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Tunable beam propagating characteristics of two-dimensional rectangular-rod photonic crystals based on self-collimation effect

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ABSTRACT

The light beam transmission characteristics of the two-dimensional photonic crystal structures consisting of a square lattice of rectangular dielectric rods are studied. Through optimizing the parameters of the structure, the self-collimated light propagation within a large frequency region is achieved, and the corresponding light propagation direction can be altered through rotating the rectangular rods in the square lattice, which is explained by the analysis of the equi-frequency surface contours. A compound structure composed of rectangular rods with different rotating angles is proposed in this paper, which has different kind of functions depending on the incident light beam's spatial width and incident location. The single-channel collimating propagation with different forward directions, two-branch-channel splitting with adjustable energy ratio, three-branch-channel splitting with different output beams' propagation directions can all be achieved. These kinds of devices can help expand the application of energy beam splitters in the optical circuits system and realize miniaturization integration.

1. Introduction

The replacement of traditional electronic devices with photonic crystal (PhC) [1,2] devices will have a major and far-reaching impact on optical communication technology. Among them, the beam splitter is suitable for connecting the local end and terminal equipment in a passive optical network and implementing optical signal splitting, which has important application in integrated optics. In the past few decades, due to the existence of photonic band gaps, PhC has attracted much interest, and various optical devices have been created for integrated optics such as fibers [3,4], switches [5,6], waveguides [7–9], channel filters [10–12], beam splitters [13–17] and so on. However, there are few studies on the properties of PhC other than bandgaps and defects. In 1999, the self-collimation effect was discovered by Kosaka's research group, characterized by the incident electromagnetic wave within a particular frequency region can propagate through a perfect PhC along a certain direction with no diffraction and the width of beam remains unchanged [18].

The beam splitters designing with the PhC waveguides can realize light transmission and separation [19], but this kind of splitters is restricted to the location of waveguides and it also has unchangeable output beams' spatial widths. It is also a challenging problem to coupling the incident light beam energy efficiently to the input waveguide of the structure. When the beam splitters use the self-collimation design, it can obtain any energy splitting ratio, large-angle bending, low transmission loss and broadband self-collimation [20,21]. In this paper, we present a single structure of light transmission along a straight line based on the principle of self-collimation, which is based on the two-dimensional (2D) square-lattice of rectangular dielectric rods. Through altering the angle from the direction of the rectangle's long side to the ΓX direction of the PhC, the long-distance non-diffraction light transmission direction can be adjusted. The self-collimation light beam propagation through above PhC structure has no restriction to the incident light beam's spatial width and location. A new kind of light energy splitter that splits the input light beam into different channels of output light with various directions is constructed. But for this proposed composite structure, it can achieve single beam transmission and triple split beams for the different widths of the incident light beam. When the light source's incident position is laterally shifted, the two-branch-channel splitting phenomenon can also be obtained. Those provide a good suggestion for designing valuable products in optical integration and miniaturization.

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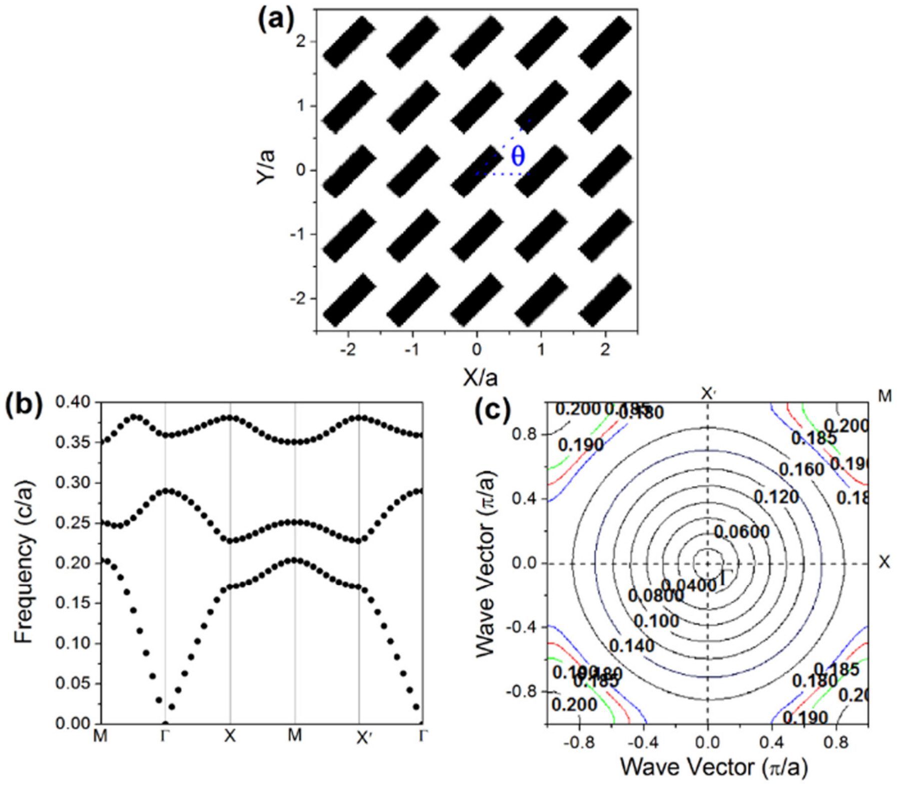

Fig. 1. Schematic geometry of the PhC consisted of square-lattice of rectangular rods immersed in air with $\theta = 45°$ (a), and the TM-polarized band structure of this PhC (b). The length of the rectangles is $l_1 = 0.9a$ and the width is $l_2 = 0.3a$. The EFC contours of each frequencies in the lowest band of the PhC (c).

2. Self-collimating light propagation through 2D rectangular-rod PhCs

The 2D PhC structure considered in this paper is composed of a square-lattice of rectangle dielectric rods embedded in the air background, whose dielectric constant is set to be $\varepsilon = 18$. In the traditional beam splitter, the light transmission is usually adjusted by changing the radius of the circle, while the rectangle has controllable variables such as length, width and inclined angle in the primitive unit cell. We set the length of the rectangles to be $l_1 = 0.9a$, and the width of the rectangles is $l_2 = 0.3a$, where "a" represents the length of the PhC's lattice constant. The oblique angle from the PhC's ΓX direction to the rectangle's long side is represented by the character "θ" (counterclockwise as positive). The geometry of the rectangular-rod PhC is displayed in Fig. 1(a) with the value of θ equals to 45°. According to the relationship between the direction of the electric field vector and the light propagation direction, the light is divided into TE and TM polarized modes. The TM-polarization as the incident light, whose electric field direction is parallel to the central axis of the rods. Comparing to the traditional circular rods, the rectangular rods of the PhC are anisotropic in space, so the wave propagation and the band diagrams are asymmetric between the ΓX and $\Gamma X'$ directions. In order to have a full knowledge about the band diagrams of the rectangular-rod PhC, the one-fourth of the first Brillouin Zone must be discussed, while only one-eighth of that is considered for circular rods. It is shown in Fig. 1(b) that the lowest photonic band gap exists from 0.204 to 0.228c/a, where c is light velocity in vacuum.

The classical method to prove the existence of self-collimation is to observe the flat equi-frequency contour (EFC) in the inverted-lattice space. The direction of EFC should be oriented perpendicular to the group velocity (as an envelope constituted by superposition of waves). The electromagnetic wave transmits through a PhC, and its forward propagation direction is as same as that of group velocity, which is depicted by $v_g = \nabla_{\boldsymbol{k}}\omega(\mathbf{k})$. In this equation, v_g is the group velocity, ω is the angular frequency and $\mathbf{k}$ is the wave vector. By studying the gradient directions of EFC, we can determine the propagation direction of the electromagnetic waves. We utilize the conventional plane-wave expansion (PWE) method to calculate the EFC contours of the corresponding PhC [22,23], and the results are shown in Fig. 1(c). The EFC contour lines show that the equal frequency line near point Γ is a circle, and the shape of EFC contours away from point Γ becomes several flat lines, and the frequency gradually increases in the process of far from the point Γ. In most part of the 0.04 contour, where PhC behaves like an effective homogeneous and isotropic medium at this long wavelength. When the frequency spans from 0.180 to 0.190c/a, the curves are quite flat and with a surface normal pointing to the ΓM direction, it means that the direction of light propagation through above PhC at this frequency region is 45° deviation from the direction of the unit cell's side length, representing that the group velocities in this region would point dominantly along the ΓM direction of the PhC. The linear tendency at the first band of TM modes can get strong self-collimation effect, which is centered about Γ-M symmetrical line in Fig. 1(c). According to the formula $\omega a/2\pi = a/\lambda$, the solid line with a frequency of 0.185c/a can be converted to a wavelength of 1550 nm for the length of PhC's lattice constant $a = 286.75$ nm, which is an important window for the communication band. In this frequency range, the self-collimation phenomenon will occur. The structure shown in Fig. 1(a) can be used as a non-channel "virtual waveguide", which does not require the introduction of line defects or dielectric waveguides to confine light to propagate along a straight line [24,25]. It can make the light beam overcome the diffractive effect and transmit along a straight line, and it also has the advantages of high integration in the optical circuits. In addition to analyzing the shape of equi-frequency curves, the group velocity dispersion (GVD) and third-order dispersion (TOD) are two important parameters to characterize the self-collimation performance accurately. GVD can be calculated from the relationship of ω and k-vector, depicted by GVD $= (\partial^2 k)/\partial\omega^2$, indicating the group velocity's alteration influenced by the variation of the angular frequency [26].