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Manipulation of Acoustic Waves Based on Coupled-Resonator Acoustic Waveguides

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Abstract: Guidance in a sonic or phononic crystal is not limited to linear lines of defects. Actually, any chain of defects acting as cavities can become a waveguide, providing the cavities are not too far away from one another and they have the same initial resonant frequency. This is the basic idea of the coupled-resonator acoustic waveguide. Here, we first investigate dispersion relations of CRAWs based on a two-dimensional phononic crystal composed of cylindrical mercury in water in a square lattice. Cavity is introduced by replacing one mercury cylinder with water. Then, transmission properties of CRAWs with different circuits are examined. Numerical results suggest that manipulation of acoustic waves can be realized based on CRAWs. The work is this paper is relevant to the design of new acoustic wave devices.

Phononic crystals (PCs) are a kind of acoustic functional composite materials/structures with some forms of spatial periodicity[1]. They can exhibit elastic/acoustic bandgaps in some frequency ranges, within which the wave propagation is prohibited. One significant consequence of such a unique property is the possibility to control and manipulate the propagation of acoustic and elastic waves in integrated technological circuits. Consequently, numerous applications of PCs were proposed such as filtering, multiplexing, sound isolation, frequency dependent waveguiding[2,3], and mass sensing.

Influence factors of band gaps and their modulation have become one of the research concerns. ‘Banggap engineering’ is thus proposed to realize the control of wave propagation. Mechanisms of band gap generation are mainly Bragg scattering, local resonance and their hybridization[4]. Frequency ranges of band gaps are dependent on the material parameters, lattice forms, topology of unit cells, and the connection form between scatters and matrix. For Bragg phononic crystals, the influential material parameters are the ratios of velocities and impendences between different components. The locally resonant band gaps, however, are generaly generated by the weak connection between scatters and matrix.

In addition to the analysis of band gaps, study of wave propagation in PCs also includes the confinement and guiding of elastic/acoustic energy through the use of defects in perfect PCs. Guidance in a sonic or phononic crystal is not limited to linear lines of defects[3]. A different guiding mechanism is coupling the evanescent fields of a linear chain of defect cavities or resonators inside the channel[5,6], similar to coupled resonator optical waveguides in photonic crystals[7]. In such waveguides, the dispersion relation is determined by coupling strength of the resonators allowing its fine tuning by varying their distance.

In this paper, we discuss the dispersion relations of coupled resonator acoustic waveguides (CRAWs) based on a two-dimensional PC composed of cylindrical mercury embedded in water in a square lattice. Defect cavity is introduced by replacing the

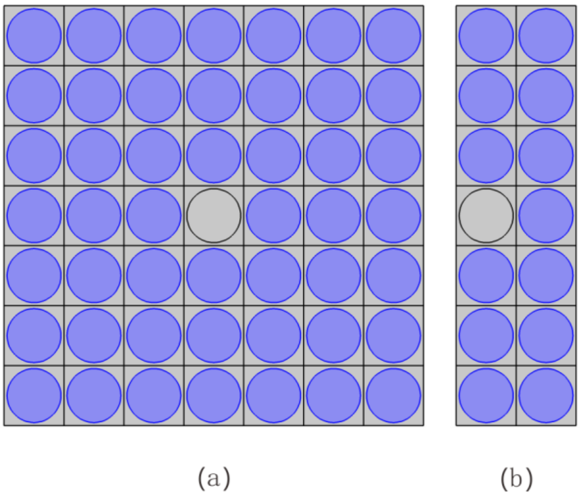
(a) (b)

Figure 1 Supercells used for the calculation of the band structures for (a) a cavity formed by a single point defect in the two-dimensional square lattice PC and (b) a coupledre sonator acoustic waveguide (CRAW) created in the same PC. The gray and blue parts represent for water, and mercury, respectively. The lattice constant between adjacent cylinders is *a*.

mercury with water. Numerical simulation are implmented by finite element method (FEM). Cavities with different spearations are considered. Pressure distributions of eigenmodes at the band gap edges are also calculated. A theoretical model of linear chain of coupled resonators is also used to predict the CRAW dispersion relations. Then, we also investigate transmission properties of CRAWs with different circuits.

Numerical simulation is carried out by using the finite element software COMSOL. Numerical model of an isolated cavity is shown in Fig. 1(a). It is based on the two-dimensional PC composed of mercury cylinders embedded in water. The radius of the cylinder is $r/a=0.45$, with a being the lattice constant. Cavity is introduced by replacing one mercury cylinder with water. The super cell contains of 7×7 unit cells, which is big enough to neglect the coupling between adjacent cavities. Periodic Bloch boundary conditions are applied on the opposite boundaries. For simplicity, only the localized waves are plotted in Fig. 2 by scatter-solid lines. The white part between the two gray ones represents for the bandgap of the original perfect PC.

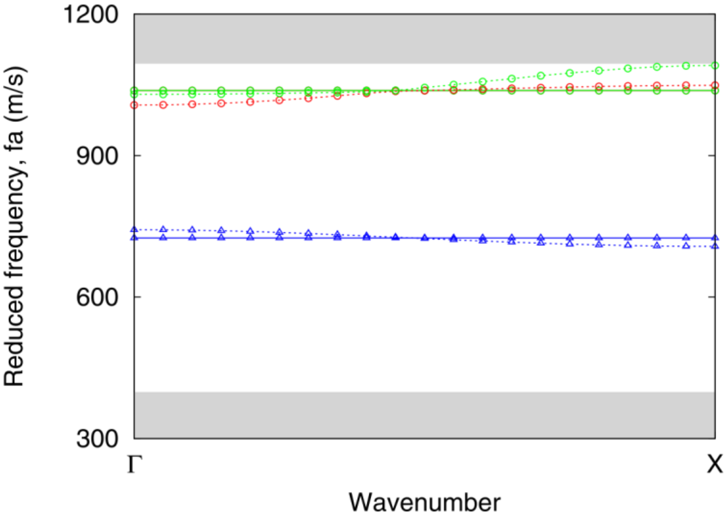

Figure 2 CRAW dispersion for the cavity separation with $\Lambda = 2a$ illustrated by scatter-dashed lines. The scatter-solid lines are resonant frequencies for the isolated cavity. The gray area indicates the passing bands for the original perfect PC.

When the separation between adjacent cavities, Λ, is not too large, as shown in Fig. 1(b) with $\Lambda = 2a$, cavities can be coupled with each other by evanescen fields outside of them, creating a channel for guided waves. Band structures of the CRAW along x-direction is shown by scatter-dashed lines in Fig. 2. Guided waves are clearly found around resonance of a single cavity inside the bandgap: the dispersion curve bends gently. Analysis of the eigenmodes also suggests that these guided waves are generated owing to the excitation of the defect modes. And these CRAW dispersion can be predicted by using a theoretical model of a linear chain of coupled resoantors.

Then we also design CRAWs with different circuits in a finite structure. Transmission properties of these circuits are investigated, the shape of which is similar to the channeled spectrum in optics. Pressure distributions of some transmission modes are shown to under the physical meanchism of transmission peaks and wave guiding. Novel acoustic wave devices, such as a wave splitter, are also designed and demonstrated numerically.

The work in this paper can be extended for the control of elastic wave propagation by introducing fluid cavity in a solid-matrix PC[8]. Reconfigurable PC circuits are expected based on the coupled acousto-elastic resonators.

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