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Guiding and bending of photons via hopping in three-dimensional photonic crystals

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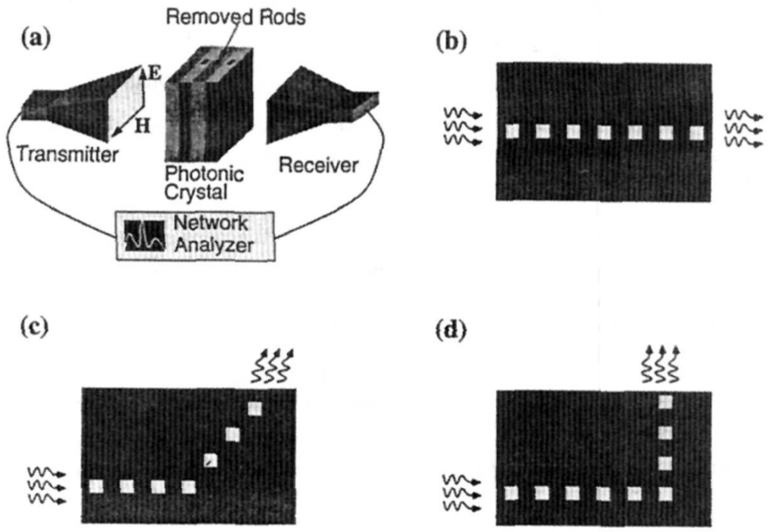
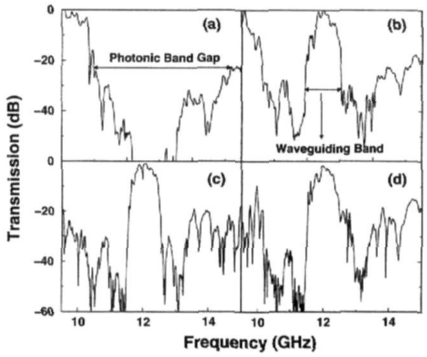
For the past decade, photonic crystals, also known as photonic bandgap (PBG) materials, have inspired great interest because of their novel scientific and engineering applications such as the inhibition of spontaneous emission, thresholdless lasers, optical circuits, antennas, waveguides, detectors, fibers, and so on. Creating defect states within the PBG are very important for such applications. Recently, we have reported the eigenmode splitting due to coupling of the localized defects and guiding of the electromagnetic (EM) waves through a periodic arrangement of such defects in three-dimensional (3D) photonic crystals. Although the modes of each cavity were tightly confined at the defect sites, overlapping between the nearest-neighbor modes is enough to provide the propagation of photons via hopping.[1]

In this work, we report on the observation of guiding and bending of EM wave through



QWA6 **Fig. 1.** (a) Schematic view of the experimental setup. Top views of three different waveguides: (b) straight, (c) $\theta = 40°$ bended, (d) L-shaped.



QWA6 **Fig. 2.** (a) Transmission characteristics along the stacking direction of the photonic crystal. The full photonic bandgap is ranging from 10.6 GHz to 12.8 GHz. (b) Transmission amplitude as a function of frequency for straight path waveguide [correspond to Fig. 1(b)]. A complete transmission is observed within the guiding band. (c) Transmission spectra for bended waveguides: (c) $\theta = 40°$ [correspond to Fig. 1(c)] and (d) $\theta = 90°$ [correspond to Fig. 1(d)]. In both cases, the losses are <10 percent.

evanescent defect modes for three different PBG waveguide structures [Fig. 1(b–d)]. We used the layer-by-layer dielectric based photonic crystal[1,2] based on square shaped alumina rods (0.32 cm × 0.32 cm × 15.25 cm). The experimental setup consists of a HP 8510C network analyzer and microwave horn antennas to measure the transmission-amplitude and transmission-phase properties. As shown in Fig. 2(a) the six unit cell crystal exhibits a 3D photonic bandgap extending from 10.6 to 12.8 GHz. The defects were created by removing a single rod from a single layer of the unit cell, where each cell consists of 4 layers having the symmetry of a face centered tetragonal (fct) structure. The electric field polarization vector of the incident EM wave **e** was parallel to the rods of the defect layer for all measurements.

We first measured the transmission characteristics of the straight path waveguide, which consists of 11 unit cell fct crystal [see Fig. 1(b)]. The defect array was created by removing a single rod from each unit cell. The distance between defects is $L = 1.28$ cm. Nearly a complete transmission was observed throughout the entire waveguiding band [Fig. 2(b)]. To test bending of the EM wave around a photonic crystal corner, we used two different structures with 40° and 90° bending angles [see Figs. 1(c) and 1(d)]. The results are shown in Figs. 2(c) and 2(d), respectively. In the both cases, we observed that the transmission is greater than 90% for all frequency range within the waveguiding band. The guiding and bending can be improved by increasing the number of unit cells.

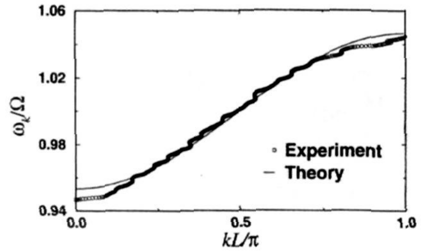
The guiding or bending of EM waves through the localized defect modes via hopping is different from previously proposed photonic crystal waveguides,[2–4] in which the complete transmission can be obtained only at certain frequencies.[5]

We obtained the dispersion relation of the waveguiding band from the transmission-phase measurements for the straight path waveguide [see Fig. 1(b)]. The dispersion relation can also be calculated within the tight-binding (TB) approximation

$$\omega_k = \Omega[1 + \kappa \cos(kL)], \quad (1)$$

where Ω is resonance frequency of a single defect, κ is a TB parameter which can determined from the splitting of two coupled cavities or the waveguiding bandwidth, and L is the distance between the two consecutive defects.[1] Figure 3 shows comparison of the measured and calculated dispersion relations. Except the band edges, there is an excellent agreement between experiment and theory. Based on our observations, we think that this discrepancy can be further reduced by taking more numbers of unit cells.

It is very important to note that the group velocity, $v_g(k) = d\omega_k/dk = -\kappa\Omega \sin(kL)$, vanishes at the band center and the band edges. 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 the enhancement of stimu-



QWA6 Fig. 3. Dispersion diagram of the waveguiding band within the photonic bandgap predicted from the transmission-phase measurements and calculated by using tight-binding picture with $\kappa = -0.047$ [Eq. 1].

lated emission since the effective gain is proportional to $1/v_g(k)$.[5,6]

In conclusion, we have proposed and demonstrated a new 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 percent) transmission 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 tight-binding method. Because Maxwell's equations have no fundamental length scale, our microwave results can easily be extended to the visible spectrum.

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