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Tailoring 2D phononic crystal sensor properties by lattice symmetry reduction

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Abstract

We propose a novel method of tailoring the band structure of 2D phononic crystals (PnC) by reducing the lattice symmetry. Specifically, symmetry reduction by stretching and distorting the crystal face is explored. The transmission spectrum of the PnC was numerically calculated using the layer multiple-scattering method. Change in the shape and size of the band gaps is demonstrated as well as form of pass bands inside the stop band. The practical feasibility of the PnC sensor concept was evaluated for the case of synthetic quartz matrix and water inclusions. A distinct pattern of the pass band transformation inside the stop band which is induced by changing the distortion angle was demonstrated. The approach is in particular useful in adjusting the size and position of the gap and tailoring the size and position of the pass band in PnC sensors.

Keywords: Phononic crystal sensor; phononic crystals; reduced symmetry.

1. Motivation

The first work dealing with PnC sensors [1] has revealed the significance of properly arranged pass band inside the complete gap for the sensor purposes. In artificial periodic structures like PnC the resulting combined effect of interference caused by Bragg diffraction and the Mie resonances is usually assumed to be the conceptual base of a complete band gap. The proper choice of the lattice parameters and the matching of the materials may give requisite band structure, especially when continuum properties of the matrix and inclusions are substantially different. However, if we keep on the track of silicon based batch fabrication we are strictly limited in the kind of materials we can use. Moreover, when the inclusion material, which is preferably a liquid, is in fact given with the material to be analyzed, the sensor design must account for this restriction as well.

Usually five mismatched parameters are considered being involved in the problem, namely, the ratio of the mass densities, ratio of the longitudinal velocities, ratio of the transverse velocities, ratio of the longitudinal and

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transverse velocities, and the filling fraction. In the case of periodic structures composed of liquids and solids only three parameters will effectively be involved since only longitudinal modes are supported therein. Input from resonance properties of the individual scatters, which mainly depends on their size and shape may also be involved in some occasions. Unfortunately none of these parameters can be employed as an adjustment factor in tailoring the band gap structure appropriate for the intended sensor design. The resonance properties of the individual scatters are variables rather than parameters since the change in these properties is expected to be a measure for the sensor. It has been also observed that the band structure characteristics are relatively independent of the lattice structure and the scatters filling ratio [2]. Thus, neither period of the structure nor the size of the scatters can be used to tailor the band gap appropriately. The choice of matrix materials determining the coupling parameters is also limited as stated above.

It is known in the art that the band gap can be varied reducing or breaking the lattice symmetry. The addition of an extra inclusion into the center of each lattice unit cell or varying the size or shape of one or some of the inclusions result in lift or reduction of the band degeneracies and form larger band gaps. The subtraction of an inclusion from the initial unit cell may also change the effective width of the band and may even open an additional pass band for the more symmetric structures. Both an addition and subtraction of the inclusion give rise to defect modes by disturbing the ordered structures. Unfortunately an effect of these modes is rather limited in terms of their usefulness since defect modes depend on the same structural and material factors like the eigenmodes of the system.

More complex higher-symmetric quasiperiodic or randomized structures which are devoid of inherent structural anisotropy of periodic arrangements can be an alternative. Quasiperiodic PnCs combining structures with purely point-diffractive spectra of arbitrarily high rotational symmetry into perfectly ordered translationally periodic lattices may have a dense set of discrete Bragg diffraction patterns. Each set of symmetrically equivalent peaks may form a pseudo-Brillouin zone of arbitrarily high symmetry, which can induce a requisite band structure. However, formation of the Bragg gaps in quasiperiodic heterostructures still remains under intensive discussions and it is still obscure what factors has the dominant effect on the transmission property.

2. Implementation

Our research on this subject showed that probably the simultaneous and coherent change in both Bragg diffraction and resonance scattering properties may be an optimal choice so far as complete gaps depend on the joint effect of the Bragg diffraction and the Mie scattering. The gradual change of the face of the lattice into the distorted state from its common crystallographic shape, typically they are square, triangle or hexagonal, effects on both Bragg diffraction and resonance scattering. Both stretching and distorting the face perpendicular to the out-of-plane z-axis change the coupling parameters as well as they depend on the distance between scatters. The stretching or shrinking of the face of the initial unit cell results in the change of the coupling strength between individual scatters, which in turn results in the change of the resonance band-widths. Similar, stretching or shrinking the face changes the distance between scattering planes which leads to the change in the position of the Bragg gap, since the condition for interference from successive planes depends on the distance between these planes. The distortion of the face may also change the position of the Bragg gap so far the distortion changes the distance between scattering planes, as well. Furthermore, the distortion may create an additional Bragg gap because it introduces additional scattering planes while changing simultaneously both parameters in the Bragg's law.

Proceeding from this base, we have calculated the transmission spectrum for 2D PnC with both stretched and distorted lattices. The transmission spectrum was calculated using modified layer multiple-scattering (LMST) method described in detail in [3]. We adopt the LMST since the method shows significant advantages of fast convergence speed that makes it useful for the PnC design modeling. The model finite two-dimensional PnC slab consists of a number of stacked infinite layers (infinite planes of infinite cylinders) of scatters. Individual cylinder scatters in a monolayer are arranged periodically along the *x*-axis with $\mathbf{a}_1$ being a primitive vector. Identical monolayers are stacked one by one along the *y*-axis with the other primitive vector $\mathbf{a}_2$ that finally builds a finite phononic crystal slab (see Fig. 1).

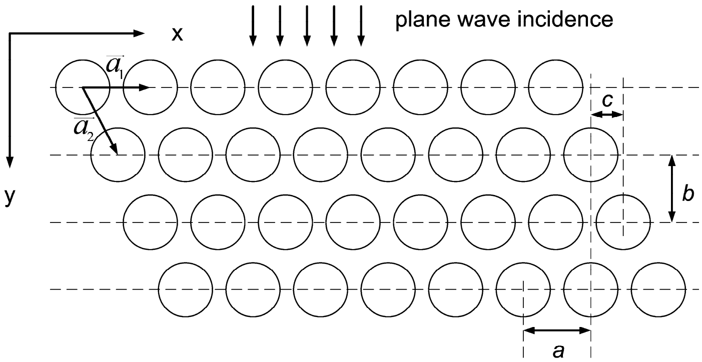

Fig. 1. The LMST model schematic for a two-dimensional PnC consisting of *n* identical monolayers with $\mathbf{a_1}$ and $\mathbf{a_2}$ being primitive vectors; a,b and c denote, respectively $|\mathbf{a_1}|$, $|(\mathbf{a_2})_y|$ and $|(\mathbf{a_2})_x|$.

3. Results

An eight-layer arrangement of infinite length cylinders has been chosen because it provides a band structure with sufficiently developed stop bands in a wide range of filling fractions for given materials. As a result we have demonstrated both expected changes in the shape and size of the band gaps as well as form of the pass band inside the stop band.

The example in Fig. 2 displays a transmission spectrum simulation for the above described LMST model with undisturbed square lattice (black) and square lattice stretched in Y-direction (green). We use following parameters in this simulation: the matrix material is synthetic quartz with longitudinal sound speed v_L=67200 m/s and density ρ_q= 2.53 g/cm^3; the inclusion is sea water with sound speed v_w=1500 m/s and density ρ_w= 1.028 g/cm^3; the undisturbed lattice constant is equal 1.0 mm; and the filling fraction is 0.28.

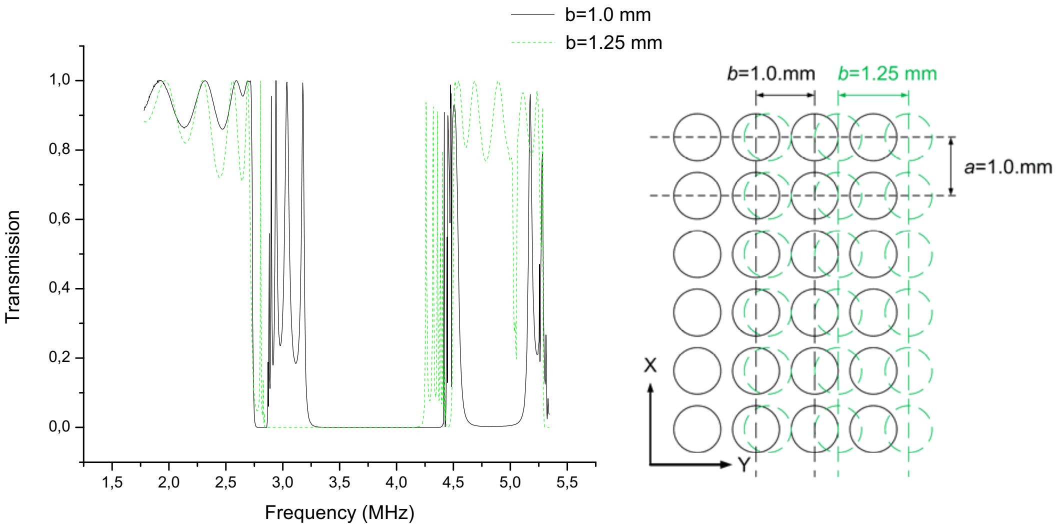

Fig. 2. Transmission spectrum of longitudinal waves in theY direction through undistorted and stretched phononic crystals. The holes in the quartz matrix are filled with sea water. The insert shows the schematic of the LMST model for two-dimensional undistorted (black) and stretched (green) PnCs.

We can see that transmission spectrum for the undisturbed PnC shows well developed composition of Bragg-like band gaps and complete band gaps. Symmetry reduction by stretching the lattice alongside the Y-direction causes simultaneous widening and downward shift of the first complete band gap. In contrast, the stretch alongside the X-direction causes also simultaneous downward shift of the first complete band gap but contraction (not shown).

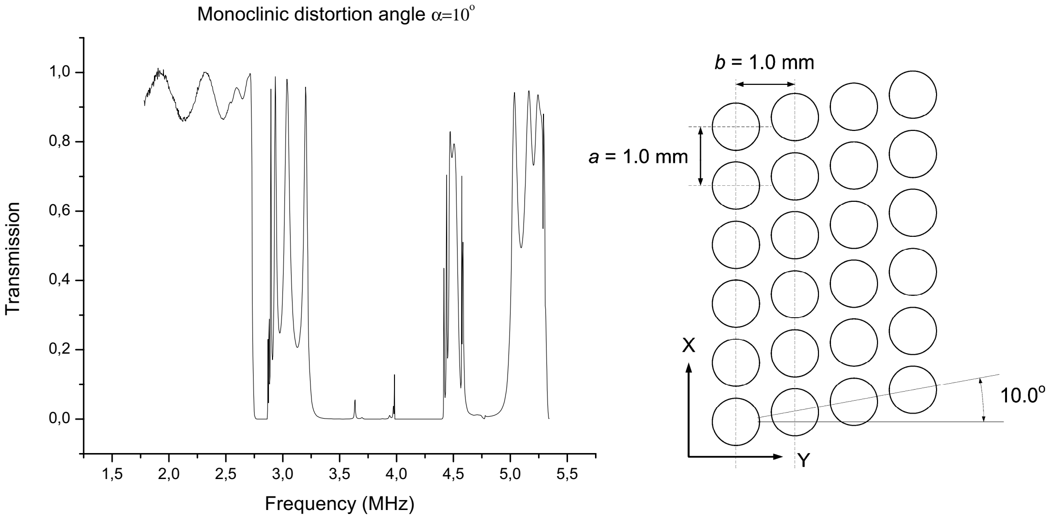

Fig.3. Transmission spectrum of longitudinal waves in the Y-direction through monoclinically distorted PnC. The matrix and inclusion materials are the same as above: the quartz matrix which is filled with sea water. The insert shows the schematic of the LMST model for two-dimensional monoclinically distorted lattice.

Fig. 3 illustrates another interesting phenomenon we observe. Monoclinic distortion of the square lattice in PnC causes formation and change of the Bragg-like pass band inside the stop band. Thus, combining stop and pass band reshaping by gradual lattice stretching and distortion we can realize almost any required for PnC sensor applications band structure features.

In conclusion, our results apparently confirm that this approach is useful in adjusting the size and position of the gap and tailoring the size and position of the pass band which has to be used as liquid properties measure. More generally, reduction of the face symmetry provides a rational method to optimize both the PnC sensor design and its relevant parameters thereby opening up an alternative route to PnC sensor engineering and enabling its further improvements.

Acknowledgements

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References

[1] Lucklum R, Li J. Phononic crystals for liquid sensor applications. *Meas. Sci. Technol.* 2009; **20:** 124014.

[2] Sigalas M, Kushwaha MS, Economou EN, Kafesaki M, Psarobas IE, Steurer W. Classical vibrational modes in phononic lattices: theory and experiment. *Z. Kristallogr*. 2005; **220**: 765–809.

[3] Qiu C, Liu Z, Mei J, Ke M. The layer multiple-scattering method for calculating transmission coefficients of 2D phononic crystals. *Solid State Commun.* 2005; **134:** 765-70.