Line-defect-induced bending and splitting of self-collimated beams in two-dimensional photonic crystals

Sun-Goo Lee, Sang Soon Oh, Jae-Eun Kim, and Hae Yong Park[a)]
Department of Physics, Korea Advanced Institute of Science and Technology, Daejon 305-701, Korea

Chul-Sik Kee[b)]
Advanced Photonics Research Institute, GIST, Gwangju 500-712, Korea

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We show that line defects can give rise to the bending and splitting of self-collimated beams in two-dimensional photonic crystals from the equifrequency contour calculations and the finite-difference time-domain simulations. The power ratio between two split self-collimated beams can be controlled systematically by varying the radii of rods or holes in the line defect. We also show that the bending and controllable splitting of self-collimated beams can be useful in steering the flow of light in photonic crystal integrated light circuits. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2112186]

Photonic crystals (PCs) are dielectric materials whose refractive index is periodically modulated in space. With a proper design, PCs can exhibit photonic band gaps (PBGs),[1] the frequency ranges in which light propagation is completely prohibited in any direction. There have been a number of attempts made to control the flow of light by utilizing the effect of PBG.[2–6] In recent years, there has been a growing interest in anomalous dispersion properties of PCs.[7–9] One of the most interesting phenomena originating from complex spatial dispersion is the self-collimated propagation of light beam in PCs. This interesting phenomenon, an incident light propagating with almost no diffraction along a definite direction,[9] could provide a new way to control the flow of light in PCs.

Kosaka *et al.* experimentally demonstrated the self-collimated propagation of light in PCs and Witzens *et al.* theoretically studied the propagation properties of self-collimated beams in detail.[9,10] In recent studies, it has been reported that the bending and splitting of self-collimated beams are possible.[11–14] It has been also reported that the frequency range in which the self-collimation phenomenon occurs is sufficient for this effect to be a basis for photonic integrated circuits (PICs).[14] To implement PICs based on the self-collimation phenomena, however, a simple and efficient way to bend and split self-collimated beams in planar PCs is required.

In this letter, we show that self-collimated beams can be easily bent and split by introducing line defects in PC structures and moreover, the power ratio between two split self-collimated beams can be controlled systematically by varying the radii of rods or holes in the line defect. We also show that self-collimated beams can be effectively steered by arranging line defects appropriately.

When light is incident from an optically dense medium (high refractive index, n_h) onto a less dense medium (low refractive index, n_l), the incident wave is totally reflected back into the denser medium at the interface provided that the incident angle is larger than the critical angle given by $\theta_c = \arcsin(n_l/n_h)$. Our idea is based on the fact that self-collimated beams can also be totally reflected at the interface of a PC and air, where a PC and air corresponds to an optically dense and a less dense medium, respectively.[11] When light undergoes total internal reflection, the field amplitude of light decays exponentially into the less dense medium. Thus, it is expected that self-collimated beam would be totally reflected at the interface of a PC and an air layer of finite thickness, the line defect created by removing a few rods in a row. Such total reflection can cause self-collimated beam to bend inside a PC. What is more, self-collimated beam can also be partially reflected by a line defect formed by reducing the radii of rods instead of eliminating them totally, due to the tunnelling of the evanescent wave. Hence we expect that an incoming self-collimated beam can be split into the transmitted and reflected beams by the line defect.

In order to verify our conjecture, we first consider a 2D square lattice PC composed of dielectric rods in air and the case of a 2D square lattice PC composed of air holes in a dielectric background follows next. The radius and dielectric constant of rods are taken as $0.35a$ and 12.0, where a is the lattice constant. We restrict our attention to the case of the E-polarized mode whose electric-field is parallel to the rod axes. To find the frequency range in which the self-collimation phenomenon occurs and the propagation direction of light beam, we calculated the equifrequency contours (EFCs) as a function of $\mathbf{k}$. It is known that, in an inhomogeneous medium, the propagation direction of light is identical to the direction of group velocity of light given by $\mathbf{v_g} = \nabla_\mathbf{k}\omega(\mathbf{k})$, which means that the group velocity is perpendicular to the EFC.[15] We employed the plane wave expansion method to plot the EFCs of the 2D PC.[16] We found from the EFC calculations that the self-collimation phenomenon occurs when lights of frequencies around $f = 0.194c/a$, where c is the speed of light in free space, propagate along the (11) direction of square lattice ($\Gamma\mathbf{M}$ direction). We also found that self-collimated beam can be totally reflected at the PC-air interface created by truncating a PC along the (10) direction of square lattice ($\Gamma\mathbf{X}$ direction) because of the conservation of momentum component parallel to the interface. Thus self-collimated beams can be bent at the (10) PC-air interface.

a)Electronic mail: hypark@kaist.ac.kr
b)Electronic mail: cskee@gist.ac.kr

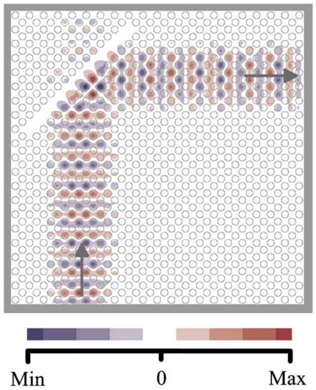

FIG. 1. (Color online) Simulated spatial distribution of the steady-state electric-field of the *E*-polarized mode at $f=0.194c/a$ when light propagates along the $\Gamma\mathbf{M}$ direction. Electric-field is parallel to the rod axes. Note that the line defect created by removing 15 rods in the $\Gamma\mathbf{X}$ direction acts as a total internal reflection mirror for self-collimated beams propagating along the $\Gamma\mathbf{M}$ direction. The outer dark gray region means the absorbing region with the PML boundary condition and arrows indicate the propagation direction.

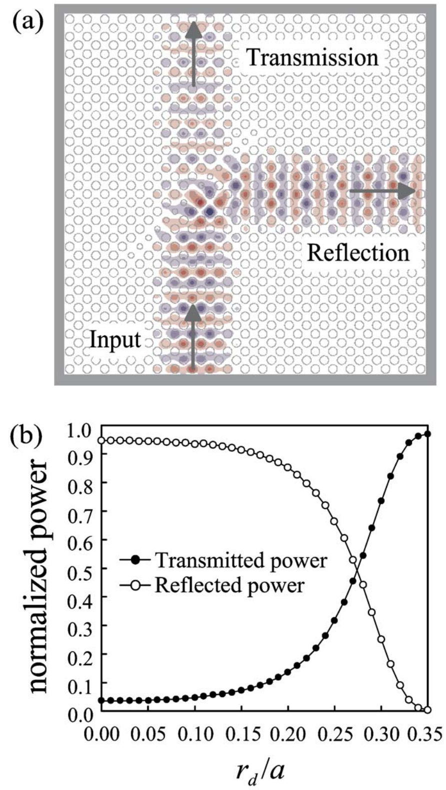

FIG. 2. (Color online) (a) Simulated spatial distribution of the steady-state electric-field of the *E*-polarized mode at $f=0.194c/a$ in the line defect beam splitter composed of 15 defect rods with the radii r_d aligned in the $\Gamma\mathbf{X}$ direction. (b) Reflected and transmitted powers which are normalized with respect to the input power as a function of r_d.

From the finite-difference time-domain (FDTD) simulations with the perfectly matched layer absorbing boundary conditions,[17,18] we observed that the (10) PC-air interface yields the 90° bending of self-collimated beam at the frequencies in the vicinity of $f=0.194c/a$. We also observed that, when self-collimated beam undergoes total internal reflection at a (10) PC-air interface, the field amplitude decays very rapidly into air, becoming negligible at a distance within one lattice constant. Thus an air layer created by removing a few rods in a row, a line defect, is expected to give rise to the total internal reflection. Figure 1 shows that a line defect created by removing 15 rods in the $\Gamma\mathbf{X}$ direction almost totally reflects self-collimated beam propagating along the $\Gamma\mathbf{M}$ direction. However, we observed that when the air layer is doubled, i.e., two rows of line defects (15 rods each) are introduced, the structure yields total internal reflection. In the FDTD simulations, we considered $20\sqrt{2}a\times 20\sqrt{2}a$ of the square PC composed of dielectric rods with $r=0.35a$ and a Gaussian beam with the full width at half maximum $5a$ was used. We excited a monochromatic wave of the frequency $f=0.194c/a$ and launched it into the PC along the $\Gamma\mathbf{M}$ direction. Then we monitored the propagation of input beam by observing the spatial variation of the electric- and magnetic-field distributions as a function of time.

Based on the line defect induced beam bending phenomenon, we constructed a line defect beam splitter shown in Fig. 2(a), which is composed of 15 rods aligned in the $\Gamma\mathbf{X}$ direction with the radii r_d different from those of host rods. One can expect a gradual transition from no reflection to total reflection to occur as r_d is varied from $0.35a$ to zero. In order to study the quantitative relation between the value of r_d and the power ratio between two split beams, we measured the time averaged power before and after the beam splitting by integrating the Poynting vector across the beam cross section. The reflected and transmitted powers are normalized with respect to the input power and the results are shown in Fig. 2(b). The result clearly shows that an incoming self-collimated beam can be split into the reflected and transmitted beams with an arbitrary power ratio by adjusting the value of r_d. The sum of the reflected and transmitted power is always less than the input power by about 3%. This small amount of propagation loss may have been caused by the scattering in the splitting structure which has been also observed in the previous study.[12]

We also studied the beam splitting phenomenon induced by a line defect in hole-type PCs. We employed a 2D square lattice of air holes with the hole radius $r=0.25a$ and the dielectric constant of high index background $\epsilon=12.0$. The calculations were done for the *H*-polarized mode which has the magnetic-field parallel to the hole axes. We observed that a line defect can cause the beam splitting phenomena for the light of frequencies near $f=0.183c/a$ propagating in the $\Gamma\mathbf{M}$ direction. The time averaged power before and after the beam splitting is obtained for the light of $f=0.183c/a$ and the resulting normalized power is shown in Fig. 3. The inset represents the top view of the beam splitting structure. This result also shows that the power ratio between the reflected and transmitted beams can be controlled systematically by varying the radii of air holes r_d in the line defect.

The line defect induced beam bending and splitting effects can be useful in routing light beams in 2D PCs. We designed a one-to-four beam splitter composed of four line defects in rod-type PC as shown in Fig. 4. Radii of rods in the line defects are chosen to be $0.301a$, $0.292a$, $0.275a$, and 0, successively, so that an input beam is divided into four output beams of an equal power. We found that the power of each output beam can be easily controlled by varying the radii of rods in the corresponding line defect.

As concluding remarks, as the self-collimation phenomenon occurs due to the dispersion properties of propagation modes in PCs, not due to the existence of PBGs, low index

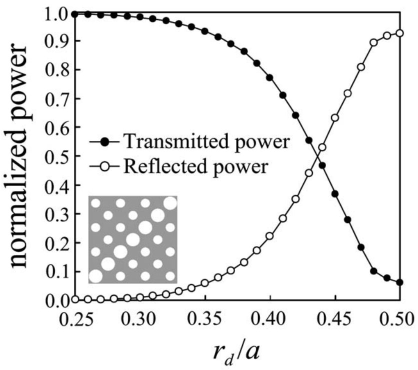

FIG. 3. The power spectra for the split beams by a line defect in a 2D square PC composed of air holes with the radius of $r=0.25a$ as a function of r_d, the radii of defect holes. The inset represents the top view of the beam splitter structure. The calculations were done for the H-polarized mode at the frequency $f=0.183c/a$ propagating in the Γ**M** direction with the magnetic-field parallel to the hole axes. The dielectric constant of high index background is 12.0.

contrast PC structures can exhibit the diffractionless propagation of light.[19] Thus, optical devices based on the bending and splitting of self-collimated beams may be realized by utilizing low refractive index dielectric materials such as polymers. Recently, it has been demonstrated that nanoimprint lithography is suitable for periodic patterning of various polymer thin-films[20] and passive optical devices for the infrared and visible wavelength range are realized on 150 mm wafers with feature sizes of about 50 nm.[21] Hence the periodically patterned polymer thin-films fabricated by such a technique may be useful for the implementation of the optical devices based on self-collimated beams. Besides, proposed beam bends and splitters have simple geometric structures and clear operating mechanism. Thus our results may have an important role in the realization of PICs based on the self-collimated light propagation.

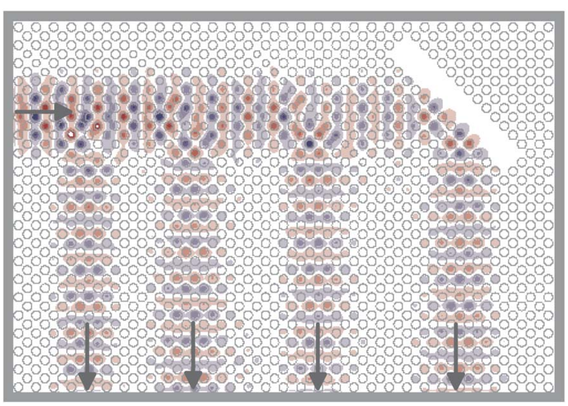

FIG. 4. (Color online) Simulated spatial distribution of the steady-state electric-field of the E-polarized mode at $f=0.194c/a$ in a one-to-four beam splitter composed of four line defects. Radii of rods in each line defect are chosen to be $0.301a$, $0.292a$, $0.275a$, and 0, successively, so that an input beam is divided into four output beams of an equal power. Arrows indicate the propagation direction of the input and four output beams.

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