Reconfigurable microfiber-coupled photonic crystal resonator

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Abstract: We propose and demonstrate reconfigurable microfiber-coupled photonic crystal (PhC) lasers. In this generic configuration, the position of a PhC resonator can be defined (and redefined) repeatedly by simply relocating a curved microfiber along the linear PhC waveguide. In the proximity of the PhC waveguide in contact with the microfiber, the cutoff frequency (effective index) of the PhC waveguide becomes smaller (larger) than that of a bare PhC waveguide. Accordingly, when a curved microfiber is in contact with the PhC waveguide, a linear PhC resonator having Gaussian-shaped potential well is formed. Experimentally we confirm the formation of the reconfigurable resonator by observing laser operation slightly below three available band edges.

OCIS codes: (230.5298) Optical devices; Photonic crystals, (130.5296) Integrated optics; Photonic crystal waveguides, (140.3410) Lasers and laser optics; Laser resonators, (160.0160) Materials; Photonic crystals.

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1. Introduction

Owing to the advancement of photonic crystal (PhC) technologies, various small and high-Q optical cavities have been reported recently [1-3]. These high-Q PhC resonators have long been a topic of interest in lasers and quantum optics, because of strong light-matter interactions. Recently, many groups investigated the PhC resonator based on quantum dots as a potential single photon source [4, 5]. In order to realize meaningful single photon sources, the precise control is required for the spatial and spectral overlap of the cavity resonance with that of a quantum dot. For this reason, the post trimming of the cavity properties is in great demand, not only to relax fabrication tolerances but also to optimize individual components. The spectral tuning of photonic crystal resonators has previously been achieved through various techniques, such as thermo-optic approaches [6], liquid crystal infusion [7], integration of nanofluidic circuitry [8], digital etching technique [9], mechanical deformation [10], mechanical perturbation of the electro-magnetic environment with an atomic force microscopy tip [11] or a taper-fiber [12], and exploitation of photosensitivity in chalcogenide glass [13]. However, the spatial overlap of the cavity resonance with a quantum dot has been nontrivial although the spatial reconfigurable PhC resonators have been reported using fluid infiltration [14].

In this report, we propose and demonstrate a novel microfiber-coupled linear PhC slab waveguide resonator that can be spatially reconfigured. This reconfigurable PhC resonator is expected to provide the accurate overlap of the resonant cavity with a quantum dot spatially and spectrally, in addition to the simple photon out-coupling with high efficiency.

2. Reconfigurable photonic crystal resonator

The linear PhC slab waveguide is prepared by leaving out one row of air-holes, as shown in Fig. 1(a). When a straight microfiber is placed right on top of the PhC waveguide, the dispersion curve of the guided mode is perturbed slightly as shown in Fig. 1(b). The net downward shift of the normalized frequency is a sensitive function of the size of the air-gap *d*. In other words, the cutoff frequency of the PhC waveguide in contact with the microfiber is reduced in comparison to that of the PhC waveguide without a fiber. As the straight microfiber approaches the PhC waveguide, the evanescent field of the PhC waveguide mode feels the presence of the microfiber and the effective refractive-index of the waveguide is increased accordingly.

We take advantage of this effect to make the double-heterostructure type cavity by placing a highly-curved microfiber in contact with a PhC waveguide [3, 15-17]. In this case, the spatial profile of the cutoff frequency follows the Gaussian shape as shown in Fig. 2(a). This Gaussian dependency is understandable if one considers the overlap of the exponentially-

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decaying evanescent tail of the PhC guided mode with the microfiber at a distance of air-gap (*d*) that varies parabolically. A PhC resonator, therefore, can be defined repeatedly by simply relocating the curved microfiber along the PhC waveguide. Moreover, the physical size of the resonator can also be controlled by adjusting the curvature of the microfiber. Namely, the spatial and spectral properties of the PhC resonator can be controlled by the position and the curvature of the microfiber, repeatedly.

We study the formation of the fiber-coupled reconfigurable resonator using 3D finite-difference time-domain (FDTD) computation. The radius of curvature (*R*) and the diameter of microfiber are 70 μm and 1.5 μm, respectively. The thickness of the PhC slab is 200 nm and the radius of air hole is 0.30*a* (*a*=lattice constant). In Fig. 2(b), the optical field is well confined in the proximity of the contact point. This fact tells us that a new resonator is newly created slightly below the band edge of the guided mode. The frequency gap between the cavity resonance and the band edge is 0.0011, equivalent to $\Delta\lambda$=5.8 nm. The Q-factor is calculated to be 1,300,000 at normalized frequency of 0.2911. The mode-volume is $2.6(\lambda/n)^3$ and the coupling efficiency into the microfiber is 26%.

If one wishes to improve the coupling efficiency using a microfiber of *R*=70 μm, the size of nearest air-holes of the PhC waveguide need to be adjusted. With the radius of nearest air-holes increased to 0.33*a* from 0.30*a*, the coupling efficiency is increased up to 90% at the moderate expense of the Q-factor (Q=54,000). The excellent coupling here manifests the good mode-matching between the fiber-coupled PhC resonator and the fiber. Both the mode volume and Q-factor decrease with the radius of curvature, because the lateral size of the Gaussian well becomes smaller. In case of the smaller radius of curvature *R* of 20 μm, the Q-factor and the mode-volume are 70,000 and $1.9(\lambda/n)^3$, respectively. And the coupling efficiency is 80%.

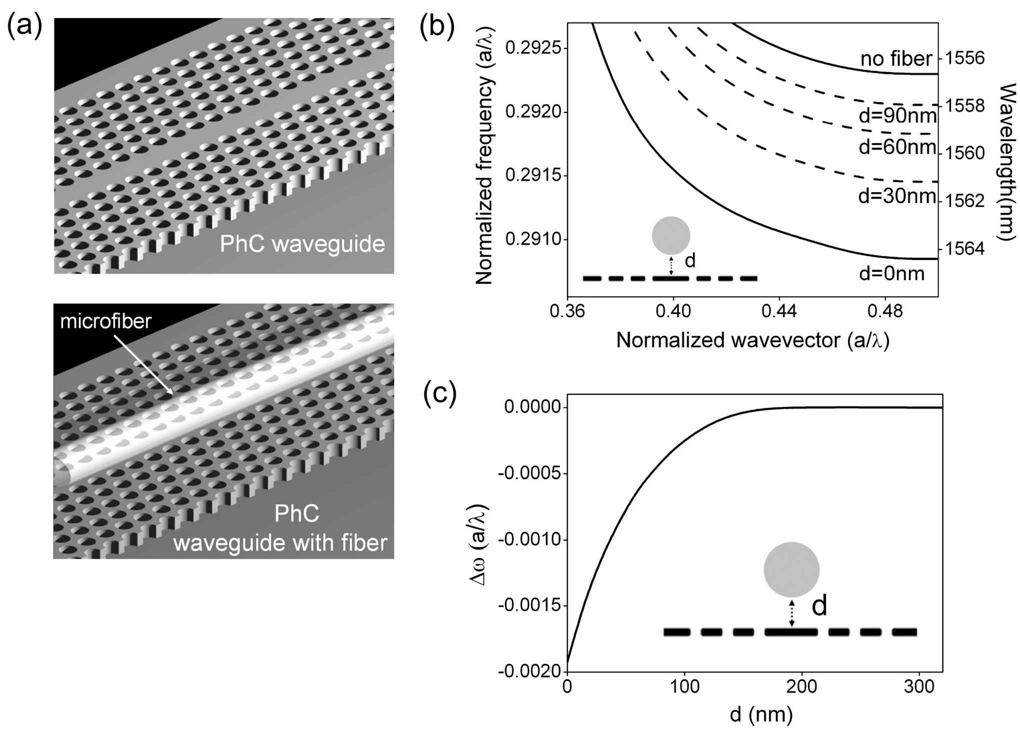

Fig. 1. (a) PhC slab waveguide without and with a microfiber, (b) Dispersion curves of PhC waveguide for different values of air gap, (c) Shift of cutoff frequency of the PhC slab waveguide mode as a function of air gap.

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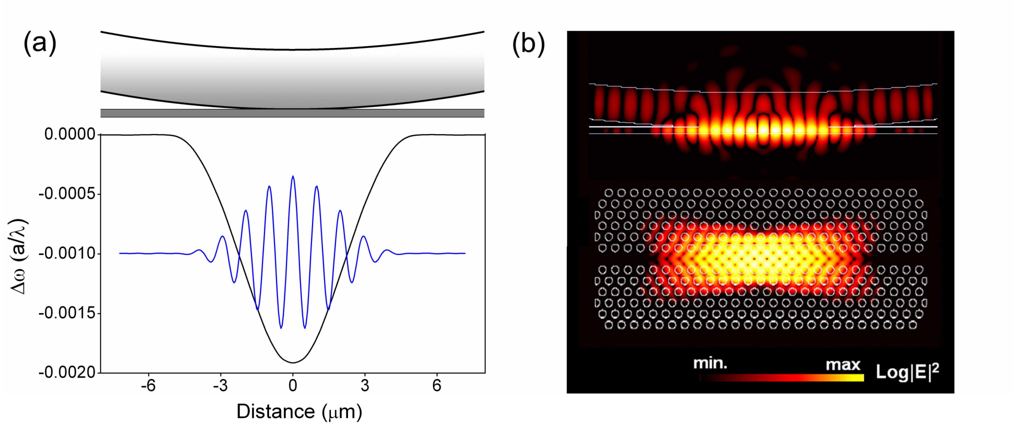

Fig. 2. (a) Spatial profile of the cutoff frequency that follows a Gaussian shape. Here, the radius of curvature of the microfiber is 70 µm, (b) Energy distribution of the curved microfiber-coupled PhC resonator calculated by 3D FDTD simulation.

3. Experiment

In order to confirm the proposed concept experimentally, we fabricate linear PhC slab waveguides and highly-curved microfibers (Fig. 3) [15, 18]. The 200-nm-thick InP slab contains the InGaAsP four quantum wells in the middle as an active medium. The fabricated PhC InGaAsP slab linear waveguide is 33-µm-long with air hole radius of 0.30*a*. The radius of curvature and the diameter of the microfiber are ~70 µm and 1.5 µm, respectively.

The 980-nm InGaAs laser diode is pulse-pumped through one end of the fiber and the output is collected from the other end using a wavelength division multiplexing coupler [15, 19]. The duty cycle of the pulse train is 1 %. The thick red curves in Fig. 4 (a)-(c) show emission spectra when the microfiber is in complete contact with PhC waveguides of lattice constants of 512nm, 460nm and 418nm. The three PhC waveguides of different lattices are chosen to cover the entire photonic bandgap. The black spectral curves are taken when the microfiber is placed ~100 nm above the PhC waveguide for comparison purposes. In this case no observable fiber-coupled resonator is formed. These black spectra can be regarded as the reference representing the characteristics of the PhC waveguide mode without the microfiber, because the pump laser is still able to generate electron-hole pairs that recombine to produce photoluminescence.

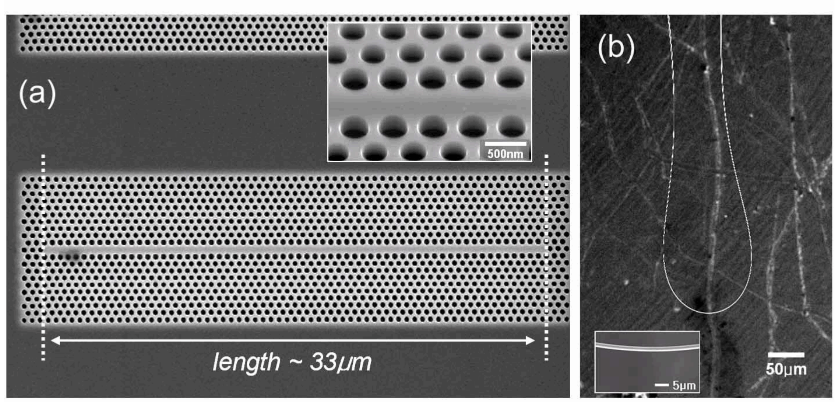

Fig. 3. (a) Linear PhC slab waveguide, (b) Curved microfiber.

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When the curved microfiber is in complete contact, the reconfigurable PhC laser (RPCL) modes are observed in samples of different lattice constants slightly below the band edges of respective guided modes. The dotted lines in Fig. 4 indicate the spectral positions of the respective band edges. For all the spectra shown in Fig. 4, the peak pump power into the fiber is fixed at 6.5 mW. As shown in Fig. 4, the 512-nm and 460-nm samples show single mode lasing operation is observed at 1604.6 nm and 1589.3 nm (red curves), respectively. However, when the fiber is not in contact (black curve), no lasing is observed.

In contrast, for a sample with lattice constant of 418-nm (Fig. 4(c)), many band edge modes are observed, in addition to the rightmost RPCL mode at 1547.6 nm (red curve). Even without the microfiber in contact (black curve) we can observe lasing in the wavelength region shorter than 1542.2 nm which corresponds to the band edge. When the pump power is reduced to 2.5 mW from 6.5 mW, only two lasing modes is excited as shown in the inset of Fig. 4(c). Two lasing peaks at 1547.6 nm and 1542.2 nm are associated with the RPCL mode and the waveguide mode of the first band [20], respectively. Note that the group velocity of the guided mode of the first band at 1542.2 nm is smaller than those of the upper bands. Therefore, the condition of lasing is satisfied more easily with pump power smaller than those of samples with larger lattice constants. The wavelength gap ($\Delta\lambda$=5.4 nm) between the RPCL mode and the band edge mode agrees well with that ($\Delta\lambda$=5.8 nm) obtained previously by FDTD computation. The lasing threshold and the Q-factor of this RPCL mode are measured to be 1.2 mW and 5,500, respectively.

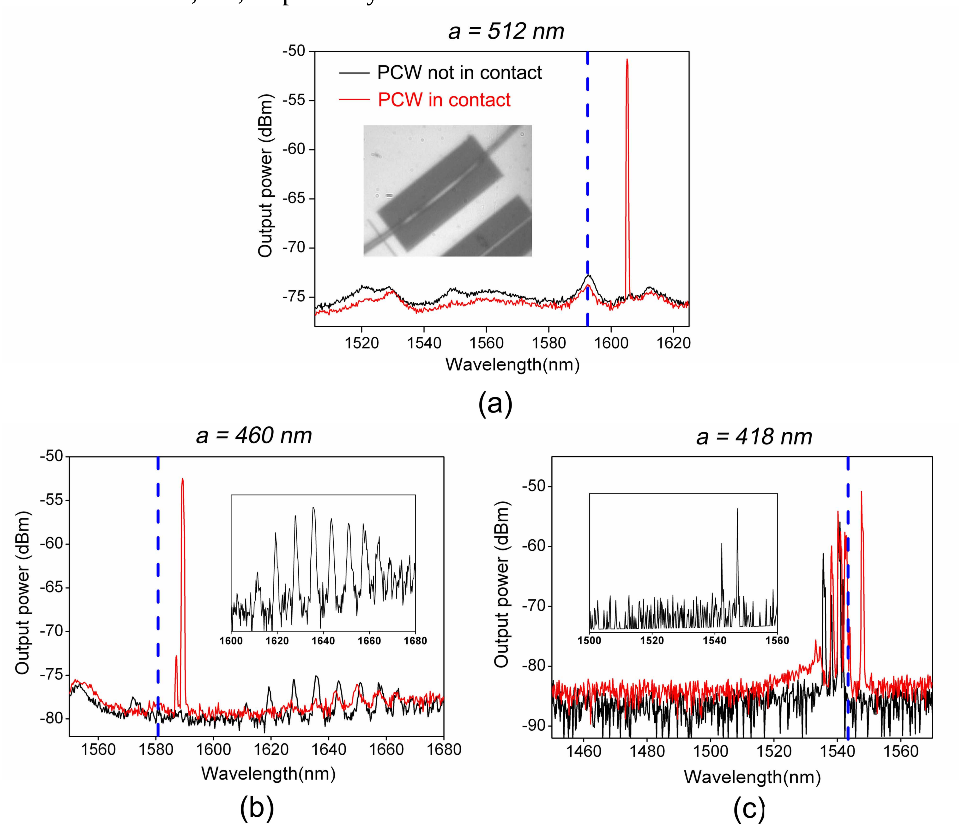

Fig. 4. Measured spectra for three different lattice constants of (a) 512 nm, (b) 460 nm and (c) 418 nm. The red curves show the spectra when the microfiber is in complete contact with PhC waveguide. The black spectral curves are taken when the microfiber is placed ~100 nm above PhC the waveguide. Blue dashed line indicates the band edge of the PhC waveguide mode. Inset of (b) shows the expanded interference pattern. The inset of (c) is the spectrum at low pump power of 2.5 mW.

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In order to understand these observations, we calculate dispersion characteristics of the PhC waveguide by the 3D contour FDTD method and compare measured spectra with this calculated dispersion curve as shown in Fig. 5. There exist three possible locations available for the formation of the RPCL mode within the photonic bandgap. These three RPCL modes are associated with different waveguide modes, TE1-like (even), TE1-like (odd) and TE2-like (odd) modes, respectively. Each mode-profile is shown in the inset of Fig. 5. Note that the measured normalized RPCL lasing frequencies at 0.2913, 0.3119, and 0.3563 are found slightly below the three PhC guided modes, respectively.

The peaks other than the RPCL modes can also be understood from this figure. In fact, the other lasing modes are excited from the band edge modes where the group velocity is very low. The Fabry-Perot fringes in Fig. 4(b) come from the finite length of the fabricated PhC waveguide [21]. The estimated length of the PhC waveguide obtained from the measured fringe spacing ($\Delta\lambda$=8.3 nm) is 35 μm, in reasonable agreement with the length (~33 μm) of the fabricated PhC waveguide. The broad photoluminescence from 0.3130 to 0.3240 (Fig. 4(b)) is attributed to the broad hill near the center of the TE1-like odd mode dispersion curve where the group velocity is small.

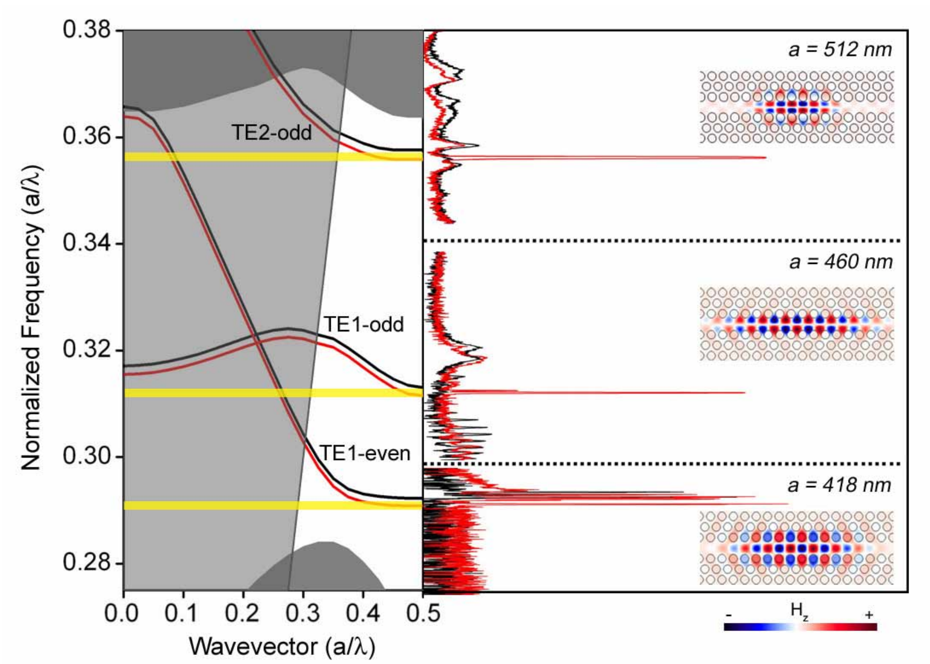

Fig. 5. Calculated dispersion of PhC waveguide and measured emission spectra. There exist three possible locations (yellow regions) for the formation of the RPCL mode within photonic bandgap. The vertical magnetic field (H_z) of each mode is shown in the inset on the right.

4. Summary

We propose and demonstrate the generic reconfigurable microfiber-coupled PhC laser. The formation of the reconfigurable photonic crystal resonator is confirmed by observing the lasing action at all three possible spectral locations within the bandgap. This scheme is advantageous in that the physical location and size of a PhC laser resonator can be defined repeatedly, by simply relocating a highly-curved microfiber on a PhC slab waveguide. With this reconfigurable scheme, the overlap of the cavity resonance and the quantum dot resonance can be achieved through simple movement of the microfiber. We believe that this new conceptual PhC resonator can be a good potential platform for the single photon source based on quantum dots.

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