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One-to-three and T-shaped beam splitters based on self-collimating photonic crystals

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In this paper, a one-to-three beam splitter and a T-shaped one-to-two beam splitter are proposed by introducing a V-shaped air gap into a self-collimating photonic crystal (PC). By adjusting the width of the introduced air gap to proper values, the incident beam can be divided into two or three sub-beams. The plane wave expansion method is employed to obtain the equifrequency contours and the band diagram of the PC. The splitting ratios between the sub-beams as a function of the width of the air gap are calculated by using the finite-difference time-domain method. Meanwhile, the field distributions of the light propagation in the structure are presented.

Keywords: photonic integrated circuits, beam splitter, photonic crystals, self-collimation.

1. Introduction

Photonic crystals (PCs), which were first introduced by YABLONOVITCH and SAJEEV JOHN in 1987 [1, 2], have attracted great interests for their extraordinary ability to control the propagation of light. PCs have been extensively used in photonic device design and are recognized as one of the most promising structures to realize compact and highly functional photonic integrated circuits (PICs) [3]. A beam splitter plays an important role in the signal processing in the PICs. It is a fundamental passive device which divides the light beam into multiple sub-beams. The photonic crystal beam splitters are usually realized with the combination of line defects in PCs such as T-, Y-, and cross-type waveguides [4–7].

In recent years, there has been a growing interest in the unusual dispersion properties of PCs [8, 9], such as negative refraction [10, 11], superprism [12] and self-collimation [13, 14]. Among them, a self-collimation phenomenon in PCs provides a brand new way of confining the light propagation besides the conventional PC waveguide. A self-collimated light beam can propagate without diffraction in the PC. In recent studies, it has been reported that the frequency range in which the self-collimating phenomenon occurs is sufficient to be a basis for PICs [3]. Light wave guiding via self-collimation has a lot of advantages. For example, it can usually achieve a wider bandwidth than PC waveguide [3], it needs no precise alignment for wave coupling in and can even work in the condition of oblique incidence. Based on self-collimation effect, various optical devices are investigated, such as virtual waveguides [13], beam bends and splitters [15, 16], interferometers [17], optical switches [18], optical routers [19], resonators [20], and filters [21, 22].

XIAOFANG YU and SHANHUI FAN [15] and SHOUYUAN SHI *et al.* [16] have designed one-to-two beam splitters by introducing PC–air interfaces (air gap) and line defects in self-collimating PCs, respectively. PUSTAI *et al.* and MATTHEWS have experimentally demonstrated one-to-two beam splitting at optical frequencies and microwave frequencies, respectively [3, 23]. A one-to-three beam splitter can be achieved by combining two one-to-two beam splitters, but a more efficient way is to split the incident beam into three sub-beams in one go. PUSTAI *et al.* have realized one-to-three beam splitting at a single point by introducing a layer of lattice-mismatch defects into square lattice PCs [3]. However, it is hard to control the splitting ratio for the one-to-three splitting only occurs when the modes of the coupled beam and the defects are matched.

In this paper, we propose one-to-three and T-shaped one-to-two beam splitters by introducing a V-shaped air gap into self-collimating PCs. The splitters have a simple structure and a clear operating mechanism. Moreover, the splitting ratio can be adjusted easily by changing the width of the air gap. With proper air gap widths, the splitter can act as a one-to-three splitter or a T-shaped one-to-two splitter. With the one-to-three beam splitter, a self-collimated incident light beam can be split into three sub-beams in one go, which is more compact than the combination of two one-to-two beam splitters. The T-shaped splitter has a different splitting way from YU and SHI'S. According to YU and SHI's designs, the two sub-beams are perpendicular to each other. However, in a T-shaped splitter, which is more frequently used in practical applications, the two sub-beams have opposite directions. All the proposed devices operate at 1550 nm.

2. Structure design and analysis

In this paper, we design a one-to-three splitter and a T-shaped splitter for TE polarizations. The structures for TM polarizations can be investigated in a similar way. The proposed splitter consists of two parts as shown in Fig. 1: the self-collimating PC structure and the V-shaped air gap. The structure for self-collimation is designed by engineering the dispersion properties of the PC, while the width of the V-shaped air gap is optimized to achieve beam splitting.

Light propagation in a PC structure is governed by its dispersion surfaces. The group velocity v_g is given by the relationship $v_g = \partial\omega/\partial k$ [24], where ω is the frequency at

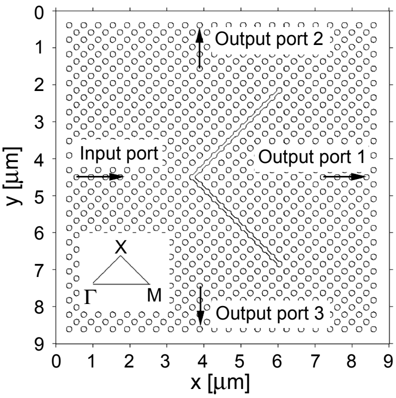

Fig. 1. Schematic of the beam splitter consists of a self-collimating PC structure and a V-shaped air gap defect. The PC structure is composed of air holes arranged in a square lattice in a silicon background ($n = 3.5$). The lattice constant of the PC is $a = 270$ nm. The radius of the air holes is $r = 0.25a$ (67.5 nm).

the wavevector k. It implies that the direction of light propagation coincides with the direction of the steepest ascent of the dispersion surface and is perpendicular to the equifrequency contours (EFCs). The self-collimating phenomenon occurs where the EFC corresponding to a frequency is flat. The EFCs can be obtained by the plane wave expansion (PWE) method, which is frequently used to solve the eigenvalue problem of the Maxwell's equations.

Here we consider a two-dimensional (2D) square lattice PC composed of 42×42 air holes in a silicon background ($n = 3.5$). The radius of the air holes is $r = 0.25a$ (67.5 nm), where $a = 270$ nm is the lattice constant of the square lattice. The proposed structure has a very compact size of about 8.56×8.56 μm^2. The plane wave expansion method is employed to obtain the EFCs of the PC by computing the eigenfrequencies at all

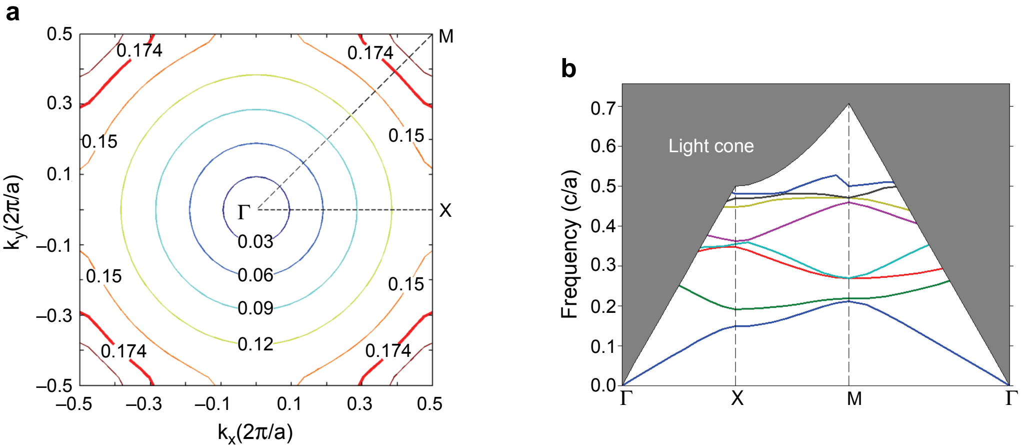

Fig. 2. EFCs of the first band (**a**) and band diagram (**b**) for TE mode of the designed PC. Radius of the air holes is $r = 0.25a$. The shaded area represents the light cone.

k points in the first Brillouin zone (FBZ). Figure 2**a** shows the EFCs of the first band for TE mode whose magnetic-field is parallel to the axes of the air holes. It is observed that the EFCs for frequencies around $f = 0.174c/a$ ($\lambda = 1550$ nm) are perpendicular to the ΓM direction, where *c* is the speed of light in free space. As depicted above, a self-collimation phenomenon will occur in the ΓM direction for these frequencies. The band diagram is also calculated with the PWE method as shown in Fig. 2**b**. It can be seen that the frequencies around $f = 0.174c/a$ are not in any photonic band gaps, so they can be coupled and propagate in the PC structure.

To split the incident beam, a V-shaped air gap with inner angle of 90° is introduced in the designed PC. The two sides of the V-shape air gap are along the ΓX direction as shown in Fig. 1. According to YU's study [15], light will be reflected or separated by the PC–air interface, which behaves as a total internal reflection mirror. When a light beam is incident on the apex of the V-shaped air gap, the beam will be split into two sub-beams if the incident light is totally reflected by the PC–air interface of the V-shaped air gap; otherwise, if the incident light is partly reflected and partly passed through, it will be split into three sub-beams.

To find a proper width for one-to-three and one-to-two beam splitting, the normalized powers of the three sub-beams as a function of the air gap width are calculated as shown in Fig. 3. The normalized power is defined as the output power of the sub-beam divided by the input power. The 2D finite-difference time-domain (FDTD) method with a perfectly matched layer (PML) absorbing boundary conditions is employed to accomplish this work. An *H*-polarized Gaussian beam with a width of 4*a* (1.08 μm) at frequency $f = 0.174c/a$ ($\lambda = 1550$ nm) is launched from the left-hand side of the PC. Three monitors with a width of 8*a* (2.16 μm) are placed at the exits of port 1, 2 and 3 to collect the output powers respectively. For the symmetry of the structure along the direction of the incident light beam, the normalized powers of output port 2

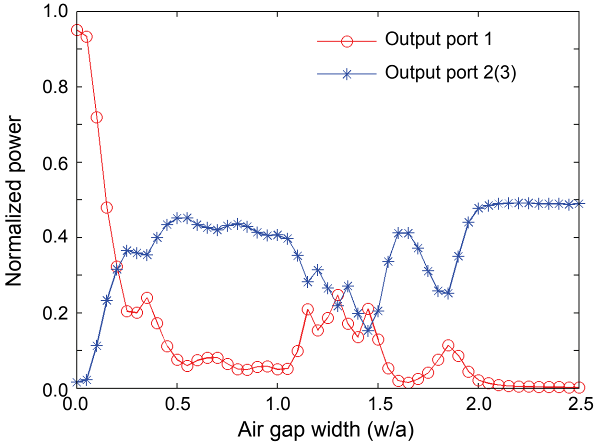

Fig. 3. The normalized power as a function of the air gap width calculated with the FDTD method. The source is an *H*-polarized Gaussian beam at frequency $f = 0.174c/a$ with a width of 4*a* (1.08 μm), launched from the left-hand side of the PC.

and output port 3 are of the same. If different splitting ratio between output port 2 and 3 is required, it can be realized just by changing the widths of the two sides of the V-shaped air gap individually.

From Figure 3, it can be clearly seen that there are five intersection points of the two curves, at which the normalized power of output port 1 equals to that of output port 2(3). At these intersection points, the highest normalized powers are 32.35% for output port 1 and 31.52% for port 2(3) when the air gap width is $w = 0.20a$ (54 nm). In this way, the incident beam is split into three sub-beams with a splitting ratio of nearly 1:1:1. The total efficiency is about 95.39% of the splitter. The small amount of propagation loss is caused by diffuse scattering of the splitting structure. The energy loss has also been observed in previous studies [16]. The propagation of light in the designed splitter is simulated with the FDTD method as shown in Fig. 4**a**. It can be clearly seen that the incident beam is split into three sub-beams with almost identical powers.

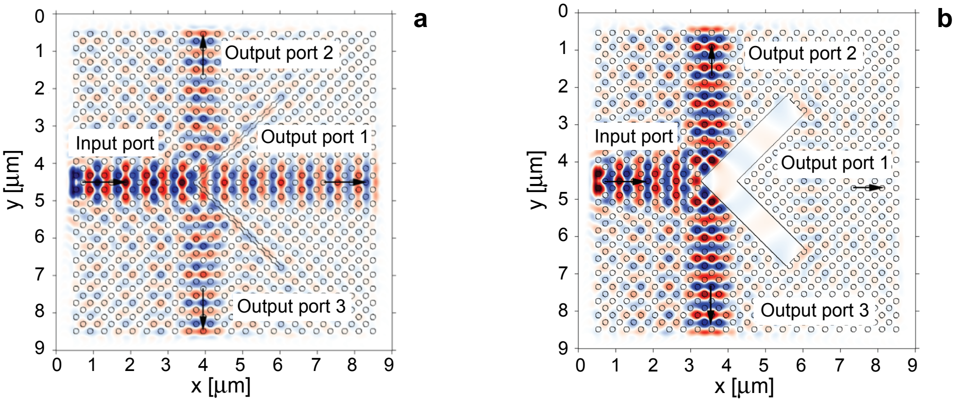

Fig. 4. Steady-state field distributions of the H_z component in the one-to-three beam splitter (**a**) and the one-to-two beam splitter (**b**) simulated with the FDTD method. The air gap widths are $w = 0.20a$ (54 nm) and $w = 2.50a$ (675 nm) for (**a**) and (**b**), respectively. The source is an H-polarized Gaussian beam at frequency $f = 0.174c/a$ with a width of $4a$ (1.08 μm), launched from the left-hand side of the PC.

It is also noticed that, when the air gap width is $w = 2.50a$ (675 nm), the normalized power of output port 1 is nearly zero and that of output port 2(3) reaches a peak value of 48.93%. The total efficiency of the splitter is 97.86%. In this condition, the splitter works as a T-shaped one-to-two splitter. To verify the calculation, the field distribution in the T-shaped splitter is simulated with the FDTD method and presented in Fig. 4**b**. It is observed that all energies are reflected by the air gap and transmitted to output port 2 and 3. The energies exited from output port 1 are nearly zero. The incident beam has been split into two sub-beams in opposite directions.

Based on the combinations of the one-to-three and one-to-two splitters, one can realize an arbitrary one-to-N splitter. As an illustration, a one-to-five splitter is proposed as shown in Fig. 5. The splitter is composed of two one-to-three splitters and

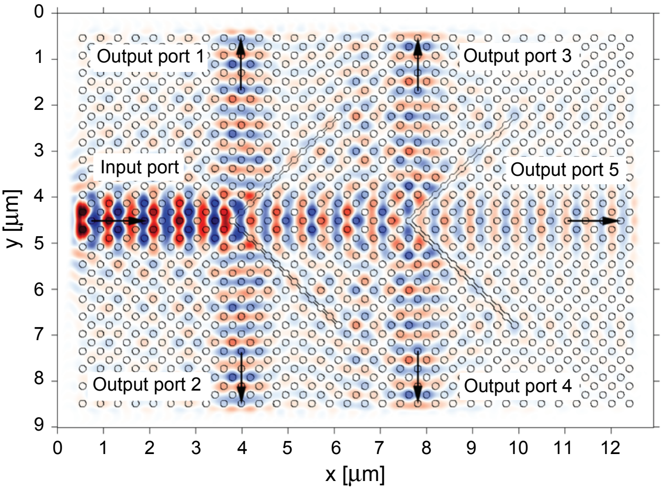

Fig. 5. Steady-state field distribution of the H_z component in the one-to-five beam splitter simulated with the FDTD method. The widths of the first and second V-shaped air gaps are 0.14*a* (37.8 nm) and 0.20*a* (54 nm), respectively. The source is the same as that used in Fig. 4.

has a compact size of 11.84×8.56 μm^2. The widths of the first and second V-shaped air gaps are $w = 0.14a$ (37.8 nm) and $w = 0.20a$ (54.0 nm), respectively. A FDTD simulation with the same parameters as those used in the previous study is performed to calculate the normalized powers. The normalized powers of the five output ports are 18.17% (port 1, 2), 17.81% (port 3, 4) and 18.74% (port 5). The splitting ratios between the five ports are nearly identical. Shown in Fig. 5 is the steady-state field distribution of the H_z component in the one-to-five splitter simulated with the FDTD method. It can be seen that the incident beam has been split into five sub-beams in two goes in a compact structure. The one-to-five splitter can also be realized by combining four one-to-two beam splitters, but it is inefficient compared to the combination of two one-to-three splitters.

3. Conclusions

In summary, a one-to-three and a T-shaped one-to-two beam splitters are proposed by introducing a V-shaped air gap into a self-collimating PC. With the one-to-three beam splitter, the self-collimated incident light beam can be split into three sub-beams in one go. The structure is more compact than the combination of two one-to-two beam splitters. Moreover, the splitting ratio can be precisely controlled by adjusting the width of the air gap. The T-shaped one-to-two splitter for self-collimated beams is also realized by increasing the air gap width to 2.5*a*. High efficiencies of total output powers of about 95.39% and 97.86% for the designed one-to-three and one-to-two beam splitters are achieved respectively. The proposed beam splitters may find important applications in the realization of PICs.

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