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# Direct fiber-coupled single photon source based on a photonic crystal waveguide

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A single photon source plays a key role in quantum applications such as quantum computers and quantum communications. Epitaxially grown quantum dots are one of the promising platforms to implement a good single photon source. However, it is challenging to realize an efficient single photon source based on semiconductor materials due to their high refractive index. Here we demonstrate a direct fiber coupled single photon source with high collection efficiency by employing a photonic crystal (PhC) waveguide and a tapered micro-fiber. To confirm the single photon nature, the second-order correlation function $g^{(2)}(\tau)$ is measured with a Hanbury Brown-Twiss setup. The measured $g^{(2)}(0)$ value is 0.15, and we can estimate 24% direct collection efficiency from a quantum dot to the fiber. © 2015 AIP Publishing LLC.
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The field of quantum information processing has been growing rapidly over the last two decades. Unique properties of quantum states allow us to develop new applications such as quantum computers and quantum communications.[1–3] Several experiments have shown possibilities of implementation of quantum applications based on a single atom[4,5] or a single ion.[6–8] However, the scalability has been a big practical issue in these schemes. Semiconductor technologies using quantum dots (QDs) have been spotlighted as one of alternative ways to resolve it.[9] Thanks to the modern epitaxial growth and nano-fabrication capabilities, quantum experiments in small scale become possible.[10,11] However, the high refractive index of semiconductor materials hinders efficient extraction of photons, which degrades the quality of quantum states. Thus, it is essential to collect photons from a semiconductor-based emitter with high efficiency.

Single photons from a quantum dot have shown clear quantum features.[9,12,13] Recently, various types of single photon sources have been demonstrated with photonic crystals, micropillars, nanotrumpets, and photonic nanowires,[13–19] and many groups are in efforts to realize single photon sources with high quantum efficiency, high photon extraction efficiency, high single photon purity, and fast repetition rate.[13–15,18–22] However, it is very challenging to satisfy all of these properties simultaneously. Micropillars and photonic nanowires show better collection with high numerical aperture objective lenses due to their vertical structure. However, planar type sources like photonic crystals are also important to chip scale integration applications. In this study, we demonstrate a single photon source with high extraction efficiency based on a PhC waveguide by coupling to a tapered micro-fiber. Though photons cannot escape easily from a high refractive material because of the total internal reflection, the perfect phase matching can improve the extraction efficiency dramatically. Direct collection of single photons with a tapered micro-fiber enables us to transfer them directly to a distance without going out of the fiber.

A photonic crystal (PhC) waveguide is a PhC pattern with one line of filled air holes as shown in Fig. 1(a).[23] Dispersion characteristics of a PhC guided mode are summarized in Fig. 1(b).[24,25] There are two guided modes whose $E_y$ fields show different symmetries. The *even* guided mode has an electric field maximum at the center of waveguide, which encourages photons from quantum dots to couple into the waveguide mode efficiently. However, these guided modes are not allowed to couple with the free space by definition. In this study, we employ a tapered micro-fiber that has a diameter comparable to the waveguide width in order to funnel photons from a PhC waveguide. In the dispersion curve (Fig. 1(b)), one can find a cross point of phase matching between two k-vectors of the *even* PhC guided mode and the fiber guided mode. Once the phase matching condition is satisfied, photons in waveguide can couple seamlessly to the micro-fiber.[26]

In the experimental setup shown in Fig. 2(a), a 780-nm femto-second laser is fed through one end of the fiber to generate excitons in quantum dots. The signal from quantum dots is collected at the other end of the same fiber. It is delivered to a spectrometer through lens and mirrors. A Si array detector is used to record QD spectra, and two avalanche photodiodes (APDs) and a time amplitude converter are used for the second correlation measurement. To move the fiber close to the intended position, low magnification imaging was used first. Then, the lens was changed to a $50\times$ magnification objective lens. The contact point of curved tapered micro-fiber is shown in Fig. 2, and the position of the fiber

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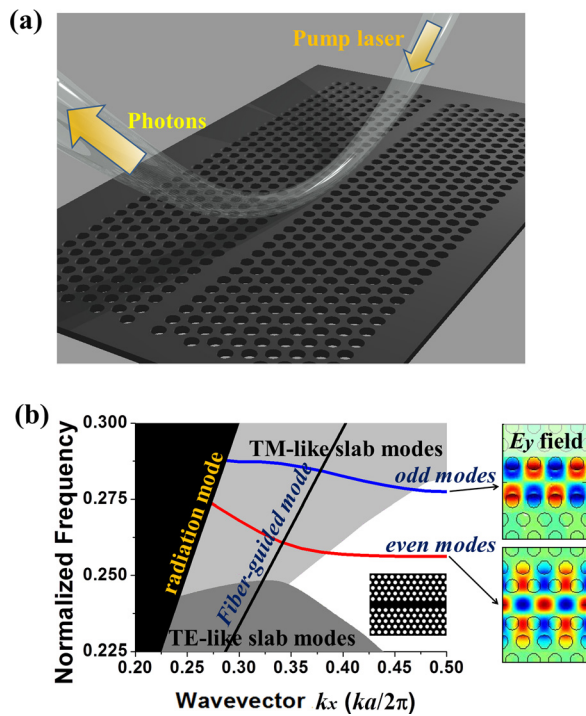
**(a)**



**(b)**



FIG. 1. Photonic crystal waveguide. (a) Schematic diagram of integrated system of photonic crystal waveguide and a tapered-fiber. (b) Dispersion of photonic crystal waveguide. Blue line shows *odd* modes, and red line shows *even* modes in photonic crystal waveguide. Field distributions of *even* and *odd* modes are at k = 0.5.

was controlled by piezoelectric motor stages. A photonic crystal waveguide was fabricated with 170-nm-thick GaAs slab containing a few InAs quantum dots per square micron, emitting near 950 nm in wavelength (Fig. 2(b)).

The tapered micro-fiber was fabricated using heat-and-pull techniques with a conventional single mode optical fiber having 125-$\mu$m cladding.[27,28] Fiber tapering was performed by heating an optical fiber with a small oscillating flame and simultaneously pulling the fiber in opposite directions by motorized translational stages. 1550-nm probe light was inserted and monitored during the pulling process to check the single mode condition of the air-cladding mode, which shows up when the diameter is ~1.0 $\mu$m. The probe light transmission through the tapered region was over 80%. The tapered micro-fiber was then curved to a loop whose radius of curvature is 100–150 $\mu$m. The curved tapered micro-fiber was fixed to a small aluminum unit by epoxy.

Theoretically, the guided mode of an infinite waveguide should be continuous. However, the finite PhC waveguide causes the mode to be discrete as shown in Fig. 2(c). Measured data are compared with those of 3D finite-difference time-domain (FDTD) computations in Fig. 3(a) where the vertical scale is expressed in photon energy. The length of measured waveguide is 41$a$ (~10 $\mu$m), where $a$ is the lattice constant of the PhC waveguide. The dispersion curve is divided by 42 (41$a$-long waveguide acts as effectively 42$a$-long waveguide[29]). The measured peaks in the spectrum agree well with the predicted points on the dispersion curve. This spectrum was taken with sufficiently strong pump power to expose all the discrete and weak PhC guided modes. Under weak pump conditions, those peaks near the k-vector matching point are relatively
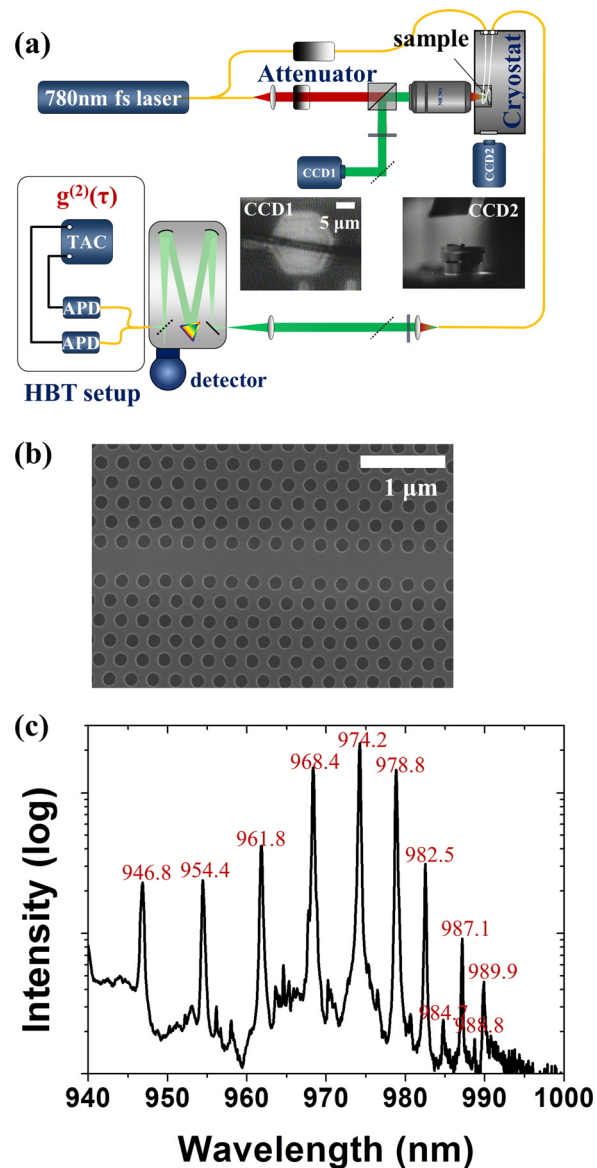
**(a)**



**(b)**



**(c)**



FIG. 2. Measurement. (a) An experimental measurement setup. CCD1 is monitoring the fiber and PhC waveguide on top and CCD2 is monitoring them by side. (b) SEM image of fabricated sample of PhC waveguide containing a few QDs. (c) Measurement of photonic crystal waveguide modes through the tapered micro-fiber.

brighter than other peaks. Electric field intensity distributions of FDTD calculations show very different behaviors at two coupling points designated as b and c in Fig. 3(a). When the phase matching condition is satisfied (point b), light in the PhC waveguide funnels smoothly into the fiber (Fig. 3(b)). In comparison at point c, photons in the PhC waveguide are unable to escape (Fig. 3(c)). This observation agrees well with that of the measurement as shown in Fig. 3(a).

A spectrum with pump power of 45 nW is shown in Fig. 4(a). Among several peaks the 978-nm peak is the strongest. The strength of this peak was measured as a function of the pump power as shown in Fig. 4(b). It shows linear dependence in the weak pump regime and becomes saturated in the strong pump regime. The inset of Fig. 4(b) is a reproduction in linear scale in both axes. This saturation behavior is typical of a single QD emitter. We measured the second-order correlation to confirm the single photon
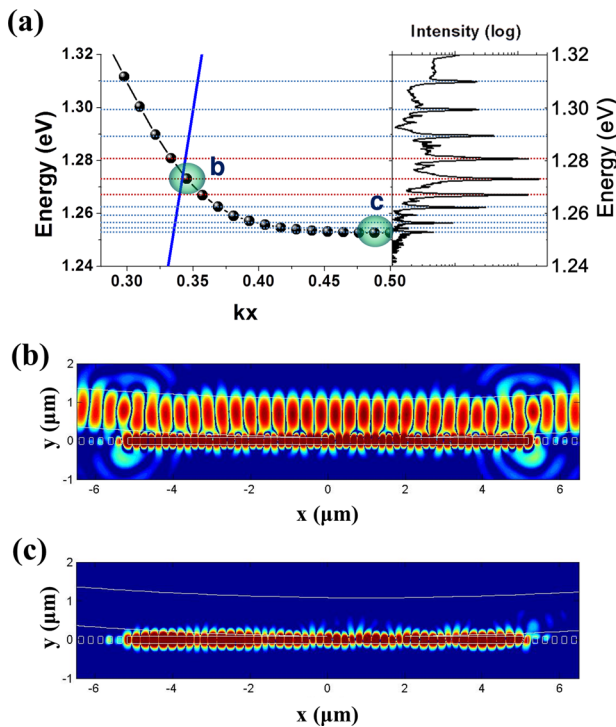
**(a)**



**(b)**



**(c)**



FIG. 3. Coupling efficiency to the tapered micro-fiber. (a) Comparison of dispersion and measurement of PhC waveguide. (b) Electric field intensity (log scale) in XZ plane of the mode near tapered-fiber guided line (point b). (c) Electric field intensity (log scale) in XZ plane of the mode near the edge (point c).

characteristics with a Hanbury Brown-Twiss setup. Measured results are shown in Figs. 4(c) and 4(d) after 2-h integration. $g^{(2)}(0) = 0.15$ and $g^{(2)}(0) = 0.30$ were obtained with pump powers of 26 nW and 700 nW, respectively. In this measurement, two photon emissions and correlation with dark counts of the detectors were also included in addition to the single photons. We would like to emphasize

that the generated single photons remain in the fiber all the time.

To estimate the collection efficiency, we measured transmissions of all optics in the setup (Fig. 2(a)). The total transmission was 3.1% including those from the tapered micro-fiber section (0.69), the transmission of lenses and spectrometer (0.42), the splitting ratio of fiber splitter (47:53), and the detection efficiency of APD at 978 nm (0.20). Based on the count rate in APD and the corrected photon count rate by the factor of $[1 - g^{(2)}(0)]^{1/2}$,[22] we estimate that $1.9 \times 10^7$ photons/s was coupled to the fiber at the saturated pump power. The repetition rate of the pump laser was $8.0 \times 10^7$/s. Therefore, the collection efficiency to the fiber is estimated to be 24%, which includes internal quantum efficiency, spontaneous emission factor $\beta$, and output coupling efficiency $\eta$. The internal quantum efficiency is typically over 0.90,[22] and the spontaneous emission factor of a similar structure is around 0.80.[30,31] Thus, we can roughly estimate the coupling efficiency $\eta$ between PhC waveguide and the tapered micro-fiber is around 33%. This value of coupling efficiency compares well with the other group's results.[15–17,32,33] Theoretically, the coupling efficiency can be over 90% depending on the slab thickness.[25] The thinner slab allows the better coupling, but the thin slab causes fabrication difficulty. The discrepancy between the calculation and the measurement estimation is due to the fabrication imperfection of PhC and the tapered micro-fiber.

In conclusion, we demonstrated an efficient single photon source combined with a tapered micro-fiber and confirmed it by measuring the second order correlation of the signal. The collection efficiency of photons was estimated to 24%. The proposed scheme here can be applied to quantum communication applications since single photons exist inside of the fiber from the birth. In addition, photons can be delivered to anywhere with very small losses, which is advantageous in various quantum applications using light quanta.

**(a)**
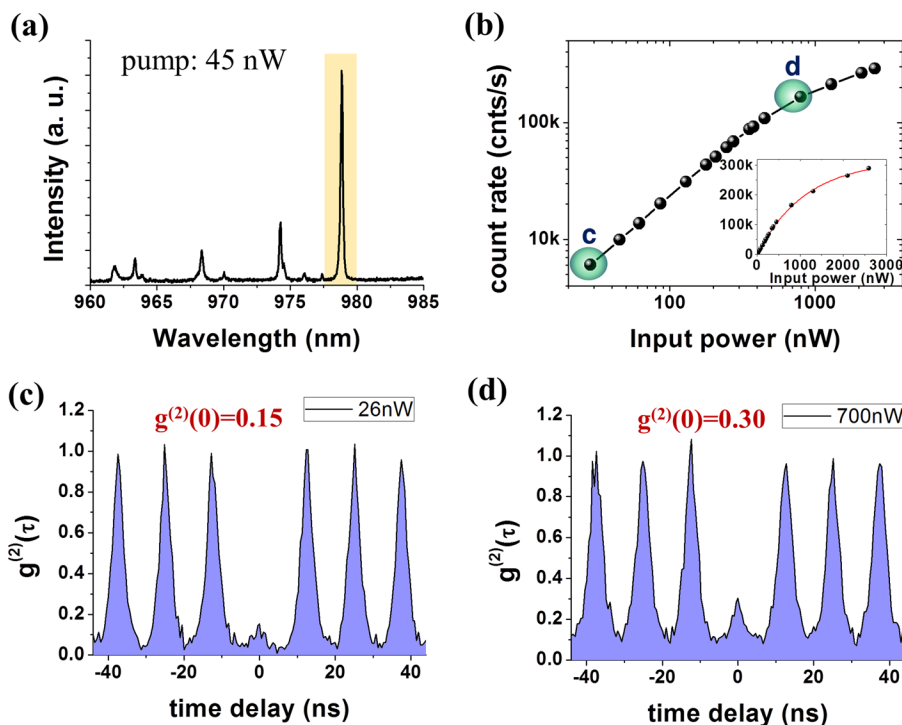


**(b)**



**(c)**



**(d)**



FIG. 4. Spectrum and $g^{(2)}(\tau)$ correlation. (a) Measured spectra with 45 nW of pump power. (b) Pump power dependence (log-log scale) of the peak 978.8 nm. Inset shows linear-linear power dependence. (c) and (d) Measured $g^{(2)}(\tau)$ correlation at 26 nW and 700 nW pump power.

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