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Extractions of Reflection and Velocity Parameters for Surface Acoustic Wave in Two-Dimensional Piezoelectric Phononic Crystals

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***Abstract*—Two-dimensional (2D) piezoelectric phononic crystals (PnCs) have richer properties of band gaps than 1D PnCs but not enough study on the calculation of designing parameters such as reflection and velocity. This paper proposed a model to calculate these parameters of 2D piezoelectric PnCs with finite element method (FEM). In the model, by comparing two SAW delay line structures respectively with/without PnCs and using time domain window to wipe out triple reflection, reflection and velocity can be achieved. Through an example of 2D Nickel/128°YXLiNbO$_3$, it shows that the transmission and reflection of 2D piezoelectric PnCs change rapidly in the frequency band, which is different from the 1D IDTs, and the velocity of the SAW in the 2D PnCs is slower than in the free surface of the piezoelectric substrate.**

Key words—piezoelectric phononic crystals, three-dimensional finite element method, reflection, velocity

I. INTRODUCTION

Interdigital transducers (IDTs), as one-dimensional (1D) piezoelectric phononic crystals (PnCs) [1], have obtained much attention for many years because of the advantages of being conveniently excited and detected, high energy density in surface and slow velocity of surface acoustic wave (SAW). IDTs have been widely used in applications of resonators [2], filters [3] and sensors [4]. Much effort has been done to calculate the parameters such as reflection and velocity for designing SAW devices [5]. Recently, two-dimensional (2D) piezoelectric PnCs obtained more attention as they have richer properties of band gaps than 1D PnCs, such as forbidden bands, high reflection and localized state control, ultra broadband, negative refraction, low loss and acoustic focus [6]. In 2005, SAW on the micro air/silicon PnCs were theoretically and experimentally demonstrated by T.T. Wu [7] and then are applied to SAW devices such as waveguides [8] and high-Q resonant cavity [9], which indicates the 2D piezoelectric PnCs have potential in the applications of SAW devices.

Most of the literatures focus on deriving the transmission [10] and electromechanical coupling coefficients of 2D piezoelectric PnCs [11], in which the method of approximating 2D PnCs as 1D IDT was adopted for analyzing the 2D piezoelectric PnCs. However, the other important parameters such as reflection and velocity were not achieved for 2D PnCs.

This paper proposed a model to calculate the reflection and velocity of 2D piezoelectric PnCs with finite element method (FEM). In the model, two SAW delay line structures were introduced. Commercial software COMSOL MULTIPHYSICS was used to calculate the Y parameters of

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these two structures. Expression of reflection and transmission were derived by the analysis of S parameters with P matrix model. Then group delay time was obtained in the time domain by inverse Fourier transform (ifft) and thus the velocity of the SAW in the 2D PnCs was obtained. In this paper, firstly the theory for the calculation of reflection in 2D piezoelectric PnCs was introduced. Then as an example reflection and velocity of nickel/ 128ºYXLiNbO$_3$ piezoelectric PnCs were calculated. In the end results of the analysis were discussed.

II. THEORY FOR THE CALCULATION OF REFLECTION IN 2D PIEZOELECTRIC PNCS

The models of two three-dimensional (3D) SAW delay line structures used in reference [12] were adopted in this paper, which were both composed of several pairs of input IDTs and output IDTs, with and without 2D piezoelectric PnCs respectively. The 2D piezoelectric PnCs consisted of metal stubs on the piezoelectric substrate.

Firstly the received signal in frequency domain was calculated with FEM. Then the time domain signal can be obtained by ifft of the frequency signal. Afterwards by adding suitable window function in time domain to remove the reflection of triple-transition, the value of reflection and transmission can be extracted by comparing received signals of these two delay line models with and without PnCs. Group delay time can be also obtained in the above method and thus group velocity can be achieved.

A. *Introduction of the FEM model for calculation*

In the model, perfect matching layer (PML) was used in the direction of wave propagation (X direction) and the bottom of the substrate (Z direction) to absorb the reflective waves of the boundary. A period boundary condition (PBC) was used in the direction perpendicular to the wave propagation direction (Y direction) to reduce time and memory cost of the model.

In the PML area of the model, due to the high lossy media the waves can quickly decay [12]. PBC was adopted with all the field value which satisfies the Bloch periodic theorem, including displacement u, the strain S and the stress T. Free surface boundary conditions were adopted on the upper surface of the piezoelectric substrate, except for the area of the IDT and metal stubs. Expressions of these boundary conditions can be found in the reference [12].

B. *Analysis for the reflection of the 2D PnCs*

To analyze the reflection of 2D PnCs, P matrix model was used. As shown in Fig. 1, the models in reference [12] can be simplified with P matrix respectively.

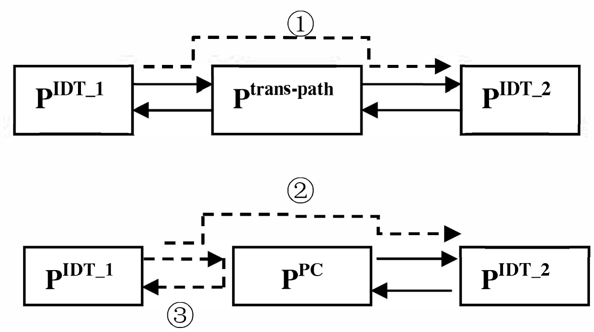

Fig.1. The P matrix of the model.

Comparing the transmitting path □ and the path □, and wiping out the triple reflection, the transmission of PnCs P_{21}^{PnC} can be obtained:

$$P_{21}^{PnC} = \frac{S_{21}^{PnC}}{S_{21}^{0}} P_{21}^{0} \qquad (1)$$

Where the S_{21}^{0}、S_{21}^{PnC} is the first signal received by the SAW delay line without and with PnCs respectively. P_{21}^{0} is the transmission of the transmitting path without PnCs, which is considered to be one in ideal.

Comparing the transmission path ①and the path ③, the reflection of PnCs P_{11}^{PnC} can be obtained:

$$P_{11}^{PnC} = \frac{S_{11}^{PnC\_r}}{S_{21}^{0}} P_{12}^{0} \qquad (2)$$

Where the $S_{11}^{PnC\text{-}r}$ is the first reflected signal received by the SAW delay line with PnCs.

To analyze this model, FEM commercial software COMSOL MULTIPHYSICS was employed. The emitting IDTs were employed with the sinusoidal voltage. Then through the simulating, the Y parameters can be obtained by analyzing the received signal of receiving IDTs. In order to analyze the propagation of the SAW in the 2D piezoelectric PnCs, S parameters should be derived by the Y parameters as follows :

$$S_{11} = \frac{\left(1 - Z_1^* Y_{11}\right)\left(1 + Z_2 Y_{22}\right) + Y_{12} Y_{21} Z_2 Z_2^*}{\left(1 + Z_1 Y_{11}\right)\left(1 + Z_2 Y_{22}\right) - Y_{12} Y_{21} Z_1 Z_2} \tag{3}$$

$$S_{21} = \frac{-2\sqrt{R_1 R_2} Y_{21}}{\left(1 + Z_1 Y_{11}\right)\left(1 + Z_2 Y_{22}\right) - Y_{12} Y_{21} Z_1 Z_2} \tag{4}$$

Where the Z_1, Z_2 are the impedances of the port1 and port 2 respectively.

Further to analyze the transmission and reflection, according to the expression (1) and expression (2), the useful signal should be extracted by adding the time domain window for the first received signal through Matlab program with wiping out triple reflection and the other useless signal.

III. REFLECTION AND VELOCITY OF NICKEL/ 128ºYXLiNbO$_3$ PIEZOELECTRIC PNCs

As an example, the calculation model for nickel(Ni) /128ºYXLiNbO$_3$ piezoelectric PnCs was conducted, in which two SAW delay line structures were built with four pairs of input IDTs and output IDTs. The 2D PnCs consisted of nickel stubs on the 128ºYXLiNbO$_3$ piezoelectric substrate. The period of the IDTs was 28um with the metallization ratio of 0.5. The distance between input IDTs' and output IDTs' edges was 130um. The lattice constant of the 2D PnCs was 10um, the radius and height of nickel stubs was respectively 4um and 2.2um.

The FEM model above with the commercial software COMSOL Multiphysics was used to calculate the Y parameters of these two structures. Based on the theory in part II, the received signals in time domain can be obtained by the ifft of the S parameters. To obtain the useful signal, the appropriate time domain window function of rectangular was applied as displayed in the Fig. 2, in which the triple reflection and the other useless signal were wiped out.

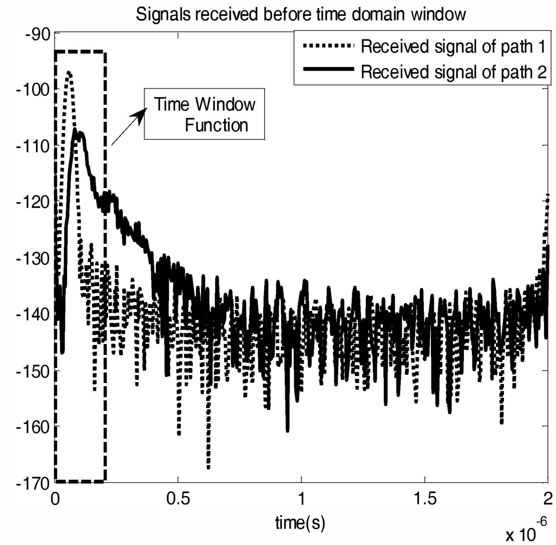

Fig.2 Received signals before and after time domain window.

Then the transmission and reflection parameters of the SAW in the 2D Ni/ 128ºYXLiNbO$_3$ were calculated as shown in Fig. 3. From Fig. 3, it can be seen in the band gaps (where the transmission is close to zero), the wave was mostly reflected (the reflection is close to 1). It also can be seen that the transmission and reflection changed rapidly in the frequency band studied here, which was different from the transmission and reflection of IDTs. Furthermore, from the Fig. 2 it can be obtained the calculated group delay time was 45ns and the distance of IDTs was 130um, so the group velocity was 2889m/s, which is smaller than the 3979m/s, the free surface velocity of the 128ºYXLiNbO$_3$ substrate.

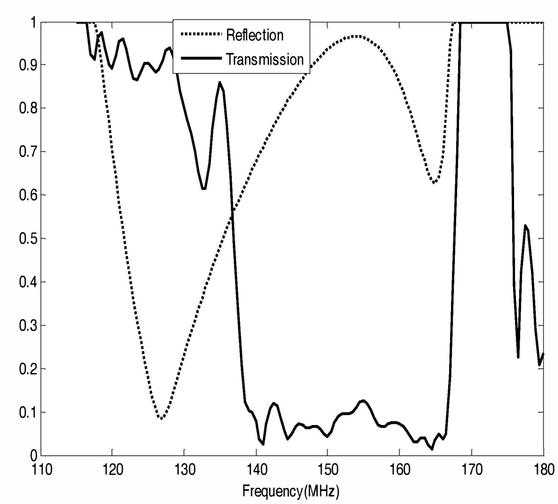

Fig.3 Reflection and transmission of Ni/128ºYXLiNbO$_3$ piezoelectric PnCs

IV. CONCLUSIONS

This paper has proposed a method to calculate the reflection and velocity of 2D piezoelectric PnCs by FEM. This method is based on the P matrix model and the extraction of useful signal with the time domain window. Through the calculated example of 2D Ni/ 128ºYXLiNbO3 piezoelectric PnCs, it is shown that the transmission and reflection of 2D piezoelectric PnCs change rapidly in the frequency band, which is different from the 1D IDTs, and also the velocity of the SAW in the 2D PnCs is slower than in the free surface of the piezoelectric substrate. The extracted parameters of 2D PnCs can be promising for future designing of SAW devices with PnCs.

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