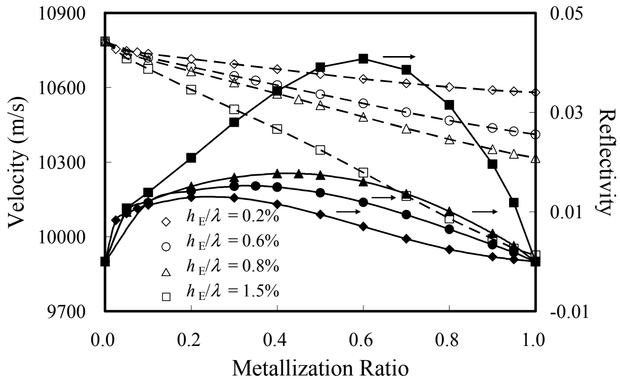


Figure 4. Reflectivity and effective phase velocity of an electrode with different electrode thickness ratios versus MR.

To enhance the sidelobe suppression of grating reflectors, the Chebyshev function is applied to modulate the reflectivity distributions of reflectors. In this study, the number of electrode for grating reflectors was assumed to be 240 and the sidelobe level (SLL) was 60dB [5]. The generated reflectivity distributions with different electrode thicknesses are presented in Fig. 5. The maximum value of each reflectivity curve in Fig. 5 is determined using the FEM as presented in Fig. 4. To retain the reflective distribution with a Chebyshev function, the MR of each electrode can be obtained numerically from Fig. 4 by using an interpolation technique. The MR distributions of the reflectors with different electrode thicknesses are shown in Fig. 6. And the corresponding effective phase velocities calculated using the FEM are also presented in Fig. 6.

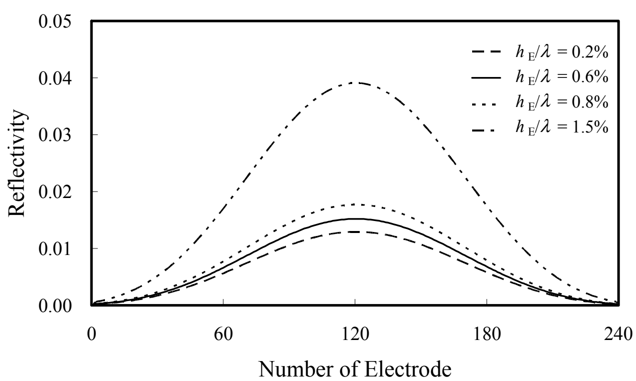


Figure 5. Reflectivity distribution, a Chebyshev function, of the reflector with different electrode thickness ratios.

With given effective phase velocity and reflectivity of each electrode, the reflection coefficients of width-modulated reflectors calculated using the transmission matrix method are plotted in Fig. 7. Note that the period of each electrode has been adjusted according to the corresponding effective phase velocity such that the operating frequency for each electrode is identical. It can be seen that the 1.5% curve has the largest bandwidth among all four cases in Fig. 7 but with poorest sidelobe suppression level. As shown in Fig. 4 or 5, the 1.5% curve has the largest maximum reflectivity among all cases studied in this research. This implies that the larger the maximum reflectivity, the larger the bandwidth and the poorer the sideband suppression. The corresponding transmission coefficients of the two-track filter with these width-modulated reflectors calculated using the transmission matrix method are presented in Fig. 8. For the 0.2, 0.6, 0.8, and 1.5% curves, the 5dB bandwidth values are 2.65, 1.4, 1.25, and 1.15MHz and the sidelobe suppression are 50.42, 54.69, 56.3, and 57.46dB, respectively. These simulation results can not meet the requirements for the CDMA system.

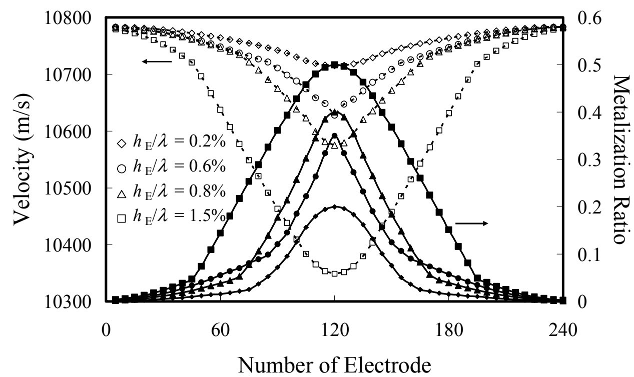


Figure 6. The retrieved MR distribution and calculated effective velocity curve for the reflector to retain the reflectivity distribution with a Chebyshev function as presented in Fig. 5.

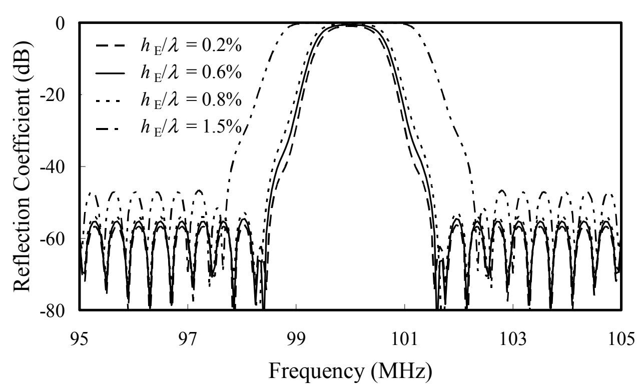


Figure 7. Reflection coefficient of width-modulated reflectors.

As mentioned above, the value of the maximum reflectivity will affect the bandwidth as well as the sideband suppression level of the width-modulated reflectors and the transmission characteristics of the two-track SAW filters. Therefore, by trial and error, we multiple the reflectivity distributions in Fig. 5 by different scaling factors and then recalculate MR distributions and effective phase velocity curves of the reflectors with different electrode thickness ratios. It is found out that if the maximum reflectivity of reflectors is around 0.014 the tailored two-track SAW filters are applicable for the CDMA system. The corresponding transmission coefficients are presented in Fig. 9. Table I lists the transmission characteristics of the tailored two-track SAW filters with three different electrode thickness ratios.

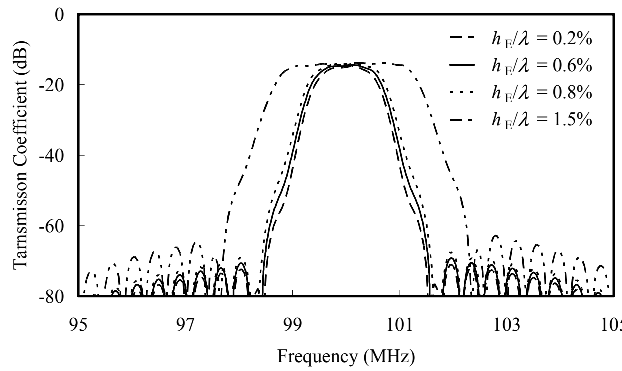


Figure 8. Transmission coefficient of two-track filters with width-modulated reflectors.

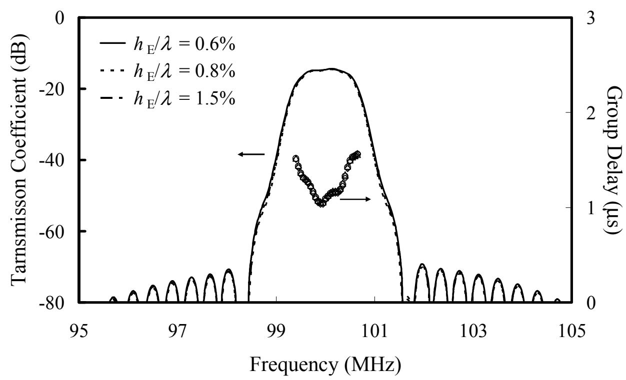


Figure 9. Transmission coefficient and group delay of two-track SAW filters with width-controlled reflectors when the maximum reflectivity of an electrode is around 0.014.

TABLE I. THE TRANSMISSION CHARACTERISTICS OF TWO-TRACK SAW FILTERS.

h_E/λ (%)	Shape factor	Insertion loss (dB)	Sidelobe suppression (dB)	Group delay (μs)
0.6	1.48	14.38	54.85	1.04–1.57
0.8	1.48	14.55	55.47	1.06–1.56
1.5	1.48	14.47	56.82	1.05–1.56

IV. CONCLUSION

In this paper, the FEM is employed to calculate propagation characteristics of SAWs in the Cu IDT/(100) AlN/diamond structure. The extracted COM parameters are used to evaluate the frequency responses of the two-track SAW filters. The Chebyshev function is applied to design the MR distributions of width-modulated reflectors. Simulation results indicate that if the maximum reflectivity of width-modulated reflectors is around 0.014 the tailored SAW filters can meet the specifications of a current CDMA IF filter.

ACKNOWLEDGEMENT

The authors would like to thank the National Science Council of the Republic of China for financially supporting of this research under Contract NSC 97-2221-E-214-023 and NSC 98-2922-I-214-001.

REFERENCES

[1] K. Hashimoto, Surface Acoustic Wave Devices in Telecommunications: Modeling and Simulation, Springer Verlag, 2000.

[2] V. Plessky, J. Koskela, "Coupling-of-modes analysis of SAW devices," International Journal of High Speed Electronics and Systems, vol. 10, pp. 867–947, 2000.

[3] C. K. Campbell, Surface Acoustic Wave Devices for Mobile and Wireless Communications, Academic Press, 1998.

[4] D. P. Morgan, Surface Acoustic Wave Filters, 2nd ed., Academic Press, 2007.

[5] R. Ro, H. Tung, and S. Wu, "Design of two-track surface acoustic wave filters with width-controlled reflectors," Japanese Journal of Applied Physics, vol. 43, pp. 688–694, February 2004.

[6] T. Omori, M. Tajima, J. Akasaka, K. Hashimoto, and M. Yamaguchi, "Design of weighted reflectors and their application to surface acoustic wave bandpass filter," Japanese Journal of Applied Physics, vol. 39, pp. 3024–3027, February 2000.

[7] T. Omori, J. Akasaka, M. Arai, K. Hashimoto, and M. Yamaguchi, "Optimisation of weighted SAW grating reflectors with minimized time delay deviation," IEEE International Frequency Control Symposium & PDA Exhibition, pp. 666–670, June 2001.

[8] S. Wu, R. Ro, Z. X. Lin, and M. S. Lee, "Rayleigh surface acoustic wave modes of interdigital transducer/(100) AlN/(111) diamond," Journal of Applied Physics, vol. 104, pp. 064919-1–064919-4, September 2008.

[9] C. S. Hartmann, and B. P. Abbott, "Overview of design challenges for single phase unidirectional SAW filters," Proceedings of the IEEE Ultrasonics Symposium, pp. 79–89, October 1994.

[10] A. Bergmann, J. Machui, K. Wagner, and R. Weigel, "Two-track-reflector-filters for CDMA mobile telephones," Proceedings of the IEEE Ultrasonics Symposium, pp. 57–60, November 1996.

[11] T. Yamada, H. Nakamura, and S. Tsuzuki, "A miniaturized SAW reflectors filter for IF stage of CDMA cellular phone applications," Proceedings of the IEEE Ultrasonics Symposium, pp. 405–408, October 1999.

[12] Y. Yong, "Analysis of periodic structures for BAW and SAW resonators," Proceedings of the IEEE Ultrasonics Symposium, pp. 781-790, October 2001.

[13] M. Benetti, D. Cannat'a, F. D. Pietrantonio, and E. Verona, "Growth of piezoelectric film on diamond for high-frequency surface acoustic wave devices," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 52, pp. 1806–1811, October 2005.

[14] J. G. Gualtieri, J. A. Kosinski, and A. Ballato, "Piezoelectric materials for acoustic wave applications," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 41, pp. 53–59, January 1994.