Efficient Single-Mode Photon-Coupling Device Utilizing a Nanofiber Tip

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Single-photon sources are important elements in quantum optics and quantum information science. It is crucial that such sources be able to couple photons emitted from a single quantum emitter to a single propagating mode, preferably to the guided mode of a single-mode optical fiber, with high efficiency. Various photonic devices have been successfully demonstrated to efficiently couple photons from an emitter to a single mode of a cavity or a waveguide. However, efficient coupling of these devices to optical fibers is sometimes challenging. Here we show that up to 38% of photons from an emitter can be directly coupled to a single-mode optical fiber by utilizing the flat tip of a silica nanofiber. With the aid of a metallic mirror, the efficiency can be increased to 76%. The use of a silicon waveguide further increases the efficiency to 87%. This simple device can be applied to various quantum emitters.

Single-photon sources are indispensable in many applications in optical quantum information science, including quantum key distribution 1 and linear-optical quantum computing 2,3. In such applications, it is required to couple photons emitted from a single quantum emitter to a single propagating mode, preferably to the guided mode of a single-mode optical fiber, with high efficiency. A variety of quantum emitters, such as atoms 4,5, ions 6, dye molecules 7, semiconductor quantum dots 8,9, and defect centers in diamond crystals 10, have been used in single-photon sources.

A cavity quantum electrodynamics (QED) system enables one to efficiently couple photons from such an emitter to a single spatial mode 11. When an emitter is placed in a cavity, the selective coupling of emitted photons into the cavity mode can be achieved owing to the enhancement of spontaneous emission (the Purcell effect) 12. However, further coupling of the photons collected by the cavity to a single-mode optical fiber results in losses, which greatly reduce the total coupling efficiency. The use of a fiber-coupled optical microcavity 13 is a more elaborate way to efficiently couple photons from an emitter to a single-mode optical fiber. The efficient coupling of a fiber input/output mode to an atom in a cavity has been demonstrated using toroidal 14 and bottle 15 microresonators coupled to a tapered optical fiber with low losses. A fiber-coupled cavity QED system with a quantum dot embedded in a semiconductor microdisk has also been realized 16. Recent development of fiber Fabry-Perot cavities with small mode volumes and high finesse 17 has sparked realizations of fiber Fabry-Perot cavity QED systems with ions 18,19, quantum dots 20, and NV centers in diamond 21,22.

On the other hand, efficient coupling of photons from an emitter to a single spatial mode can also be achieved by using an optical waveguide. Near-unity coupling efficiency of photons from an emitter embedded in a photonic crystal waveguide has been theoretically predicted 23 and experimentally demonstrated with quantum dots 24,25. It has also been proposed to use guided surface plasmons on metallic nanowires to achieve near-unity coupling efficiency 26,27, and efficient coupling of photons from quantum dots to surface plasmons on silver nanowires has been demonstrated 28. However, further coupling of photons collected in these systems to single-mode optical fibers again results in additional losses.

These additional losses in coupling to single-mode fibers can be minimized by the use of a subwavelength-radius cylindrical silica waveguide (i.e., a silica nanofiber) 29. It has been theoretically shown that efficient coupling of photons to the guided mode of a nanofiber can be achieved when an emitter is located near the surface of the side of the nanofiber 30,31. The fundamental guided mode of a silica nanofiber can be transferred to the guided mode of a standard single-mode fiber through an adiabatically tapered region with low losses 32,33. Therefore, the efficient coupling of photons from an emitter to a single-mode optical fiber can be realized with such systems. Recent experimental progress has demonstrated the efficient interaction between the evanescent field of the nanofiber-guided mode and atoms 34,35. Direct collection of photons emitted from quantum dots and nitrogen-vacancy centers in diamond placed on the nanofiber surface to the nanofiber-guided mode has also been reported 36–40. Efficient coupling of photons from emitters embedded in semiconductor membranes or waveguides

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has also been theoretically predicted\textsuperscript{44,45} and experimentally demonstrated\textsuperscript{46}. These devices utilize the evanescent field of the nanofiber-guided mode by placing the emitter near the surface of the side of the nanofiber. Here we propose a device utilizing a nanofiber tip. Because of the interference between the radiation from the emitter and that from the emitter’s mirror image on the tip surface, the coupling efficiency is even higher than in the case in which the emitter is embedded in a continuous nanofiber, or the case in which the emitter is placed near the side of the nanofiber. We numerically simulate the coupling efficiency of radiation from a point dipole source located in the vicinity of the tip of a nanofiber to the fundamental guided mode of a nanofiber and obtain an efficiency as high as 38%. When flat and spherical mirrors are placed in front of the nanofiber tip, the efficiencies reach values as high as 73% and 76%, respectively. The use of a silicon waveguide further increases the efficiency to 87%.

**Results**

Figure 1a shows a schematic of the proposed device. A silica nanofiber with a flat tip is connected to a standard single-mode optical fiber through an adiabatically tapered region. Such a structure can be fabricated by cutting a tapered optical fiber\textsuperscript{29} at its waist. We calculate the coupling efficiency of the radiation from a point dipole source to the fundamental guided mode of the nanofiber, with a geometry shown in Fig. 1b. Figure 1c shows the calculated intensity of radiation for the case of $r = z = 0$ and $a = 0.32\lambda$, which clearly shows that the radiation from the point dipole source is efficiently guided to the nanofiber. Note that the fundamental guided mode of the nanofiber...
is transferred to the guided mode of the single-mode fiber without coupling to the higher-order or radiation modes through the adiabatically tapered region. The adiabatic limit for the modal conversion in the tapered region is given by \( V = r \beta_1 / (2\pi) \), where \( V, r, \beta_1, \beta_2 \) respectively denote the local taper angle, the local fiber radius, and the propagation constants of the fundamental and the first excited modes. In this limit, the mode conversion in the tapered region is adiabatic, and there are no modal coupling losses. Therefore, the coupling efficiency calculated here can be interpreted as the coupling efficiency from the source to the guided mode of a single-mode fiber.

First, we calculate the coupling efficiency for various fiber radii, with the location of the point dipole source fixed at the center of the nanofiber tip surface \((z = r = 0)\). Figure 2a shows the dependence of the coupling efficiency on the nanofiber radius \( a \) for the case of radial source polarization. A maximum coupling efficiency of 37% is obtained at \( a = 0.32\lambda \), where \( \lambda \) is the vacuum wavelength of light. Note that the single-mode cut-off radius is \( a = 0.42\lambda \). The obtained efficiency is considerably higher than that for the case in which the source is placed on the surface of a continuous nanofiber. In contrast, we obtain zero coupling efficiency for any value of \( a \) for the case of axial source polarization, which reflects the fact that the electric field of the fundamental (HE_{11}) mode of the nanofiber has no axial component of the electric field at \( r = 0 \).

For comparison, we calculate the coupling efficiency of the radiation from a source embedded at the center of a continuous nanofiber of radius \( a \). Figure 2b shows the dependence of the coupling efficiency on the fiber radius \( a \). (A continuous fiber has two output ports, and the radiation from the source is coupled to each of the two counter-propagating modes with equal coupling efficiency. We calculate the coupling efficiency for one of the two modes as shown in the inset of Fig. 2b.) The maximum coupling efficiency is 27%, which is smaller than that when the source is placed on the nanofiber tip surface. This fact can be understood by considering the effect of the mirror image of the source created by the tip surface. The electric field of the radiation from the mirror image, or the reflected field, and that from the source destructively interfere on the vacuum side. This interference distributes more of the power of the source radiation to the fiber side than to the vacuum side. Indeed, the calculation using the amplitude transmission coefficient \( t = 2/(1 + n) \approx 0.81 \) and the amplitude reflection coefficient \( r = (1 - n)/(1 + n) \approx -0.19 \) for the vacuum-silica boundary gives the power distribution ratio of \( n |t|^2 : |1 + r|^2 \approx 3:2 \) between the fiber side and the vacuum side, which agrees well with the efficiencies obtained above.

The coupling efficiencies obtained above correspond to the ratio \( \Gamma_{\text{guided}} / \Gamma_{\text{total}} \) of the decay rate into the fundamental guided mode, \( \Gamma_{\text{guided}}^{(1)} \) to the total decay rate, \( \Gamma_{\text{total}} \), and they do not directly give the amount of the enhancement (or inhibition) of the spontaneous emission (the Purcell effect). We also calculate the ratio of \( \Gamma_{\text{total}} \) to the decay rate of a dipole in free space, \( \Gamma_{\text{free}} \) and obtain \( \Gamma_{\text{total}} / \Gamma_{\text{free}} = 1.28 \) for \( a = 0.32\lambda \). That is, the spontaneous emission of the dipole is enhanced compared to that in free space.

Figure 3 | Dependence of the coupling efficiency on the axial and radial positions of the source. (a), Dependence of the coupling efficiency on the nanofiber radius \( a \) and the axial position \( z \) of the point dipole source with radial polarization located on the fiber axis \((r = 0)\). (b-d), Dependence of the coupling efficiency on \( r \) and \( z \) with a fixed fiber radius \( a = 0.32\lambda \) for radial, azimuthal, and axial polarizations of the source, respectively. The insets show schematics of the spatial directions of polarizations.
The coupling efficiency of the radiation from a quantum emitter to the guided mode of a continuous nanofiber has been studied by several groups. In order to compare the results obtained in the above calculation with these theories, we calculate the coupling efficiency based on the model in Ref. [31]. Specifically, the decay rate into the i-th guided mode and that into the radiation modes are respectively given by

\[
\Gamma_{\text{guided}}^{(i)} = \frac{2\omega_0\beta_i^*}{\varepsilon_0\hbar} \left| d_i e_\text{guided}^{(i)} \right|^2, \\
\Gamma_{\text{radiation}}^{(i)} = \frac{2\omega_0}{\varepsilon_0\hbar} \sum_m \int_0^{\beta_m} d\beta |d_i e_\text{radiation}^{(i)}(\beta_m)|^2,
\]

where \(\omega_0\), \(k_0\), \(\beta\), \(\beta^*\), \(d\), \(e_\text{guided}^{(i)}\), and \(e_\text{radiation}^{(i)}\) respectively denote the resonance frequency of the two-level atom, the vacuum wavenumber, the propagation constant, the derivative of \(\beta\) with respect to the frequency \(\omega\), the atomic dipole moment, the normalized electric field of the i-th guided mode, and the normalized electric field of the radiation mode with the propagation constant \(\beta\) and the mode order \(m\). The red solid line in Fig. 2b shows the coupling efficiency, which is given by

\[
\frac{\Gamma_{\text{guided}}^{(i)}}{\Gamma_{\text{total}}} = \frac{\Gamma_{\text{guided}}^{(i)}}{\Gamma_{\text{radiation}} + \sum_i \Gamma_{\text{guided}}^{(i)}}.
\]

Discussion

This scheme of using a nanofiber tip and a metallic mirror for coupling photons to the guided mode of a single-mode fiber can be applied to various kinds of quantum emitters. A semiconductor quantum dot or a diamond nanocrystal containing an NV center can be directly placed on the nanofiber tip surface in a manner similar to that in Refs. 41–43, where continuous nanofibers were used.

An atom can be laser-trapped by a dipole potential created by red-detuned laser light using the nanofiber tip, and high coupling efficiency of 30–38% can be obtained.

The coupling efficiency can be increased with the aid of a mirror. We consider a flat metallic mirror oriented so that it is parallel to the face of the fiber, with a distance \(b\) from the fiber tip. Figure 4a shows the calculated intensity of the radiation for the case of a source position of \(r = z = 0\), a fiber radius of \(a = 0.32\lambda\), and a tip-mirror distance of \(b = 0.15\lambda\). The white and magenta lines represent the surfaces of the nanofiber and the metallic mirror, respectively. (b), Dependence of the coupling efficiency on the tip-mirror distance \(b\), for the case of a flat mirror. The inset shows a schematic of the geometry. (c), Same as (b), for the case of a spherical mirror with a radius of curvature of \(5\lambda\).
the center between the tip and the mirror as shown in Fig. 5, which is suitable for creating a microscopic dipole trap. In the case of a cesium atom, for example, laser light at the wavelength of 935 nm (the so-called magic wavelength) with a power of 50 mW launched into the fundamental mode of a 355-nm-radius nanofiber creates the trap minimum at a position 85 nm away from the tip when the tip-mirror distance is 374 nm, as shown in Fig. 6. For the radiation on the $6S_{1/2} F = 4 \rightarrow 6P_{3/2} F' = 5$ transition of a cesium atom at this trap minimum, the coupling efficiency to the fundamental guided mode of the nanofiber reaches 61%. This is in stark contrast to the continuous nanofiber case, where the coupling efficiency for an atom trapped in a dipole potential created by a two-color evanescent field is less than 10% for each side of the guided mode.

In a real experiment, there can be various imperfections. Although cleaving of a nanofiber to form a flat surface has been demonstrated, the shape of the nanofiber tip may be distorted from the ideally flat surface as considered above. In order to investigate the sensitivity of the coupling efficiency to the shape of the nanofiber tip, we also calculate the coupling efficiencies for nanofibers with hemispherically shaped tips. Note that we have demonstrated fabricating nanofibers with hemispherical tips recently. The obtained coupling efficiencies for $0 < r/\lambda < 1$ coincide with those for flat tips within 5%. This indicates that the precise shape of the nanofiber tip does not strongly affect the coupling efficiency. Also, losses in the propagation in the device can be made negligible by fabricating low-loss tapered optical fibers. Indeed, fabrication of a tapered optical fiber with a subwavelength waist having a transmission in excess of 99.95% has been realized. It should be straightforward to apply the proposed device to, e.g., the recent experiments demonstrating the efficient coupling (22% in two ports) of photons from single quantum dots into the nanofiber-guided mode via the evanescent field, and to experimentally achieve the high coupling efficiencies presented here.

The coupling efficiency can be even further increased by using a dielectric waveguide with a higher refractive index. For example, silicon has a refractive index of 3.5 and is transparent in the telecom wavelength. Here we consider a silicon waveguide with a square cross-section. Figure 7a shows the dependence of the coupling efficiency on...
the waveguide width \( w \), with the location of the point dipole source fixed at the center of the waveguide tip surface. A maximum coupling efficiency of 80% is obtained at \( w = 0.235 \). When combined with a flat metallic mirror, the efficiency can be increased up to 87%, as shown in Fig. 7b. Such a silicon waveguide can be adiabatically coupled to a tapered optical fiber with low losses.  

In conclusion, we have studied a novel single-mode photon-coupling device utilizing a nanofiber tip. We have shown that a nanofiber with a flat tip can couple up to 38% and 76% of light from a point dipole source to a single-mode optical fiber without and with a mirror, respectively. When a silicon waveguide is used, a maximum coupling efficiency of 87% can be achieved. The proposed device directly couples photons from a quantum emitter to a standard single-mode optical fiber. In addition, the robust structure of this device is suitable for various experimental conditions including cryogenic temperature and ultra-high vacuum.

**Methods**

We employ a three-dimensional finite-difference time-domain method for the simulations. Figure 1b is a schematic of the simulation geometry. We consider a silica nanofiber with index \( n = 1.46 \) with one end cut being a plane normal to the fiber axis. A point dipole source is placed near the tip of the nanofiber, with an axial distance \( z \) and a radial distance \( r \) from the center of the nanofiber tip surface, respectively. We calculate the coupling efficiency of the radiation from the source to the fundamental guided mode of the nanofiber. The fundamental guided mode is numerically calculated using a mode solver.

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**Author contributions**

T.A. conceived and led the study. S.C. and S.K. carried out the calculations and analyzed data. T.A. prepared the manuscript. All authors reviewed the manuscript.
Additional information

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