A WEIGHTED WAVEGUIDE FOR SURFACE ACOUSTIC WAVES BASED ON TWO-DIMENSIONAL PIZOELECTRIC PHONONIC CRYSTALS

Ya-hui TIAN[1], Hong-lang LI[1 *], Wen-jia TIAN[1], Ya-bing KE[1], Jin-ling Chen[2], Shi-tang HE[1]

[1] Institute of Acoustics, Chinese Academy of Sciences, Beijing, P.R. China, 100190
[2] Santai Crystal Electronic, Sichuan, P.R. China, 621100
*Corresponding author, E-mail: lhl@mail.ioa.ac.cn; Tel.: 010-82547805

This paper has proposed a weighted waveguide for surface acoustic waves (SAW) based on two-dimensional piezoelectric phononic crystals (PnCs). In order to analyze the transmission of the weighted waveguide based on PnCs, SAW delay line model was built. In the model, period boundary condition was adopted to reduce the time and memory of model cost and perfect matching layer was adopted to absorb the reflection of the waves. Three-dimensional finite element method (FEM) was used to calculate the transmission coefficients and analyze the acoustic field distribution. Results showed that the band gaps and band passes are separated in the x and y direction. Thus the weighted waveguide can prohibit the waves in one direction while permit the waves in another direction. This property of weighted waveguide can be used in the SAW devices in the future study.

Keywords: Phononic crystal; Piezoelectric; Weighted waveguide; Surface acoustic waves

1. INTRODUCTION

Phononic crystals [1] (PnCs) composed of periodic elastic materials have been proved to have a property of band gaps. With the unique properties, PnCs have potential in applications such as elastic filters [2], couplers [3], resonators [4] and waveguides [5]. Much research has been conducted with the bulk acoustic waves (BAW) waveguides based on the two-dimensional (2D) PnCs. The designs include straight waveguides with various widths [5], waveguides with stubs [6], a waveguide with hollow cylinders [7] and a coupler of joined parallel waveguides. In contrast, study of waveguides based on PnCs for surface acoustic waves (SAW) has had less progress. Tananka and Tamura analyzed the surface and surface-guided waves in phononic crystals lattices [8] in 2007. Jia-hong Sun and Tsung-tsong Wu [9] proposed a sharply bent waveguide base on 2D PnCs in 2006. However most of the waveguides are based on the defect PnCs, and neither of investigations on other SAW waveguides are studied.

Since one-dimensional PnCs, interdigital transducers (IDTs), have been studied for many years, many weighted IDTs such as apodized, withdraw, width and series of weighted IDTs [10], appeared to obtain specified response through different weighting shape in one dimension. However, 2D PnCs which can be weighted in two dimension, are not reported to be used for weighted waveguides.

This paper proposed a weighted SAW waveguide structure based on 2D piezoelectric PnCs without introducing defect. The weighting function of waveguide was achieved through different lattice constants in the x and y direction. To analyze this waveguide a SAW delay line model was introduced. For an example, the piezoelectric PnCs consisted of Cuprum (Cu) stubs on the 128°YXLiNbO3 substrate was adopted for weighted SAW waveguide, and the transmission coefficients and acoustic field distribution of this weighted waveguide was calculated using the above model..

2. ANALYSIS OF THE WEIGHTED SAW WAVEGUIDE

The band gaps and band passes of 2D piezoelectric PnCs are most related to its lattice constants. With different lattice constants in the x and y direction, band gaps and band passes in the x and y direction will be separated, from which the frequency band of prohibiting the waves in one direction while permitting the waves in another direction will be found so that the weighted SAW waveguide can be realized.

In order to analyze the character of the above weighted SAW waveguide, a SAW delay line model was first introduced to calculate its transmission coefficients, through whichband passes and band gaps with different lattice constants can be calculated. In the model, the acoustic field distribution of the weighted waveguides can also be extracted.

978-1-4799-6425-3/14/$31.00

2.1 Model for analysis of 2D piezoelectricPnCs

Three-dimensional (3D) finite element method (FEM) was adopted in the calculating model to analyze. In order to calculate the transmission of the PnCs, SAW delay line structure model was built as shown in the Figure1. In the model, four pairs of emitting and receiving interdigital transducers (IDTs) were introduced to emit and receive the Rayleigh SAW and the 2D piezoelectric PnCs were on the transmitting path.

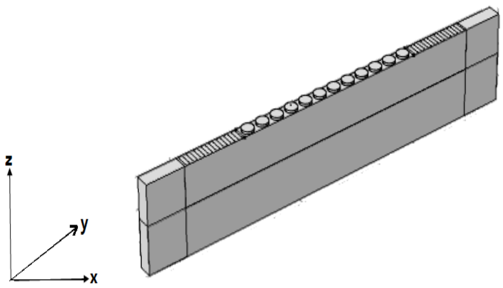

Figure1. The SAW delay line model for calculation

For the piezoelectric materials of substrate, the piezoelectric constitutive equation exits as following：

$$D = \varepsilon^S \cdot E + e : S \quad (1)$$

For the elastic materials, the Newton motion equation was as formula (2)：

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

Then the coupling wave equation for piezoelectric substrate can be obtained by combing the equation (1) and equation (2) without external force and electrical fields:

$$\rho \frac{\partial^2 u_i}{\partial t^2} - c_{ijkl}^E e_{kij} \frac{\partial^2 \varphi}{\partial x_k \partial x_j} = 0 \quad (3)$$

In the model, perfect match layer (PML) was adopted in the direction of wave propagation to absorb the reflection of the wave. In the PML area, high lossy media was introduced in which the waves can quickly decay. Therefore, with finite thickness of the PML layer, the wave can be completely absorbed without reflection in the boundary areas. In practice, the attenuation factor of the PML is usually expressed by the following expression [11]:

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

Periodic boundary condition (PBC) shown in formula (5) was adopted in the direction perpendicular to the wave propagation to reduce the time and memory:

$$\Phi \mid_{y=0} = \Phi \mid_{y=b} \quad (5)$$

Where the Φ denotes all the field value which satisfies the Bloch periodic theorem, including the displacement u, the stress T and the strain S ; b is the period 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 as following:

$$T_{ij} \mid_{z=0} = 0 \quad (6)$$

In the model, two interdigital transducers (IDT) were used as the emitter and the receiver for wave signal. With the FEM commercial software COMSOL Multiphysics and post-processing using Matlab to analyze the above model, transmission coefficients of the PnCs can be obtained.

2.2 Results of the transmission coefficients

Using the above method, transmission of SAW in the x and y direction were respectively analyzed both with common 2D PnCs and the weighted waveguide 2D PnCs. As an example, the Cu/128°YXLiNbO3 PnCs were adopted.

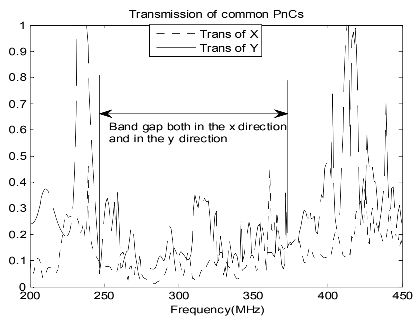

Figure 2. The transmission coefficients of PnCs with the ratio of 1.

For the common 2D PnCs, the lattice constant ratio of x direction and y direction is 1. The transmission coefficients of this structure was calculated and its results were shown in the Figure2. From this figure, it can be seen that in the frequency from 260MHz to 355MHz band gap existed both in the x direction and in the y direction.

In order to find the weighted waveguide for prohibiting wave in one direction and permitting wave in another direction, the transmissions coefficients of different lattice constant ratio for the Cu/128°YXLiNbO$_3$ PnCs were calculated, which results are listed as the table 1.

Table 1. Results of the transmission for the different lattice constant ratio.

b/a(lattice constant ratio in the x direction and in the y direction)	Band gaps distribution
1	260-355MHz: Band gap both in the x direction and in the y direction
2	290-310MHz: Band pass in the x direction but band gap in the y direction
3	260-320MHz: Band pass in the x direction but band gap in the y direction
5	260-315MHz: Band pass in the x direction but band gap in the y direction

From the table 1, it can be seen that when the ratio of the lattice constant in the x direction and in the y direction is changing from 1 to 5, band pass and band gap separates in these two directions. As shown in the table 1, when b/a equals 1 band gap exists both in the x direction and in the y direction in the frequency range of 260-355MHz. When the b/a equals 2, band pass exists in the x direction while band gap exists in the y direction in the frequency range of 290-310MHz. When the b/a equals 3, band pass exists in the x direction while band gap exists in the y direction in the frequency range from 260MHz to 320MHz. When the b/a equals 5, band pass exists in the x direction while band gap exists in the y direction in the frequency range of 260-315MHz. Thus when the lattice constant in these two directions are not equal, it can be found that the frequency band exists with prohibiting the waves in one direction while permitting the waves in another direction, which can be used for the weighted waveguide. . Figure3 shows the transmission coefficients of weighted waveguide based on 2D piezoelectric PnCs with the lattice constant ratio of 5.

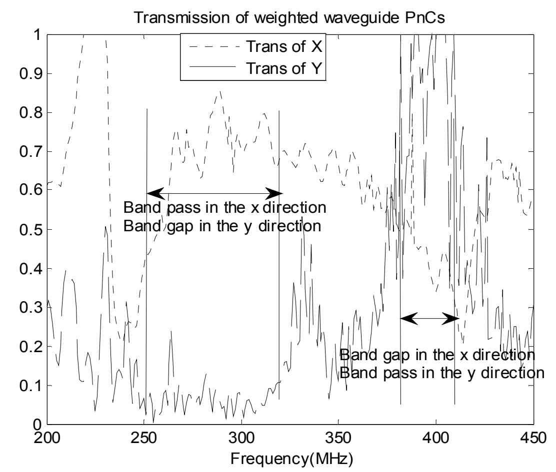

Figure 3. The transmission coefficients of PnCs with the ratio of 5

2.3 Results of the acoustic field distribution

In order to further analyze the properties of the weighted waveguide based on 2D piezoelectric PnCs structure, acoustic fields in the x direction at 300MHz of the common PnCs and the weighted waveguide PnCs were respectively extracted as shown in the Figure 4 and Figure 5. From these figures, it can be seen that in the x direction the wave was prohibited by the common PnCs while it was permitted by the weighted waveguide PnCs. Moreover the acoustic field on the surface at 300MHz in the y direction was extracted as shown in the Figure6 and Figure7. Comparing these figures, it can be seen that at 300MHz where band pass existed in the x direction of weighted waveguide, most energy has passed through the PnCs while band gap existed in the y direction of weighted waveguide, the energy is reflected by the PnCs.

From the acoustic field distribution analysis, it can be concluded that the weighted waveguide proposed in this paper based on 2D piezoelectric PnCs with different lattice constant in the x direction and the y direction can achieve prohibiting the waves in one direction while permitting the waves in another direction.

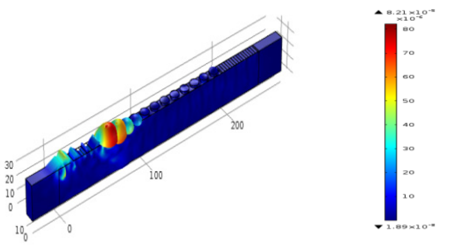

Figure 4. The acoustic field in the x direction at 300MHz when b/a is 1.

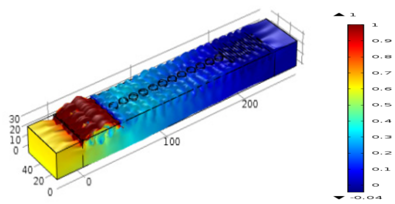

Figure 5. The acoustic field in the x direction at 300MHz when b/a is 5.

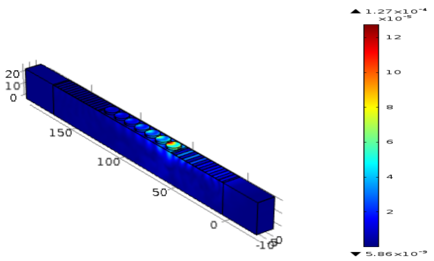

Figure 6. The acoustic field in the y direction at 300MHz when b/a is 1.

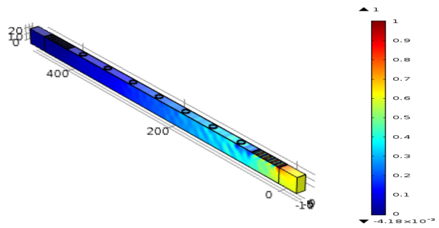

Figure 7. The acoustic field in the y direction at 300MHz when b/a is 5.

3. DISCUSSION AND CONCLUSIONS

Comparing the transmission of common PnCs and the weighted waveguide, it is shown that the weighted waveguide with altering the lattice constant ratio can be used as the waveguides which prohibits the waves in one direction while permits the waves in another direction. The distributions of the acoustic field was also extracted to confirm the SAW waveguides.

This paper also proposed a model to analyze the weighted waveguide and to calculate the transmission coefficients of this weighted waveguide, which is useful for designing 2D piezoelectric PnCs in the SAW devices such as resonators and sensors. Also experiments are awaited for this structure to verify the theoretical results.

ACKNOWLEDGEMENTS

The work was supported by the National Natural Science Foundation of China (11174318, 11304346), National High Technology Research and Development Program (863 Program) (SS2013AA041103), Beijing Municipal Science and Technology Commission Project (Z141100003814016) and Tianjin Municipal Science and Technology Commission Project (13RCHZGX01093).

REFERENCES

[1] Sigalas MM. Elastic and acoustic wave band structure. *J. Sound Vib.* 158: 377-382, 1992.

[2] Sun JH, Lan CW, et al. A ZnO/silicon Lamb wave filter using phononic crystals. In: *Proc. IEEE Frequency Control Symp.*, pp:1-4, 2012.

[3] Olsson RH, Fleming J G, et al. Micromachined bulk wave acoustic bandgapdeices. *Transducers & Equrosensors*. pp.317-321, 2007.

[4] Wu TT, Hsu CH, et al. Design of a highly magnified directional acoustic source based on the resonant cavity of two-dimensional phononic crystals. *Appl. Phys. Lett.* 89: 171912, 2006.

[5] Sun JH, Wu TT. Analyses of surface acoustic wave propagation in phononic crystal waveguides using FDTD method. In: *Proc. IEEE UltrasoncisSymp.,* pp.73-76, 2005.

[6] Hsu JC, Wu TT, et al. Measurement of frequency gaps and waveguiding in phononic plates with periodic stepped cylinders using pulsed laser generated ultrasound. *J. Appl. Phys.* 113: 083511, 2013.

[7] Kuo NK, Piazza, G. Evidence of acoustic wave focusing in a microscale 630MHz Aluminum Nitride phononic crystal waveguide. *In: Proc. 2010 IEEE International Frequency Control Symp*., 530-533,2010.

[8] Tanaka Y, Yano T, et al. Surface guided waves in two-dimensional phononic crystals. Wave Motion, 44 : 501-512, 2007.

[9] Sun JH, Wu TT. Guided surface acoustic waves in phononic crystal waveguides. *In: Proc. 2006 IEEE Ultrasonics Symp*., pp. 673-676, 2006.

[10] Hashimoto K. *Surface acoustic wave divices in telecommunications modelling and simulation.* National defence industry Press, Beijing, 2002.

[11] Allen T. *Computational Electrodynamics: The Finite Difference Time Domain Method.* Second Edition. Boston London: Artech House, 2000: 285-625, 2000.