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Y-shaped beam splitter by graded structure design in a photonic crystal

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We propose a method to bend a self-collimated beam in a photonic crystal. The beam bending relies on the gradual variation of the constitutive parameters of the photonic crystal. A new Y-shaped beam splitter is designed with a composite structure constructed using two graded photonic crystals. We demonstrate that the incident beam is divided into two output beams by the designed splitter. The power ratio of the two beams can be adjusted easily by changing the location of the input beam.

beam splitter, beam bending, graded photonic crystal, self-collimation

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Photonic crystals (PC) are periodic dielectric structures. With proper design, PCs exhibit photonic band gaps, i.e. frequency ranges in which light propagation is prohibited [1]. This property makes them excellent candidate structures for control of an electromagnetic wave. PCs are promising as a platform for compact photonic integrated circuits. In particular, planar PCs have attracted a great deal of attention for their advantages of small size and easy fabrication using mature microelectronics patterning techniques. Various PC devices based on the introduction of defects have been realized in semiconductor slabs patterned with 2D lattices, such as waveguides [2], directional couplers [3] and channel drop filters [4].

Also, the dispersion surfaces of PCs show different shapes depending on the lattice type, pitch, fill factor and refractive index. Because the propagation direction of light in a PC is determined by the group velocity normal to the equal-frequency contour (EFC), the ability to shape the EFC offers a new way to design optical devices. A number of attempts have been made to engineer the dispersion properties of PCs for possible applications. The self-collimation effect, by which an electromagnetic wave with a certain angular range is naturally collimated along a definite direction, is of particular interest. The self-collimation phenomenon originates from the flat region of the EFC. Light propagates along the direction perpendicular to the flat part of the EFC, leading to propagation in a straight line inside a perfectly periodic PC [5]. One advantage of self-collimation-based devices is that they do not require a physical boundary to achieve narrow lateral confinement. Also, guiding can be achieved over a larger bandwidth when compared to their line-defect counterparts. Self-collimation promises a variety of applications, such as self-guiding [6], spatial beam routing [7], and device applications [8].

To implement photonic integrated circuits, bending and splitting of self-collimated beams is required. Several PC beam splitter structures related to the self-collimation effect have been reported. A line defect has been introduced to bend and split self-collimated beams [9–12]. The power ratio between the two splitted beams can be controlled systematically by varying the radii of the rods or holes in the line defect [11,12]. A beam splitter combining self-collimation with the partial band gap of a PC has been pro-

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posed [13]. Using the surface modification method, a self-collimation-based directional emitter and beam splitter in a 2D PC was also realized [14].

In this paper, we design a Y-shaped beam splitter by combining the self-collimation effect with the structural gradient of PCs. The design of a graded photonic crystal (GPC) structure is detailed in Section 1. We show that by controlling the structural parameters of the PC, a GPC can modulate the direction of wave propagation. The input beam is divided into two output beams using two combined graded PCs. The splitting ability of the beam splitter is discussed further.

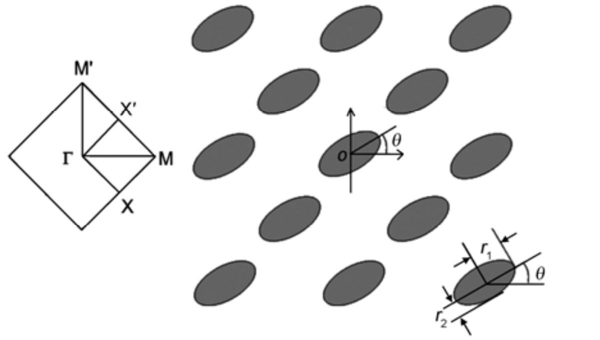

Figure 1 The schematic of a 2D square array of elliptical dielectric rods embedded in an air background. The surface normal of the PC slab is along the Γ-M direction. The major axis of the ellipse is oriented at an angle θ to the Γ-M direction. The left side is the first Brillouin zone.

1 Bending light using a graded PC

The PC structure under consideration comprises a square lattice of elliptical dielectric rods embedded in an air background. The dielectric constant of the elliptical rods is ε=12 (e.g. Si at 1.55 μm). The schematic configuration of the PC is shown in Figure 1. The left side is the first Brillouin zone (BZ) of the PC. The elliptical rod is spatially anisotropic and therefore has more structural freedoms than a regular circular rod. The major and minor half axes of the elliptical rod are r_1 and r_2, respectively. We choose r_1=0.424a, and r_2=0.212a, where a is the lattice constant. The major axis is oriented by an angle to the Γ-M direction. The angle is denoted by θ, taking a value in the [−π/2, π/2] range.

It is known that the propagation direction is given by the group velocity of the wave, and is perpendicular to the EFC of the PC. To bend light, we need to modify the direction of the group velocity during propagation. GPCs have the property of making the group velocity location dependent. A GPC is an engineered PC with gradual variation of the constitutive parameters in a specific direction in space, such as the lattice period [15], the refractive index [16] or the radius [17]. Using GPCs, the continuous bending of waves has been realized [18,19].

To achieve beam bending, we design a GPC structure and discuss beam propagation through the study of EFCs in wave-vector space. Choosing the orientation angle of the ellipse as the variable parameter, we restrict our attention to the case of the TM mode, where the electric field is parallel to the extension axis of the dielectric rods. The frequency and direction of propagation of the self-collimated beam are obtained using an EFC plot, which is calculated using the plane wave expansion method [20]. To have full knowledge of the dispersion diagrams of the crystal, we must consider one quarter of the first BZ. In comparison, we would only need to consider one-eighth of the irreducible BZ for a crystal made from circular rods.

Figure 2 shows the EFCs of the lowest band for perfect PCs with different values of the orientation angle θ. Only one quarter of the first BZ is displayed. The blue line represents a frequency of f=0.212c/a. It is seen that in most parts of the 0.212 contour, the curve is quite flat. When θ=0 or π/2, the contour is symmetrical about the Γ-M direction. The normal of the flat contour points in the Γ-M direction. When we rotate the elliptical rods counterclockwise, such that $\theta\in$(0, π/2), the curve is still quite flat in most parts of the 0.212 contour. However, the normal of the flat contour no longer points in the Γ-M direction, but points in a certain direction between the Γ-X′ and Γ-M directions. Such a tilted EFC results in upward propagation of the light beam. Also, the flat curve for θ= π/4 is slightly counterclockwise inclined from the flat curve for θ= π/6. Therefore, in a PC with larger θ, the light will travel upward. When we rotate the elliptical rods counterclockwise, such that $\theta\in$(−π/2, 0), the normal of the flat contour points in a certain direction between the Γ-X and Γ-M directions. Such a tilted EFC results in downward propagation of the light beam. The EFC also shows that the 0.212 contour for $\theta\in$(0, π/2) and θ $\in$(0, − π/2) is mirror symmetrical about the Γ-M direction (see Figure 2(b) and (e), or Figure 2(c) and (f)). This symmetry indicates that the beam path in both cases has mirror symmetry about the Γ-M direction, i.e. the beams have the same deflection angle from the input direction.

Based on the above analysis, the GPC structure can be obtained by gradually changing θ while keeping the other parameters constant. Although PCs with angle gradients are not strictly periodic, when the gradient is very small, the optical properties can be deduced at each specific position inside the GPC from that of the corresponding perfectly periodic PC [18]. Because of the gradual rotation of the ellipse in PCs, the group velocity becomes location dependent, and therefore the propagation direction of light changes smoothly during propagation. Let θ vary linearly from 0 to π/2 along the x direction with the number of layers i, i.e. θ=(i–1)σ, where σ is the gradient coefficient. A schematic of the GPC is shown in Figure 3(a). For clarity, a simplified structure comprising only seven layers of rods is plotted.

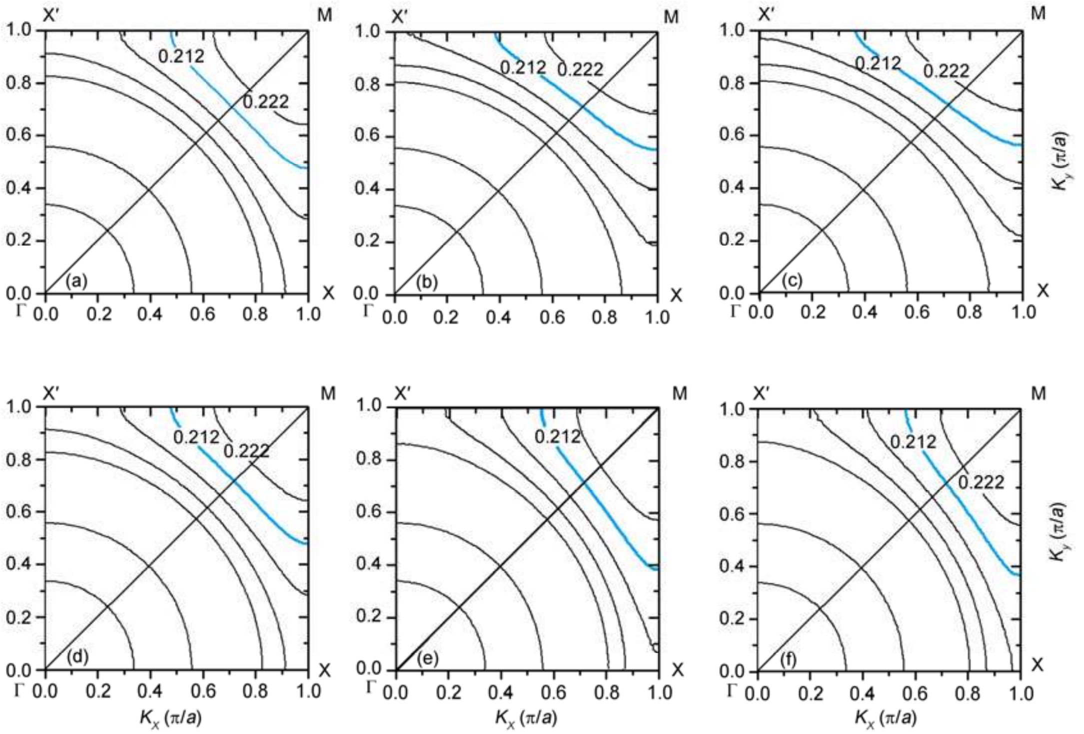

Figure 2 (Color online) Equi-frequency contours in one quarter of the first Brillouin zone of perfect PC structures with different orientation angles. The blue curves depict the frequency of 0.212(c/a). (a) θ=0; (b) θ= π/6; (c) θ= π/4; (d) θ= π/2; (e) θ=− π/6; (f) θ=− π/4.

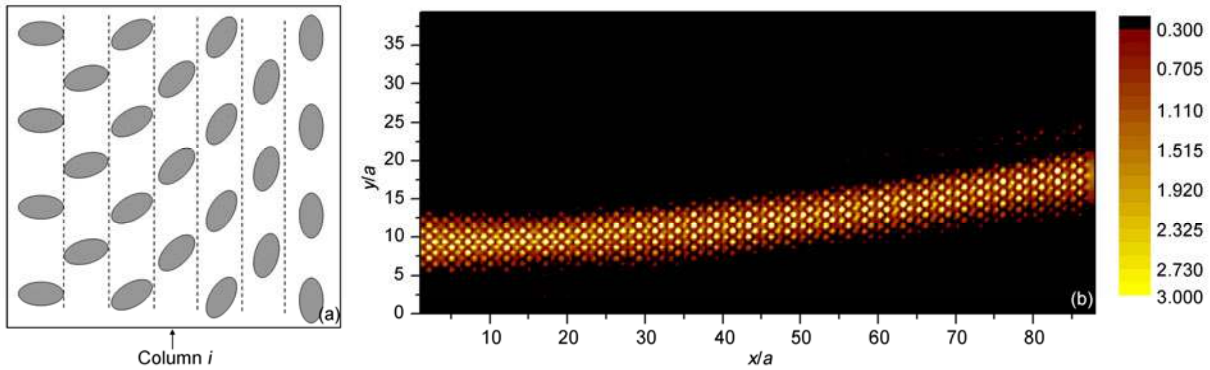

Figure 3 (Color online) (a) The schematic configuration of elliptical rods in a GPC. The orientation angle of each ellipse varies gradually from 0 to π/2 with the column i. (b) The electric field distribution in such a GPC. The frequency of the incident beam is 0.212(c/a).

The self-collimated beam propagation is simulated using the finite-difference time-domain (FDTD) method with perfectly matched layer absorbing boundary conditions [21,22]. The size of the PC is $88a \times 40a$ and its surface normal is along the Γ-M direction. In the simulation, a beam with a width of $6a$ and a frequency of $0.212c/a$ is launched into the GPC along the Γ-M direction, i.e. the x direction. Figure 3(b) depicts the electric field pattern. It can be seen that the light beam is deflected from the original direction and smoothly bends within the GPC while keeping the beam width nearly constant. This demonstrates that light can be bent by gradually rotating the ellipse in the PC. The beam bending relies on gradual modifications to the GPC structural parameter that makes the group velocity location dependent. The FDTD results confirm the prediction based on the EFC.

2 Beam splitter using composite GPCs

To realize a Y-shaped beam splitter for self-collimated beams, we construct a composite structure using two graded PCs. One is GPC1, in which θ varies linearly from 0 to π/2 along the x direction with the number of layers, and the other is GPC2, in which θ varies linearly from 0 to − π/2 with the same gradient coefficient. The sizes of the two GPCs are

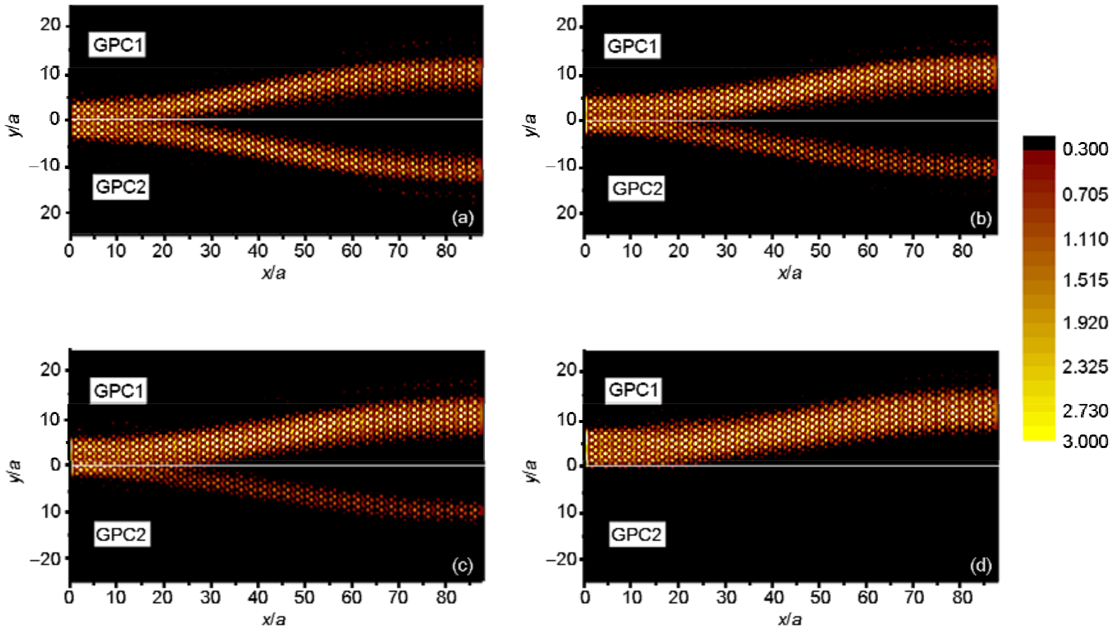

Figure 4 (Color online) The field distribution inside a composite structure constituted by GPC1 and GPC2 for several different source positions. The beam centers are (a) y_c=0a, (b) y_c=4/3a, (c) y_c=2a, and (d) y_c=4a.

identical. The whole structure has a size of 88a × 49a. To investigate the propagation behavior in such a composite GPC, we performed the FDTD simulation. A beam with a width of 8a impinges on the composite GPC along the Γ-M direction. The beam center y_c is located at 0a. Figure 4(a) shows the corresponding results at the frequency of 0.212c/a. The white line shows the interface between GPC1 and GPC2. It is clearly seen that the input beam is divided into two output beams with a symmetrical energy distribution. The simulation validates the design of the beam splitter. The beam splitting results from the gradient of the PC structure. As shown above, when light propagates in the PC, the orientation of the ellipse can modulate the propagation direction of light. When the beam center is at 0a, the upper and lower beams are modulated by different GPCs. It is the difference in redirection of the beam that leads to the beam splitting.

We then moved the input beam upward to examine the performance of the splitter. The field patterns at the other incident locations are also shown in Figure 4. With the beam shift, a single beam is split into two beams with an asymmetrical energy distribution. When y_c=4/3a, the power ratio of the two beams is 1:2. When y_c=2a, a power ratio of 1:3 is obtained. When y_c=4a, all of the light enters GPC1, and no splitting phenomenon occurs. The simulations show that, depending on the spatial position of the input beam, equal or unequal energy distributions can be realized. These results suggest a new way to tune the properties of PC devices.

3 Conclusion

We have accomplished beam bending and designed a beam splitter based on the self-collimation effect combined with the graded constitutive parameters of a PC. The gradient of the PC is achieved by gradually varying the orientation of the elliptical rods. The beam redirection relies on gradual modifications of the GPC structural parameters that make the group velocity location dependent. We constructed a Y-shaped beam splitter, through which one input beam can be split into two output beams. We have demonstrated that it is simple to obtain equal or unequal energy splitting using our beam splitter design.

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1 Ren X B, Zhai T R, Ren Z, et al. The effect of nonlinear exposure on bandgap of three-dimensional holographic photonic crystal. Acta Phys Sin, 2009, 58: 332–337
2 Tokushima M, Yamada H. Light propagation in a photonic-crystal-slab line-defect waveguide. IEEE J Quant Electr, 2002, 38: 753–759
3 Yamamoto N, Ogawa T, Komori K. Photonic crystal directional coupler switch with small switching length and wide bandwidth. Opt Express, 2006, 14: 1223–1229
4 Ren H, Jiang C, Hu W, et al. Photonic crystal channel drop filter with a wavelength-selective reflection micro-cavity. Opt Express, 2006, 14: 2446–2458
5 Zhang L, Zhan Q, Zhang J, et al. Diffraction inhibition in two-dimensional photonic crystals. Opt Lett, 2011, 36: 651–653
6 Chigrin D N, Enoch S, Torres C M S, et al. Self-guiding in two-dimensional photonic crystals. Opt Express, 2003, 11: 1203–1211
7 Prather D W, Shi S, Pustai D M, et al. Dispersion-based optical routing in photonic crystals. Opt Lett, 2004, 29: 50–52
8 Prather D W, Shi S Y, Murakowski J, et al. Self-collimation in pho-

tonic crystal structures: A new paradigm for applications and device development. J Phys D: Appl Phys, 2007, 40: 2635–2651
9 Shi S Y, Sharkawy A, Chen C H, et al. Dispersion-based beam splitter in photonic crystals. Opt Lett, 2004, 29: 617–619
10 Chen X, Qiang Z, Zhao D, et al. Polarization beam splitter based on photonic crystal self-collimation Mach-Zehnder interferometer. Opt Commun, 2011, 284: 490–493
11 Kim T T, Lee S G, Park H Y, et al. Asymmetric Mach-Zehnder filter based on self-collimation phenomenon in two-dimensional photonic crystals. Opt Express, 2010, 18: 5384–5389
12 Lee S G, Oh S S, Kim J E, et al. Line-defect-induced bending and splitting of self-collimated beams in two-dimensional photonic crystals. Appl Phys Lett, 2005, 87: 181106–181111
13 Yao P J, Chen B, Zhang J Y, et al. Y-shaped beam splitters for self-collimated beams in 2D photonic crystals. Europhys Lett, 2005, 70: 197–203
14 Liang W Y, Dong J W, Wang H Z. Directional emitter and beam splitter self-collimation effect. Opt Express, 2007, 15: 1234–1239
15 Cakmak A O, Colak E, Caglayan H, et al. High efficiency of graded index photonic crystal as an input coupler. J Appl Phys, 2009, 105: 103708
16 Luo D, Alagappan G, Sun X W, et al. Superbending effect in two-dimensional graded photonic crystals. Opt Commun, 2009, 282: 329
17 Kotlyar M I, Triandaphilov Y R, Kovalev A A, et al. Photonic crystal lens for coupling two waveguides. Appl Opt, 2009, 48: 3722–3730
18 Akmansoy E, Centeno E, Vynck K, et al. Graded photonic crystals curve the flow of light: An experimental demonstration by the mirage effect. Appl Phys Lett, 2008, 92: 133501
19 Lin S S, Huang T J. Acoustic mirage in two-dimensional gradient-index phononic crystals. J Appl Phys, 2009, 106: 053529
20 Li Z Y, Wang J, Gu B Y. Creation of partial band gaps in anisotropic photonic-band-gap structures. Phys Rev B, 1998, 58: 3721–3729
21 Taflove A. Computational Electrodynamics: The Finite Difference Time-Domain Method. Boston: Artech House, 1995
22 Berenger J P. A perfectly matched layer for the absorption of electromagnetic waves. J Comput Phys, 1994, 114: 185–200