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Propagation of photons by hopping: A waveguiding mechanism through localized coupled cavities in three-dimensional photonic crystals

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A new type of waveguiding mechanism in three-dimensional photonic band-gap structures is demonstrated. Photons propagate through strongly localized defect cavities due to coupling between adjacent cavity modes. High transmission of the electromagnetic waves, nearly 100%, is observed for various waveguide structures even if the cavities are placed along an arbitrarily shaped path. The dispersion relation of the waveguiding band is obtained from transmission-phase measurements, and this relation is well explained within the tight-binding photon picture. The coupled-cavity waveguides may have practical importance for development of optoelectronic components and circuits.

In the past decade, photonic crystals, also known as photonic band-gap (PBG) materials,[1,2] have inspired great interest because of their scientific and engineering applications such as the inhibition of spontaneous emission,[3] lasers,[4–6] waveguides,[7–10] fibers,[11] antennas,[12,13] detectors,[14] optical circuits,[15,16] and ultrafast optical switches.[17,18] By introducing a defect into the photonic crystals, photons with certain wavelengths can be locally trapped. This property, localization of photons,[19] can be used in various applications.

Recently, we have reported the eigenmode splitting, formation of bonding and antibonding modes (analogous to the electronic states in the diatomic molecules), due to the coupling of the evanescent defect modes in three-dimensional (3D) photonic crystals. Moreover, a transition from the discrete atomiclike states to the continuous spectrum (formation of a photonic band) was observed while increasing the number of defect cavities.[20,21] Although the modes of each cavity were tightly confined at the defect sites, overlap between the nearest-neighbor modes is enough to provide the propagation of photons via hopping [Fig. 1(a)]. This picture can be considered as the classical wave analog of the tight-binding (TB) method in solid state physics.[20,23–26]

In this paper, we report on the observation of guiding [Fig. 1(b)] and bending [Fig. 1(c)] of the electromagnetic (EM) wave through highly localized defect modes in a 3D photonic crystal. Previously, Stefanou and Modinos,[24] and Yariv *et al.*[26] have developed the tight-binding formalism of guiding and bending of EM wave along impurity modes (or cavity modes). The most important feature of these coupled-cavity waveguides (CCW's) is the possibility of constructing lossless and reflectionless bends. This ability has a crucial role to overcome the problem of guiding light around very sharp corners in the optical circuits.

A layer-by-layer dielectric based photonic crystal[27–29] was used to construct the CCW's. The crystal consists of square shaped alumina rods having a refractive index 3.1 at the microwave frequencies and dimensions 0.32 cm $\times$0.32 cm$\times$15.25 cm. A center-to-center separation between the rods of 1.12 cm was chosen to yield a dielectric filling ratio of $\sim$0.26. The unit cell consists of four layers having the symmetry of a face-centered tetragonal (fct) crystal structure. The crystal exhibits a three-dimensional photonic band gap extending from 10.6 to 12.8 GHz.

The experimental setup consists of a HP 8510C network analyzer and microwave horn antennas to measure the transmission-amplitude and transmission-phase spectra (Fig. 2). The defects were formed by removing a single rod from each unit cell of the crystal. It was previously shown that, removing a single rod from an otherwise perfect crystal leads to confined modes with high Q factors, quality factor defined as the center frequency divided by the full width at half

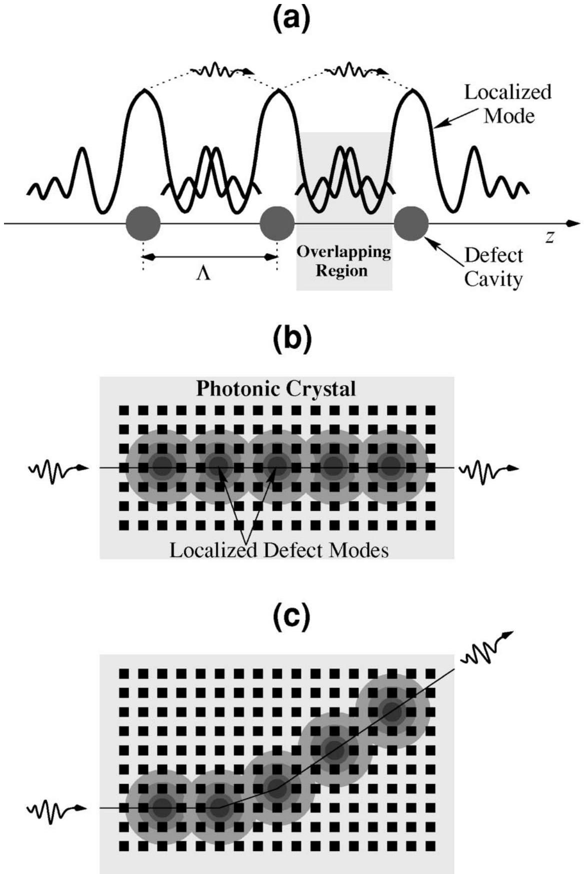

FIG. 1. (a) Schematics of propagation of photons by hopping between the coupled evanescent defect modes. The overlap of the defect modes is large enough to provide propagation of the EM waves along tightly confined cavity modes. (b) A mechanism to guide light through localized defect modes in photonic crystals. (c) Bending of the EM waves around sharp corners.

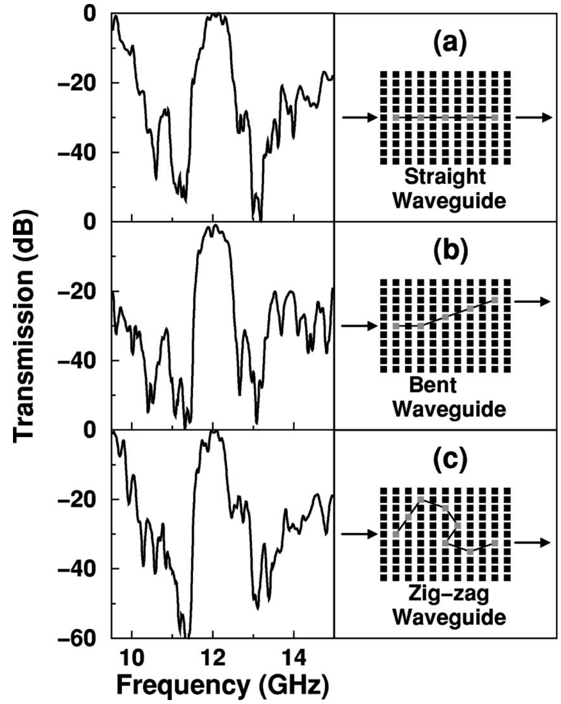

FIG. 3. (a) Transmission amplitude as a function of frequency for a straight waveguide geometry which is shown in the right panel. The gray squares represent the missing rods. A full transmission was observed throughout the entire waveguiding band ranging from 11.47 to 12.62 GHz. (b) Transmission spectra for a $\theta = 40°$ bent waveguide. (c) Transmission characteristics of a zig-zag shaped waveguide which is formed by removing randomly chosen rods while keeping the distance between adjacent defects constant. In all cases, nearly 100% transmission amplitudes were measured.

maximum, around 1000.[20] The electric-field polarization vector of the incident EM field was parallel to the rods of the defect lines for all measurements.

We first measured the transmission characteristics of a straight waveguide which consists of 11 unit-cell fct crystal. The defect array was created by removing a single rod from the first layer of each unit cell with a periodicity of $\Lambda = 1.28$ cm. As shown in Fig. 3(a), a defect band (guiding

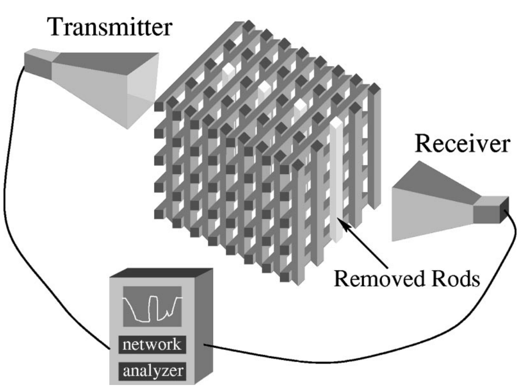

FIG. 2. Experimental setup for measuring the transmission-amplitude and transmission-phase spectra of the coupled cavity waveguides (CCW) in 3D photonic crystals.

band) was formed within the photonic band gap analogous to the impurity bands in the disordered semiconductors. The width of this guiding band can be adjusted by changing the coupling strength between the cavities (for instance, the coupling increases when the distance between adjacent defects decreases). For this waveguide structure, nearly a complete transmission of the EM wave was observed within a frequency range extending from 11.47 to 12.62 GHz. It is interesting to note that when we placed one of the removed rods into its original position, we observed almost vanishing transmission amplitude throughout the above frequency range. This result is expected since the second nearest-neighbor coupling amplitude is negligibly small in our structures.

To develop an optical circuit, the problem of the guiding light around sharp corners must be addressed. Conventional dielectric or metallic waveguides have large scattering losses when sharp bends are introduced. In order to test the bending of the EM wave around a sharp corner, we used a waveguide structure with 40° bending angle ([Fig. 3(b)], right panel). The result is presented in Fig. 3(b). It is observed that the transmission is greater than 90% for all frequency range within the waveguiding band.

Within the TB approximation, we can guide or bend the EM waves along an arbitrarily shaped path by connecting the defects. To verify this idea experimentally, we constructed a zig-zag shaped waveguide while keeping the distance between the consecutive cavities constant. In this waveguide, the propagation direction of photons was randomly changed. As shown in Fig. 3(c), we observed full transmission similar to the results obtained from the straight waveguide. Our results clearly indicate that the sharp corners have no influence on the propagation of EM waves in CCW's. By using CCW's one can achieve the bending of light around a sharp corner without any radiation losses. Therefore, this method may have great practical importance in certain applications.

As shown in Fig. 3, the band edges of CCW's are very sharp compared to the PBG edges. This property is important for the switching applications. Conventionally, the switching mechanism is achieved by dynamical shifting of the photonic band-gap edges[17] or the position of defect frequency[18] via the nonlinear processes. In our case, the on-off modes of the switch can be achieved by shifting the waveguiding band edges. Therefore, the efficiency of a photonic crystal based switch can be enhanced by using the CCW's.

The dispersion relation of the waveguiding band can be obtained from the transmission-phase measurements.[30,31] By using the net phase difference $\delta\varphi$ between the phase of the EM wave propagating through the photonic crystal and the phase of the EM wave propagating in free space for a total crystal thickness L, one can determine the wave vector k of the crystal at each frequency from

$$k = \delta\varphi/L + 2\pi f/c, \tag{1}$$

where f is the frequency of the EM wave and c is the speed of the light. The dispersion relation can also be determined within the TB approximation[24,26,20]

$$\omega_k \simeq \Omega[1 + \kappa\cos(k\Lambda)], \tag{2}$$

where $\Omega = 12.15$ GHz is the resonance frequency of a single defect, κ is a TB parameter which can be experimentally determined from the splitting of two coupled cavities or the width of waveguiding band,[20] and Λ is the distance between two consecutive defects.

We obtained the theoretical and experimental dispersion relations of the zig-zag shaped CCW by using Eq. (2) and the transmission-phase measurements. Figure 4(a) shows the comparison of measured and calculated dispersion relations. There is a good agreement between experiment and theory. In spite of the fact that the propagation direction of EM waves changed arbitrarily, nearly the same straight waveguide dispersion was obtained.[20]

Group velocity of photons along the waveguide can be deduced from

$$v_g(k) = \nabla_k \omega_k = -\kappa\Lambda\Omega\sin(k\Lambda). \tag{3}$$

Figure 4(b) displays the normalized group velocity as a function of wave vector k. Experimental group velocity was obtained from derivative of the best fitted function to the dispersion data. It is important to note that v_g vanishes at the band edges and the maximum group velocity is two order of magnitude smaller than the speed of light. The small group velocity plays a critical role in the nonlinear optical processes. For example, sum-frequency generation can be enhanced at the band edges. In addition, the small group velocity leads to enhancement of the stimulated emission since the effective gain is proportional to $1/v_g$.[32]

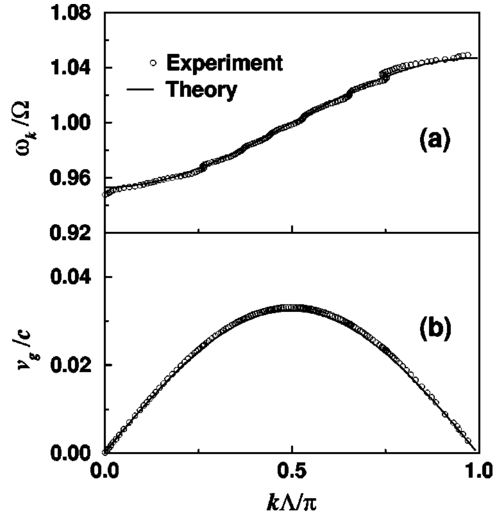

FIG. 4. (a) The dispersion relation of the waveguiding band for the zig-zag shaped CCW. Experimental curve was obtained from the transmission-phase measurements via Eq. (1). (b) Group velocity v_g as a function of wave vector k. The measurements are in good agreement with the tight-binding predictions.

The guiding or bending of EM waves through the localized defect modes via hopping is fundamentally different from previously proposed photonic crystal waveguides.[7–9,11] Although, the structural imperfections such as misalignment of rods during the fabrication process affected the efficiency of the CCW's, we have observed nearly 100% transmission for various CCW's throughout the entire waveguiding band. Our observation differs from that of Ref. 8 in which the unity bending efficiency[33] can be obtained only at certain frequencies.

In conclusion, we have demonstrated a mechanism to manipulate propagation of EM waves in 3D photonic crystals. Photons hop from one evanescent defect mode to the next one, regardless of the direction of propagation. A complete (near 100%) transmission of the EM wave along a straight path and around sharp corners were observed experimentally. The measured dispersion relation of the waveguiding band agrees well with the results of the classical wave analog of the tight-binding method. In our opinion, this propagation mechanism shows scientific and technological promise. Since the Maxwell's equations have no fundamental length scale, our microwave results can be extended to the optical frequencies.

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