Curved-microfiber photon coupling for photonic crystal light emitter

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Highly-efficient evanescent coupling between a photonic crystal resonator and a curved fiber taper is demonstrated. The coupling is utilized to pump the photonic crystal laser and funnel its output photons through a single optical fiber, making it an all-fiber photon source. Photon collection efficiency of ~70% into the fiber and output power of 27 nW are achieved. Highly local pumping results in the record-low threshold of ~35 μW. This scheme provides an ideal platform for an on-demand single photon source based on two-dimensional photonic crystal. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2061851]

The ultimate wavelength-scale, high-Q light source has long been a topic of central interest in laser and quantum optics and recently gained renewed attentions with the aid of the photonic crystal (PC) that enables a strong photon confinement.[1–4] However, the practicality of these novel structures suffer from the long-standing problems of funneling photons into and out of a very small PC resonator. A PC-based light emitter typically requires an optical pump beam carefully focused on the cavity to be activated, and only a small fraction of the output photons can be collected by a bulky lens due to its complicated radiation pattern unless the emission diagram is adequately shaped. The efficient collection of the output photons becomes very critical when only one photon is emitted at a time to be used for quantum cryptography or quantum computations. The micropillar structures based on a one-dimensional PC enjoyed partial success reporting a single photon emission efficiency of ~40% into a Gaussian propagating wave, to be effectively coupled to an optical fiber.[5,6] It is believed that a two-dimensional high-Q PC cavity may exhibit much stronger Purcell effect and, thus, more efficient single photon generation is expected. Therefore, if one finds efficient ways to collect photons into a fiber, then one can envision a practical single photon generator.

There have been various efforts to collect more photons from a wavelength-scale PC microcavity. Among many trials, the evanescent coupling from PC cavities to adjacent PC waveguides has been often investigated.[7,8] However, this scheme requires additional nontrivial coupling from the waveguides into an optical fiber or other conventional optics.[9,10] The situation becomes worse when the PC waveguides are to be formed in an absorptive heterostructure containing quantum wells or dots, where the propagation loss becomes prohibitively large. The direct evanescent coupling between a PC cavity and a tapered optical fiber has been recently demonstrated.[11] This coupling scheme was well suited to measure the high Q-factors of passive microresonators, operating in the weak coupling regime for minimal disturbance of the resonator properties.

Here we demonstrate simple, and highly efficient evanescent coupling from a modified three-lattice-long low-threshold PC laser into a single mode fiber through a sharply curved taper section. In the proposed scheme, a conventional single mode fiber is tapered down to ~1.5 μm and very strongly bent such that the radius of curvature is ~50 μm as shown in Fig. 1. This sharply-curved microfiber is positioned above the PC laser cavity. The small curvature radius of the microfiber enables easy and highly local access to the ultrasmall PC resonator with minimal interaction with the absorptive region outside of the mode of interest. To obtain the mechanical stability of the curved microfiber, the tapering process was controlled to minimize the length of the taper section keeping the adiabatic condition. 980-nm pump laser light is injected through the tapered microfiber into the cavity by evanescent coupling and the pump laser is absorbed in the InP/InGaAsP quantum wells located in close proximity to the microfiber. Once the resonant mode at around 1550 nm is excited, photons are collected into the curved microfiber, in both forward and backward directions. With the help of a commercial fiber coupler, it is straightforward to collect all the photons coming out of the two ends into a single fiber. Then the PC light source can be compactly packaged to have only two fiberoptic channels for the pump and the output, respectively, with no bulk optics included.

To efficiently funnel photons from the PC resonator into the curved microfiber, the modified three-lattice-long linear cavity was used.[12] The inset of Fig. 1(a) shows the scanning

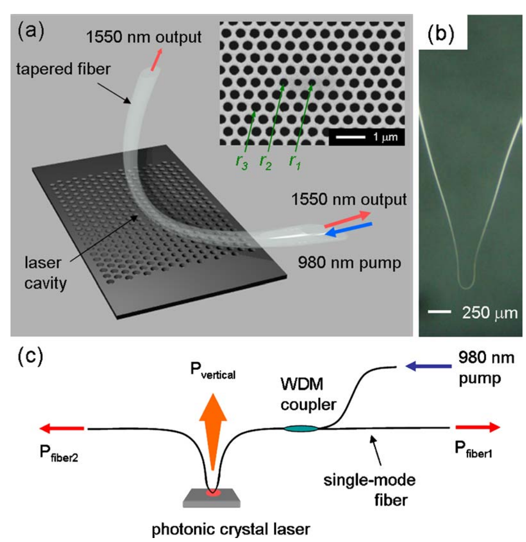

FIG. 1. (Color online) (a) Illustration of the device scheme with an optical fiber channel for pumping and output coupling. The inset shows the SEM image of the fabricated PC laser. (b) Photo of the curved microfiber used in the experiment. (c) Configuration of the device.

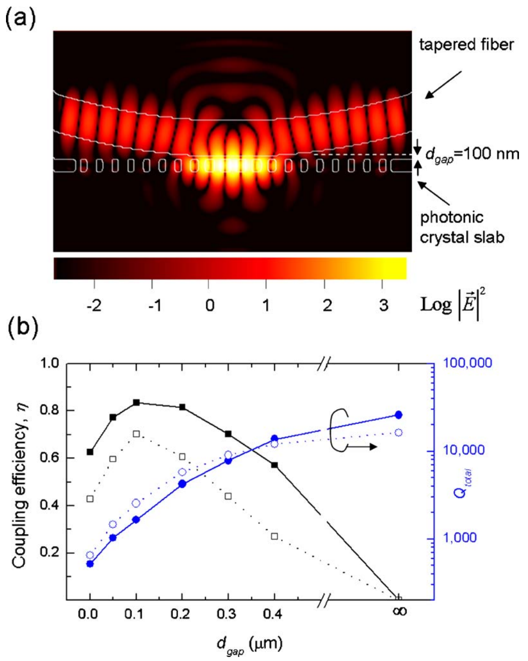

FIG. 2. (Color online) (a) Cross-sectional view of optical field intensity calculated by FDTD. (b) Fiber coupling efficiency (squares) and total Q factor (circles) as functions of d_{gap}. The open symbols are from the simulation results for the SEM image of Fig. 1(a) while the filled symbols are for the ideal cavity structure.

electron microscopy (SEM) image of the modified PC laser cavity structure. The slab thickness was 300 nm. The lattice constant was $a=500$ nm, and the hole radii were $r_1=0.25a$ for the three middle holes, $r_2=0.30a$ for the two side holes, $r_3=0.35a$ for the others. This modification enabled good modal overlap with the propagating mode of the microfiber, and also helped increasing the cavity Q factor. The calculated intrinsic Q-factor of this structure was 26 000.

Interaction between the PC cavity and the curved microfiber was investigated by the 3D finite-difference time domain (FDTD) method as shown in Fig. 2(a). In this case, the taper was laid on the plane orthogonal to the PC slab, and the air gap between the fiber and the cavity was $d_{\mathrm{gap}}=100$ nm. The resonance mode with normalized frequency of $a/\lambda=0.330$ was excited. A total of 84% output was found to be collected from the two ends of the fiber, 42% from each end of the fiber. About 9% of the total output photons coupled to the lossy TM-like propagation mode of the PC slab due to the symmetry breaking induced by the fiber, and the rest leaked into the air. It is encouraging to confirm that such a high coupling efficiency can be achieved by the simple evanescent coupling through a-few-μm-long interaction length.

To investigate the effect of the imperfection of the fabricated structure on the coupling efficiency, we ran the simulation again using the SEM image of Fig. 1(a) for the computation structure. The total Q factor and output coupling efficiency, η, for the two cases are summarized in Fig. 2(b) as functions of fiber-cavity gap separation, d_{gap}. The coupling efficiencies reached a maximum when $d_{\mathrm{gap}}\approx 100$ nm in both cases. The fabrication error resulted in the significant reduction of the intrinsic Q factor (to 16 000) and also the fiber coupling strength (to a half of the original) probably due to the smaller hole sizes of r_1 than designed that made the phase matching worse.[12] However, the maximum coupling efficiency was not degraded so much, which indicates robustness of this coupling scheme. For a gap less than 100 nm, photons tend to find TM-like propagation modes, and the relative portion coupling to the fiber decreases. The total Q factor drops to 2 600 when $d_{\mathrm{gap}}=100$ nm, and a higher Q value is available with a larger d_{gap} at the expense of the coupling efficiency. The maximum coupling efficiency and the total Q can be further increased by enhancing the intrinsic Q through a finer tuning of the cavity structure.

In the experiment, 980-nm InGaAs laser was injected into a micro-tapered single mode fiber through a 980/1550-nm WDM coupler [see Fig. 1(c)]. The output photons were measured at three different ports, P_{fiber1}, P_{fiber2}, and P_{vertical}. The vertically-emitted photons into the air (P_{vertical}) were collected by using 50× long-working-distance lens having numerical aperture of 0.4. The microfiber was fixed on a mount at 8 mm apart from the curved section, and its position relative to the laser was adjusted by piezoelectric actuators. The insertion losses of the curved microfiber with fiber connectors at its ends were 35% and 50% at 1550 nm and 980 nm, respectively. Typically ~10% loss is induced at the curved microfiber section, and the rest comes from fiber splices, connectors, and accidental contaminations of the taper.

The lasing characteristics were investigated when the microfiber was in direct contact with the surface of the PC resonator. In this configuration, the major portion of the pump leaked out of the fiber and <10% of the input pump power was transmitted through the taper and detected at the other end of the fiber. The width of the pump pulse was 10 ns at the repetition rate of 5 MHz (duty cycle of 5%). Figure 3(a) shows the average laser output power of P_{fiber1} versus the incident peak pump power measured between the taper and the WDM coupler. The measured value of P_{fiber2} was smaller than that of P_{fiber1} by a factor of about 2, probably due to the asymmetry in the taper shape and the transmission losses. The threshold pump power was ~35 μW, an order of magnitude smaller than those reported previously.[13,14] The net incident pump power at the position of the laser cavity was estimated to be about 70% of this value. The very low threshold originates from the evanescent local pumping into the region (~2×1 μm^2) that overlaps well with the profile of the mode of interest. Such extremely local pumping was practically impossible with conventional optics because of the diffraction limit. The measured maximum output power ($P_{\mathrm{fiber1}}+P_{\mathrm{fiber2}}$) was 27 nW, an order of magnitude stronger than other results,[3,14] indicating efficient out-coupling from the wavelength-scale PC resonator. The inset in Fig. 3(a) shows the output spectrum measured from P_{fiber1}. Single mode lasing with a side mode suppression ratio of >30 dB and a laser linewidth of ~0.2 nm were observed. A linewidth of the photofluorescence light was ~2.5 nm at the subthreshold level. This gives a rough estimate of Q factor of ~600 close to the theoretical value of Fig. 2(b). The other peaks at 1445 and 1485 nm originated from higher-order cavity modes.

The fiber coupling efficiency, η, cannot be directly measured because the total power generated inside the cavity is hard to measure. Instead, we tried to estimate the coupling efficiency by measuring the powers into the microfiber (P_{fiber1}) and into the air (P_{vertical}). P_{fiber1} and the ratio $P_{\mathrm{fiber1}}/P_{\mathrm{vertical}}$ at the fixed pump power are plotted as a function of the cavity-fiber gap d_{gap} in Fig. 3(b). As the gap

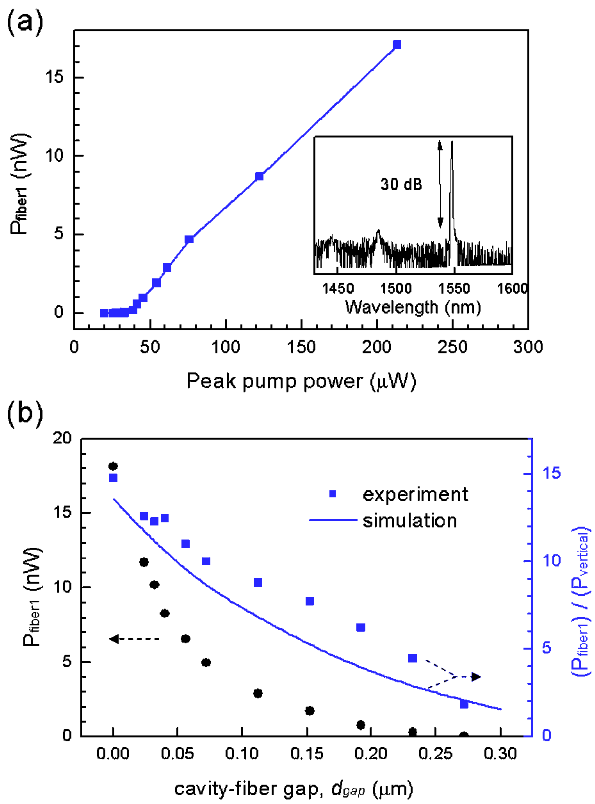

FIG. 3. (a) The laser output power (P_{fiber1}) vs peak pump power (inset: the output spectrum) (b) Output power of P_{fiber1} (circles) and its ratio to P_{vertical} (squares and line) at various fiber-cavity gap, d_{gap}.

became smaller, P_{fiber1} increased monotonically since more pump power was injected into the cavity and also the laser output coupling increased. As evidenced from the large values of $P_{\text{fiber1}}/P_{\text{vertical}}$, the major portion of the laser emission was funneled into the microfiber rather than into the air. For P_{fiber1}, the optical fiber loss from the cavity to the end of the fiber was neglected, while the optical component losses from lens to detector were compensated in P_{vertical} to give a lower bound for the ratio. For comparison, the simulation results of $P_{\text{fiber1}}/P_{\text{vertical}}$ computed with the actual cavity structure are plotted in blue squares in Fig. 3(b). In this simulation, P_{vertical} was obtained by integrating the radiated power that fell within the solid angle of the objective lens (N.A.=0.4). The reasonably good agreement over a wide range of d_{gap} was obtained between the experimental and the simulation data, which supports the validity of the curves of Fig. 2(b). The maximum fiber coupling efficiency η is thus estimated to be $\sim$70% at d_{gap}=100 nm. This value is much higher than those achieved from micropillar structures used for single photon generation ($\sim$40%).[6] The theoretical value of 84% can be reached with the help of state-of-the-art fabrication techniques.

The modal volume was 0.55 $(\lambda/2n)^3$, and the Purcell factor was estimated to be 650 in the worst case of d_{gap} =0 nm. The large enhancement of spontaneous emission rate together with the highly efficient output coupling makes this approach a very attractive platform for a realistic single photon source. Well-localized pumping and coupling through the fiber microbend can also be of great advantage to probing a single quantum dot of interest localized inside the cavity. The chance to excite unwanted quantum dots outside the cavity can be significantly reduced. Moreover, any irrelevant photons not originating from the cavity mode can hardly be captured by the microfiber.

In conclusion, we have demonstrated a simple and effective optical fiber interface for ultrasmall photonic crystal resonator. The highly efficient and well localized coupling enabled to achieve an output collection efficiency of $\sim$70% and the laser threshold of 35 μW. This scheme can be widely exploited to develop practical photonic crystal devices as well as explore more physics in photonic crystal resonators.

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