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Light collimator made of photonic crystal by partial band gap

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Abstract. Basing on finite-difference time-domain method and partial band gap effect of photonic crystal, we obtain collimated light beams from point optical source and two-dimensional photonic crystal structure. The diffusive light with some special frequencies can be collimated and propagate along a special direction within photonic crystal structure. Our study presents a new method to make light collimator.

PACS. 42.70.Qs Photonic bandgap materials – 41.85.Si Beam collimators, monochromators – 42.15.Eq Optical system design

1 Introduction

The most important function of photonic crystal (PC) structures is their ability to control the flow of light [1]. The ability comes from the complex spatial dispersion properties of PC. On one hand, the effect of "photonic band gap" (PBG) makes PC as insulator and prevents the propagation of light from PC in some frequency ranges, which has important applications in quantum optics, high-efficiency lasers, filters, waveguides and optoelectronic devices [1–6]. When a defect is introduced in the perfect crystal, localized modes associated with the defects are created in the PBG. On the other hand, PC can be photonic conductors whose conductance is determined by their band structure. Recently, it is even found that at some frequency regions, PC can also refract light as if it has a negative refractive index [7–11], which has many potential applications such as self-focusing or imaging. As two-dimensional (2D) PC is easier to be fabricated than three-dimensional PC, more and more optical counterparts have been presented and investigated theoretically or experimentally [12–14]. For example, light bends and splitters made of PC were presented recently in a 2D PC by Yu et al. [12]. The mechanism for bends and splitters is that the k_x value lies outside the constant frequency contour for air. Therefore, a (10) crystal-air interface should behave as a total internal reflection mirror for self-collimated beams propagating along the (11) direction, and can be used to create a sharp 90° bend of light [12]. Then a beam splitter can be designed by bringing two of such (10) crystal-air interfaces in close proximity to each other. However, the power-splitting ratio is only controlled by adjusting the distance between the two interfaces. It may be difficult to obtain two same beams by the splitter. Up to now, the studies on PC have been focused on its properties of complete pass band or complete band gap. There were little researches on the properties of PC with partial band gap. In this paper, we design a kind of optical device made of 2D-PC, with which we can obtain four absolute-equivalent-collimating beams from one point source. Different from reference [12], this device is based on partial band gap effect of PC.

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2 The band structure of 2D-PC

For the 2D-PC, we select a square lattice with lattice constant a, which is composed of air holes with same radius $r = 0.35a$ in a dielectric matrix with dielectric constant $\varepsilon = 15$. We only consider the TE modes (the magnetic field is parallel to the axis of air holes) here. The band structure (normalized frequency $\omega = a/\lambda$ vs. wave vector $\boldsymbol{k}$ in the reciprocal space) and the equifrequency-surface contour for this PC are plotted in Figures 1 and 2. Figure 1b only shows the second band from Figure 1a. In the second band, light with frequencies in the vicinity of $\omega = 0.24$ (indicated by one solid horizontal line) is allowed to propagate along the ΓX direction and is forbidden in the ΓM direction, because there is no transmitting mode in the ΓM direction. The range of these frequencies is 0.2345–0.2450. Moreover, the ΓX directions just point to the normal direction of contours of these frequencies (for simplicity, Fig. 2 only plots the contour of $\omega = 0.24$). Owing to the symmetry, the ΓX directions are the most preferable paths for the light, which will be verified by later simulation.

3 Numerical method and calculating results

The size of 2D-PC slab is $15a \times 15a$. A small square area with size of $5a \times 5a$ is removed from its center (Fig. 3).

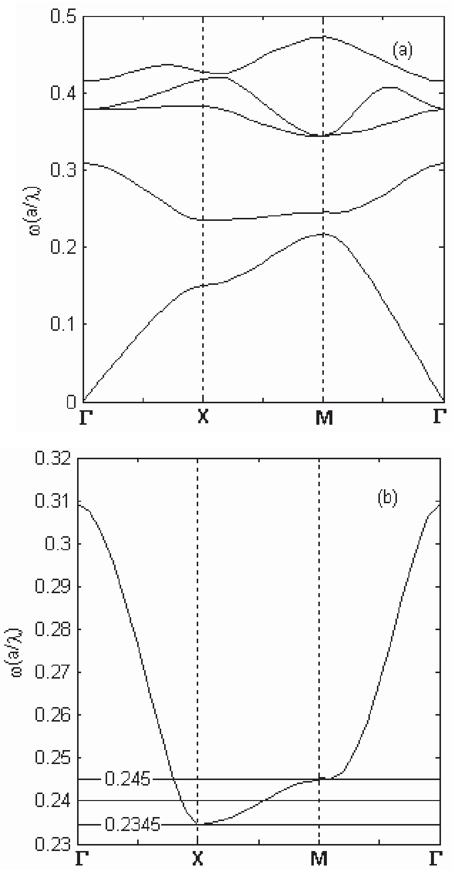

Fig. 1. The band structures of the 2D-PC in this paper. Figure 1b shows the second band from Figure 1a.

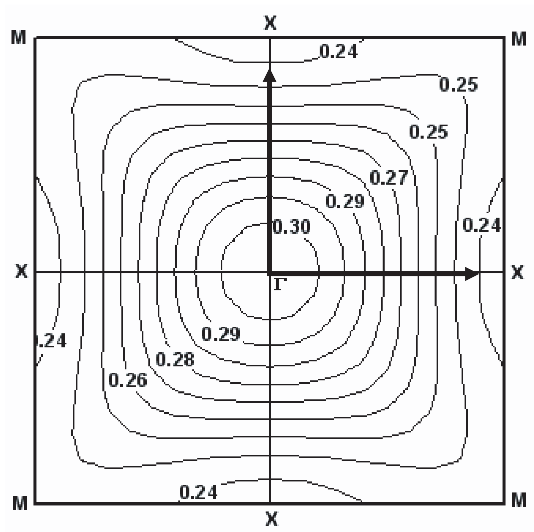

Fig. 2. The equifrequency-surface contour of the 2D-PC.

All normal directions of the 2D-PC surfaces are along the ΓX direction (Fig. 3a). In order to simulate the propagating behaviors of electromagnetic waves in the 2D-PC, we use finite-difference time-domain (FDTD) method with perfectly matched layer boundary conditions [15]. A computation domain is set 600×600 cells and the 2D-PC slab is placed at the center of the domain occupying

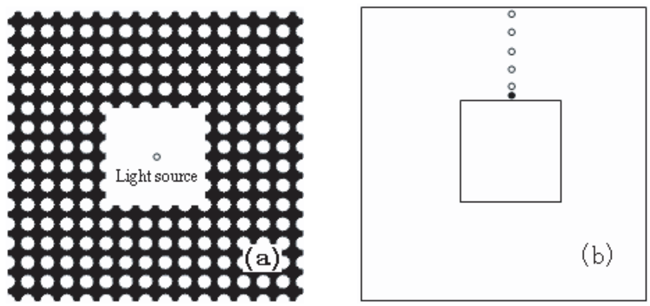

Fig. 3. The model of the 2D-PC (a) and the monitor position in the model (b).

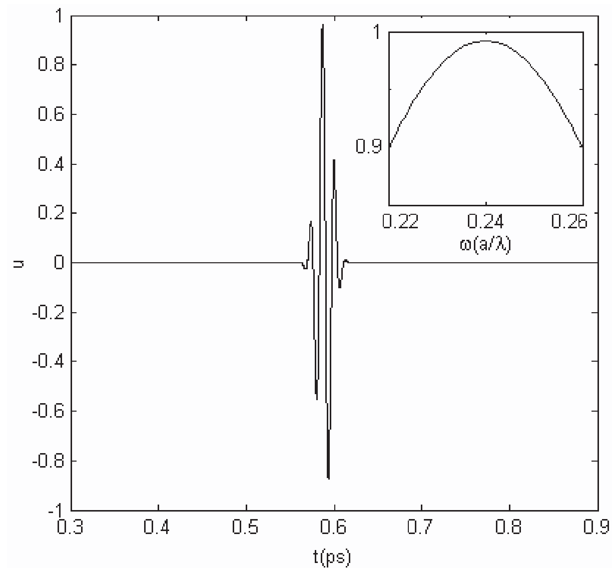

Fig. 4. The field amplitude as a function of time and the corresponding frequency spectra from the point source.

300×300 cells. Firstly, in order to verify the partial band gap effect of the PC, we place a point-pulse source with a form of $u = \sin(\omega n \times dt) \exp[-(n - 5000)^2/10000]$ at the center point of the model, where dt and n denote one time step length and the number of time steps, respectively, and $\omega = 0.24$. The field amplitude as a function of time steps and the corresponding frequency spectra are plotted in Figure 4. We set some monitor points to study their intensity spectra. These monitor points are on the midline of the model and along the ΓX direction, which are shown in Figure 3b. The first point is set a distance of $a/4$ from the inner interface (denoted by a black point). The second point is set a distance of $a/2$ from the inner interface and other points are all set equal interval of a for each other (denoted by circles). The relative intensity is obtained with respect to the intensity of the first point (Fig. 5). Clearly, from $\omega = 0.235$ to $\omega = 0.24$, the relative intensities quickly increase. Furthermore, we notice that the intensities increase with the propagation distance. All the results can be explained by partial band gap effect. Because light from a point source is diffusive before it goes into the PC, only small part of light just travels in the ΓX direction. For light with frequencies in the partial

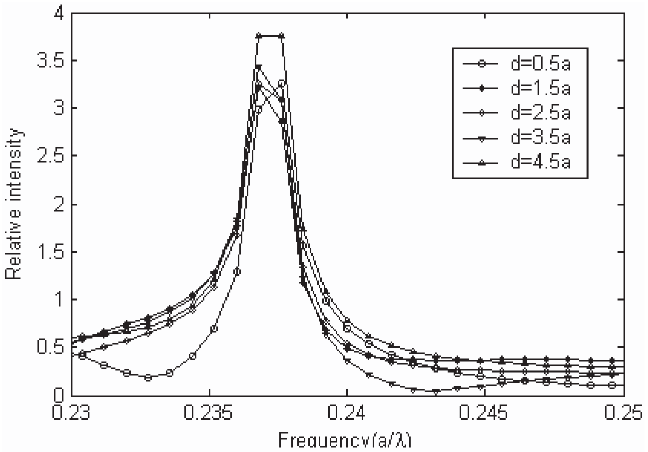

Fig. 5. The relative intensity spectra at the monitor points with distances of $0.5a$, $1.5a$, $2.5a$, $3.5a$, and $4.5a$ from the interface (see Fig. 3b).

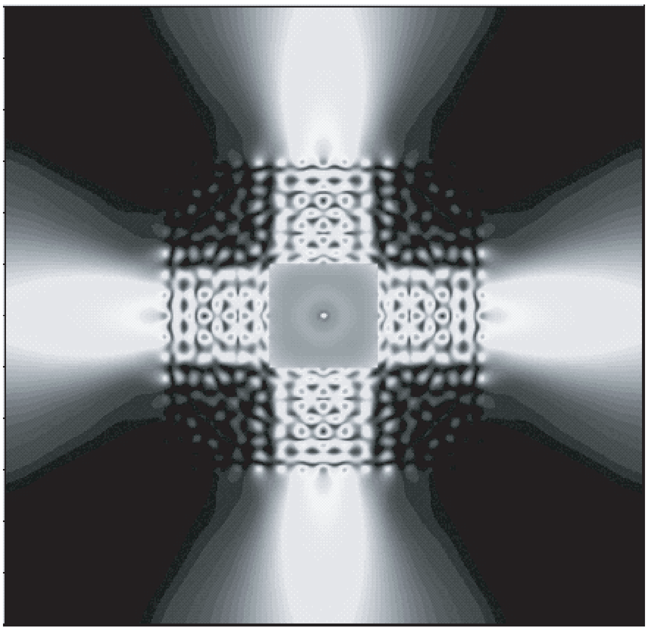

Fig. 6. The average magnetic-field intensity distribution for a CW point source with a frequency $\omega = 0.238$.

band gap travels not in the ΓX direction initially will undergo complex Brag diffraction within the PC. It deflects and gathers to the ΓX direction gradually, thus light intensity increase in this direction. As Figure 1b shows, the frequencies from $\omega = 0.235$ to $\omega = 0.24$ are just within the partial band gap, then the relative intensities in these frequencies are much bigger than those in other frequencies, and with the propagation distance increasing, the relative intensities become bigger. For light with frequencies not in the partial band gap will scatter in different directions.

Basing on the above results, we select a continuous-wave (CW) point source with frequency $\omega = 0.238$ placed at the same position of the former source. Figure 6 plots the average magnetic-field intensity distribution. It shows that four separate and parallel light beams with equivalent

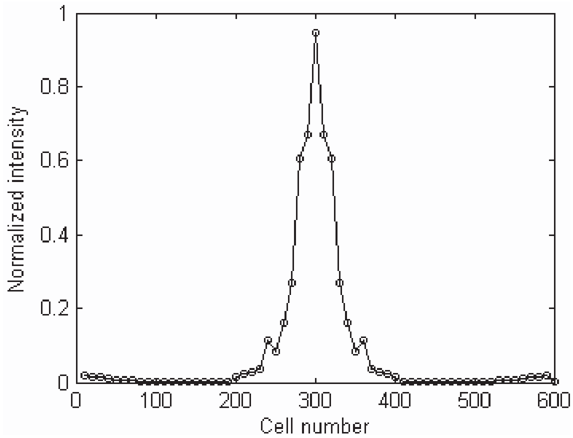

Fig. 7. The average magnetic-field intensity distribution along a line, which is parallel to the outer interface and has a distance of a from the interface.

intensity propagate through the 2D-PC in four different directions. Although the light from the source is diffusive, when it goes through the PC structure, it is collimated and gathered in the ΓX directions. Thus this model can be used as collimator in optical device. In order to further observe the light propagation behavior, we also plot the average magnetic-field intensity distribution along a line, which is parallel to an outer interface and has a distance of a from it. Figure 7 shows the result, in which the center peak corresponds to the ΓX direction and shows that the light is mainly concentrated in the ΓX direction.

4 Summary

In conclusion, we have designed a new kind of light collimator made of the 2D-PC. With it, we can obtain four parallel light beams from a point optical source. It is hoped that our works can provide a basis for on-chip integrated photonic circuits.

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