Efficient Single Photon Collection using a μ-Fiber-Coupled Microcavity

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Abstract

Efficient single photon collection is demonstrated based on a μ-fiber-coupled photonic crystal cavity. 249 kHz of single photons are detected, and estimated single photon count rate(overall collection efficiency) is 20 MHz(25 %).

I. Introduction

Efficient and fast on-demand single photon source(SPS) is essential for realizing various quantum information processes. Single semiconductor quantum dot(QD) is a qualified quantum emitter for SPS due to its brightness and stability[1]. However, since it is embedded in a high refractive index semiconductor material, it is hard to extract the generated single photons from a QD out of the material. There has been much effort to couple single photons to engineered cavity modes to elevate the out-coupling efficiency and make fast SPSs aided by Purcell effect[2,3]. In this work, a highly curved μ-fiber is used as an efficient photon funneling channel from a photonic crystal cavity, and we obtain a high collection efficiency from the QD embedded in the cavity to μ-fiber. Besides, coupling efficiency and second order autocorrelation are investigated at different detuning between the QD emission and the cavity mode.

II. μ-Fiber-Coupled Photonic Crystal Cavity

A curved μ-fiber is in contact on top of the photonic crystal L3 cavity as shown in Fig. 1(a). InAs/GaAs QDs are embedded in the slab. The contact between the μ-fiber and PhC slab is robust supported by electrostatic force. The total collection efficiency ξ is defined as $\xi = \beta\eta$, where β is spontaneous emission factor and η is fiber coupling efficiency of the cavity mode.

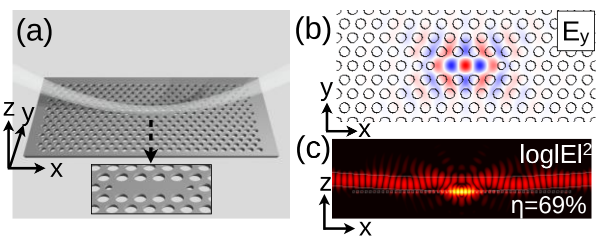

Fig. 1 (a) A schematic of curved μ-fiber coupled photonic crystal L3 cavity. Inset is a magnified image of the L3 cavity region. (b) In-plane(E_y) electric field component of the fundamental mode of the L3 cavity. (c) Electric field intensity profile at XZ plane.

In this structure, fiber coupling efficiency η and cavity characteristics are investigated by finite-difference time-domain(FDTD) numerical simulations. The electric field profile is similar to that of a typical L3 cavity(Fig. 1(b)). The quality factor of the fundamental mode is ~ 4000 regardless of the perturbation of the μ-fiber. In Fig. 1(c), electric field intensity of the cavity mode is shown. The fiber coupling efficiency η is obtained by the ratio between the fiber-coupled Poynting flux and the total generated Poynting flux. 69 % of the cavity mode energy is coupled to the μ-fiber by evanescent coupling. Rest of the generated energy is mainly leaked to air.

Our QD wafer is grown by molecular beam epitaxy(MBE). InAs QDs are embedded in the GaAs slab grown on top of $Al_{0.8}Ga_{0.2}As$ sacrificial layer. PhC cavities are fabricated by e-beam lithography followed by Cl_2-assisted argon ion beam etching and selective wet etching with hydrogen fluoride solution. A conventional optical single-mode fiber is tapered using flame-brushing techniques[4] down to a diameter of 0.8 μm, and bent such that the radius of curvature is ~ 100 μm.

III. Efficient Single Photon Collection through the Curved μ-Fiber

Optical measurements are performed at cryogenic temperature(7K-30K). A 780-nm femtosecond laser is pumped at a repetition rate of 80 MHz through the curved μ-fiber. Photons are generated from the QD embedded in the cavity, and collected by the same curved μ-fiber. The photons are spectrally filtered by a monochromator, and detected by a CCD to measure spectra or by single photon detectors to measure single photon counts and coincidences. All the measurements are carried out in the fiber, except spectral filtering. We calibrated the total detection efficiency of the measurement setup including detector's efficiency, which is 2.5 %.

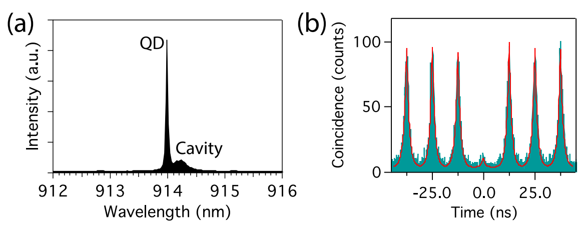

Fig. 2 (a) PL spectrum of QD emission and the cavity mode. (b) Second-order autocorrelation measurement of the QD emission. Peaks are fitted with exponential decaying functions(red line).

A typical photoluminescence(PL) spectrum is shown in Fig. 2(a). A QD spectrally close to a cavity mode is chosen. The QD emission is spectrally filtered with 0.1-nm window to measure second order autocorrelation and single photon count rate. From the coincidence measurement(Fig. 2(b)), strong antibunching behavior is confirmed.

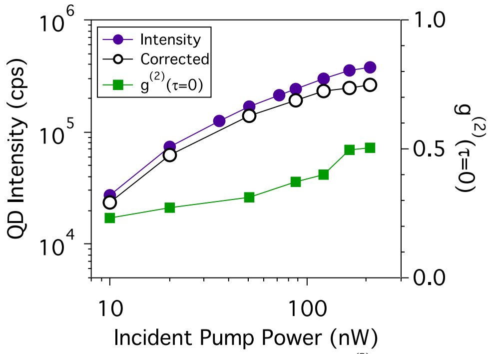

Fig. 3 Single photon count rate(purple dots) and $g^{(2)}(0)$(green squares) as a function of incident pump power.

We measure the collected single photon count rate and $g^{(2)}(0)$ as a function of the incident pump power(Fig. 3). $g^{(2)}(0)$ increases with the pump power because the excited state of the QD is saturated, while the contributions of the cavity mode from the other states increase and deteriorate the sub-Poissonian statistics of the photons[3]. In order to compensate for the multiphoton effect, the photon count rate is corrected by a factor of $\sqrt{1 - g^{(2)}(0)}$ [2]. Corrected single photon count rate at $g^{(2)}(0)$ = 0.5 is 249 kHz. Assuming that the same amount of single photons are fired into the other arm of the μ-fiber, and taking the total detection efficiency into account, the estimated single photon count rate at the μ-fiber is 20 MHz and the corresponding fiber collection efficiency is 25 %. Because QDs are positioned randomly, the QD is not located at the anti-node of the cavity mode. Thus, if we locate the QD spatially matched with the cavity mode[5], higher fiber collection efficiency approaching 69 % is expected.

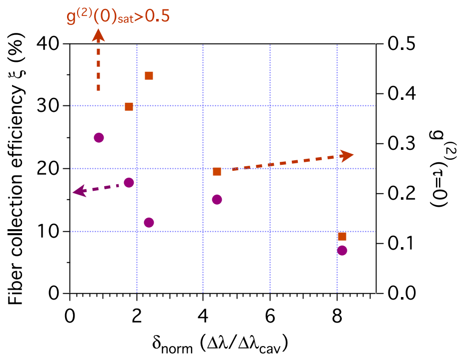

Fig. 4 Fiber collection efficiency(purple) and $g^{(2)}(0)$(brown) as a function of δ_{norm}.

Using wet digital etching[6] and gas deposition technique[7], fiber collection efficiency ξ and the $g^{(2)}(0)$ at high pump power are measured at different detuning (δ_{norm} = $\Delta\lambda/\Delta\lambda_{cav}$, $\Delta\lambda$ = λ_{cav}-λ_{QD}). The fiber collection efficiency decreases as the cavity mode spectrally moves away, due to degradation of the spontaneous emission factor β. Still, it remains over 5 % at the δ_{norm} = 8.15. As the detuning increases, $g^{(2)}(0)$ at high pump power decreases because the cavity-enhanced light originated from other background signal is spectrally filtered out.

IV. Conclusions

In summary, an efficient single photon collection from a single QD is demonstrated with a curved μ-fiber coupled photonic crystal cavity. Single photons at a repetition rate of 249 kHz are detected, and the total single photon count rate(total collection efficiency) is estimated as 20 MHz(25 %). When the cavity mode is detuned spectrally far(8 times of the cavity linewidth), the collection efficiency remains over 5 %.

We highlight that single photons are extracted directly into an optical fiber. Therefore, they are ready for further processing such as quantum cryptography and quantum teleportation. This μ-fiber coupled photonic crystal cavity could be a competitive platform for the on-demand single photon source.

Acknowledgment

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