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Analysis of Rayleigh Surface Acoustic Waves Propagation on Piezoelectric Phononic Crystal with 3-D Finite Element Model

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***Abstract*—In this paper, two surface acoustic wave (SAW) delay line structures respectively with and without phononic crystals (PCs) were applied to analyze the propagation of Rayleigh SAW in the 2D piezoelectric PCs in theory. Three-dimensional (3D) finite element method (FEM) was adopted to analyze the model using the commercial software COMSOL MULTIPHYSICS. Experiments were also designed to verify the theoretical results, which show good consistency with the theoretical results. Thus this model can be used to analyze more other structures of 2D piezoelectric PCs, which can be applied to improve the performance of SAW devices.**

***Key words*—piezoelectric phononic crystals, three-dimensional finite element method, transmission, surface acoustic wave**

I. INTRODUCTION

Phononic crystals [1] (PCs) are periodic elastic structures composed of scattering inclusions located in a homogeneous by the structure. In recent years, for applying PCs to micro-electro-mechanical systems, band gaps of PCs at hundreds of MHz and GHz with micro size were studied. It's reported that two-dimensional (2D) micro-PCs with integrated piezoelectric couplers suspended from the host substrate using Si micromachining located in a SiO_2 matrix [3-5] for bulk acoustic waves (BAW) devices. Thus devices with ultra high frequency PCs operating in mobile communication bands were realized [6]. Also with the 2D micro piezoelectric PCs, high performances of BAW cavities and waveguidings were studied [7-8]. However, comparing with BAW devices, SAW devices are widely used for many years because of the advantage of slow velocity of SAW [9-10]. To apply the PCs to SAW devices, SAW on the micro air/silicon PCs were theoretically and experimentally demonstrated by T.T. Wu [11] in 2005 and then were applied to SAW devices such as waveguides [12] and high-Q resonant cavity [13]. Thus 2D micro piezoelectric PCs have potential in applications.

For the novel 2D piezoelectric PCs composed of aluminum (Al) stubs on the 128^{o}-YXLiNbO$_3$ piezoelectric substrate, which were easily realized in the SAW devices by wet etching, Zhao [14] has proposed the 2D FDTD model to analyze the propagation of SAW on the PCs. However the results show large deviation because of taking hypothetic line exciting source and not considering the mechanical loading effect of finite-thickness stubs.

In this paper, two SAW delay line structures were introduced respectively with and without 2D Al/128 ^{o}

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-YXLiNbO$_3$ PCs, which were analyzed by three-dimensional (3D) finite element method (FEM) using commercial software COMSOL MULTIPHYSICS. Through this model, Rayleigh SAW can be excited and received by the interdigital transducers (IDTs). Transmission coefficients of 2D PCs are obtained through S parameters of these two structures, which were derived by the Y parameters. Experiments were then designed to verify the theoretical results. The calculation results show well consistent with the experimental results comparing with the 2D FDTD, which indicates the 3D FEM model is more efficient.

II. THE 3D FEM MODEL OF 2D PIEZOELECTRIC PCS

Fig. 1 displays the 3D SAW delay line structures composing of several pairs of emitting and receiving IDTs, and respectively with and without PCs on the transmitting path. With these two SAW delay line structures the transmission coefficients of PCs can be obtained.

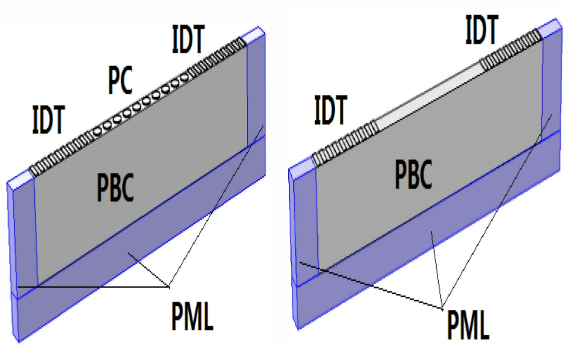

Fig.1. The SAW delay line structures used in the calculation.

FEM was used in the model to analyze the propagation of SAW in the 2D piezoelectric PCs. In the calculating model, the direction of wave propagation and perpendicular to the wave propagation plane was adopted as x direction and z direction respectively. Perfect matching layers (PML) are adopted in the direction of wave propagation to prevent the reflection of the boundary. Perpendicular to the wave propagation in the plane, considering countless periods, periodic boundary condition (PBC) was adopted to reduce the cost of time and memory of computing.

A. *Analysis of piezoelectric coupling equations*

For the piezoelectric materials of substrate, there exits the piezoelectric constitutive equation:

$$D = \varepsilon^S \cdot E + e : S \tag{1}$$

And the Newton motion equation of elastic materials:

$$\nabla \cdot T = \rho \frac{\partial^2 u}{\partial t^2} - F \tag{2}$$

Without external force and electrical fields, combining the equation (1) and equation (2), coupling wave equation can be obtained:

$$\rho \frac{\partial^2 u_i}{\partial t^2} - c^E_{ijkl} e_{kij} \frac{\partial^2 \varphi}{\partial x_k \partial x_j} = 0 \tag{3}$$

High lossy media was introduced in the PML area, in which the waves can quickly decay. Therefore, with finite thickness of the PML layer, the wave can be completely absorbed without the reflection of the boundary. In calculation, the attenuation factor of the PML is usually expressed by the following expression [15]:

$$\sigma(x) = \sigma_{\max} (x/d)^2 \tag{4}$$

Where d is the thickness of the PML layers, x is the distance away from the inner boundary of the PML area, σ_{max} is the maximum of the attenuation on the PML outer boundary.

PBC was adopted in the y direction:

$$\Phi|_{y=0} = \Phi|_{y=b} \tag{5}$$

Where the Φ denotes all the field value which satisfies the Bloch periodic theorem, including displacement u, the stress T and the strain S ; b is the periodic of 2D piezoelectric PCs in the y direction.

On the upper surface of the piezoelectric substrate, except for the area of the IDT and metal stubs, free surface boundary conditions were adopted:

$$T_{ij}|_{z=0} = 0 \tag{6}$$

The emitting IDTs were employed with the sinusoidal voltage through the FEM commercial software COMSOL MULTIPHYISCS. Then the transmission parameters can be obtained comparing the signal of the receiving IDTs with the emitting signal.

B. The calculation of 2D piezoelectric Al/128^o-YXLiNbO$_3$ PCs

Based on the theory above, as an example, transmission of 2D piezoelectric Al/128^o-YXLiNbO$_3$ PCs were analyzed with the structure parameters: the period, the thickness and the diameter of aluminum stubs are 10um, 0.6um and 7um respectively. To obtain wide range of working frequency band, only four pairs of emitting and receiving IDTs were adopted in the SAW delay line model with the period of 12um and the metalization ratio of 0.5. Then two SAW delay line structures with and without PCs respectively were simulated by the COMSOL MULTIPHYISCS. Thus the Y parameters of these two structures were extracted. Using the Y parameter, S parameters can be derived through the Matlab program. Then the transmission coefficients of SAW on the 2D piezoelectric PCs can be obtained through data post-processing using Matlab. The results were displayed in the Fig. 2.

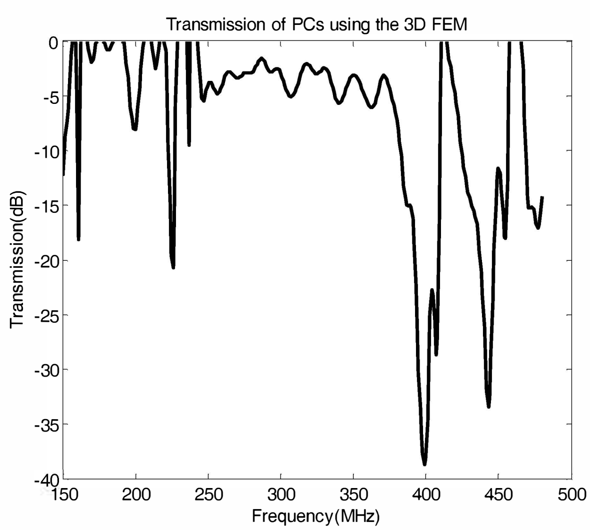

Fig.2. The transmission coefficients of the 2D PCs.

Furthermore, the displacement field was extracted from the calculation results as shown in Fig. 3. From the Fig. 3, it can be seen that the energy of the wave are mainly concentrated on the surface and the displacement component are mainly distributed in the x and z direction, which satisfied the characters of the Rayleigh SAW. This indicated that the model is efficient to simulate the excitation, transmission and reception of the Rayleigh SAW.

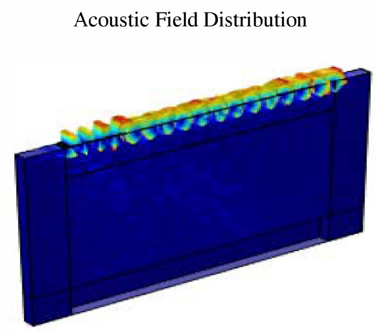

Fig.3. The acoustic field distribution after calculation.

III. EXPERIMENTS AND ANALYSIS

To verify the theoretical results, experiments were designed. Firstly, two SAW delay line structures composed of four pairs of emitting and receiving IDTs, and 2D piezoelectric Al/128^o YX-LiNbO$_3$ PCs were fabricated with the technology of MEMS fabrication process, which includes photolithography and wet etching. The structures adopted the same structural parameters with the theory. Then transmission coefficients of S parameters in the x direction of SAW delay line structures with and without PCs were measured by the network analyze respectively. Afterwards, in order to filter the mixing wave including the triple reflection signal, time domain window was adopted to extract the useful signal. Through this, the transmission coefficients of SAW propagation on the 2D piezoelectric PCs can be obtained by subtracting these two S_{21} parameters.

Fig. 4 displays the results of transmission from experiments, 2D FDTD calculation in [14] and 3D FEM calculation in this paper. From the Fig. 4, it can be seen that the 3D FEM calculation model proposed in this paper was more accurate than the 2D FDTD calculation comparing with the experimental results, which indicates the model proposed in this paper was efficient.

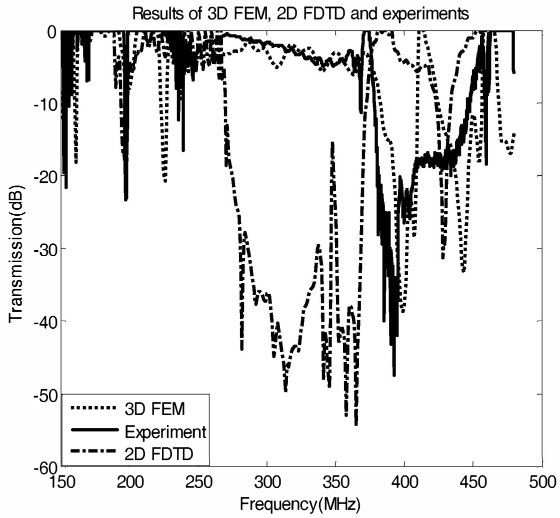

Fig.4. The results of 3D FEM, 2D FDTD and experiments.

IV. CONCLUSIONS

This paper has proposed a 3D FEM model with two SAW delay line structures to analyze the transmission of Rayleigh SAW in the 2D piezoelectric PCs. Experiments were also designed to verify the theoretical results. Comparing results of experiments, 2D FDTD calculation and 3D FEM calculation, the 3D FEM calculation method in this paper was more accurate, which indicates the method is efficient. This method can be used to analyze other more 2D piezoelectric PCs to make full use of the PCs in SAW devices.

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