Quantum Photonics on a Tapered Optical Fiber

Kali Prasanna Nayak
Department of Engineering Science
University of Electro-Communications
Tokyo, Japan
kalipnayak@uec.ac.jp (ORCID: 0000-0001-6220-3258)

***Abstract*— A tapered optical fiber with subwavelength diameter waist, an optical nanofiber, provides a unique and all-fiber platform for manipulating atoms and photons. This paper presents some recent results towards quantum photonics on a nanofiber platform. In one direction, we demonstrate a quantum interface between trapped single atoms and fiber-guided photons using a nanofiber cavity. In the other direction, we demonstrate a polarized fiber-in-line quantum light source using a hybrid system of a single gold nanorod and single quantum dot deposited on a nanofiber.**

Keywords*— *Quantum Optics, Nanophotonics, Quantum Information Science, Quantum Photonics, Single Atom Quantum Interface, Single Photon Generation

I. Introduction

The emerging field of quantum photonics deals with coherent control of individual quanta of light, *photons*. It is a crucial route towards future quantum networks, the so-called *quantum internet* [1]. A key challenge is that photons do not interact with each other. However, one can control photons using a atomic medium. Therefore, it is essential to realize a platform where light-matter interaction can be engineered at single quanta level. This requires to isolate and confine atoms and photons to realize an efficient *quantum interface*. A quantum interface should be capable of efficient generation of single photons and coherent quantum-state exchange between photonic and atomic qubits.

Cavity quantum electrodynamics (QED) approach for realizing a single atom quantum interface has been extensively studied and developed for several decades using free-space Fabry- Perot cavities [2, 3]. On the other hand, strong confinement of photonic mode in nanophotonic waveguides and resonators have recently attracted diverse attention to be implemented as a quantum interface [3, 4, 5].

In this context, a tapered optical fiber with subwavelength diameter waist, an optical nanofiber, provides a unique and all-fiber platform for manipulating atoms and photons [6 - 9]. The key point of the technique is that the fiber-guided light can have strong transverse confinement while interacting with the surrounding medium in the evanescent region. The nanofiber cavity also provides unique possibilities for cavity QED with moderate longitudinal confinement [9, 10]. Furthermore, the fiber in-line capability of nanofiber enables easy integration to fiber network for potential applications in quantum information. This paper presents some recent results towards quantum photonics on a nanofiber platform. In one direction, we demonstrate a quantum interface between trapped single atoms and fiber-guided photons using a nanofiber cavity. In the other direction, we demonstrate a polarized fiber-in-line quantum light source using a hybrid system of a single gold nanorod and single quantum dot deposited on a nanofiber.

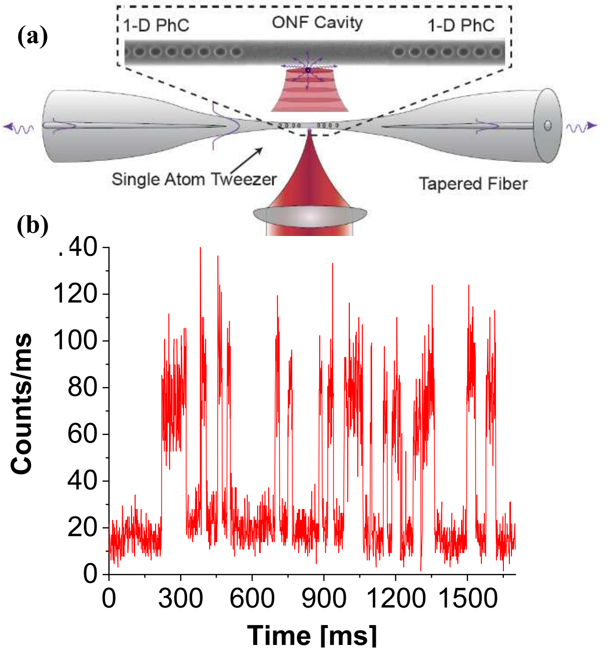

Fig. 1: A single atom quantum interface on a nanofiber [11]. (a) Schematic diagram of the experiment. (b) Real-time observation of fluorescence photon counts from single atoms trapped and interfaced to the nanofiber cavity. Photon counts are observed through the fiber guided modes.

II. A Single Atom Quantum Interface

We demonstrate an optical tweezer based side-illumination trapping scheme to trap and interface individual single atoms to a nanofiber cavity [11]. A schematic diagram of the experiment is shown in Fig. 1(a). The nanofiber is located at the waist of a tapered optical fiber. The cavity is formed by fabricating two 1-D photonic crystal (PhC) structures on the nanofiber using femtosecond laser ablation [12, 13, 14]. Single atoms are trapped on the nanofiber segment between the two PhCs. The dipole trap beam is tightly focused on the nanofiber and forms an optical tweezer for single atoms. When the tweezer beam hits the nanofiber, it forms standing-wave like nanotraps close to nanofiber due to the interference of the incident and the reflected lights from the fiber surface. The nanofiber diameter and trapping laser wavelength is designed to create the first nanotrap within 200 nm from the nanofiber surface enabling efficient coupling to nanofiber guided modes. The fluorescence of trapped single atom coupled to the nanofiber cavity mode are detected at either ends of the fiber using single photon counting modules.

We show that the fluorescence of single atoms trapped on the nanofiber cavity can be readily observed in real-time through the fiber guided modes. The typical photon count measured through the nanofiber guided mode is shown in Fig. 1(b). It can be seen that discrete step-like fluorescence signal are observed. The typical step height is 60 counts/ms with a temporal duration of 10 to 100 ms. The signal resembles the single atom fluorescence signal measured in a conventional tightly focused dipole trap operating in collisional blockade regime [15]. This is a clear signature of single atoms trapped and interfaced to the nanofiber cavity. The atom number and trap dynamics are further clarified from the photon correlation measurements of the nanofiber trap signal. The antibunching observed in the photon correlations confirms that indeed single atoms are trapped [11]. The efficient channeling of the trapped single atom fluorescence into nanofiber guided modes enables the real-time observation of the step-like fluorescence signal. The trap lifetime was measured to be 52±5 ms [11]. From the photon statistics, the effective coupling rate of the atom-cavity interface is estimated to be 34±2 MHz. This yields a cooperativity of 5.4± 0.6 (Purcell factor: 6.4±0.6) and a cavity enhanced channeling efficiency as high as 85±2% for a cavity mode with a finesse of 140 [11]. These results may open new possibilities for quantum photonics applications on an all-fiber platform.

III. Polarized Fiber-Coupled Single Photons

We demonstrate a hybrid quantum system by combining a single quantum dot (QD) and a single gold nanorod (GNR) coupled to a nanofiber [16]. We show that emission properties of single QDs can be strongly enhanced in presence of GNR leading to a bright and strongly polarized single photon emission into nanofiber guided modes.

Figure 2(a) shows the schematic diagram of the experiment. The experimental setup is based on a hybrid system of a single QD and a GNR deposited on a nanofiber. Nanofibers used for the experiment had a waist diameter of 310±10 nm and transmission of >99%. The QDs used for the experiment were thick-shell CdSe/ZnS QDs dispersed in toluene colloidal solution [17]. At room temperature, the QDs emit at a wavelength of 640 nm. The GNRs (E12-25-650, Nanopartz) used for the experiment were also dispersed in a toluene colloidal solution. The localized surface plasmon resonance (LSPR) of the GNRs matches and covers the emission band of the QDs. The GNRs and QDs were deposited together on the nanofiber using a computer-controlled sub-pico-liter needle-dispenser system installed on an inverted microscope [18]. The single QDs were excited using a CW or a pulsed laser at a wavelength of 532 nm. The photo-luminescence (PL) emission characteristics of both coupled (GNR+QD) and uncoupled (only QD) single QDs were investigated via the guided mode of the nanofiber and eventually through a single mode optical fiber (SMF). The scattered excitation laser light was filtered using a 560 nm long-pass color glass filter (CF; (O56, HOYA)).

A typical scanning electron microscope (SEM) image of single GNR-QD deposited on nanofiber is shown in Fig. 2(b). The estimated size distribution of the GNR is 71±4 nm in length and 31±2 nm in diameter. Figure 2(c) shows the typical PL decay curves and the histogram of estimated PFs is shown as inset. One can see that the decay time for the coupled QD (τ_c=1.2 ns) is drastically shortened compared to uncoupled QDs (τ_{uc}=65 ns) indicating strong Purcell enhancement. From different trials, we infer that for majority of trials the Purcell factor (PF = τ_{uc}/τ_c) lies between 20-140 [16]. Figure 2(d) shows the estimated degree of polarization (DOP) and typical polar plots for the polarization resolved

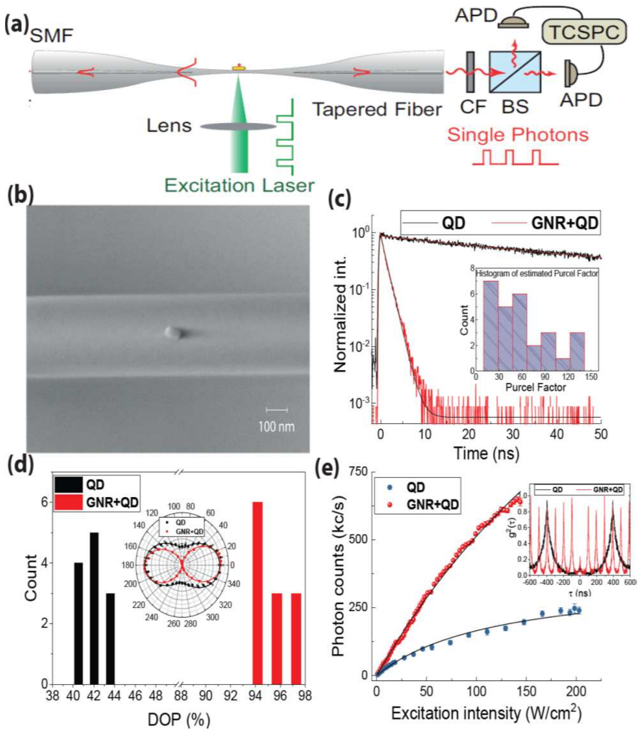

Fig.2: Plasmon-enhanced polarized single photon generation on a nanofiber [16]. (a) Schematic of the experimental setup. (b) A typical scanning electron microscope (SEM) image of single GNR-QD deposited on nanofiber. (c) Photoluminescence (PL) decay curve and Purcell factor, (d) degree of polarization (DOP) and (e) photon count rate and single photon purity ($g^2(\tau)$) for coupled (GNR+QD) and uncoupled (QD) QDs measured through nanofiber guided modes.

normalized photon counts are shown as inset. The DOP is estimated from the maximum (N_{max}) and minimum (N_{min}) photon counts, as DOP = $(N_{max} - N_{min})/(N_{max} + N_{min})$. From different trials, we infer that the DOPs for uncoupled QDs are in the range of 40-44%, whereas that for the coupled QDs are in the range of 94-97% [16]. This clearly indicates that the DOPs of single QDs can be strongly enhanced due to coupling to localized plasmon field of GNR.

Figure 2(e) shows the intensity dependence of photon count rate. From the saturated photon count rates, we estimate the brightness (fiber-coupled photon count rate) for the coupled and uncoupled QDs to be 12.2 ±0.6MHz and 1.8 ±0.8 MHz, respectively [16]. Typical normalized photon correlations $g^2(\tau)$ for coupled and uncoupled QDs measured by pulsed excitation at a repetition rate of 10 MHz and 2.5 MHz, respectively, are shown as inset in Fig. 2(e). The single photon purity for the coupled and uncoupled QDs are estimated to be $g^2(0)$=0.20±0.04 and 0.07±0.02, respectively [16]. It should be noted that the reduced decay time for coupled QD enables excitation with a high rate.

The hybrid quantum system (QD+GNR+ONF) takes the advantages of both state-of-the-art field confinement in GNR for engineering the emission properties of the QD and coupling the single photons into ONF guided modes enables low-loss propagation of single photons for long-distance communication. The device can be easily integrated into the fiber networks. The polarized and fiber-coupled single photons can be implemented for potential applications in quantum photonics and quantum networks.

ACKNOWLEDGMENT

KPN acknowledges support from a grant-in-aid for scientific research (Grant No. 21H01011) from the Japan Society for the Promotion of Science (JSPS).

REFERENCES

[1] H. J. Kimble, "The quantum internet," Nature **453,** 1023 (2008).

[2] H. J. Kimble, "Strong interactions of single atoms and photons in cavity QED," Phys. Scr. **1998(T76),** 127 (1998).

[3] A. Reiserer and G. Rempe, "Cavity-based quantum networks with single atoms and optical photons," Rev. Mod. Phys. **87,** 1379 (2015).

[4] K. Vahala, "Optical microcavities," Nature **424,** 839 (2003).

[5] A. V. Akimov, A. Mukherjee, C. L. Yu, D. E. Chang, A. S. Zibrov, P. R. Hemmer, H. Park and M. D. Lukin, "Generation of single optical plasmons in metallic nanowires coupled to quantum dots," Nature **450,** 402 (2007).

[6] F. L. Kien, V. I. Balykin and K. Hakuta, "Spontaneous emission of a cesium atom near a nanofiber," Phys. Rev. A **72,** 032509 (2005).

[7] K. P. Nayak, P. N. Melentiev, M. Morinaga, F. L. Kien, V. I. Balykin and K. Hakuta, "Optical nanofiber as an efficient tool for manipulating and probing atomic Fluorescence," Opt. Express **15,** 5431 (2007).

[8] G. Sagué, E. Vetsch, W. Alt, D. Meschede and A. Rauschenbeutel, "Cold-Atom Physics Using Ultrathin Optical Fibers: Light-Induced Dipole Forces and Surface Interactions," Phys. Rev. Lett. **99,** 163602 (2007).

[9] K. P. Nayak, M. Sadgrove, R. Yalla, F. L. Kien and K. Hakuta, "Nanofiber quantum photonics," J. Opt. **20,** 073001 (2018).

[10] F. L. Kien and K. Hakuta, "Cavity-enhanced channeling of emission from an atom into a nanofiber," Phys. Rev. A **80,** 053826 (2009).

[11] K. P. Nayak, J. Wang, and J. Keloth, "Real-Time Observation of Single Atoms Trapped and Interfaced to a Nanofiber Cavity," Phys. Rev. Lett. **123,** 213602 (2019).

[12] K. P. Nayak and K. Hakuta, "Photonic crystal formation on optical nanofibers using femtosecond laser ablation technique," Opt. Express **21,** 2480 (2013).

[13] K. P. Nayak, P. Zhang, and K. Hakuta, "Optical nanofiber-based photonic crystal cavity," Opt. Lett. **39,** 232 (2014).

[14] J. Keloth, K. P. Nayak, and K. Hakuta, "Fabrication of a centimeter-long cavity on a nanofiber for cavity quantum electrodynamics," Opt. Lett. **42,** 1003 (2017).

[15] N. Schlosser, G. Reymond, and P. Grangier, "Collisional Blockade in Microscopic Optical Dipole Traps," Phys. Rev. Lett. **89,** 023005 (2002).

[16] K. M. Shafi, R. Yalla, and K. P. Nayak, "Bright and Polarized Fiber In-Line Single-Photon Source Based on Plasmon-Enhanced Emission into Nanofiber Guided Modes," Phys. Rev. Applied **19,** 034008 (2023).

[17] K. M. Shafi, W. Luo, R. Yalla, K. Iida, E. Tsutsumi A. Miyanaga and K. Hakuta, "Hybrid system of an optical nanofibre and a single quantum dot operated at cryogenic temperatures," Sci. Rep. **8,** 13494 (2018).

[18] R. Yalla, K. P. Nayak, and K. Hakuta, "Fluorescence photon measurements from single quantum dots on an optical nanofiber," Opt. Express **20,** 2932 (2012).