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Analysis of air waveguides in three-dimensional photonic crystal

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1. Introduction

Photonic crystals are artificial optical materials of periodic dielectric structures with a photonic band gap (PBG) in which light emission and propagation are prohibited. Various novel optical devices such as the zero-threshold laser, compact waveguides with low-loss sharp bends, ultra-small optical integrated circuits, and so on, are expected through the use of the PBG and the artificially introduced defect states [1]. Three-dimensional (3D) photonic crystals are used to realize a complete PBG and to control the light efficiently. One of the basic functional elements inside a 3D photonic crystal is a waveguide network formed by individual waveguides extending along the three orthogonal principal axes of the structure [2].

In this paper, we present a numerical analysis of an air waveguide in a semiconductor-based 3D photonic crystal with a stacked stripe structure [3]. The dispersion relation of the guided mode for different waveguide configurations are investigated by using the plane wave expansion method. We try to find the optimum waveguide structures that support single-mode operation with as wide as possible bandwidths.

2. Model and Calculation Method

A stacked stripe structure is constructed in air by stacking layers of dielectric rods, with each layer consisting of parallel rods with a center-to-center separation of a (Fig. 1). The rods are rotated by 90 degrees in each successive layer and the second neighboring layer is shifted by a distance of $a/2$. Thus, the four layers of parallel rods correspond to a period d in the stacking direction.

We use the plane-wave expansion method with a supercell technique to examine the dispersion relations of the guided modes of the waveguide [4]. The refractive index of the rod is assumed to be 3.309, corresponding to semiconductor materials such as GaAs. The width and height of the rod with a rectangular cross section are chosen to be $0.25a$ and $0.3a$, respectively. Then, the stacking period $d = 1.2a$. When there is no waveguide in the crystal, the complete PBG exists in the normalized frequency range from 0.3789 to $0.4613c/a$, where c is the speed of light in the vacuum.

3. Results and discussions

The in-plane waveguide is simply formed by removing a single rod, as shown in Fig. 2(a). Calculated dispersion diagram shows that the lower band in the PBG spans the wide frequency range from 0.3894 to $0.4412c/a$. Periodic defect waveguides are also formed by removing some segments of rods periodically as shown in Figs. 2(b) and 2(c).

Next we consider the off-plane waveguide which have guided mode in the stacking direction of the photonic crystal. The off-plane waveguide is constructed by removing some segments of rods along the stacking direction. Figures 3(a) and 3(b) shows the waveguides created by removing segments in rods in the first layer consecutively every four layers with width $l = 0.5a$. Though the single-mode operation can be obtained by these guided modes, the bandwidths are quite narrow (0.3969 – $0.3990c/a$ and 0.4068 – $0.4181c/a$ for Fig. 3(a), 0.4184 – $0.4246c/a$ for Fig. 3(b)). To improve the bandwidth we consider the waveguide created by removing segments in rods in the first and third layer as shown in Figs. 3(c). In this case, the upper guided mode supports the single-mode operation with the wider frequency range from 0.4147 to $0.4389c/a$. However the lower three modes have overlapped frequency regions. To avoid this we consider the waveguide whose location is shifted by $a/4$ as shown in Fig. 3(d). Then the single-mode operation is achieved with wide frequency ranges from 0.4005 to $0.4185c/a$ and from 0.4188 to $0.4412c/a$. Moreover, it is confirmed that the two bands simultaneously sifted to the higher (lower) frequency by removing wider (narrower) segments of the rods. Therefore the frequency range of the bands can be easily controlled by simply changing the width of the removal of segments (i.e. size of the defects).

3. Conclusions

We have demonstrated that the single-mode operation of a waveguide can be achieved by appropriate adjustment of geometrical parameters such as the location and the size of the defect. It is found that much greater improvement in the bandwidth of off-plane guided mode is obtained by introducing the defects in the first and third layers of staked stripe structure.

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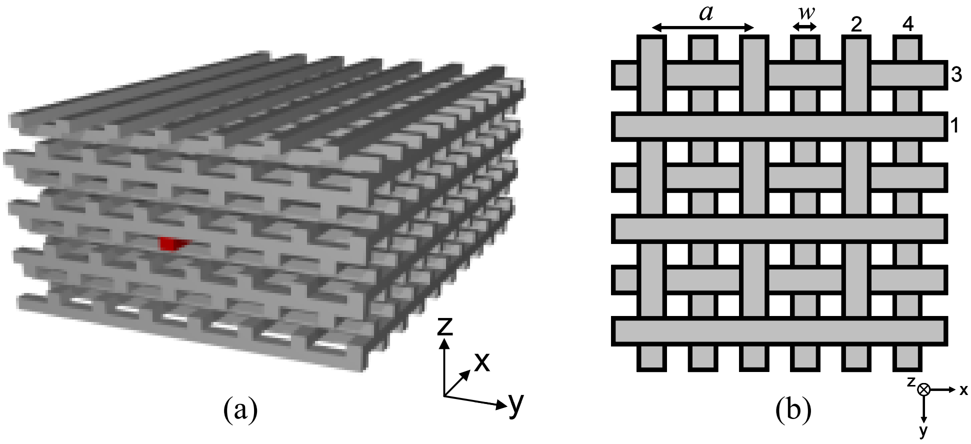

Fig. 1. (a) Schematic of the stacked stripe 3D photonic crystal. (b)Top view.

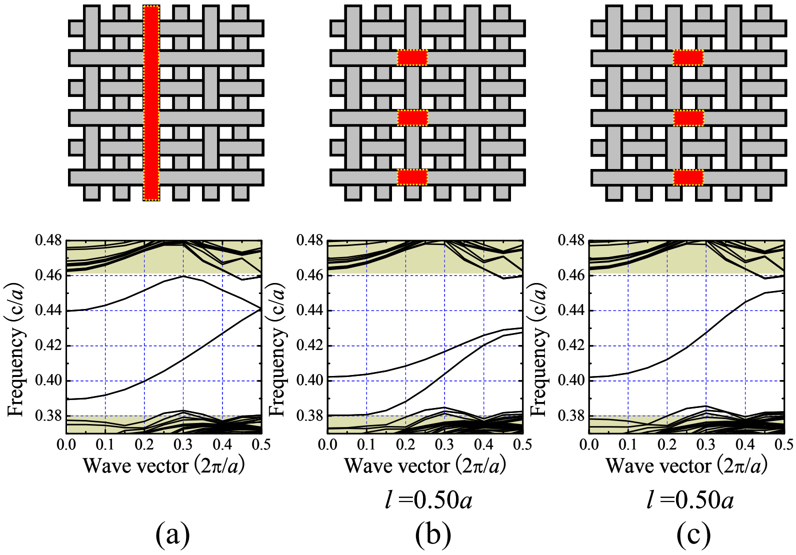

Fig. 2. Dispersion diagrams of guided modes for in-plane waveguide.

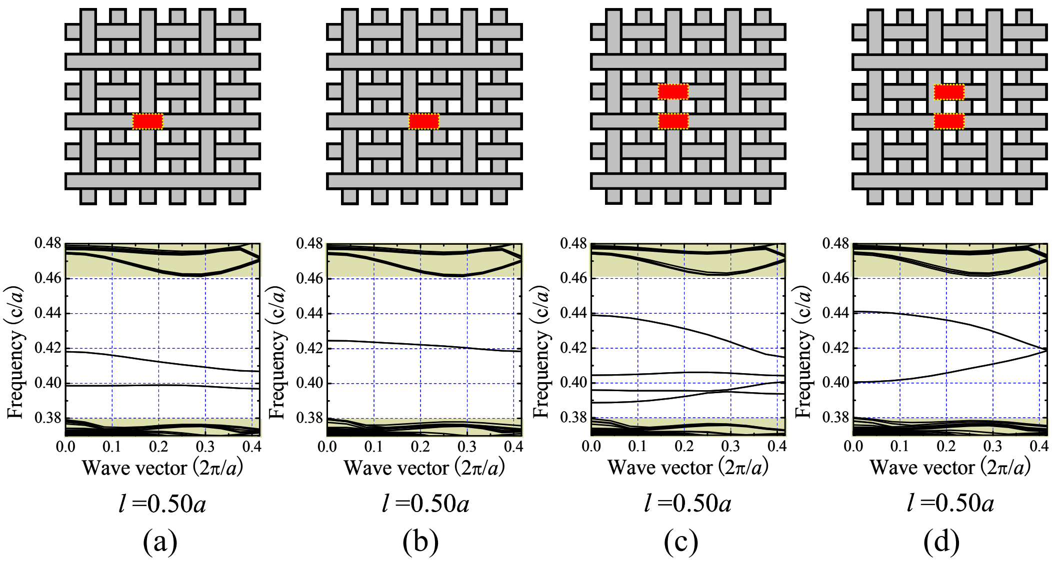

Fig. 3. Dispersion diagrams of guided modes for off-plane waveguide.