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Proof of the existence of large complete band gaps in high frequency silicon phononic crystal plates

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We show, for the first time, the evidence of the existence of large phononic band gaps (PBGs) in two-dimensional phononic crystal (PC) plates formed by etching a hexagonal (honeycomb) array of air holes through a free standing plate of silicon (Si). A CMOS compatible fabrication process is used on a Si on insulator (SOI) substrate to realize the PC devices. More than 30dB attenuation is observed for eight periods of the hexagonal lattice PC at high frequency region, i.e. 133MHz with a band gap to mid gap ratio of 27%. We show that the experimental results agree very well with the theoretical predictions for the PBG. This result opens a new direction in the implementation of high frequency practical PC structures for a variety of applications especially wireless communication, and sensing.

1 Introduction

Phononic crystals (PCs) [1] are special types of materials with periodical variations in their elastic properties. One of the most interesting phenomena that can be obtained in the PC structure is the existence of frequency ranges in which elastic waves are prohibited from propagation. The existence of these frequency ranges, called phononic band gaps (PBGs), is very important as it can be used to realize fundamental functionalities like mirroring, guiding, entrapment, and filtering for acoustic/elastic waves by creating defects in the PC structure [2]. Possibility of implementation of these functionalities in the PC structures can lead to integrated acoustic devices with superior performance over the conventional MEMS devices used in wireless communication and sensing systems. Recently, there has been a growing interest in PC structures with periodicity induced in two directions, and confinement within a finite thickness in the third dimension. These PC structures, called PC slabs (or plates) are very promising as they can utilize the powerful functionalities of PCs in the plane of periodicity, while confining the acoustic energy within the thickness of the slab, preventing any out of plane loss. Possibility of achieving PBGs in such a structure is of strong interest since they can be realizable using micromachining technology, and hence to be used as part of the integrated micromechanical platforms used in wireless communication and sensing systems. Ref. [3] we showed that it is possible to achieve very large complete PBGs in honeycomb (hexagonal) lattice of perforated holes in a silicon (Si) plate.

2 Complete PBGs in PC slabs

We have recently shown using plane wave expansion (PWE), and the finite element (FEM) techniques that large complete PBGs can be achieved in silicon (Si) phononic crystal plates made by perforating hollow holes in a Si slab [3]. Both square and hexagonal (honeycomb) lattices have been analyzed for a variety of geometries, and we showed that with practical structures, the hexagonal lattice can provide larger PBGs that are appropriate for all foreseen practical applications. The schematic of the hexagonal PnC slab structure is shown in Figure 1 along with the associated Brillouin zone. The PBG maps for the honeycomb lattice are shown in Figure 2 for both constant thickness of the slab, and constant radius of the perforated holes. It can be observed that more than 34% of gap to mid gap ratio can be achieved with thickness of $d=a$, and $r=0.45a$, in which d stands for the thickness of the plate, a

denotes the spacing between the nearest holes, and r is the radius of the holes.

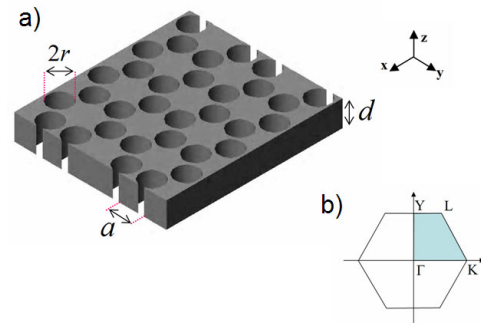


Fig. 1: (a) Schematic of the structure of the PC slab, and (b) the associated Brillouin zone based on the periodicity of the hexagonal lattice and the anisotropy of the silicon plate.

3 Fabrication of PC slabs

To practically evaluate the theoretical predictions of possibility of achieving a complete PBG in PC plates, and to ensure the possibility of realizing them especially in high frequency applications, we fabricated PC plate devices with theoretically proven complete PBGs in silicon. A variety of transducers with the same PC structure were fabricated to on the sides of the PC structure to measure the transmission in a wide range of frequencies covering the whole predicted PBG region.

A schematic of the fabricated structure is shown in Figure 1(a), and a scanning electron microscope (SEM) image of the structure is shown in Figure 1(b). The lattice spacing a was chosen to be $15\mu\text{m}$, the radius of the holes r to be approximately $6.5\mu\text{m}$, and the thickness of the slab, d being $15\mu\text{m}$.

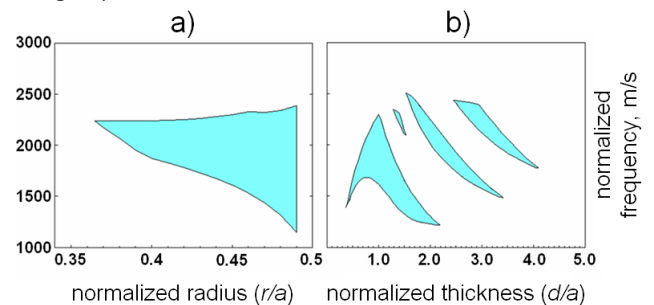


Fig. 2: Normalized PBG maps for (a) constant thickness of the slab and (b) constant radius of the holes.

4 Characterization of PC slabs

As discussed, a variety of structures were fabricated to cover a wide range of frequencies in measuring the transmission through the PC plate in the ΓK direction of the lattice.

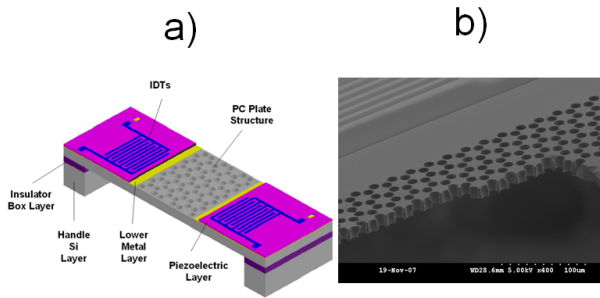


Fig. 3: (a) schematic of the fabricated structure, and (b) a scanning electron microscope image of the fabricated PC plate.

The transmission of several different slab modes was measured in a wide range of frequencies and sharp drops in the transmission spectrum were observed. The average transmission of different modes was calculated and is shown in Figure 4 along with the predicted PBG of the crystal. As it can be seen from Figure 4, the region with low transmission region matches very well with the predicted PBG region.

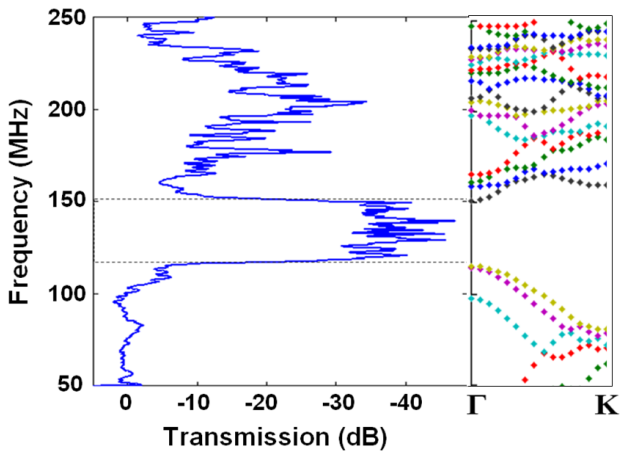


Fig. 4: Averaged transmission through the PC plate structure shown in Figure 3 (left), and the ΓK section of the band structure of the PC calculated using PWE technique. The transmission spectrum matches very well with the theoretical calculation of the PBG.

5 Conclusion

It was shown theoretically supported with experimental verification, that large, high frequency complete phononic band gaps are achievable in phononic crystals made by perforating holes in a solid plate using micro-fabrication technology. This result can lead to high performance micromechanical devices based on phononic crystal plates which might improve the characteristics of the current communication and sensing devices.

Acknowledgments

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