Manipulating single atoms and photons using optical nanofibers

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Abstract
We discuss how optical nanofibers, subwavelength-diameter fibers, can open new perspectives in quantum optical technologies theoretically and experimentally. Discussions are mainly focused on the manipulation of spontaneous emission for atoms around the nanofiber. We show that photons from single quantum emitters can be efficiently channeled into guided modes of the nanofiber. Especially by fabricating a cavity structure of the nanofiber, the channeling efficiency can be improved to exceed 80% although the cavity finesse is moderate. We discuss also how to realize such a nanofiber cavity experimentally.

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1. Introduction
The progress of modern quantum optics has opened a door to a new type of technology, which is known as quantum information technology. The technology is expected to grow as a new type of information technology in the coming decades via the methods of quantum communication and/or quantum computing. One of the key issues of such technology is how to manipulate single atoms and photons, since quantum information is carried not by coherent light but by deterministic flow of single photons and/or twin photons. In this context, various methods to manipulate single atoms and single photons have been proposed and demonstrated so far. Examples would include ultra-high finesse cavity with single atoms [1], semiconductor micro-pillar with quantum dots [2] and silver nanowire with quantum dots [3].

In the present work, we show that subwavelength fibers, termed optical nanofibers, may open a new route to manipulate single atoms and single photons. We discuss using optical nanofibers how a small number of atoms can be observed, and how spontaneous emission of atoms can be manipulated. Moreover, we show theoretically that the emitted photons can be channeled into the guided modes of the fiber with efficiency greater than 80% by fabricating cavity structure with a moderate finesse on nanofibers. We discuss a technology to create such cavity structure on nanofibers.

2. Spontaneous emission of ‘atom’ around a nanofiber
Figure 1(a) shows the conceptual diagram of the present optical nanofiber scheme. The nanofiber locates at the midpoint of a tapered optical fiber which satisfies the adiabatic tapering condition so that the single-mode propagation can be maintained for the whole fiber length. Atoms distribute in the vicinity of the nanofiber. Since mode density is strongly confined around the nanofiber, spontaneous emission of atoms around the nanofiber may be very different from that for atoms in the free space; that is, an appreciable amount of fluorescence photons are emitted into the guided mode of the nanofiber. Figure 1(b) shows theoretical results for the coupling efficiency of spontaneous emission into each direction of the nanofiber guided modes. Diameter of nanofiber is chosen to satisfy condition $k_0a = 1.45$, where $k_0$ is the free-space propagation constant and $a$ is the radius of the nanofiber. Condition $k_0a = 1.45$ is the optimum condition for coupling the fluorescence into the guided mode [4]. One can see that the nanofiber can collect fluorescence photons very efficiently. For atoms on the nanofiber surface, 11% of the fluorescence photons are channeled into each side of the guided mode, and for atoms at one radius away from the surface it is still 3%.
Figure 1. (a) Conceptual diagram of the scheme. The nanofiber locates at the midpoint of tapered optical fiber. Coupling efficiency of spontaneous emission into each direction of nanofiber propagation mode, $\eta_g$, versus atom position $r/a$, where $r$ and $a$ are distance from nanofiber axis and radius of nanofiber, respectively.

Figure 2. Schematics for photon-correlation measurements.

3. Atom on a nanofiber

As quantum emitters, we use laser-cooled Cs-atoms and CdSe/Te nanocrystal quantum-dots. Here, we describe the results on Cs-atoms. Experimental setup is sketched in figure 2.

Cold atom cloud is overlapped to the nanofiber, and the atoms are excited by a probe laser beam which is focused to the nanofiber. Fluorescence photons which are emitted into the fiber mode are detected by two avalanche photodiodes APD1 and APD2, and photon coincidences at two APDs are measured. Results are shown in the left column of figure 3. The right column exhibits the coincidences measured for photons emitted to both sides of the fiber. Parameter $I_D$ denotes the heater current to generate Cs-atoms.

One can readily see a dip at the center of the coincidences for atom number less than one for one-end coincidences and for both-side coincidences. The dip corresponds to so-called anti-bunching dip which is a signature of single photon emitter. It means that one can readily generate single photons into a fiber mode by using the nanofiber/one-atom system. Details of the observations and discussions, especially on the different behaviors for one-end and for both-end correlations, are found in [5].

4. Enhancement of the coupling efficiency

The nanofiber method would become useful for generating single photons; in particular, its feature of emitting single photons into the fiber guided mode should be beneficial for real applications. However, in order to extend the nanofiber technology to the widely usable method, one difficulty is that the coupling efficiency to the fiber mode is limited to 28% at maximum [6]. In order to extend the nanofiber technology to overcome this difficulty, we discuss here a method to enhance the coupling efficiency greater than 80% so that the nanofiber method may become much more versatile technology.

The key idea is to incorporate a cavity structure on the nanofiber as briefly sketched in figure 4. Due to the cavity structure, the fluorescence emission rate into the guided modes should be enhanced although emission rate into free space should not have any change.

The coupling efficiency of fluorescence photons from atoms on the nanofiber into the guided mode in the above structure can be expressed as below [4].

$$\eta_c \approx \frac{G \Gamma^{(g)}}{\Gamma^{(r)} + G \Gamma^{(g)}}$$

here, $\Gamma^{(g)}$ and $\Gamma^{(r)}$ are emission rates of fluorescence photons into the guided modes and radiation modes (free space), respectively. $G$ is the enhancement factor due to the cavity structure. Note that the enhancement factor is almost equal to the finesse of the cavity. We assume that the coupling efficiency $\eta_c \sim 10\%$ without cavity, namely, for $G = 1$. Then, if one substitutes $G = 30$ to the above equation, one can obtain $\eta_c \sim 80\%$. It means that once a cavity structure with a moderate finesse of 30 is fabricated on the nanofiber, most of the fluorescence photons are emitted into the guided modes. It means that one atom in the nanofiber cavity should work as a very efficient single photon generation system. One may consider that single-photon generation with cavity in free space is quite a standard method of cavity-QED. But, in

Figure 3. Left column: one-end correlations. Right column: both-end correlations.

Figure 4. Conceptual sketch for ‘single atom in the optical nanofiber cavity’.
Figure 5. Fiber Bragg grating fabricated on optical nanofiber. Grooves are milled by focused ion-beam method.

such a standard method, the cavity must have a very high finesse cavity of \( F \sim 50,000 \) or even higher [1], which is more than 1000 times larger than that for nanofiber cavity. This is simply due to a fact that for the free space cavity the strong field-confinement must be established by using only a pair of mirrors. On the other hand, for the nanofiber cavity, the field confinement is controlled by both nanofiber itself and cavity structure. Since the nanofiber confines the field in the transverse plane to a tiny area smaller than \( \lambda/2 \), additional requirements of the cavity can become rather moderate with low finesse of \( F \sim 30 \).

5. Realization of the nanofiber cavity

As discussed above, optical nanofibers may give a very promising method for generating single photons. In order to really demonstrate the method, the key issue is to experimentally realize the highly efficient single photon generation by incorporating a cavity structure on the nanofiber. The cavity can be created by fabricating a pair of fiber Bragg gratings (FBGs) on nanofibers. Although FBG technologies are quite well-established for conventional optical fibers, no method has been reported so far regarding FBG-fabrications on nanofibers. There may be two approaches to creating FBGs on nanofiber. One is to directly mill periodic grooves on nanofibers, and the other is to induce periodic refractive index change on nanofibers. Presently we are working on the direct-milling method. We use focused ion-beam (FIB) technology to mill grooves on nanofibers. One example of milled nanofiber is exhibited in figure 5. The diameter of nanofiber is about 500 nm. One can see that grooves are periodically milled on both sides of nanofiber. The pitch is 360 nm with groove depth of 100 nm.

Figure 6. Resonance characteristics for a nanofiber cavity at a wavelength of 852.3 nm. FSR and finesse are 25 GHz and 20, respectively.

The nanofiber cavity structure has been created by milling a pair of FBGs on nanofiber. Figure 6 displays resonance characteristics for a created cavity. A finesse value of 20 is obtained. Details of the measurements and analysis will be published elsewhere.

6. Summary

We discussed how optical nanofibers can open new perspectives in quantum optical technologies. We have shown using optical nanofibers how a small number of atoms can be observed and how spontaneous emission of atoms can be manipulated. We have shown also that spontaneous emission of atoms can be channeled into the guided mode of the nanofiber by fabricating a cavity structure on the nanofiber. We have demonstrated that a nanofiber cavity can be created by using the FIB method.

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