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Enhanced photonic crystal cavity-waveguide coupling using local slow-light engineering

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This Letter introduces an enhanced cavity-waveguide coupling architecture based upon slow-light engineering in a two-port photonic crystal system. After analyzing the system transmittance using coupled-mode theory, the system is probed experimentally and shown to have increased transmittance due to the enhanced cavity-waveguide coupling. Such a coupling architecture may facilitate next-generation planar lightwave circuitry such as onchip quantum information processing or high precision light-matter sensing applications. © 2012 Optical Society of America

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Photonic crystal (PhC) nanocavities in planar lightwave circuits (PLCs) offer an extremely attractive route to various scalable, next-generation devices. Integrated optical quantum computing [1], ultra-small-footprint optical switching [2], and high precision sensing [3] are capabilities derived from light-matter interactions in well-designed PhC nanocavities. However, to be of any practical use in PLCs, these functions require highly efficient coupling between the nanocavities implementing the function and the waveguides that carry the optical signals to and from the outside world.

In this Letter, we experimentally demonstrate enhanced cavity-waveguide coupling by showing that a strategically placed local region of slow-light at the cavity-waveguide interface in a two-port PhC system increases the system's in-plane transmittance while concomitantly reducing the system's cavity out-of-plane emission. While there have been extensive studies that deal with cavity-waveguide coupling configurations [4], this Letter focuses on adding slow-light to a selected two-port PhC cavity system. Figure 1(a) shows the proposed system: an H1 nanocavity [5] centered between staggered W1 waveguides. A local series of reduced-radius in-line (RRIL) holes in the waveguide near the cavity realizes the slow-light region. From the coupled-mode analysis below, the termination point of the W1 waveguides is chosen to optimize the in-plane coupling between the W1 and the cavity through the interference of forward and backward propagating modes. By having this interference occur within a slow-light medium [6], an additional enhancement of coupling occurs between the cavity and the waveguides.

To guide the optimal integration of the slow-light into the PhC cavity-waveguide system, we first derive the system's maximum transmittance using coupled-mode theory (CMT) without any slow-light regions. As shown in Fig. 1(b), we obtain the two-port system from a generalized four-port system by placing perfectly reflecting mirrors at ports b and c , a distance d_2 past the center cavity. The cavity, with unloaded resonant frequency ω_0 and electric field amplitude a_1 , is assumed to radiate out of the plane with a time constant τ_v and to be coupled to the waveguides with a time constant τ_{in} . The traveling wave amplitudes in the waveguides are represented by

$S_a^\pm$, $S_b^\pm$, $S_c^\pm$, and $S_d^\pm$, where $\pm$ indicates the propagation direction. When light, with a propagation constant β , enters the system at port a and couples through the cavity towards port d , we find from the coupled-mode analysis [7] that the maximum transmittance at port d strongly depends upon the distance d_2 . The maximum system transmittance at plane d , $|t|^2$, is

$$|t|^2 = \frac{\sin^4 \beta d_2}{(\sin^2 \beta d_2 + \tau_{in}/4\tau_v)^2} \quad (1)$$

and the system quality factor, Q_{sys} , is

$$\frac{1}{Q_{sys}} = \frac{1}{Q_v} + \frac{4}{Q_{in}} \sin^2 \beta d_2, \quad (2)$$

where $Q_v = \omega_0 \tau_v/2$ and $Q_{in} = \omega_0 \tau_{in}/2$. Because the in-plane and vertical lifetimes, τ_{in} and τ_v , are fixed in the real system through design of the H1 nanocavity and its proximity to the W1 waveguides, i.e. primarily the

Fig. 1. (Color online) (a) Scanning electron micrograph of the proposed cavity-waveguide system with local slow-light engineering implemented using reduced-radius in-line (RRIL) holes. (b) Idealized system for coupled-mode theory analysis. (c) Calculated transmittance as a function of the ratio of in-plane and vertical quality factors and the termination phase length.

Fig. 2. (Color online) Dispersion diagram of cavity-waveguide system. The system has been engineered so that input-output W1 waveguides have their fast-light symmetric modes resonant with the nanocavity while the slow-light symmetric modes of the RRIL-W1 waveguides are resonant with the nanocavity. Points 1 and 2 show where the nanocavity resonance intersects the W1 and RRIL-W1 symmetric modes.

number of lattice rows between the cavity and waveguides, the system transmittance and quality factor can now be controlled through a choice of d_2 . Figure 1(c)

shows a contour plot of the system's maximum transmittance as a function of the ratio Q_{in}/Q_v and the phase length $\beta d_2/\pi$. Given a quality factor ratio that is fixed by fabrication, we can choose a phase length of 0.5 that yields an optimal d_2 for maximum transmittance of the system. We now integrate the slow-light region by making the distance d_2 span a local series of RRIL holes. This creates a pseudocavity region where the semireflecting mirror is the fast-slow-light boundary, the complementary mirror is the perfectly reflecting mirror (e.g., port b or c) and the pseudocavity's medium is a slow-light material. This pseudocavity region increases the intensity of light available for coupling across the real cavity which therefore enhances the system's transmittance.

Because the boundary between the fast- and slow-light regimes will act as a semireflecting mirror, we need to determine the proper dispersion relations in order to couple effectively to the system's cavity. Figure 2 shows the projected band diagram [8] for the PhC cavity-waveguide system. The blue and red curves represent the symmetric and asymmetric modes of the W1 waveguides, respectively, whilst up-arrows represent the case without RRIL holes and down-arrows represent the case with RRIL holes. The input/output W1 waveguides that do not have RRIL holes were designed to have their symmetric

Fig. 3. (Color online) Calculated dispersion diagram, measured vertical emission, and transmission results for (a) no RRIL holes, (b) $r = 0.15r_0$, (c) $r = 0.18r_0$, and (d) $r = 0.2r_0$. The dashed lines indicate the position of the symmetric and asymmetric curves for the preceding smaller RRIL hole sizes. Peaks in the vertical emission are due to out-of-slab resonances while peaks in the transmission are due to the cavity-waveguide coupling at the resonant wavelength. In (c), the reduction in the cavity's vertical emission implies that the vertically excited emission is being emitted into the waveguides, while the transmission results show an increased transmission peak due to the increased waveguide-coupling inferred from the vertical emission results. The transmission in (d) disappears because there is no waveguide mode available for coupling.

fast-light mode frequencies resonant with the cavity (dashed horizontal green line), as shown by point 1. Because the presence of the RRIL holes shifts the symmetric and asymmetric modes to higher frequencies, as depicted in Fig. 2, a proper choice of RRIL hole radius can be used to align the W1's symmetric slow-light mode frequency to the cavity's resonant frequency, as shown by point 2.

A series of devices with different sized RRIL holes were fabricated. In order to target *C*-band wavelengths (1530 nm to 1565 nm), a PhC lattice constant of $\Lambda = 441$ nm, and a lattice radius of $r_0/\Lambda = 0.3$ were selected. The structures were fabricated by first using electron-beam lithography for pattern generation followed by a chlorine-based inductively coupled plasma dry etch to etch the pattern into a 300 nm thick InP membrane. During the electron-beam lithography, the RRIL holes required a slightly higher dose due to their reduced size in comparison to the regular lattice holes. The membrane contained an ensemble layer of InAs quantum dots that was used as an internal light source for vertical emission measurements of the cavity and waveguide modes [9]. The out-of-plane optical measurements were performed using a vertical photoluminescence arrangement, where visible light excitation and subsequent collection of the quantum dot photoluminescence was performed normal to the membrane surface. The photoluminescence setup included a polarizer so that the vertically emitted asymmetric mode emission of the W1 could be identified [10]. The in-plane transmission measurements were performed by butt-coupling a tapered single-mode fiber to the input waveguide of the system and collecting the transmitted light from the output waveguide using a microscope objective, for subsequent detection using an InGaAs detector. In-plane transmission spectra were then obtained by sweeping the input laser source over a broad wavelength range. Figure 3 shows the calculated dispersion diagram, out-of-plane vertical emission, and in-plane transmission measurements of the coupled cavity-waveguide system for four different RRIL hole sizes. The vertical emission data was related to the associated projected band diagram by aligning the higher frequency spectral peaks in the vertical emission data to the flat-band region of the asymmetric mode (red curve). The vertical emission and transmission measurements were normalized to the largest value measured for the four devices. The peaks seen in the vertical emission correspond to out-of-plane resonances associated with states above the light line in the projected band diagram i.e. the cavity resonance and the slow-light of the asymmetric W1 mode. Peaks in the transmission measurements occur when the input laser's wavelength is resonant with the cavity and there is an available in-plane W1 mode for cavity-waveguide coupling.

At a RRIL hole radius of $0.18r_0$, as shown in Fig. 3(c), the slow-light of the symmetric mode of the RRIL-W1 is spectrally resonant with the cavity. This produces a significant decrease in the cavity's vertical emission and a corresponding increase in the in-plane transmission of the system. The transmission of the coupled cavity-waveguide is enhanced relative to the other devices with different RRIL hole sizes. On the other hand, if the cavity is pumped vertically, the subsequent emission couples preferentially to the in-plane waveguides resulting in decreased vertically collected light. When the RRIL hole radius increases further, there is no available in-plane W1 mode for cavity coupling and the transmission disappears completely, as shown in Fig. 3(d).

In summary, a photonic crystal cavity-waveguide system with enhanced cavity-waveguide coupling has been demonstrated. By controlling the interference in an engineered slow-light cavity-waveguide interface, it was shown that the in-plane transmission of the system increases, with a corresponding decrease in the cavity's vertical emission. This implies that the cavity-waveguide in-plane coupling is enhanced because light emitted by the cavity prefers to couple to the in-plane waveguides rather than emitting vertically out-of-plane. Such a design is expected to greatly facilitate the functionality of next-generation photonic devices and optical processing in planar lightwave circuitry.

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