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Experimental demonstration of bending and splitting of self-collimated beams in two-dimensional photonic crystals

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The authors have experimentally demonstrated the bending and splitting phenomena of self-collimated microwave beams in a two-dimensional square lattice photonic crystal composed of alumina rods. The bending and splitting were achieved by introducing a line defect in the photonic crystal. The power ratio of two split beams can be controlled by varying the radii of rods in the line defect. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2713859]

Photonic crystals (PCs) are artificial structures formed by periodically modulated dielectric materials whose refractive indices are different from each other. One of the most characteristic property of PCs is the existence of the photonic band gaps, the frequency ranges in which light propagation is completely prohibited in any direction.[1,2]

In recent years, there has been a growing interest in anomalous dispersion in PCs.[3,4] Among many properties involving the anomalous dispersion, one of the most interesting phenomena is the self-collimated propagation of light, which means that light propagates with almost no diffraction along a definite direction. Self-collimated propagation of light in a PC was experimentally verified.[4] There have been several works[5–8] on bending and splitting of incoming self-collimated beam for the purpose of using these phenomena as a basis for optical integrated circuits. Very recently, it was theoretically suggested that the self-collimated beams should be bent or split by line defects in two-dimensional (2D) PC structures.[9] The splitting ratio is expected to be controlled by varying the radii of defect rods. The controllable bending and splitting enable us to steer the beams in PCs. However, experimental demonstration of the bending and splitting of the self-collimated beam has not been reported.

In this letter, we experimentally demonstrate the bending and splitting phenomena of self-collimated beam in a square PC composed of rods in microwave range. An inclined line defect created by removing a row of rods almost totally bends the beam. The variation of the radii of rods in the line defect changes the bent power, resulting in the splitting of the incident beam at the line defect. The measured split powers are compared with the numerical ones obtained by the finite-difference time-domain (FDTD) simulations.[10]

We prepared a 2D PC sample consisting of $12\sqrt{2}a \times 20\sqrt{2}a$ square array of cylindrical alumina rods in air. The lattice constant a is 1 cm and the radius of the rod r is 3 mm. The dielectric constant of the rods is approximately 9.0 in the microwave region. The length of rod is about 20 cm, which is much longer than the lattice constant. The samples are vertically fixed by two plastic plates which are drilled periodically. Defects in the samples are generated by removing a number of rods in a row or by replacing the rods with rods of smaller radii.

Schematics of the experimental setup composed of a 2D PC sample with a line defect along the ΓX direction and two horn antennas which are used as a source and a receiver is drawn in the inset of Fig. 1. The transmission spectra are obtained by reading the value of S12 parameter in a network analyzer (Agilent 8722ES) in TM polarization (the electric field parallel to the axis of alumina rods). To remove the loss or any other effect caused by cables and connecting parts of the setup, S12 parameter was measured with and without the sample between two antennas and then the difference between two values was taken for the transmittance.

Figure 1 shows the measured transmission spectrum along the ΓM direction for the uniform PC, which exhibits a band gap between approximately 8.0 and 10.0 GHz. Theoretically, the obtained band structure using the plane-wave expansion method[11] yields a band gap ranging from 7.95 to 10.08 GHz, which is in good agreement with the measurement.

To find the frequency range and the direction of the self-collimated propagation of light beam, the equifrequency contours (EFCs) are calculated and shown in Fig. 2(a). From the

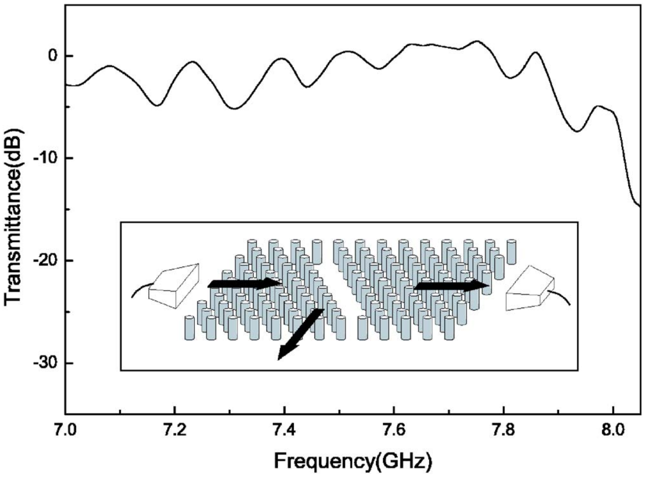

FIG. 1. (Color online) Measured transmission spectrum for the uniform 2D square lattice PC sample without any defect. The inset shows the PC with a line defect along the ΓM direction and two horn antennas.

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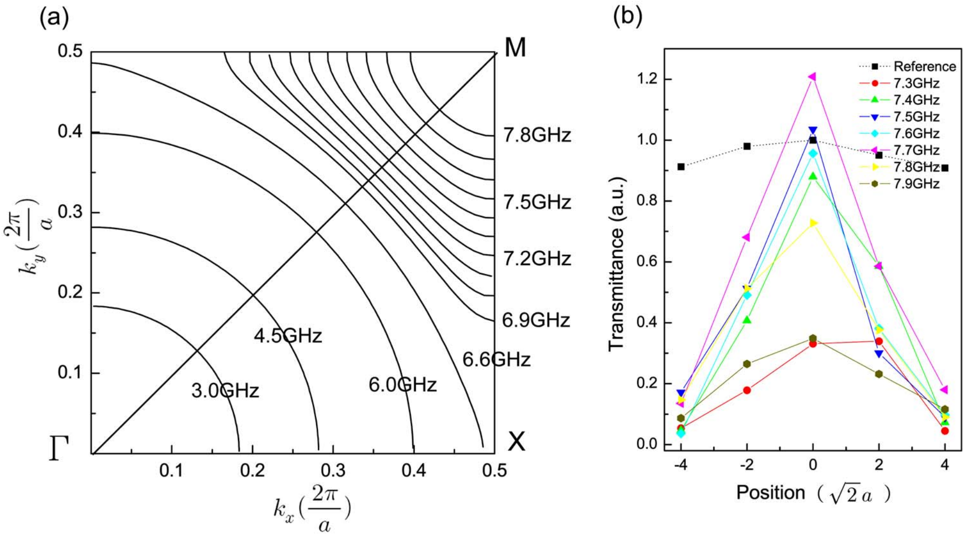

FIG. 2. (Color online) (a) Equifrequency surfaces of the 2D PC which are plotted employing the plane-wave expansion method. (b) Averaged transmittance of microwaves for the frequencies from 7.3 to 7.9 GHz propagating along the ΓM direction as a function of position. The dotted line indicates the reference transmittance which is measured without the PC at $f=7.7$ GHz.

figure we found that the microwaves of frequencies around 7.2 GHz can propagate self-collimatedly along the ΓM direction in our 2D square lattice PC. However, the experimentally measured transmission spectrum depicted in Fig. 1 clearly shows the maximum transmission region for the light of frequencies around 7.7 GHz.

The frequency range of self-collimation in our PC can also be verified by observing the beam profiles as a function of position directly. Figure 2(b) shows the averaged transmission powers for the light of frequencies from 7.3 to 7.9 GHz propagating along the ΓM direction as a function of position. The averaging comes from the size of horn antenna. The power was measured with the receiver antenna moving along the output face of the PC sample from one end to the other. The dotted line represents the transmittance measured without the PC at $f=7.7$ GHz. In the figure, as the frequency increases the beam intensity also increases, but contrary to the theoretical prediction the maximum transmission takes place at $f=7.7$ GHz, not in the region in the vicinity of 7.2 GHz, which is in good agreement with the results of the measured transmission spectrum shown in Fig. 1. Therefore, one can conclude that the self-collimation phenomenon occurs for the light of frequencies around 7.7 GHz in our PC sample. This shift in the self-collimation frequency toward higher frequency compared to the theoretically predicted value may have its origin in the finite size of the prepared sample. The position-dependent transmitted power profiles drop as the receiver antenna moves away from the center of the sample.

It was suggested that a line defect which is made by removing a few rods in a row can totally reflect the self-collimated beam. The total reflection of the beam is due to the conservation of wave vectors parallel to the interface of the PC and air, and is easily confirmed from the EFCs of the PC and air. To verify the total reflection phenomena, two different line defects are made: one by removing one row of 20 rods along the ΓX direction and another by removing two rows of 20 rods also along the same direction. Thus their lengths projected onto the ΓM direction are $10\sqrt{2}a$, which is longer than the estimated size of the collimated beam, $8\sqrt{2}a$. Figure 3 shows the experimentally obtained bent powers by the line defects (red lines) and the transmitted powers through the defects (black lines) from $f=7.2$ to 7.8 GHz. The spectra clearly show that an incoming self-collimated beam can be split into the bent and transmitted beams by a line defect. One can see that the transmitted powers are much lower than the bent powers for the frequencies shown, and the difference between the two powers is much larger for the two-row defect than for the one-row defect, as the beam intensity exponentially decays into the less dense air region. The results confirm the strong bending phenomena of self-collimated beams at the line defects in a 2D PC.

It is worth noting that the bent and transmitted powers can be varied by changing the radii of rods in the line defect. We considered three different one-row line defects where the defect radius R_d is 1.5, 2.0, and 2.5 mm, respectively, and the measured values of the transmitted and bent powers for each case are shown in Fig. 4 in the frequency range of $f=7.2-7.8$ GHz. The transmitted power increases and the bent power decreases as R_d increases, as expected. Thus, the ratio of split powers can be systematically controlled by varying the value of R_d. Note that the bent and transmitted powers became comparable to each other at $f=7.7$ GHz, when $R_d=2.5$ mm. This implies that a 3 dB power splitter for the self-collimated microwave beam of the frequency

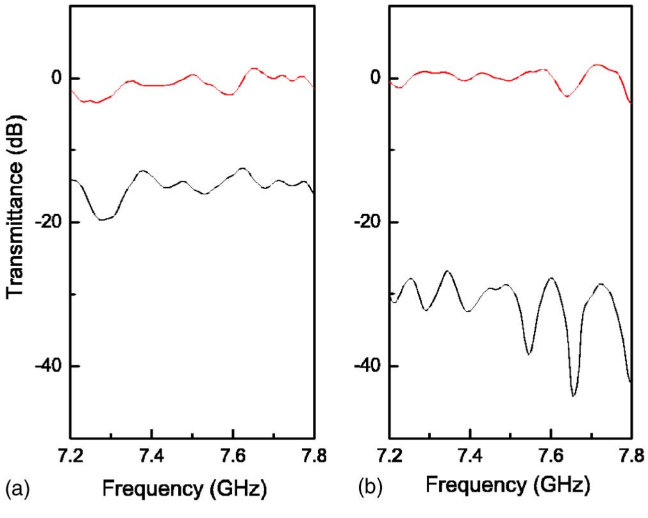

FIG. 3. (Color online) Experimentally measured transmitted (black lines) and bent (red lines) powers in the frequency range of 7.2–7.8 GHz when the line defects are made by removing (a) one row of 20 rods and (b) two rows of 20 rods along the ΓX direction.

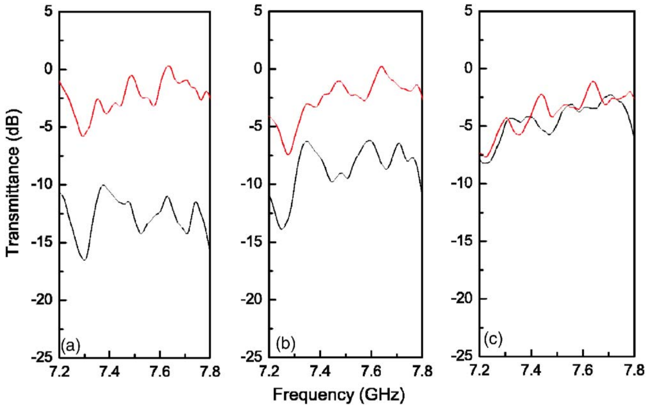

FIG. 4. (Color online) Transmitted (black lines) and bent (red lines) powers measured for one-row line defect when (a) R_d=1.5 mm, (b) R_d=2.0 mm, and (c) R_d=2.5 mm in the frequency range of 7.2–7.8 GHz.

f=7.7 GHz can be achieved when R_d is slightly smaller than 2.5 mm.

In order to compare the experimentally obtained split powers for the light of f=7.7 GHz with the theoretical split powers at f=7.2 GHz, we simulated the transmitted and bent powers using the FDTD method changing R_d from 0 to 0.3a. In the 2D FDTD simulations, the same structural parameters employed for our sample PC were used and a Gaussian beam with the full width at half maximum of 5a was used. A monochromatic wave of the self-collimation frequency f=0.24c/a was launched into the PC along the ΓM direction. The time-averaged power before and after the splitting was obtained by integrating the Poynting vector across the beam cross section. The bent and transmitted powers are normalized with respect to their sum. Shown in Fig. 5 are the measured (red symbols) and the calculated (black symbols) split powers, which agree well with each other. Thus, one can see that the powers of output beams can be easily controlled by varying the radii of rods in the line defects.

In conclusion, we have experimentally demonstrated that the line defect induced bending and splitting phenomena of self-collimated microwave beams in a 2D PC composed of a square array of alumina rods. The split powers of the beam can be controlled by varying the radii of rods in the line defect.

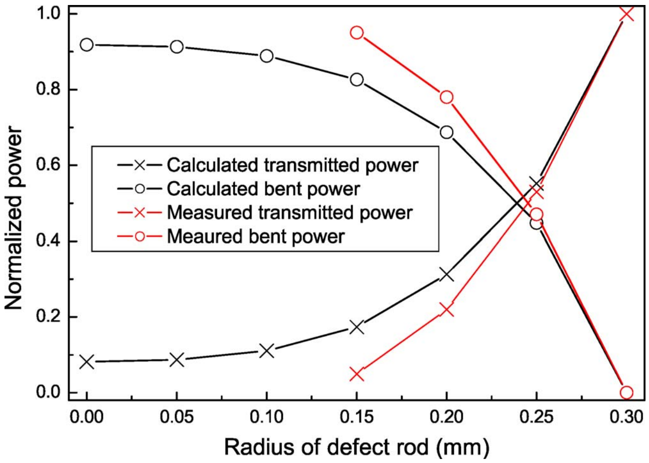

FIG. 5. (Color online) Measured powers at f=7.7 GHz and calculated powers at f=7.2 GHz for the transmitted and bent beams as a function of the radii of defect rods. The measured (simulated) powers are denoted by red (black) symbols.

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