Appl. Phys. A 72, 117–119 (2001) / Digital Object Identifier (DOI) 10.1007/s003390000700

Applied Physics A
Materials
Science & Processing

Rapid communication

Propagation of light through localized coupled-cavity modes in one-dimensional photonic band-gap structures

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Received: 21 August 2000/Revised version: 22 August 2000/Published online: 9 November 2000 – © Springer-Verlag 2000

Abstract. We report on the observation of a new type of propagation mechanism through evanescent coupled optical cavity modes in one-dimensional photonic crystals. The crystal is fabricated from alternating silicon-oxide/silicon-nitride pairs with silicon-oxide cavity layers. We achieved nearly full transmission throughout the guiding band of the periodic coupled cavities within the photonic band gap. The tight-binding (TB) parameter κ is determined from experimental results, and the dispersion relation, group velocity and photon lifetime corresponding to the coupled-cavity structures are analyzed within the TB approximation. The measurements are in good agreement with transfer-matrix-method simulations and predictions of the TB photon picture.

PACS: 42.70.Qs; 71.15.Fv; 42.60.Da; 42.82.Et

In recent years, the intense theoretical and experimental investigations of photonic band-gap (PBG) [1, 2] phenomena have generated a trend towards the use of these materials in certain potential applications. In particular, enhancement of spontaneous emission near the photonic band edges [3], second-harmonic generation [4], nonlinear optical diodes, switches, limiters [5–7], a photonic band-edge laser [8] and transparent metallo–dielectric structures [9, 10] were reported for one-dimensional (1D) PBG structures.

By introducing a defect into a photonic crystal, it is possible to create highly localized defect modes within the PBG. Photons with certain wavelengths can be trapped locally inside the defect volume [11], which is analogous to the impurity states in a semiconductor [12]. Recently, we demonstrated guiding and bending of electromagnetic (EM) waves along a periodic arrangement of defects inside a three-dimensional photonic crystal at microwave frequencies [13, 14]. It was also observed that the group velocity tends towards zero and the photon lifetime increases drastically at the coupled-cavity waveguiding band edges [15]. In the coupled-cavity structures, photons hop from one evanescent defect mode to the neighboring one due to overlapping between the tightly confined modes at each defect site, as illustrated in Fig. 1a [13, 16, 17]. Due to coupling between the localized cavity modes, a photonic defect band (waveguiding band) is formed within the stop band of the crystal. This is analogous to the transition from atomic-like discrete states to the continuous spectrum in solid-state physics. Recently, Bayer et al. observed formation of a photonic band due to coupling between the optical molecules [18].

In this communication, we demonstrate the guiding of light through localized coupled optical cavity modes in 1D PBG structures which are fabricated from silicon-oxide/silicon-nitride (SiO_2/Si_3N_4) pairs with $\lambda/2$ SiO_2 cavity layers. It is observed that nearly 100% transmission can be achieved throughout the waveguiding band. The dispersion relation, group velocity and photon lifetime of the coupled cavities are investigated within the tight-binding (TB) scheme. The transfer-matrix method (TMM) and the TB analysis agree well with the measurements.

Our PBG structures are composed of alternating silicon-oxide and silicon-nitride layers. Silicon-oxide and silicon-nitride layers were deposited on glass substrates by plasma-

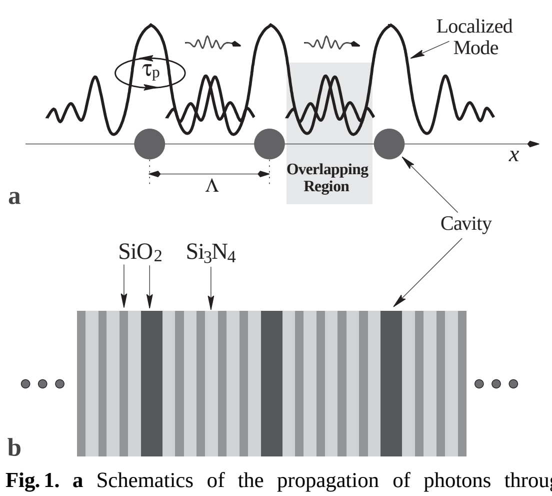

Fig. 1. **a** Schematics of the propagation of photons through localized coupled-cavity modes by hopping. **b** Schematic sketch of a multilayer coupled-cavity structure composed of $\lambda/4$ SiO_2 and Si_3N_4 pairs with $\lambda/2$ SiO_2 cavity layers

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enhanced chemical vapor deposition (PECVD) at 350 °C. Nitrogen (N_2)-balanced 2% silane (SiH_4), pure ammonia (NH_3) and nitrous oxide (N_2O) were used as the silicon, nitride and oxide sources, respectively. The refractive indices of the low- (SiO_2) and high- (Si_3N_4) index layers were measured by a Rudolph AutoEL III ellipsometer and found to be $n_L = 1.47$ and $n_H = 2.10$ at 632.8 nm. The rf power was 20 W and the chamber pressure was 1 Torr. The cavities are introduced by doubling the deposition time of the silicon-oxide layers. The thicknesses are chosen as $d_L = 100$ nm and $d_H = 70$ nm for the SiO_2 and Si_3N_4 layers and 200 nm for the cavity layers. We fabricated four samples having different intercavity distances, i.e., $\Lambda_A = 1.5$, $\Lambda_B = 2.5$, $\Lambda_C = 3.5$ and $\Lambda_D = 4.5$ pairs.

First, we simulated the transmission spectra of the samples by using the TMM [20]. As shown in Fig. 2, full transmission can be achieved throughout the guiding band. The position and bandwidth of this band can be tuned by changing the thicknesses of the layers and the distance between the cavity layers, respectively.

Next, we measured the transmission spectra by using an Ocean Optics S2000 fiber spectrometer. Figure 3 shows the comparison between the measured and the calculated transmission spectra of samples B and C. We observed nearly 100% transmission throughout the guiding band, which extends from 540 nm to 627 nm for sample B and from 554 nm to 610 nm for sample C. The experimental results are in good agreement with the TMM simulations. The minimum value (0.1%) of the measured transmission is limited by the experimental set-up.

Within the TB approximation, the dispersion relation, group velocity and photon lifetime can be characterized by a single coupling parameter κ [13–17]. We experimentally determined $\kappa \simeq 0.067$ from the splitting of two coupled cavities. This result is consistent with the result that is obtained from the bandwidth of the guiding band. A detailed TB description of the coupled optical cavities in 1D photonic bandgap structures can be found elsewhere [19].

The dispersion relation of the coupled-cavity systems is given by [13, 16, 17]:

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

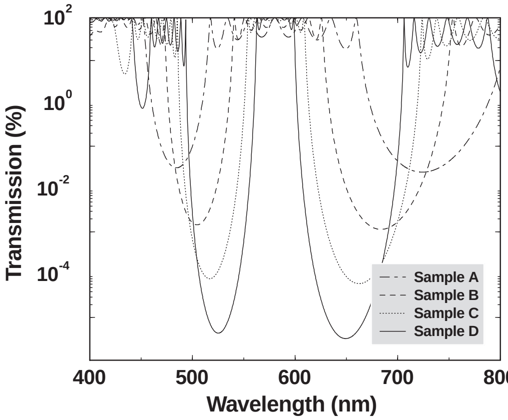

Fig. 2. Calculated transmission through several coupled-cavity structures as a function of wavelength for four different intercavity distances: $\Lambda_A = 1.5$, $\Lambda_B = 2.5$, $\Lambda_C = 3.5$ and $\Lambda_D = 4.5$ pairs. The waveguiding bandwidth decreases as the interaction between the localized modes decreases

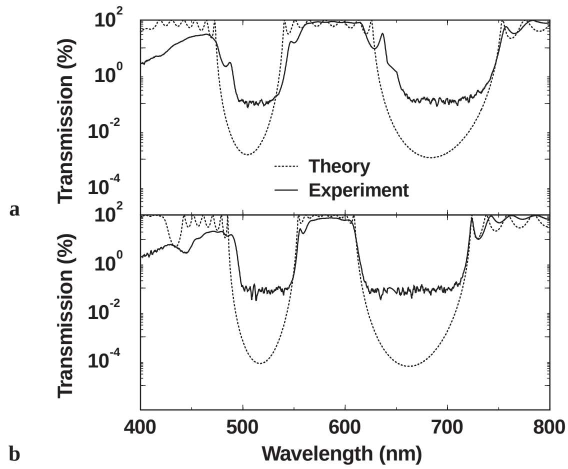

Fig. 3a,b. Transmission spectra corresponding to **a** sample B and **b** sample C. Nearly 100% transmission is observed for both samples throughout the waveguiding band. Theoretical results are obtained from TMM simulations and agree well with measurements

Here $\Omega = 517.4$ THz is the measured single-cavity resonance frequency. The dispersion relation is plotted as a function of wavevector k in Fig. 4a.

The group velocity of photons along the localized coupled-cavity modes is given by

$$v_g = \nabla_k \omega_k = -\kappa \Lambda \Omega \sin(k\Lambda) \,, \tag{2}$$

which is illustrated in Fig. 4b. We want to emphasize two important points here: (1) the maximum group velocity at the band center is one order of magnitude smaller than the speed of light in vacuum, (2) $v_g \to 0$ at the waveguiding band edges

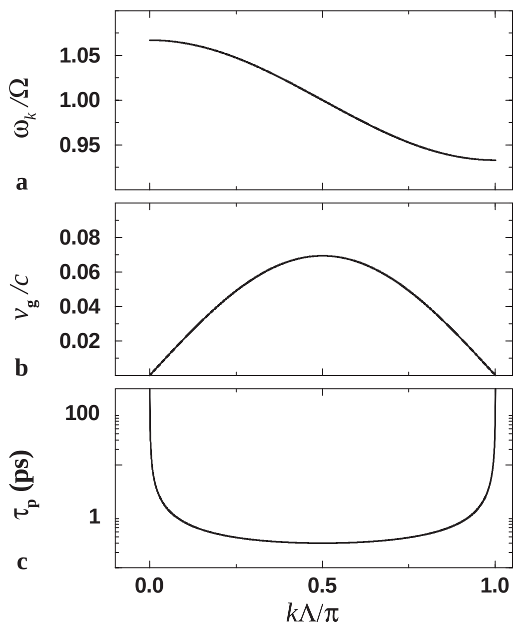

Fig. 4. **a** Calculated dispersion relation for sample B using the measured coupling parameter $\kappa \simeq 0.067$. **b** Normalized group velocity, $v_g = \nabla_k \omega_k$, of photons along the localized coupled-cavity modes. Here c is the speed of light in vacuum. **c** The photon lifetime, $\tau_p = \partial\varphi/\partial\omega$, as a function of wavevector k. Notice that $v_g \to 0$ and $\tau_p \to \infty$ at the waveguiding band edges

($k\Lambda = 0,\ \pi$). By using the TB formalism, one can determine the delay time or photon lifetime as [15]

$$\tau_{\mathrm{p}} = \frac{L}{v_{\mathrm{g}}} + \frac{2\pi L}{c}\,, \tag{3}$$

where L is the total crystal thickness. It is important to point out that $\tau_{\mathrm{p}} \to \infty$ at the band edges, and this observation is consistent with the vanishing group velocity. Recently, we have reported experimental observation of heavy photons at the waveguiding band edges of coupled-cavity waveguides (CCWs) at microwave frequencies [15].

In conclusion, we have demonstrated a new type of waveguiding mechanism in which the light propagates through highly localized cavity modes of one-dimensional photonic band-gap structures. Full transmission was observed throughout the waveguiding band. The coupled-cavity systems may offer potential applications: (1) guiding of light in optoelectronic components and circuits, (2) the efficiency of the second-harmonic generation process [4, 21] can be increased as a result of large optical field amplitude and low group velocity at the waveguiding band edges as pointed out by Yariv and coworkers [17], (3) gain enhancement can be achieved in coupled-cavity waveguiding band edges, analogous to gain enhancement in the photonic band-edge laser which was proposed by Dowling et al. [8], (4) the spontaneous emission can be drastically enhanced at the coupled-cavity band edges [22].

Acknowledgements. This work is supported by Turkish Department of Defense Grant No. KOBRA-001, NATO Grant No. SfP971970 and National Science Foundation Grant No. INT-9820646.

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