Polarization-independent self-collimating bends and beam splitters in photonic crystals

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Polarization independent bends and beam splitters for transverse electric (TE) and transverse magnetic (TM) polarizations have been demonstrated in two-dimensional (2D) photonic crystals (PhCs). In virtuel of equi-frequency contour analysis and finite-difference time-domain calculations, self-collimation behaviors for TE- and TM-polarizations are achieved at the same frequency. Simulation results show a 90-degree bend with 90% efficiency and beam splitters with about 96% total efficiency for both TE- and TM-polarizations, where the light is self-guided by the self-collimation effect. Such bends and beam splitters are expected to play important roles in optical devices where polarization insensitivity is needed.

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Photonic crystal (PhC) based integrated optical devices are attracting growing attention mainly due to their potential to control the flow of light at optical wavelength scale, which offers the advantage of dense on-chip integration. During the past decade, PhC based waveguides, bends, beam splitters, and various other devices have been intensively investigated both theoretically and experimentally[1−8]. Initially, most common implementation of PhC waveguides, bends and beam splitters found in the literature was created by introducing line defect within a photonic band gap (PBG) structure, where the PBG defect waveguide is used to route the propagation of light[1−3]. Recently, however, another confinement mechanism of light guiding has been increasingly investigated, i.e., the so-called self-collimation[9,10], supercollimation[11], and self-guiding[12,13]. It exploits the spatial dispersion properties of Bloch waves in PhC to achieve diffractionless light propagation and retain spatial width confinement without line-defected waveguide or nonlinearities. Centimeter-scale supercollimation has been achieved in a large-area two-dimensional (2D) PhC experimentally[11], bends and beam splitters for self-collimated beams have also been demonstrated experimentally and discussed theoretically[4−8,14,15]. We recently reported a polarization beam splitter which uses self-collimation effect to route the propagation of light[16]. It demonstrated that this dispersion-based non-channel virtual waveguide can play an important role in integrated optical circuit.

Much of the work reported in the literature on PhC structures has focused on one polarization, TE- or TM-polarization. They are highly polarization selective. Additional polarization preprocessing devices would be required to maintain their proper operation. One of the challenges in integrated photonic circuits is to design polarization-independent photonic devices[17,18]. Recently, Lidorikis *et al.* have designed a polarization-independent waveguide in three-dimensional (3D) PhC by introducing line defects in the hole and rod layers, resulting in the formation of defect bands inside the PBG[17]. Self-guiding for TE- and TM-polarizations at a slightly different wavelength has been achieved in PhC films[13]. In this letter, we demonstrate that self-collimation can be achieved in a properly designed 2D PhC of air holes type for TE- and TM-polarizations, respectively, at the same frequency. Polarization-insensitive bends and beam splitters based on such PhC structure are demonstrated, too.

Our 2D PhC consists of a square array of air holes introduced into a high index material. The radius of the air holes is $1/3a$, where a is the lattice constant. In the calculations, the dielectric constant of the dielectric is

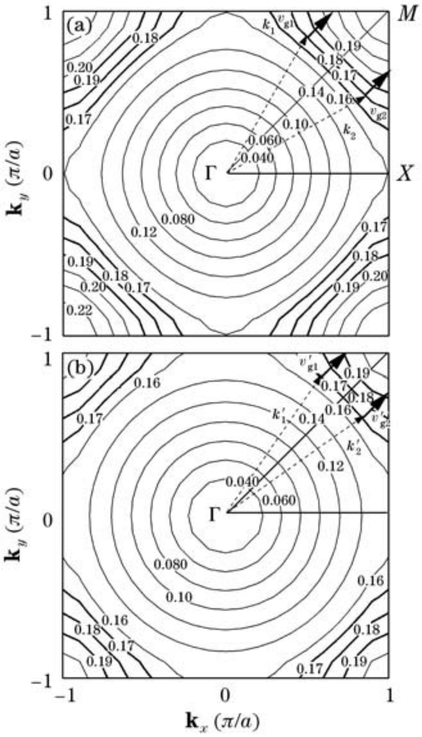

Fig. 1. First-band EFCs for (a) TE- and (b) TM-polarizations of the PhC dispersion surface in the first Brillouin zone. **k**-vectors (dashed arrows) of the same normalized frequency on a relatively flat EFC near the M point have group velocities $\vec{v}_\mathrm{g}$ (line arrows) collimated along the ΓM direction.

taken to be $\varepsilon = 12$. Figure 1 shows the first-band equi-frequency contours (EFCs) of the PhC, calculated by using a plane-wave expansion method for two orthogonal polarizations. Within a range of **k**-vectors and normalized frequencies $f = 0.16c/a - 0.19c/a$ (c is the speed of light in vacuum), near the **M** point, the EFCs are nearly flat and perpendicular to the ΓM direction. The energy flow of light propagation, which is defined by the group velocity, $\vec{v}_{\mathrm{g}} = \nabla_k \omega(\vec{k})$, coincides with the direction of steepest ascent of the dispersion surface, and is therefore perpendicular to the EFCs. As indicated in Figs. 1(a) and (b), the lightwave with **k**-vectors and normalized frequencies within such flat EFCs region has the group velocity $\vec{v}_{\mathrm{g}}$ predominantly pointing towards the ΓM direction, exhibiting self-collimating behavior for both TE- and TM- polarizations. We may call it polarization-independent self-collimation.

The finite-difference time-domain (FDTD) method was used to validate the expected polarization independent self-collimation propagation. A pulse consisting of the fundamental mode of a $4\sqrt{2}a$ wide ridge waveguide was coupled into the PhC. The Fourier transformation of the pulse yielded the propagation properties of an optical beam inside the PhC. The fields were monitored at $10\sqrt{2}a$, $18\sqrt{2}a$, $26\sqrt{2}a$, $34\sqrt{2}a$, $42\sqrt{2}a$ away from the crystal boundary, the normalization spectra were obtained with respect to the intensity spectra for a monitor located at $4\sqrt{2}a$. Figure 2 shows the plot as a function of frequency for TE- and TM-polarizations at different locations. The intensity decreases rapidly with the propagation distance increasing. But in the vicinity of frequency $f = 0.18(c/a)$, the intensity remains above 80% for both TE- and TM-polarizations, which indicates the diffractionless propagation of light at frequency $f = 0.18c/a$.

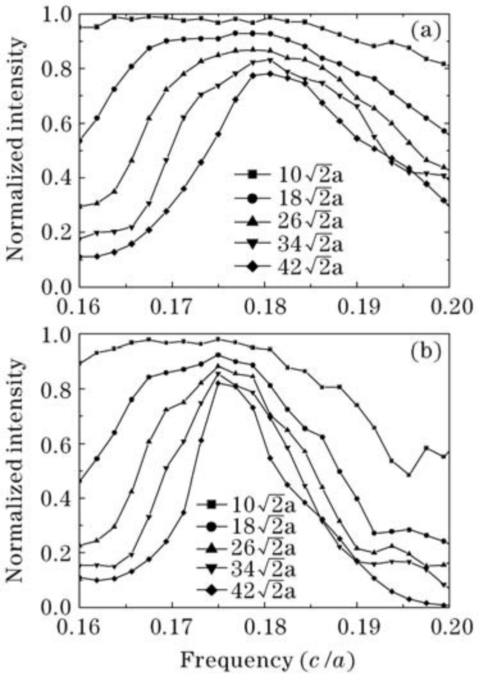

Fig. 2. Intensity spectra at distances $10\sqrt{2}a$, $18\sqrt{2}a$, $26\sqrt{2}a$, $34\sqrt{2}a$, $42\sqrt{2}a$ away from the crystal boundary, which are normalized with respect to the intensity spectra recorded at $4\sqrt{2}a$ away from the crystal boundary.

Bends and beam splitters are the fundamental elements for integrated optical circuits that allow for the bend and division of an optical beam for high-density routing. They can be realized via conventional index-guided waveguides, line-defect waveguide, and self-collimation phenomenon. Lossless guiding of light via self-collimation has attracted great interest due to its great advantages[13,19,20]. Several types of self-collimating bends and splitters have already been reported, most of them are highly polarization selective. As demonstrated previously that bends and splitters of self-collimated beams can be realized by introducing line defects[4], or by varying the radii of one row of holes or rods[5,14]. The mechanism of bend and splitter has been detailed[14]. In this letter, we show that polarization-independent self-collimating beams can be effectively steered by truncating the PhC structure mentioned above appropriately.

The bends and beam splitters are realized by truncating an air block alone (10) direction into the PhC, as indicated in Figs. 3 and 4. We observed that a line defect can cause tunable one-to-two splitter as the width of the block varies from 0 to a (a is the lattice constant). This effect can be seen in the steady state field pattern generated by FDTD simulation (see Fig. 3). The insets show the bend and transmission efficiencies which are normalized with respect to the input power. It is worth noting that the bend efficiency is equal to the transmission efficiency for TE-polarization (48%) at air-block width of $0.18a$ and TM-polarization (49.9%) at $0.33a$, respectively. Though beam splitters can be realized by introducing a line defect, it is difficult to realize the same splittering rate for two polarizations at a fixed width of air-block.

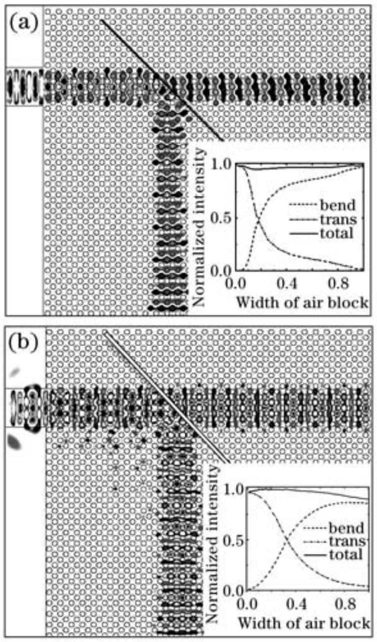

Fig. 3. (a) Steady-state magnetic field distribution for TE-polarization and (b) electrical field distribution for TM-polarization at frequency $f = 0.18c/a$ calculated using the 2D FDTD method. The insets in (a) and (b) show the corresponding splitting efficiencies for TE- and TM-polarizations, respectively.

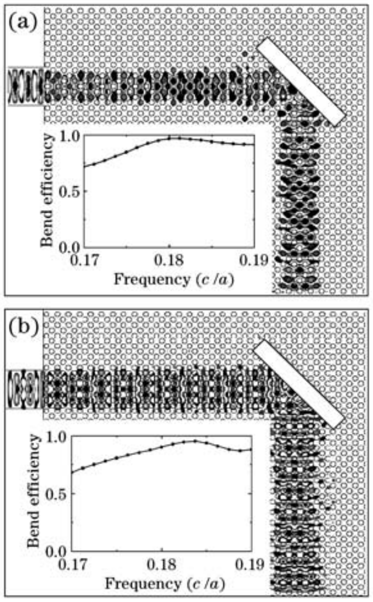

Fig. 4. (a) Steady-state magnetic field distribution for TE-polarization and (b) electrical field distribution for TM-polarization at frequency $f = 0.18c/a$ calculated using the 2D FDTD method. The insets in (a) and (b) show the corresponding bending efficiencies for TE- and TM-polarizations, respectively.

It is found that self-collimated beams can be totally reflected at the PhC air interface when the width of the air block is more than one lattice constant, due to the conservation of momentum component parallel to the interface[5]. FDTD simulations show that the (10) PhC air interface yields the 90 degree bending of self-collimated TE- and TM-polarized light with bend efficiency above 90% in the frequency range of $0.18c/a - 0.19c/a$ (see Fig. 4).

In conclusion, polarization-independent self-collimation, which can act as a non-channel virtual waveguide to route the propagation of light, can be realized in a properly designed PhC. Besides, a sharp bend with high efficiency ($> 90\%$) and tunable splitters of self-collimated beams are also demonstrated, in the case of polarization-independent light. Considering the feasibility of extending the optical components to both TE- and TM-polarizations, this material system would greatly enhance the use of PhCs in high density optical integrated circuits.

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