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Enhanced transmission and beaming of light from a photonic crystal waveguide via two collimation lenses

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ABSTRACT

Directional emission of light passing through a subwavelength photonic crystal waveguide (PCW) with the help of two collimation lenses is researched. The collimation lens is another photonic crystal with a self-collimation effect. Four different configurations of PCW and collimation lens are studied by the finite-difference time-domain (FDTD) method. Simulation results show that this collimation lens method can not only achieve a high transmission and low divergence light beam but also provide a wide band width of $\Delta\omega/\omega = 5\%$ (where, ω is the angular frequency), which is better than the mechanism of interference of surface modes.

1. Introduction

In traditional optics light can hardly transmit a subwavelength aperture due to both the poor coupling of subwavelength holes to radiative EM modes [1] and the evanescent decay of the EM fields inside the holes [2]. But, in 1998 Ebbesen et al. demonstrated an extraordinary optical transmission (EOT) phenomenon for two-dimensional periodic arrays of subwavelength holes in metals [3]. This EOT comes from the excitation of surface plasmons on the metal-dielectric interfaces. Recently it has been shown that enhanced transmission and beaming of light through subwavelength structures can be also observed in photonic crystal waveguide (PCW) system [4–9]. This beaming effect arises from the coherent interference of light emitted from the subwavelength structure and that of the excited leaky surface modes at the exit surface. However, this method does not provide any simple rules for determining which surfaces support surface modes. Moreover, the band width is very narrow due to the mechanism of coherent interference. Tang et al. [10] achieved a highly efficient beaming emission from the PCW by utilizing the self-collimation effect. They add another PC to provide the self-collimation effect. But they choose only three arrays of cylinders to form the additional PC, which is hardly to contain a good self-collimation behavior because the self-collimation effect is a bulk property of the crystal. Furthermore, the beaming effect is attributed to the interference of the multiple self-collimation beams excited by the waveguide, which means their method still can not obtain a wide band width.

In this letter, we study a Gaussian beam transmitting through a triangular lattice PCW with a subwavelength width. Utilizing the self-collimation effect we design collimation lenses composed of a square lattice PC structure to limit the diffraction effect of light beam and to improve the transmission. The cases of PCW without any lens, with a single lens at one side, and with double lenses at each side, are all researched by using the FDTD method.

2. Two-dimensional PCW and collimaton lens

The PC we considered consists of a two-dimensional triangular lattice of air holes in a background media with an effective refractive index of $n = 4.36$. The hole radius is set as $r = 0.49a$, where a is the lattice constant. In simulations, the PC system has a finite size of $10a \times 12\sqrt{3}a$ (see Fig. 1). For TM polarization (electric field is parallel to the holes axis), there is a wide band gap from $0.380c/a$ to $0.534c/a$ calculated by using the plane wave expansion (PWE) method, where c is the speed of light in vacuum. The working frequency is chosen as $0.5c/a$, which is near the center of the band gap so that this PC can be seen as a perfect mirror to restrain the transmission of light wave. To obtain a subwavelength PCW

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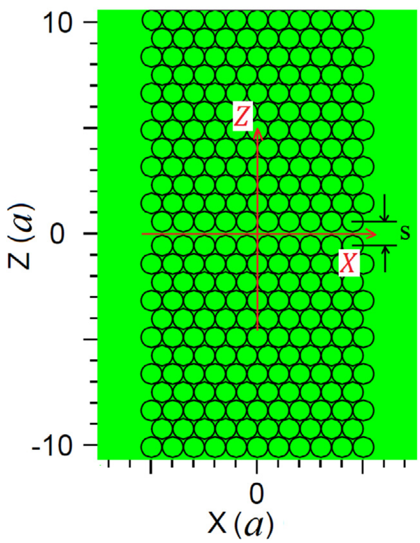

Fig. 1. Structure of photonic crystal waveguide (PCW).

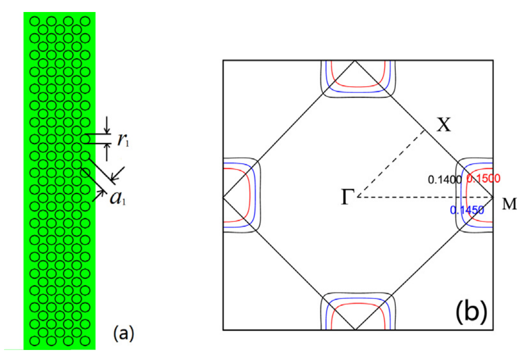

Fig. 2. (a) Collimation lens consisting of the square lattice PC. (b) EFCs of the square lattice PC. Γ, M, and X are symmetric points of the Brillouin zone. Each EFC is marked by its induced frequency.

(shown as in Fig. 1) we take the following two operations. First, remove the row of air holes on the X-axis. This operation will cut the PC into two symmetric halves along the X-axis. Second, translate all the air holes in the upper half part with a displacement along the $-z$ direction and symmetrically translate all the air holes in the lower half part along the +z direction with a same displacement so that there is a subwavelength interspace between the two halves. In our simulations, the displacement is $0.3a$, so the space between the centers of the bottom row of air holes in the upper half part and the centers of the top row of air holes in the lower half part equals to $S=\sqrt{3}a-0.3a\times 2\approx 1.13a$ (S is shown in Fig. 1). Then the interspace between the two halves has a width of $w=S-r\times 2\approx 1.13a-0.98a=0.15a$, which is less than the wavelength in the higher index material. In our simulations, the working frequency is chosen as $0.5c/a$, and the wavelength is $\lambda_n=\lambda_0/n=\frac{a}{0.5}/4.36\approx 0.46a$, where λ_0 and λ_n are the wavelengths in air and in higher index medium, respectively. So this PCW has a subwavelength width.

To obtain high transmission and a very low beam divergence we introduce an additional PC to serve as a collimation lens utilizing the self-collimation effect. This PC structure is a two-dimensional square lattice of air holes in the same background media. Fig. 2(a) shows the square lattice PC structure with a finite size of $3a_1\times 20\sqrt{2}a_1$, where a_1 is the lattice constant of the square lattice. The radius of the air holes is $r_1=0.4\times a_1$. Both the horizontal direction and the vertical direction of the square lattice PC are truncated along the $\Gamma-M$ direction. Fig. 2(b) shows the equi-frequency contours (EFCs) in the first band of the square lattice PC. The EFC of each frequency looks like a square centered at the M point with four flat edges vertical to the $\Gamma-M$ direction, which implies that the self-collimation effect takes place along this direction. Moreover, the frequency range in which the self-collimation effect will occur covers from $0.1400c/a_1$ to $0.1550c/a_1$. Thus, this collimation lens will have a wide band width. If we choose the working frequency as $0.1500c/a_1$, then it must equal to $0.5c/a$. So we can get $a_1=0.3a$.

3. Results and discussions

To illustrate the performance of the collimation lens, we perform FDTD simulations for four cases of different configurations: (1) only the PCW without a collimation lens (we call it “0-lens”); (2) PCW with a single lens at the left side (named “L-lens”); (3) PCW with a single lens at the right side (named “R-lens”); (4) PCW with two lenses at both sides (named “2-lens”). Note that in all cases the collimation lens is placed so carefully that it can be in touch the surface of the PCW. In all simulations, an incident Gaussian beam with a waist of $4a$ illuminates vertically on the PCW-lens system from the left side. The separation between the center of the Gaussian beam and the left edge of the PCW-lens system is $0.5a$. The boundary of the calculation area is chosen the perfect matched layer condition and the calculations are only for the TM polarization.

Fig. 3 shows the electric-field amplitude for the four cases. Fig. 3(a) shows the electric field distribution for the PCW without lenses (the case of “0-lens”). One can easily find that strong reflections take place near the input terminal of the PCW because of the poor coupling between the incident light field and the PCW with a subwavelength width. At the output terminal the radiated light field has a large angular distribution in an azimuthal angle range of $-32.3^\circ\leq\theta\leq+32.3^\circ$. A power monitor I with a width of 20a is launched at ($+20a$, 0) to detect the transmitting power. The whole transmission is about 20.8% in this case (see in Fig. 4) due to high reflections at the input side of the PCW. Thus, for the PCW without any modulations, the radiated light field contains a large beam divergence due to strong diffractions at the exit of the PCW. Fig. 3(b) shows the electric field distribution for the PCW with a lens at the left side (the case of “L-lens”). Note that the collimation lens is placed symmetrically along the X-axis and just touches the surface of the PCW. One can easily find that electric filed at the right side of the PCW in the case of L-lens are much stronger than that in the case of 0-lens. The transmitted power collected by the power monitor located at ($+20a$, 0) is about 61.7% (see in Fig. 4). The enhancement of the transmission implies the collimation lens at the input side can improve the coupling between the incident light field and the PCW. But the collimation lens at the input side does not depress the divergence angle of the output beam at all. Fig. 3(c) shows the electric field distribution for the PCW with a lens at the right side (the case of “R-lens”). The reflections from the input side are still very strong but the output beam keeps a very low divergence angle due to the introducing of the collimation lens. The light transmission of the PCW in the case of R-lens is about 20.4% (see in Fig. 4) just a little below the value of the 0-lens case. So we conjecture that the collimation lens introduced at the input side can improve the total radiated power while the collimation lens introduced at the output side can depress the divergence angle of the output beam. Fig. 3(d) (the case of “2-lens”) proves this conjecture. The transmission in this case is about 65.6% even larger the value of the L-lens case. The pattern of the reflection beams in the case of 2-lens is very similar to that in the case of L-lens, which suggests the collimation lens at the input side plays a same role in these two cases. That is, with the help of the collimation lens light wave can easily permeate the PCW with a subwavelength width. Moreover, Fig. 3(c) and (d) both