Analysis of frequency response of a dispersive layered SAW filter using effective permittivity and coupling of modes model

T.-T. W u, Y.-Y. Chen and T.-T. Chou

Institute of Applied Mechanics, National Taiwan University, Taipei, Taiwan

email: wutt@spring.iam.ntu.edu.tw

Abstract - This paper is an extension of the work by Wu and Chen (IEEE *UFFC*, **49** (1), 142, 2002) in which the COM model and the effective permittivity have been adopted to model the frequency response of a layered SAW filter. Matrix formalism for calculating the effective permittivity of a layered piezoelectric medium with IDT buried inside was given first. Summary of the COM model for uniform IDT was presented. Necessary modifications were made to analyze the frequency response of a two-port 1.48 GHz ZnO/Diamond layered SAW filter. The result was in accordance with the existing experimental data in the literature.

1. Introduction

The need for increasing the frequency of a surface acoustic wave (SAW) filter without decreasing the electrode spacing into the sub-micron region has aroused the researches of dispersive SAW devices [1-4]. By including a high velocity diamond layer between a piezoelectric layer and a silicon substrate, the surface wave velocity can be increased significantly.

In the design of a nondispersive SAW device, the Coupling of Mode (COM) model has been used successfully for many years [5-7]. Parameters of the COM differential equations are usually obtained by measurements or by borrowing from some related theoretical modeling [8,9]. For a layered SAW, the phase velocity of the SAW is dispersive and therefore the dispersion of the phase velocity has to be taken into account in the design. As to the modeling of a layered SAW transducer, Hachigo and Malocha [10] have employed the delta function model to calculate the null frequency bandwidth of ZnO/Diamond/Si layered SAW and found the reduction of the bandwidth due to velocity dispersion. In addition, they have proposed an equivalent circuit model for the layered SAW structures.

This paper is an extension of the paper by Wu and Chen [11] in which the COM model was employed to calculate the frequency response of a layered SAW device. Owing to the introduction of the COM model, the effects of propagation loss, electrode reflections, electrical transduction, acoustic reception, thin film loss and the distributed finger capacitance have been taken into accounts in the frequency analysis of the layered SAW.

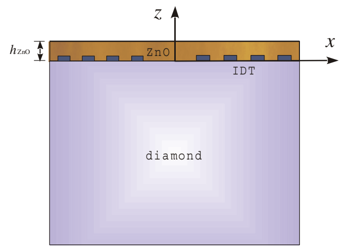
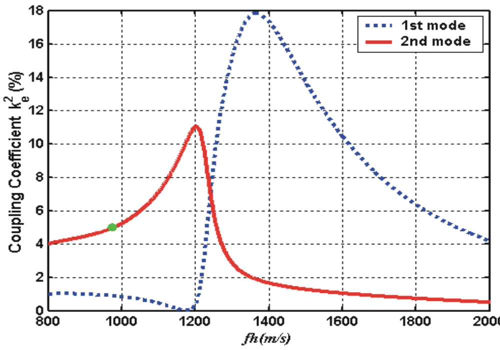


Fig. 1. ZnO/IDT/Diamond layered half space

2. Effective permittivity of a layered piezoelectric medium

In ref. [11], a formulation for the effective permittivity of a layered piezoelectric medium based on the matrix method has been presented. The effective permittivity at the interface between the vacuum and a ZnO/Diamond/Si layered half space has been given. The formulation is convenient for treating SAW problems with IDT on top of the ZnO/Diamond/Si layered half space. However, for IDT located between the ZnO and the diamond layer, the formulation has to be modified slightly. The detailed modification of the formulation can be found in reference [12]. In this paper, the dispersion of the ZnO/IDT/Diamond layered system was studied. The thickness of the diamond layer was 15 μm and that of the ZnO layer was h_{ZnO} =0.66 μm. Shown in Fig. 2 is a plot of the electromechanical coupling coefficient of the first two Rayleigh modes. As compared with the case for which the IDT was located on top of the ZnO [11], the coupling coefficient of the current IDT arrangement is much larger.



$f\,h_{ZnO}$ (km/s)

Fig. 2. Coupling coefficients of the Rayleigh modes

3. Coupling of modes model for a dispersive layered SAW

Coupling of modes equations have been derived and utilized for analyzing nondispersive SAW transducers with constant or arbitrary reflectivity weighting [6-8]. For a uniform transducer, the COM equations which governing the SAW mode amplitudes $R(x,\omega)$, $S(x,\omega)$ propagating in the $\pm x$ directions (Fig. 3) can be arranged in a concise form as [9]

$$\frac{dR(x)}{dx} = -jk_E R(x) + jK_R e^{-j2k_0x} S(x) + j\alpha_R V_0 e^{-jk_0x} \tag{1}$$

$$\frac{dS(x)}{dx} = +jk_E S(x) - jK_s e^{+j2k_0x} R(x) - j\alpha_s V_0 e^{+jk_0x} \tag{2}$$

$$\frac{dI(x)}{dx} = +j2\alpha_s R(x) e^{+jk_0x} + j2\alpha_R S(x) e^{-jk_0x} - j\left(\frac{3\omega C_F/\Lambda_T}{3+j\omega R_F C_F}\right)V_0 \tag{3}$$

where Λ_T is the wavelength of transduction, V_0 is the voltage across the IDT, I is the current flows into the bus bar, $k_0 = 2\pi/\Lambda_T$ is the transducer's synchronous wavenumber and

$$k_E = +\frac{\omega}{v_R} - \left(\frac{2\alpha^2\omega C_F R_F^2 \Lambda_T}{9+(\omega R_F C_F)^2}\right) - j\left(\gamma + \left(\frac{6\alpha^2 R_F \Lambda_T}{9+(\omega R_F C_F)^2}\right)\right) \tag{4}$$

$$\alpha_R = \frac{3\alpha e^{+j\phi_T}}{3+j\omega R_F C_F} \tag{5}$$

$$\alpha_S = \frac{3\alpha e^{-j\phi_T}}{3+j\omega R_F C_F} \tag{6}$$

$$K_R = +Ke^{+j\phi_B} + \frac{2j\alpha^2 R_F \Lambda_T e^{-j2\phi_T}}{3+j\omega C_F R_F} \tag{7}$$

$$K_S = +Ke^{-j\phi_B} + \frac{2j\alpha^2 R_F \Lambda_T e^{+j2\phi_T}}{3+j\omega C_F R_F} \tag{8}$$

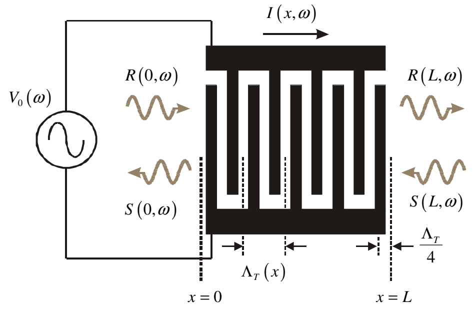


Fig. 3. Coordinates of the IDT

The COM parameters in this formulation are the Rayleigh wave velocity of the substrate v_R, the transduction coefficient α, thin film resistance in one transduction period R_F , interdigital capacitance in one transduction period C_F , Reflection parameter K and propagation loss per unit length γ.

In a dispersive layered system, the surface wave dispersion has to be considered. The propagation loss per unit length γ used in this study was adopted from the experimental measurement of ref. [2]. The electrode finger resistance was calculated based on the formulae presented in ref. [15] and the thickness dependent capacitance formula was adopted from Ref. [16]. For the purpose of comparison, the design of the ZnO/IDT/Diamond layered SAW of ref. [2] have been followed. The center frequency was 1480MHz and the finger width to grating period ratio was 0.5.

(a) Reflection parameter

The reflection parameter K represents the reflectivity of the thin film finger in IDT or grating. It can be expressed by [13,14]

$$K = \left[R_k\left(\frac{k_e^2}{2}\right) + R_m\left(\frac{h}{\lambda}\right)\sin(\eta\pi)\right]\frac{1}{p} \tag{9}$$

where R_k and R_m denote the electrical effect and mechanical effect, respectively. h is the metal film thickness, λ is the wavelength of the surface wave and k_e^2 is the electromechanical coupling coefficient. a is the finger width and $\eta = a/p$ is the finger width to grating period ratio. The functions R_k and R_m are

$$R_k = -\frac{\pi}{2}\left[\cos(\pi\eta) + \frac{P_s(-\cos(\pi\eta))}{P_{s-1}(-\cos(\pi\eta))}\right] \quad (10)$$

$$R_m = -\frac{\pi k_e^2}{\varepsilon_s(\infty)}\left[\left(\frac{U_1}{\varphi}\right)^2(\alpha_1+\rho' v_f^2)+\left(\frac{U_2}{\varphi}\right)^2(\alpha_2+\rho' v_f^2)+\left(\frac{U_3}{\varphi}\right)^2\rho' v_f^2\right] \quad (11)$$

where U_1, U_2, U_3 and φ are the displacements and the surface electrical potential of the surface wave at the interface $z=0$ under the free surface assumption. ρ', λ', μ' are the density and Lame constants of the thin film electrode. The constants α_1, α_2 are

$$\alpha_1 = \frac{4\mu'(\lambda'+\mu')}{\lambda'+2\mu'} \quad \text{and} \quad \alpha_2 = \mu' \quad (12)$$

In contrast to the half-space SAW reported in ref. [13], the displacements, the surface electrical potential and the electromechanical coupling coefficient of the surface wave in the dispersive layered SAW are no longer constant, instead, they are frequency dependent and can be evaluated using the matrix formalism presented in section 2. Fig. 4 shows the total reflection coefficient as a function of the operating frequency for the case of electrode thickness of 100Å. In this case, the electrical part dominates the reflection coefficient.

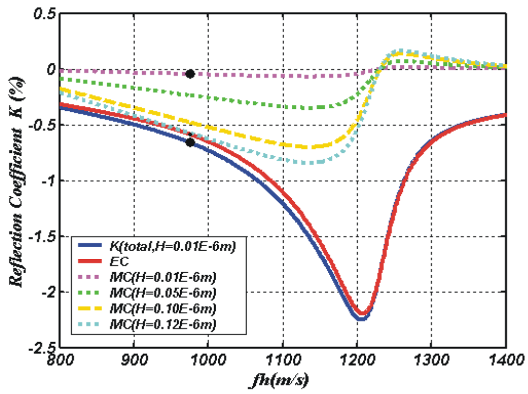


Fig. 4 Frequency dependence of the reflection coefficient

(b) Surface wave velocity

For small h/λ, the perturbed surface wave velocity v_R due to short circuit gratings can be approximated as [14]

$$v_R = v_f\left(1+\frac{\Delta v}{v_f}\right) = v_f\left(1+D_k\left(\frac{k_e^2}{2}\right)+\eta D_m\left(\frac{h}{\lambda}\right)\right) \quad (13)$$

where v_f is the free surface wave velocity of the layered structure with no electrode. D_K and D_m are changes coming from the electrical and mechanical loadings, respectively. They are

$$D_k = -\frac{\pi}{2}\left[1+\frac{P_{1/2}(-\cos(\pi\eta))}{P_{-1/2}(-\cos(\pi\eta))}\right] \quad (14)$$

$$D_m = \frac{\pi k_e^2}{\varepsilon_s(\infty)}\left[\left|\frac{U_1}{\varphi}\right|^2(\alpha_1-\rho' v_f^2)+\left|\frac{U_2}{\varphi}\right|^2(\alpha_2-\rho' v_f^2)-\left|\frac{U_3}{\varphi}\right|^2\rho' v_f^2\right] \quad (15)$$

Shown in Fig. 5 is the total velocity decrease as a function of the operating frequency for the case of electrode thickness of 100Å.

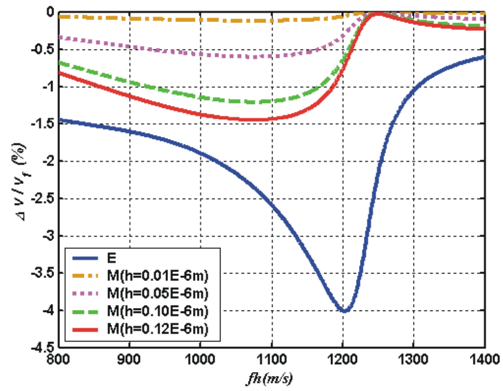


Fig. 5 Frequency dependence of phase velocity

(c) Transduction parameter

The transduction coefficient α, which is responsible for the excitation efficiency of the IDT, can be derived as [15]

$$\alpha(\omega) = \frac{Q_F(\beta)}{\Lambda_T}\sqrt{\frac{\omega W \Gamma_S}{2}} \quad (16)$$

with the Fourier transform of the elemental charge density Q_F defined as

$$Q_F(\beta) = \varepsilon_s(\infty)\frac{2\sin(\pi s)}{P_{-s}(-\cos\eta)}P_m(\cos\eta) \quad for\ m \le \frac{\beta p}{2\pi} \le m+1 \quad (17)$$

where W is the aperture of the IDT, $\varepsilon_S(\infty)$ is the surface effective permittivity as a function of the slowness, m is an integer, $s=(\beta p/2\pi)-m$, $P_{-s}(-\cos\eta)$ is a Legendre function and $P_m(\cos\eta)$ is a Legendre polynomial.

4. Insertion loss of two-port ZnO/IDT/Diamond layered SAW

In order to compare with the existing experimental data, we followed all the design parameters utilized in ref. [2] by Shikata et al. The thickness of the diamond layer was 15μm and that of the ZnO layer was h_{ZnO}=0.66μm. The design frequency was set to be 1480 MHz and at this frequency the free surface velocity of the second Rayleigh mode was calculated as $v_f = 8940$ m/s, while the coupling coefficient as 4.95%. The transduction period of the IDT was $\Lambda_T = 6\,\mu$m and the number of the IDT pairs was 40. The aperture of the SAW was W=200Λ_T, the metalization ratio $\eta = 0.5$ and the thickness of the finger electrode was 100 Å. The delay distance between the input and output IDTs was $15\frac{1}{8}\Lambda_T$.

Simulation results have shown that the proposed model could predict the bandwidth and most of the frequency characteristics of the layered SAW in quite a good accuracy. However, there is a down shift of the center frequency. The decrease of the center frequency may due to the prediction of the perturbed velocity due to the electrode gratings (Eq. (13)) was not accurate enough. We then tried the measured velocity of ref. [2], i.e., $v_f = 8880$ m/s, to calculate the insertion loss of the layered SAW as shown in Fig. 6. Results have shown that the calculated insertion loss matched quite well with that of the measured one.

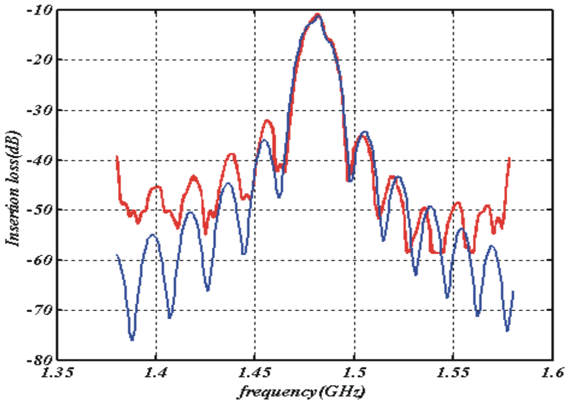


Fig. 6 Measured and calculated insertion loss

5. Conclusion

In this paper, we have extended the work of ref. [11] to calculate the effective permittivity of a ZnO/IDT/Diamond layered SAW. The effective permittivity approach was used to calculate the electromechanical coupling coefficient and the displacements and electrical potential of surface waves in the layered system. On the other hand, we have adopted the coupling of modes model to calculate the insertion loss of a two-port layered SAW. The frequency dependence of the COM parameters have been calculated for the first time and result has shown that the dispersive effect has to be considered in the design. The simulated insertion loss of a two-port ZnO/IDT/Diamond layered SAW has compared with that of the measured one in ref. [2]. Results have shown that except for a slightly center frequency shift, the proposed approach gave a very good prediction of the insertion loss of the layered SAW filter.

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