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Photonic-crystal-based beam splitters

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We proposed and demonstrated two different methods to split electromagnetic waves in three-dimensional photonic crystals. By measuring transmission spectra, it was shown that the guided mode in a coupled-cavity waveguide can be splitted into the coupled-cavity or planar waveguide channels without radiation losses. The flow of electromagnetic waves through output waveguide ports can also be controlled by introducing extra defects into the crystals. Our results may have an important role in the design of efficient power splitters in a photonic circuit. © *2000 American Institute of Physics.* [S0003-6951(00)02351-2]

Photonic crystals, also known as photonic band gap (PBG) materials, are artificial dielectric or metallic structures in which the refractive index modulation gives rise to stop bands for electromagnetic (EM) waves within a certain frequency range.[1,2] In recent years, there has been much interest in the possible realization of photonic crystals for designing optical components and circuits.[3,4] For instance, efficient guiding and bending of EM waves in PBG structures can be achieved by using planar waveguides (PW),[5–9] line defect waveguides,[10,11] or coupled-cavity waveguides (CCW).[12–15]

By breaking the periodicity of photonic crystals, it is possible to create highly localized defect modes within the photonic band gap.[16,17] This important property was used in various applications. As an example, we recently demonstrated a new type of propagation mechanism along highly localized cavity modes, i.e., photons can hop from one localized mode to the neighboring cavity modes due to interaction between these modes.[12–15] This picture can be considered as the classical wave analog of the tight-binding (TB) approximation in solid state physics.[18,19] The CCWs can be used to construct lossless and reflectionless waveguides and bends in optoelectronic components and circuits.

EM beam splitters have an important role in photonic crystal based optical components. So far, the power splitters in two-dimensional photonic crystals were theoretically investigated by Yonekura, M. Ikeda, and T. Baba,[20] Ziolkowski and Tanaka,[21] and Sondergaard and Dridi.[22] However, to our knowledge, there are not any published experimental results on three dimensional (3D) photonic crystal based splitters. In this letter, we report experimental observation of power splitting in a 3D photonic crystal. It was demonstrated that the guided EM waves inside the input CCW could be splitted into either CCW [Fig. 1(a)] or PW channels [Fig. 1(b)]. Moreover, by introducing an additional defect into the PW which broke the symmetry of the structure, we addressed the control of power that was coupled to each output waveguide port [Fig. 1(b)].

In the experiments, we used a layer-by-layer dielectric based 3D photonic crystal.[23,24] The crystal consists of square shaped alumina rods having a refractive index 3.1 at the microwave frequencies and dimensions 0.32 cm×0.32 cm ×15.25 cm. A center-to-center separation between the rods of 1.12 cm was chosen to yield a dielectric filling ratio of ~0.26. The unit cell consists of four layers having the symmetry of a face centered tetragonal (fct) crystal structure. The crystal exhibits a 3D full photonic band gap extending from 10.6 to 12.8 GHz. The experimental setup consists of an HP 8510C network analyzer and three microwave horn antennas to measure the transmission-amplitude spectra. In the CCWs, the defects were formed by removing a single rod from each unit cell of the crystal with periodicity $\Lambda = 1.12$ cm.[12] The

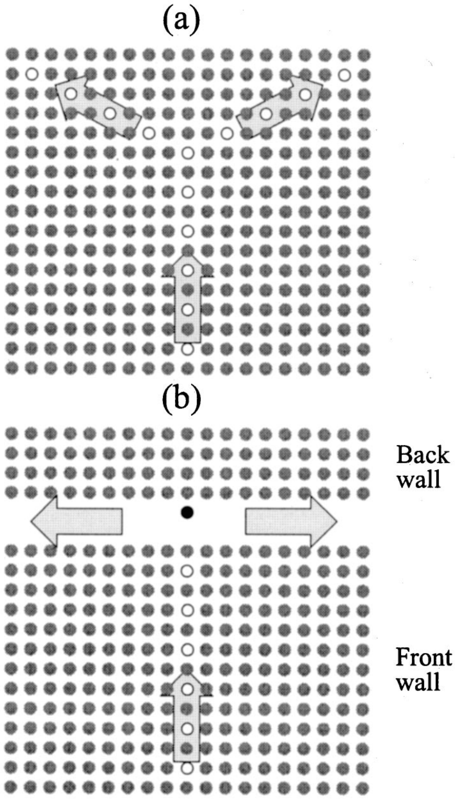

FIG. 1. Schematics of the two different mechanisms to split electromagnetic beams in photonic crystals. The guided mode, which propagates along the strongly localized defect modes (white circles), in the coupled-cavity input port can be splitted into (a) the coupled-cavity or (b) planar waveguide output channels without losses. The flow of electromagnetic waves through output ports can be controlled by changing position of the defect (black circle) inside the air gap of the planar cavity.

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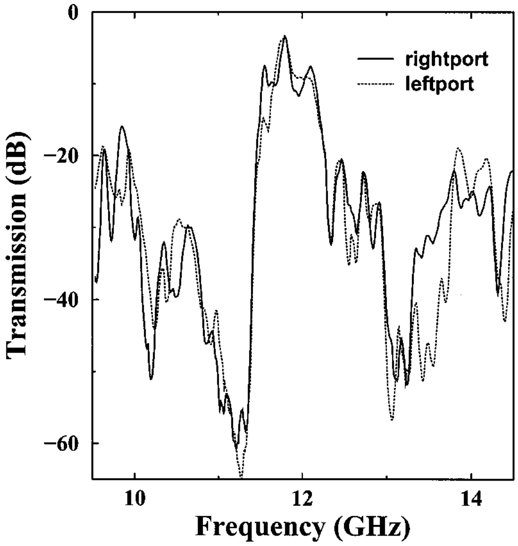

FIG. 2. Measured transmission spectra for the structure illustrated in Fig. 1(a). The electromagnetic power in the input port splits equally into the two CCW output ports throughout the waveguiding band.

electric field polarization vector of the incident EM field was parallel to the rods of the defect lines for all measurements.

In the TB approximation, two requirements must be satisfied simultaneously:[19] (1) strong localization of the individual defect modes, (2) weak interaction between these localized modes. Under these conditions, photons can move along the defect sites in photonic crystals irrespective of the change in the direction of propagation. As an example, we have recently demonstrated that even if cavities were chosen to form a random path, nearly a full transmission could be achieved throughout the defect band.[13] The CCWs can also be used to split EM waves in photonic band gap materials. We tested this power splitting argument by measuring the transmission spectra of two different splitter structures (see Fig. 1).

We first measured the transmission characteristics of the beam splitter structure illustrated in Fig 1(a). The structure consists of six and four unit cell CCWs as input and output ports, respectively. As shown in Fig. 2, we observed that the guided mode in the input channel splitted into each arm of the splitter throughout the guiding band that extends from 11.47 to 12.35 GHz. We achieved nearly 50% transmission at each arm for certain frequency ranges. We also measured the reflection power coefficient (S11 parameter) which gave us information on what fraction of the input power was reflected backward from the crystal. The backreflection was less than 1% for the frequency ranges where we obtained nearly 50% transmission at each arms.

Next, we investigated transmission spectra of the second power splitter structure [Fig. 1(b)], which was constructed by the hybrid combination of a CCW and a PW. The planar waveguide was constructed by introducing an air gap of the width $d = 1.30$ cm between two photonic crystal walls. The front wall was a six unit cell thick CCW and the back wall was a four unit cell crystal. There was a mirror type of symmetry between the rods of the two photonic crystals walls.[7] In this case, the EM waves inside the input CCW were divided into two parts throughout the guiding band and propagated along the two opposite arms of the PW. We also used an additional rod (see black circle in Fig. 1) to obtain better coupling to waveguide channels. As shown in Fig. 3(a), we observed 50% transmission at each channel of the PW for a certain frequency range. Figure 3(b) shows the regular transmission characteristics of the CCW and PW. Nearly full transmissions were obtained throughout the waveguiding bands extending from 10.24 to 12.60 GHz for PW (solid line) and from 11.45 to 12.60 GHz for CCW (dotted line). Comparing Figs. 3(a) and 3(b) yields that the 50% transmissions at each arm were achieved whenever the CCW and the PW have full transmissions.

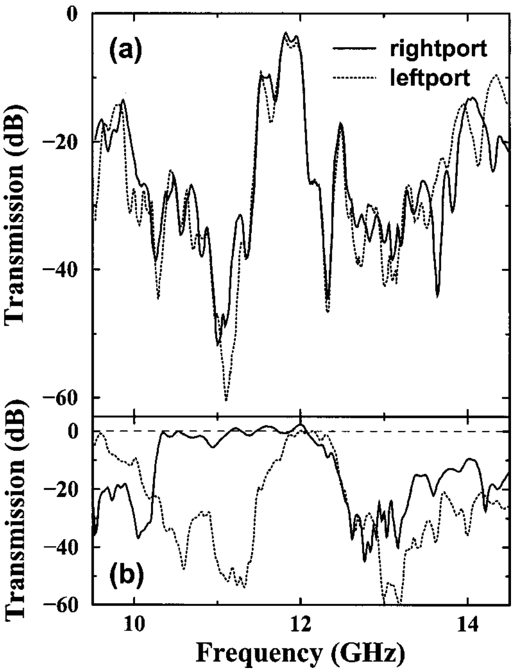

FIG. 3. (a) Measured transmission spectra for the structure illustrated in Fig. 1(b). The electromagnetic power inside the input CCW splits equally into the two PW output ports throughout the waveguiding band. (b) Transmission amplitudes measured from a PW (solid line) and a CCW (dotted line).

Changing the position of the additional defect inside the

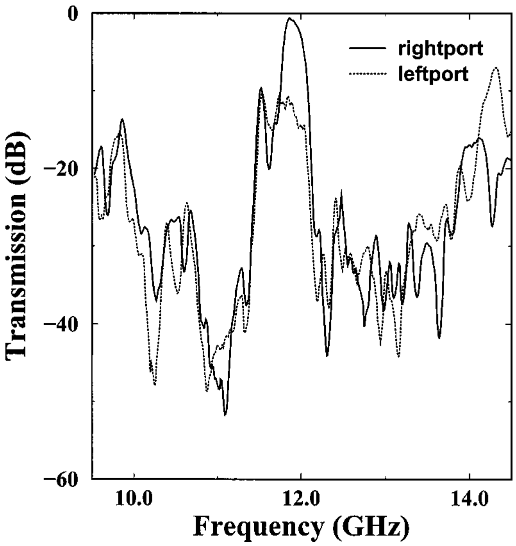

FIG. 4. Transmission amplitude as a function of frequency for the switching structure. Changing the position of the extra defect [black circle in the Fig. 1(b)], the powers in the right and left ports became around 90% and 6%, respectively.

PW section breaks the symmetry of the structure. This can be used to regulate the amount of power flow into the output ports. The structure can then be used as a switch by changing the position of the additional defect.[21] To demonstrate the switching effect, we shifted the rod towards the left arm by 1 cm with respect to the center of the PW, and then measured the output power in each port. As shown in Fig. 4, this configuration drastically changed the output power in each port. While 90% of the input power was coupled to the right port, only 6% of the input power was coupled to the left port.

In conclusion, we have experimentally demonstrated photonic crystal based power splitters in which the input EM power can be efficiently divided into the output waveguide ports. Since Maxwell's equations have no fundamental length scale, the results presented in this letter can be observed at optical wavelengths. Our structures can be used to construct power splitters in optical components and circuits.

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