Polarization control and sensing with two-dimensional coupled photonic crystal microcavity arrays

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We have experimentally studied polarization properties of the two-dimensional coupled photonic crystal microcavity arrays and observed a strong polarization dependence of the transmission and reflection of light from the structures—effects that can be employed in building miniaturized polarizing optical components. Moreover, by combining these properties with a strong sensitivity of the coupled bands on the surrounding refractive index, we have demonstrated a detection of small refractive-index changes in the environment, which is useful for construction of biochemical sensors. © 2005 Optical Society of America

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We have recently proposed[1] and experimentally demonstrated[2] two-dimensional coupled photonic crystal resonator arrays (CPCRAs), exhibiting a small group velocity over all wave vectors and in all crystal directions. These structures are interesting for construction of low-threshold devices such as photonic crystal (PhC) lasers with increased output powers and various nonlinear optical components. In our previous experimental work we measured the band diagram of such a structure by testing transmission through it at various incidence angles, thereby controlling the in-plane wave vector (k) and demonstrating small group velocity (below $0.008c$ at the Γ point) for a broad range of k vectors.[2] In this Letter we demonstrate a strong sensitivity of the light transmitted and reflected from CPCRAs to the input polarization and the surrounding refractive index, which can be employed in building miniaturized polarizing optical components or biochemical sensors.

When PhC microcavities are tilted in two dimensions, thereby forming a two-dimensional CPCRA [as shown in Fig. 1(b)], defect modes of individual cavities form coupled bands located inside the photonic bandgap of the surrounding PhC. In particular, coupled arrays in a square PhC lattice exhibit three coupled bands: monopole, dipole, and quadrupole.[1,2] Here we focus on the coupled dipole band, which is (in a structure with a fourfold rotational symmetry) doubly degenerate at the Γ point but splits into two subbands (x and y dipoles) in the ΓX direction.[1] The electromagnetic fields of the two dipole modes are related by 90° rotation, and field components of the x dipole are shown in Fig. 2(a); the dominant electric field components of the x and y dipole modes are E_x and E_y, respectively, and one can employ the input field polarization to preferentially excite a particular mode. The designed CPCRAs were fabricated in silicon on insulator,[2] and scanning electron microscope pictures are shown in Fig. 1(b). The size of the array is 100 μm by 100 μm, and the PhC parameters are periodicity $a=488$ nm, hole radius $r=190$ nm, and slab thickness $d=275$ nm. The coupled cavities have two PhC layers between them in all directions, and the unit cell size is $3a \times 3a$, as shown in the inset of Fig. 3. For this set of parameters the finite-difference time-domain (FDTD) method predicts that the dipole mode is in the scanning range of our tunable laser (1460–1580 nm). Our experimental setup is shown in Fig. 1(a). The structure is excited at the vertical incidence (in the z direction, i.e., at the Γ point) by a tunable laser whose beam is linearly polarized in the x direction and is slightly focused on the sample by a very low numerical aperture objective lens. The rotation of the structure around the z axis is used to test the polarization dependence of both the total transmitted signal through the structure and the reflected signals of the same (x) or the opposite (y) polarization. After the structure is rotated by an angle ϕ around the z axis, the excitation beam (x axis) is polarized in the direction ϕ of the structure, and the reflected signal of opposite polarization (y axis) then corresponds to a linearly polarized signal in the di-

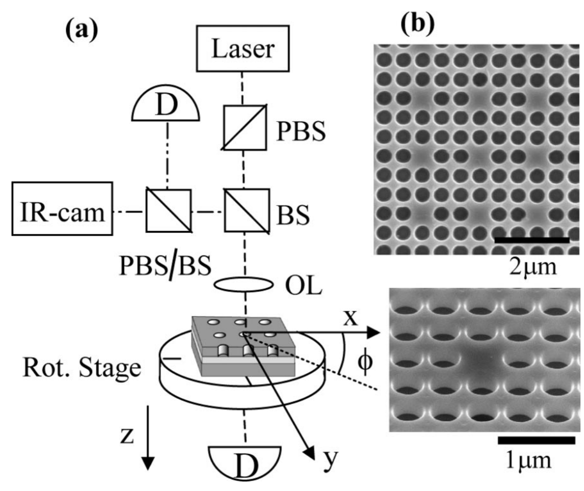

Fig. 1. (a) Experimental setup used in testing of the polarization properties CPCRA and in sensing. BS, nonpolarizing beam splitter; PBS, polarizing beam splitter; OL, objective lens; IR-cam, infrared camera; D, detector. Rotation of the structure around the z axis is controlled by a rotation stage. (b) Scanning electron microscope pictures of the fabricated CPCRA with $A=3a$.

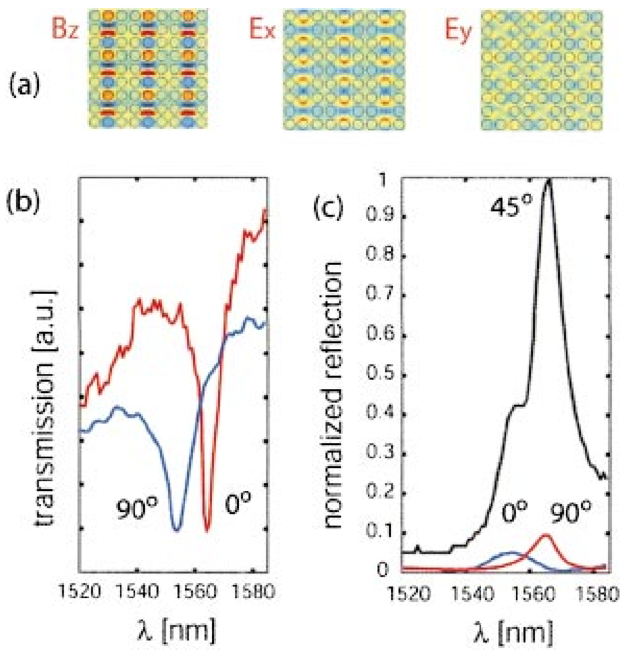

Fig. 2. (a) Electromagnetic field pattern of the coupled x-dipole band at the Γ point and at the center of the PhC slab (field components of the y dipole are obtained by first interchanging E_x and E_y and then rotating all three patterns by 90°). (b) Transmission spectra of the CPCRA for the coupled x- (red, $\phi=0°$) and y- (blue, $\phi=90°$) dipole modes at the Γ point. (c) Reflection spectra of the CPCRA at the opposite polarization relative to the excitation, polarized at $\phi=0°$, 45°, 90°.

rection $\phi+90°$ of the structure. The input polarizations ϕ of 0°, 90°, and 45° correspond to two different ΓX and the ΓM directions, respectively; the x dipole is expected to be primarily excited for $\phi=0°$ and the y dipole for $\phi=90°$.

Figure 2(b) is obtained by scanning the wavelength of the incident beam and measuring the transmission through the structure at vertical incidence (Γ point) for the input polarization in the $\phi=0°$ and $\phi=90°$ directions. The dips in the red and blue curves correspond to the x and y dipole modes with wavelengths 1564 and 1555 nm, respectively; this implies that the degeneracy of the dipole band is lifted at the Γ point as a result of the structural asymmetry under 90° rotation (the hole radius in the x direction is roughly 5% larger than in the y direction).[2] As can be seen from Fig. 2(b), for an input beam at the wavelength of the x dipole mode (1564 nm) that is vertically incident to the structure, the y component of the beam will be transmitted, while the x component will be strongly reflected. Similarly, if the input beam has the wavelength of the y-dipole mode (1555 nm), then the transmitted and reflected components will be interchanged. This implies that such structures can be used as miniaturized polarizing mirrors. Recently, another group of researchers theoretically analyzed a polarizing mirror effect in an asymmetric square PhC lattice.[3] The advantage of asymmetric CPCRAs for this application is that, because of the flat bands employed, they behave as polarizing mirrors even for the input beam that is not vertically incident, which is also useful for making polarizing beam splitters. In addition, asymmetric CPCRAs can be used to control the output polarization of a CPCRA laser.[1,2]

Figure 2(c) shows the measured reflected signal at the opposite polarization relative to the vertically incident excitation for three different input polarizations ϕ: 0°, 90°, and 45°. An incident beam polarized at an angle $\phi=0°$ (90°) and at the wavelength of the x (y) dipole preferentially excites the x (y) dipole mode; since the reflected signal is polarized the same as the excited mode, the reflected signal at the opposite polarization is minimized at 1564 nm (1555 nm), i.e., the wavelength of the x (y) dipole. However, the reflected signal with opposite polarization shows a small peak at the wavelength of the orthogonal mode, i.e., a peak at 1555 nm (1564 nm), which corresponds to the spectral position of the y (x) dipole, appears in Fig. 3 for $\phi=0°$ (90°). This weak signal results from the fact that the dipole modes are not purely linearly polarized [see Fig. 2(a)], so an input beam polarized in the x (y) direction can also weakly excite the y (x) dipole mode, which primarily reradiates in the y (x) polarization opposite to the excitation reflected signal of opposite polarization [Fig. 2(c)]. On the other hand, for input polarization in the ΓM direction ($\phi=45°$), both the x- and y-dipole modes can be excited (since both of them have nonzero field components in the direction $\phi=135°$), which leads to a strong reflected signal at the opposite polarization as can be seen from Fig. 2(c). In this particular structure the x-dipole peak is more pronounced as a result of its higher Q factor [also clear from the narrower width of transmission in Fig. 2(b)], which is also confirmed by the three-dimensional FDTD simulation. We repeated the reflectivity measurements for varying input polarization angles ϕ and recorded the peak power in the reflected signal of opposite polarization as a function of ϕ; the result is shown in Fig. 3, and the mea-

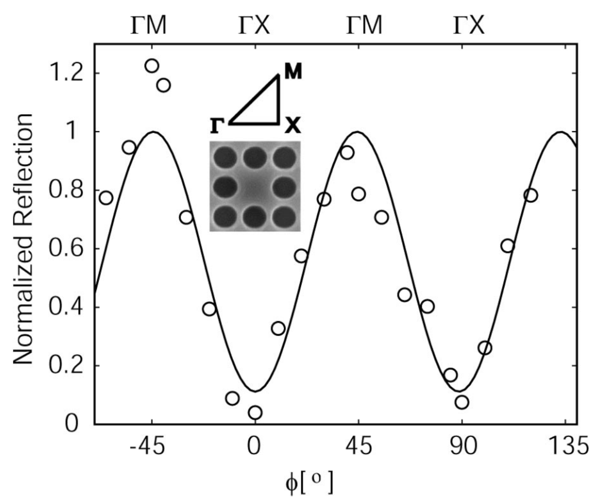

Fig. 3. Peak power of the reflected signal with opposite polarization relative to the excitation as a function of input polarization angle ϕ (circles). The solid curve is a sine square function fit to the experimental data. The inset shows a unit cell of CPCRA with $A=3a$ and high symmetry directions.

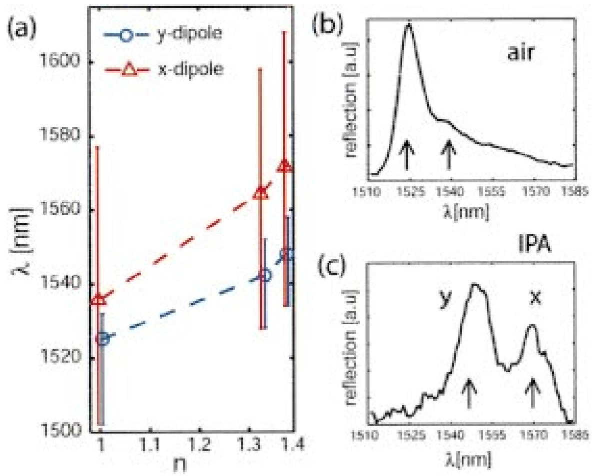

Fig. 4. (a) Resonance wavelength as a function of the surrounding refractive index. The three data points correspond to the structure in air ($n=1$), methanol ($n=1.328$), and IPA ($n=1.377$). The triangles and circles correspond to the experimental wavelength shifts of the x and y dipoles, respectively, and the vertical bars indicate the range of the wavelength shift expected from the FDTD simulations. (b) Reflection spectrum with opposite polarization with respect to the excitation for the structure in air. The arrows indicate the positions of the x- and y-dipole bands. (c) The same spectrum when the structure is immersed in IPA.

sured curve matches the fit given by $\sin^2(2\phi\pi/180)$ very well, indicating that the structure obeys the Malus law that describes linear polarizers.[4]

The position of the resonance in the reflected signal from CPCRA strongly depends on the surrounding refractive index, which can be used in biochemical sensing. To demonstrate the detection of the refractive-index change, we use another CPCRA with $a=467$ nm, $r=195$ nm, and $d=255$ nm, in which the dipole modes are shifted to shorter wavelengths (y and x dipoles at 1525 and 1536 nm, respectively) so that they remain in the wavelength range of our tunable laser even after the structure is immersed in an environment with an increased refractive index. In this structure the y-dipole mode has a higher Q as the asymmetry is introduced in a different way than previously (the periodicity in the x direction is closer to the designed value). Various ways to introduce asymmetry into the structure provide flexibility when control of the polarization is important. Sensing of refractive-index changes is performed by dropping small amounts of isopropanol (IPA, refractive index $n=1.377$) and methanol ($n=1.328$) separately on the same structure. The reflected signal of opposite polarization for the structure covered with IPA is shown in Fig. 4(c): the spectrum is clearly shifted to longer wavelengths, as expected. The reflection spectrum from the same structure with methanol is very similar to that of IPA, again with two peaks, but at shorter wavelengths relative to IPA. Before we use methanol, the structure is cleaned and the reference signal is repeated. Figure 4(a) shows the measured resonance wavelength shift as a function of the surrounding refractive index for both the x and y dipoles; the vertical bars correspond to the expected range of the mode wavelength predicted by the three-dimensional FDTD simulation (the exact asymmetric structure parameters cannot be simulated with the employed FDTD discretization). By immersing the structure in IPA instead of methanol we find that the refractive index changes by $\Delta n=0.049$ and the dipole band position shifts by $\Delta\lambda=7$ nm. Three-dimensional FDTD simulation predicts that a 0.521-nm shift in wavelength for an index change of $\Delta n=0.002$ is possible, a sensitivity similar to that observed recently in a single PhC cavity sensor.[5] The CPCRA approach simplifies the positioning of the analyzed material, since the cavities are distributed over a larger area, and it permits high sensitivity at different incidence angles because there are flat-coupled bands (i.e., because of the alignment tolerance). One can improve the sensitivity by changing the type of cavity inside a CPCRA or by embedding an active quantum-well layer inside the structure.[6]

In conclusion, we have experimentally analyzed the polarization properties of CPCRAs and observed a strong dependence of the transmitted and reflected signal on the input polarization. We have confirmed that the structures can be used as miniaturized polarizing optics (mirrors and beam splitters). Finally, we have combined detection of the reflected signal from the structure with a strong sensitivity of CPCRAs on the surrounding refractive index to demonstrate detection of refractive-index changes of 0.05. Our theoretical analysis shows that this result can be improved by at least an order of magnitude, which is interesting for construction of biochemical sensors.

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