COUPLED CAVITIES IN PHOTONIC CRYSTALS

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ABSTRACT

We investigate the localized coupled-cavity modes in two-dimensional dielectric photonic crystals. The transmission, phase, and delay time characteristics of the coupled-cavity waveguides (CCW) are measured and calculated. The corresponding field patterns and the transmission spectra are obtained from the finite-difference-time-domain (FDTD) simulations. We also develop a theory based on the classical wave analog of the tight-binding (TB) approximation in solid state physics. Experimental results are in good agreement with the FDTD simulations and predictions of the TB approximation.

INTRODUCTION

PHOTONIC band gap structures provide a promising tool to control of the flow EM waves in the integrated optical devices. Therefore, there is a growing interest in developing photonic crystal-based waveguide components which can guide and bend EM waves either along a line defect (a row of missing rods) [1], which is called planar waveguide (PW) [See Fig. 1(a)] , or through coupled cavities [2], which is known as coupled-cavity waveguide (CCW) [See Fig. 1(b)]. In the former case, while the EM waves are confined in one direction which is perpendicular to axis of missing rods, and photons can propagate in other direction parallel to the axis of the missing rods [Fig. 1(c)]. On the other hand, in the latter case, which we called coupled-cavity waveguides (CCW) [3], the EM waves were tightly confined at each defect site, and photons can propagate via hopping due to interaction between the neighboring evanescent cavity modes [Fig. 1(d)].

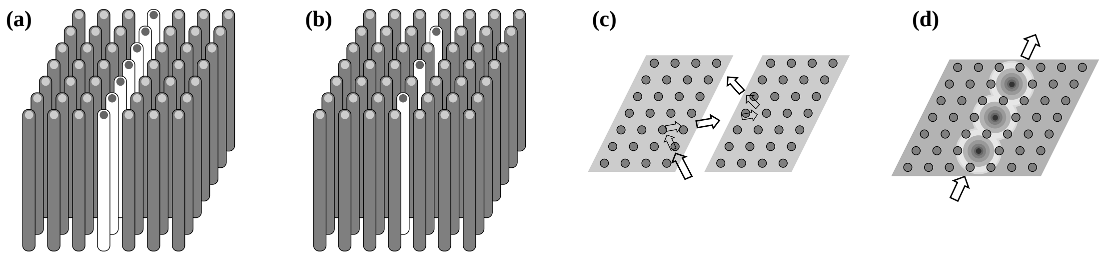

Figure 1: Schematic drawing of (a) planar and (b) coupled-cavity waveguides in photonic crystals. Propagation of EM waves in planar (c) and coupled-cavity (d) waveguides.

By removing from or adding to materials a perfect photonic crystal, it is possible to create localized EM modes inside the photonic band gap which are reminiscent of the acceptor and donor impurity states in a semiconductor. Therefore, photons with certain wavelengths can locally be trapped inside the defect volume. This important property can be used in various photonic applications. In fact, most of the aforementioned applications are based on cavity structures built around photonic crystals.

Analogy between the Schrödinger equation and Maxwell's equations allows us to use many important tools which were originally developed for the electronic systems. As an example, it is well known that the TB method has proven to be very useful to study the electronic properties of solids. By using direct implications of the TB picture, we investigated the mode splitting phenomena within the TB picture [3]. Guiding and bending of EM wave [2], heavy photons [4], and EM-beam splitting and switching effect [5] were

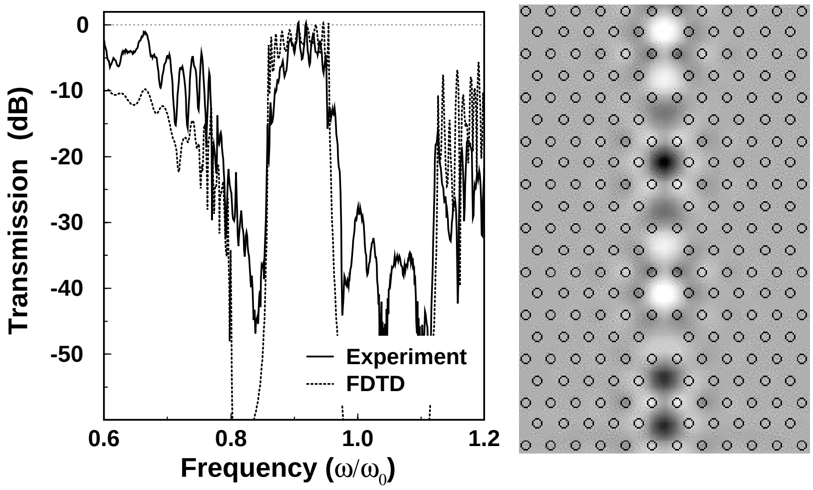

Figure 2: [Left Panel] Measured (solid line) and calculated (dotted line) transmission spectra of the straight coupled-cavity waveguide which is generated by removing 10 adjacent rods from the crystal. [Right Panel] Calculated field distribution of the CCW for a frequency within the cavity band, namely, $\omega = 0.920\ \omega_0$.

experimentally demonstrated in three-dimensional photonic crystals at microwave frequencies. In addition, we observed the strong enhancement of spontaneous emission throughout the cavity band of the one-dimensional (1D) coupled optical microcavity (CMC) structures [6].

COUPLED-CAVITY WAVEGUIDES

The efficient guiding and bending of light on integrated photonic devices are important to design optical circuits for technological and optical computing applications. Also, 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 recent years, it has been demonstrated that photonic crystal based waveguides can efficiently guide and bend EM waves [7, 2].

We constructed 2D triangular photonic crystals which consist of dielectric cylindrical alumina rods having radius 1.55 mm and refractive index 3.1 at the microwave frequencies. The lattice constant and the corresponding filling fraction are $a = 1.3$ cm and $\eta \sim 0.05$, respectively. Length of the rods is 15 cm. The experimental set-up consisted of a HP 8510C network analyzer and microwave horn antennas to measure the transmission-amplitude and the transmission-phase properties. The transverse magnetic (TM) polarization, the incident electric field was parallel to the rods, is considered in all measurements. The transmission spectra and the field patterns are obtained by using a finite-difference-time-domain (FDTD) code. In FDTD simulations, we normalized the transmission spectra with respect to the source spectra.

We first measure and calculate the transmission spectra of a straight CCW that is formed by removing an array of rods, 10 consecutive defects, along a straight line. The corresponding structure is displayed in right panel of Fig. 2. A waveguiding band, or defect band, is formed due to coupling between the evanescent defect modes. As shown in Fig. 2 (left panel) the defect band is extending from $0.857\ \omega_0$ to $0.956\ \omega_0$. The number of peaks in the transmission spectrum is equal to the number of cavities in the structure as expected. It is also observed that the complete transmission is achieved for certain frequencies within the defect band. Since each mode is strongly localized around the removed rod, and the guided mode is composed of linear combination of these individual defect modes, we expect that the radiation loss mechanism is absent in these structures. We also calculate the corresponding field distribution of the guided mode for $\omega = 0.920\ \omega_0$. Figure 2 (right panel) clearly shows that the guided mode is completely confined along with the coupled-cavity array, and propagates along with the cavity sites. In addition, the bandwidth of a CCW band can be adjusted by changing localization properties of the cavities, or the coupling strength (overlap integral) between the localized cavity modes. For instance, decreasing the intercavity distance leads to a wider bandwidth.

Based on our observations, the crystal symmetry has a crucial role in 2D photonic crystals to achieve

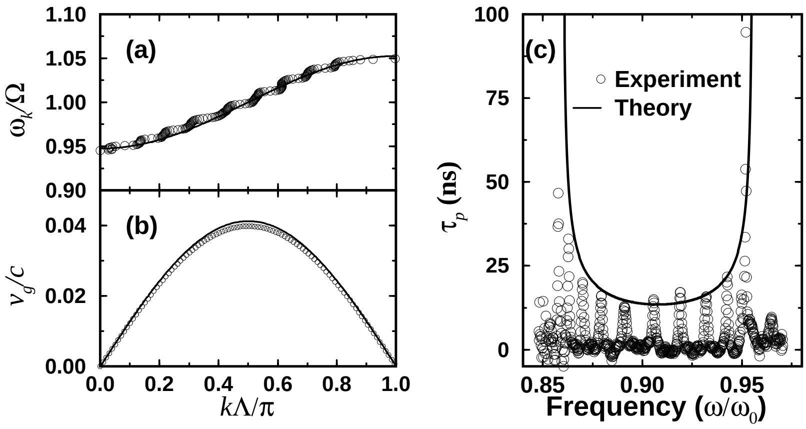

Figure 3: Comparison of the measured and calculated (a) dispersion relation, (b) group velocity, and (c) delay time corresponding to the straight CCW.

complete transmission of EM waves through CCWs. For instance, even if the triangular symmetry leads nearly full transmissions, one can obtain only 10% transmission for the square photonic crystals. We think that this observation is related with localization properties of the cavity mode, and the nature of interaction between the cavity modes.

Previously, Scalora *et al.* have proposed a switching mechanism which can be achieved by dynamical shifting of the photonic band gap edges via the nonlinear processes [8]. As shown from Fig. 3, the defect band has very sharp band edges compared to the PBG edges, and therefore this property can be used to construct photonic switches by changing position of the defect band [2].

We also determine dispersion relation, group velocity, and delay time corresponding to the straight CCWs. The dispersion relation $\omega(k)$ is obtained from the transmission-phase information [3]. By measuring the net phase difference $\Delta\varphi$, as a function of frequency ω, the wave vector k of the crystal can be determined directly by using

$$kL - k_0 L = \Delta\varphi \ ,$$

where L is the total crystal thickness, $k_0 = 2\pi\omega/c$, and c is the speed of the light in vacuum. Figure 3(a) exhibits comparison of measured and calculated dispersion relation as a function of wave vector k.

The theoretical curve is obtained by using

$$\omega(k) = \Omega\left[1 + \kappa\cos(k\Lambda)\right] \ ,$$

where the TB parameter $\kappa = -0.0525$ was extracted from the experimental results.

We also plot group velocity of the propagating mode by $v_g(k) = \nabla_k \omega_k = -\kappa\Lambda\Omega\sin(k\Lambda)$. The experimental curve is determined from the measured dispersion relation. As shown in Fig. 3(b), group velocity vanishes at the defect band edges, and also the maximum value of the group velocity is one order of magnitude smaller than speed of light.

Within the TB approximation, we can obtain a formula for delay time as

$$\tau_p(\omega) = \frac{L/\Lambda}{\Omega\sqrt{\kappa^2 - (\omega/\Omega - 1)^2}} - 2\pi L/c \ .$$

Measured and calculated delay time characteristics is displayed in Fig. 3(c). The delay time increases drastically at the CCW band edges. This result agrees well with our TB analysis (dotted line). The number of observed peaks in the delay time spectrum is equal to the number of cavities used in the structure. Physically, *heavy photon* concept in the photonic band gap structures is reminiscent of *heavy electron* in semiconductors having energies near the band edges. The corresponding eigenfunctions are standing waves rather than the propagating waves, and therefore the effective mass of electrons becomes very large. [9]

CONCLUSION

A new type of waveguiding mechanism, propagation of photons by hopping, is demonstrated in two-dimensional photonic crystals. Nearly full transmission of electromagnetic waves is achieved even if the coupled-cavity waveguides contain very sharp bends and the propagation direction is arbitrarily changed. These results are very important for designing efficient waveguide components in photonic crystal based optical circuits. The simulated mode patterns and the transmission characteristics by using FDTD code agree well with our tight-binding model's predictions. This excellent agreement is an indication of the usefulness of the tight-binding formalism to investigate interaction between evanescent electromagnetic modes in photonic structures.

ACKNOWLEDGMENTS

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