13D2-1 (Invited)

Photon Funneling from Photonic Crystal Nanolasers

Yong-Hee Lee, In-Kag Hwang, and Se-Heon Kim

Department of Physics, KAIST
373-1 Kusung-dong, Yusung-gu, Taejon, Korea 305-701
E-mail; yhlee@kaist.ac.kr

ABSTRACT

Efficient photon out-coupling from photonic crystal nanolasers are to be discussed. Specifically the vertical beaming scheme and the all-fiber coupling scheme are discussed in detail.

The ability to localize photons into photonic bandgap semiconductor microcavities [1, 2] having wavelength-scale volumes and high quality factors is expected to enable us to study the cavity quantum electrodynamics [3] in semiconductor material systems. Several ultra-small, photonic crystal lasers have been recently reported [4-6]. Once we identify the high-Q small-V resonator, the next issue to collect these valuable photons generated from this nano-cavity efficiently. In general, the far-field radiation pattern coming from the wavelength-scale resonator is diverging over a wide solid angle and the output beam is hard to be collected by using conventional optics. Here we are discussing two possibilities: vertical beaming and all-fiber coupling schemes.

For the efficient vertical beaming, the hexapole single-cell photonic crystal resonator was chosen and studied. The hexapole mode has a central node and suitable electrical pumping. The nondegeneracy of the mode is also advantageous to satisfy the condition of the single-modeness. The distribution of the electric field in the hexapole mode is delicately balanced. And this balance can be perturbed by simple structural modification. In fact, we break the symmetry along the horizontal axis by moving two nearest air holes slightly outward as indicated in Fig. 1(a). As one can witness in Fig. 1(b), the far field pattern does converge along the vertical direction. In essence, this can be thought of the loss engineering. Remember that the original hexapole mode has a Q factor in excess of 100,000. In other words, in the beginning the original hexapole mode is almost lossless. In fact, by adjusting the two nearest air holes, we are controlling the loss channel of output photons and the total Q of the cavity becomes smaller. When the vertical beaming condition is optimized, the Q factor is degraded down to ~10,000, still large enough to provide a large Purcell factor. It is interesting to find that, through this structural perturbation, the DC component of E_x-field is newly created and escape into the free space. Therefore, the far field radiation mostly x-polarized becomes available. It is confirmed that over 70% of the photons generated in the resonator is contained within the angular span less than 30 degrees from the vertical direction under the optimum condition. In other words, photons can be easily collected by using a commercial microscope objective lens. Moreover, the collection efficiency can be increased up to 84% with the help of bottom distributed feedback reflector

In addition to the vertical beaming, we proposed and demonstrated the all-fiber coupling scheme. To this end, photonic crystal small-linear-resonator that has a high-Q value and small mode volume was investigated. The waveguide-type linear photonic crystal resonator was modified to introduce the better overlap of the resonant mode with the micro-fiber, in both k-space and real space. To achieve efficient coupling, the optical fiber was tapered to its extreme. The final diameter of the micro-fiber is ~ 1 micron where only one propagating mode is allowed. For longitudinal phase matching, a few small air holes are inserted inside the linear waveguide-type resonator. This simple modification brings two main advantages over the conventional linear photonic crystal resonator. The first merit is that the wave vector of the modified cavity could now have a reasonable overlap with those of the silica waveguide. In other words, two modes share a certain region of overlap in k-space to ensure efficient optical coupling. The second point is that of better spatial overlap along y-direction. Even after the modification, the linear resonators still have Q-factors in excess of 10,000. The modal volume of the cavity is somewhat larger than that of the single-cell cavity. The Purcell factor can be easily made larger than 1,000.

In this configuration, pump light from a laser diode is to be injected through the tapered microfiber into the cavity by very local evanescent coupling. Once the resonant mode of interest is excited, photons will be collected into the curved microfiber, in both forward and backward directions. The photons coming out of the two ends into a single fiber can be collected straightforwardly by using a commercial fiber coupler. In this scheme where photons are coupled directly into the fiber without the help of conventional bulk optics, the photon coupling efficiency in excess of 70% is realized [7]. Since the photon generator unit contains only a miniature photonic crystal resonator integrated with a micro-fiber, the final unit can be very simple and mechanically robust. When optically pumped using a 980-nm InGaAs diode lasers, this all-fiber coupled modified photonic crystal resonator functions as a laser with small threshold pump power of 25 μW and generates continuous wave output optical power larger than 10 nW.

In summary, we demonstrated two efficient ways to collect photons from the wavelength-scale photonic crystal resonators and lasers.

REFERENCES

1. E. Yablonovitch, Phys. Rev. Lett. 58, 2059 (1987).
2. O. Painter et al., Science 284, 1819 (1999).
3. K. J. Vahala, Nature 424, 839 (2003).
4. H. G. Park et al., Appl. Phys. Lett. 79, 3032 (2001).
5. H. Y. Ryu et al., Appl. Phys. Lett. 80, 3883 (2002).
6. H. G. Park et. al., Science 305, 1444 (2004).
7. I. K. Hwang et al., Apply. Phys. Lett. 87, 131107 (2005).

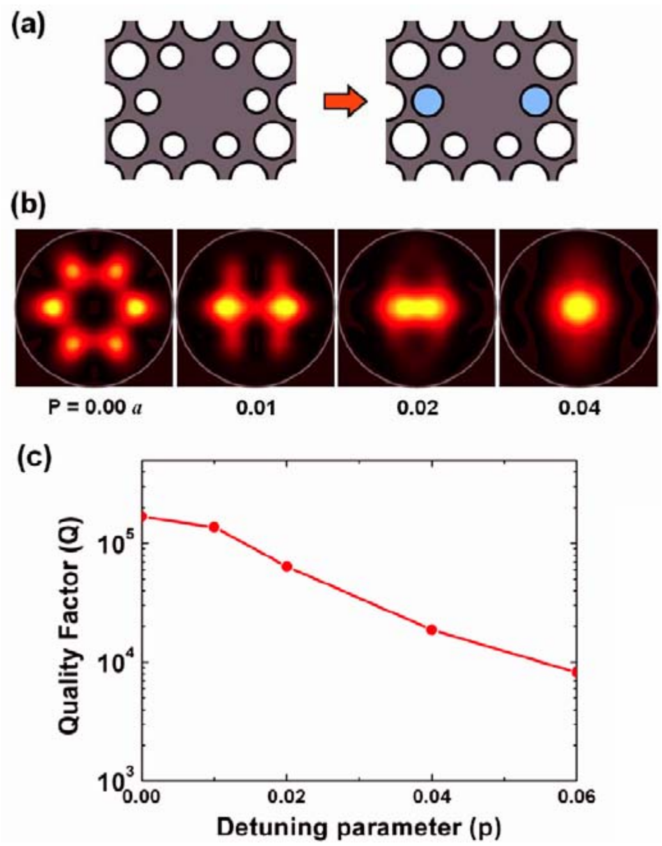

Fig. 1 Vertical beaming. (a) Modification of nearest air holes. (b) Far field pattern with various air hole size. (c) Q factor as a function of detuning parameter.