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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 distribution¹ 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}, ions⁶, dye molecules⁷, semiconductor quantum dots^{8,9}, and defect centers in diamond crystals¹⁰, 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 mode¹¹. 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 microcavity¹³ 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 toroidal¹⁴ and bottle¹⁵ 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 realized¹⁶. Recent development of fiber Fabry-Perot cavities with small mode volumes and high finesse¹⁷ has sparked realizations of fiber Fabry-Perot cavity QED systems with ions^{18,19}, quantum dots²⁰, 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 predicted²³ 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 demonstrated²⁸. 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 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^{32–34}. 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^{35–40}. 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^{41–43}. Efficient coupling of photons from emitters embedded in semiconductor membranes or waveguides

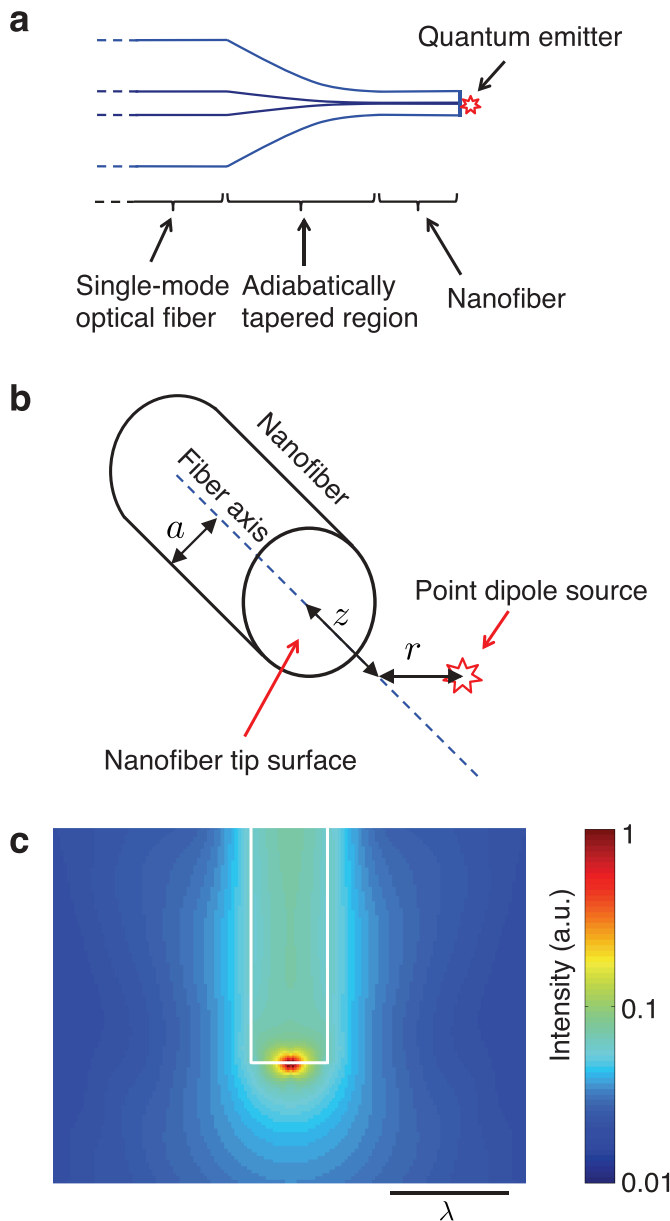


Figure 1 | Nanofiber-tip-based coupling of photons from a single quantum emitter to a single-mode optical fiber. (a), Schematic of a nanofiber with a flat tip connected to a standard single-mode optical fiber via an adiabatically tapered region. (b), Simulation geometry. a is the radius of the nanofiber, and z and r are the axial and radial distances from the center of the nanofiber tip surface to the point dipole source, respectively. (c), Calculated intensity of the radiation from a point dipole source located at the center of the nanofiber tip surface ($r = z = 0$) for the case of a nanofiber radius of $a = 0.32\lambda$. The white line indicates the surface of the nanofiber.

has also been theoretically predicted^{44,45} and experimentally demonstrated⁴⁶. 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 fiber²⁹ 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

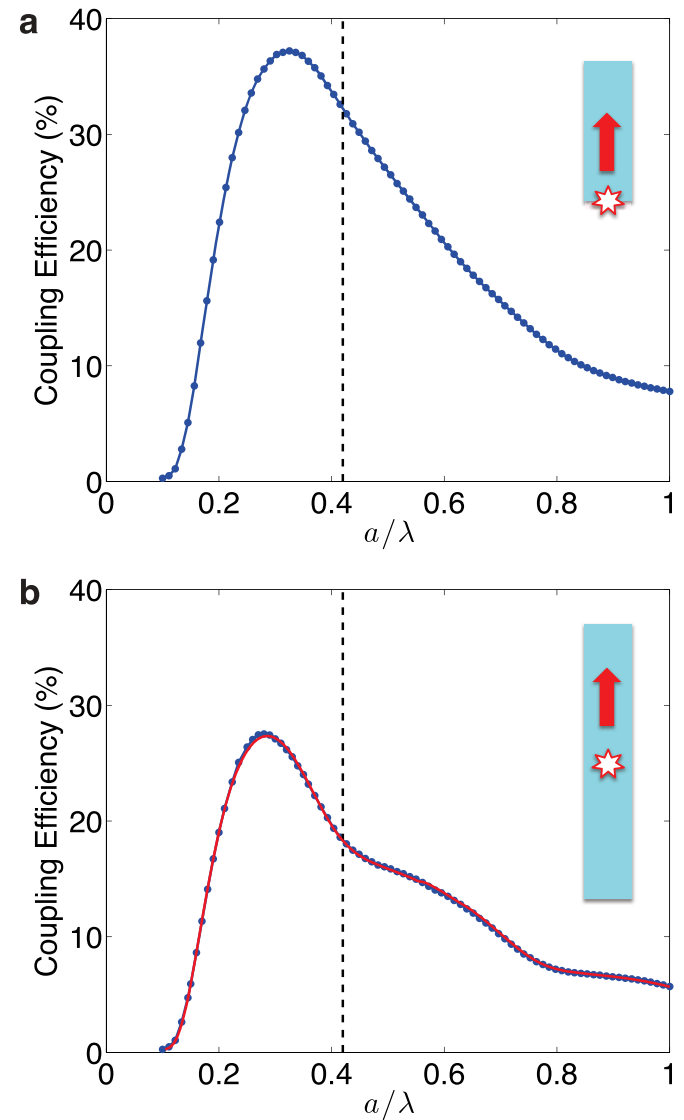


Figure 2 | Coupling efficiency of radiation from a point dipole source located on the fiber axis ($r = 0$) to the fundamental guided mode of the nanofiber. a, Dependence of the coupling efficiency on the nanofiber radius a for the case of a nanofiber tip with a tip-source distance $z = 0$. The inset shows a schematic of the geometry. The vertical dashed line indicates the single-mode cut-off radius. b, Same as a, for the case of a continuous nanofiber. The red solid line shows the coupling efficiency calculated based on the model in Ref. 31.



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^{32–34}. The adiabatic limit for the modal conversion in the tapered region is given by $\Omega \ll r(\beta_1 - \beta_2)/(2\pi)$, where Ω , r , β_1 , β_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 λ 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 nanofiber³⁰. 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 $\Gamma_{\text{guided}}^{(1)}/\Gamma_{\text{total}}$ of the decay rate into the fundamental guided mode, $\Gamma_{\text{guided}}^{(1)}$, to the total decay rate, Γ_{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 Γ_{total} to the decay rate of a dipole in free space, Γ_{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.

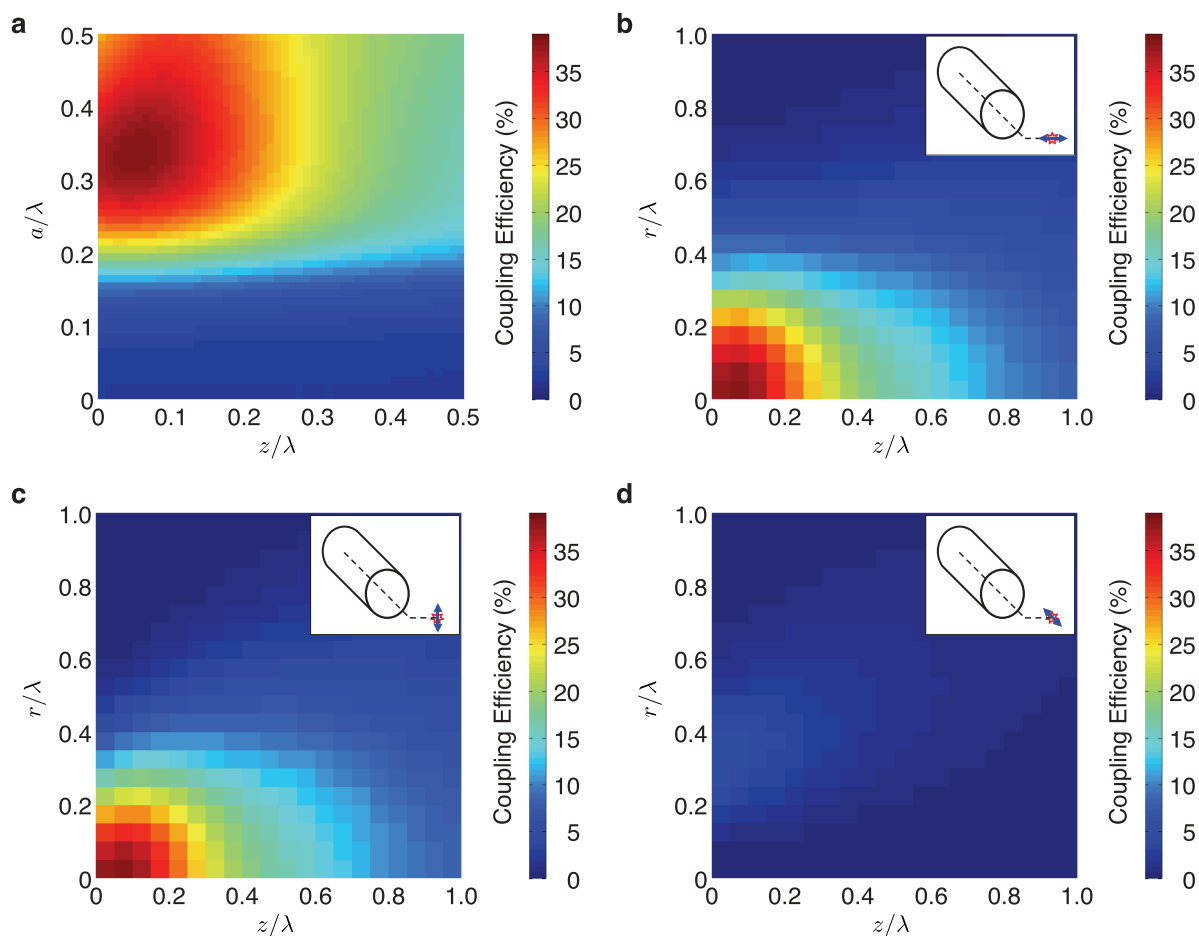


Figure 3 | Dependence of the coupling efficiency on the axial and radial positions of the source. (a), Dependence of the coupling efficiency on the nanofiber radius a and the axial position z of the point dipole source with radial polarization located on the fiber axis ($r = 0$). (b–d), Dependence of 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.

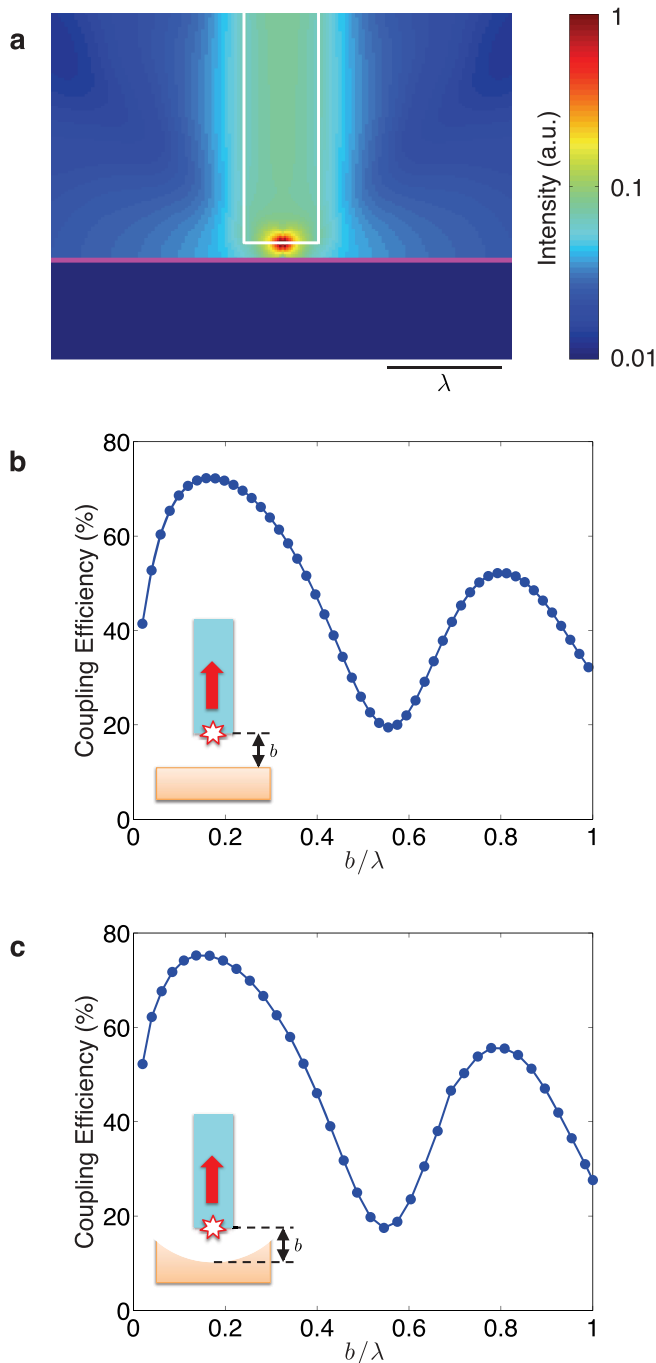


Figure 4 | Increasing the coupling efficiency with the aid of a metallic mirror. (a), Calculated intensity of radiation for the case of a source position of $r = z = 0$, a fiber radius of $a = 0.32\lambda$, and a tip-mirror distance of $b = 0.15\lambda$. The white and magenta lines represent the surfaces 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 5λ .

The coupling efficiency of the radiation from a quantum emitter to the guided mode of a continuous nanofiber has been studied by several groups^{30,31,47}. 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

$$\Gamma_{\text{guided}}^{(i)} = \frac{2\omega_0\beta'}{\varepsilon_0\hbar} \left| \mathbf{d} \cdot \mathbf{e}_{\text{guided}}^{(i)} \right|^2, \quad (1)$$

$$\Gamma_{\text{radiation}} = \frac{2\omega_0}{\varepsilon_0\hbar} \sum_m \int_0^{k_0} d\beta \left| \mathbf{d} \cdot \mathbf{e}_{\text{radiation}}^{(\beta,m)} \right|^2, \quad (2)$$

where ω_0 , k_0 , β , β' , \mathbf{d} , $\mathbf{e}_{\text{guided}}^{(i)}$, $\mathbf{e}_{\text{radiation}}^{(\beta,m)}$ respectively denote the resonance frequency of the two-level atom, the vacuum wavenumber, the propagation constant, the derivative of β with respect to the frequency ω , 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 β and the mode order m . The red solid line in Fig. 2b shows the coupling efficiency, which is given by

$$\frac{\Gamma_{\text{guided}}^{(1)}}{\Gamma_{\text{total}}} = \frac{\Gamma_{\text{guided}}^{(1)}}{\Gamma_{\text{radiation}} + \sum_i \Gamma_{\text{guided}}^{(i)}}. \quad (3)$$

Its excellent agreement with our results clearly shows the validity of our FDTD calculations.

We next calculate the dependence of the coupling efficiency on the axial and radial position of the source. Figure 3a shows the dependence of the coupling efficiency on a and z with a fixed radial source position $r = 0$. The maximum coupling efficiency of 38% is obtained for $a = 0.32\lambda$ and $z = 0.04\lambda$. Figure 3b–d show the 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. These results show that if a quantum emitter with a radial or azimuthal polarization is attached to or brought close to the center of the nanofiber tip with a position accuracy of 0.2λ , a 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 $b = 0.15\lambda$. It shows that the radiation from the source is guided to the nanofiber more efficiently than in the case without a mirror (Fig. 1c). Figure 4b shows the dependence of the coupling efficiency on the tip-mirror distance b for the case of $r = z = 0$ and $a = 0.32\lambda$. The maximum coupling efficiency of 73% is obtained at $b = 0.15\lambda$. This can be slightly improved by using a spherical mirror; we obtain an efficiency of 76% for a mirror radius of curvature of 5λ , as shown in Fig. 4c.

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 light using the nanofiber tip, and high coupling efficiency of atomic emission to the fundamental guided mode of the nanofiber can be achieved. The van der Waals potential strongly shifts atomic energy levels in the vicinity of the surface of a dielectric or a metal within a distance of a few tens of nanometers⁴⁸. In order to stably trap an atom with a dipole potential created by far-detuned laser light under practical conditions, its potential minimum has to be located at a distance of more than a few tens of nanometers from the surface. When a flat mirror is placed in front of the fiber tip, the output mode of the fiber forms a standing wave. For a tip-mirror distance of $0.4\lambda \lesssim b \lesssim \lambda$, an anti-node of the standing wave is located around

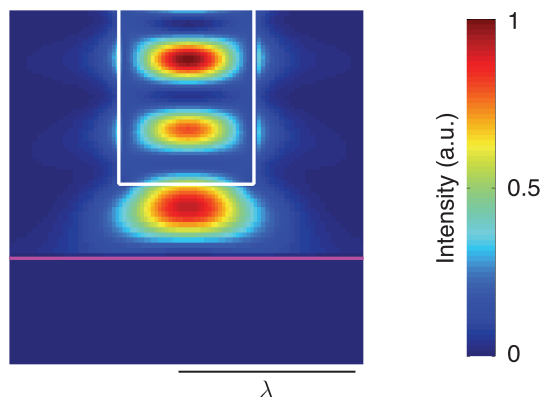


Figure 5 | Calculated intensity of the output mode of the nanofiber tip for the case of a wavelength of $\lambda = 935$ nm, a fiber radius of $a = 355$ nm, and a tip-mirror distance of $b = 374$ nm. The white and magenta lines indicate the surfaces of the nanofiber and the metallic mirror, respectively.

the center between the tip and the mirror as shown in Fig. 5, which is suitable for creating a microscopic dipole trap⁴⁹. In the case of a cesium atom, for example, laser light at the wavelength of 935 nm (the so-called magic wavelength⁵⁰) 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 mode³⁶.

In a real experiment, there can be various imperfections. Although cleaving of a nanofiber to form a flat surface has been demonstrated²⁹, 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,

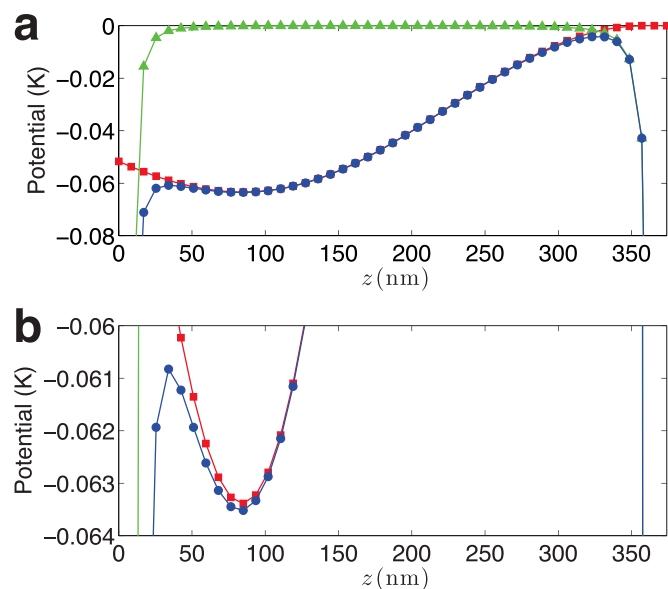


Figure 6 | (a) The red squares, the green triangles, and the blue circles represent the dipole potential U_d for laser light at the wavelength of 935 nm and an input power of 50 mW, the van der Waals potential U_{vdW} , and the total potential $U = U_d + U_{vdW}$, respectively, on the fiber axis ($r = 0$). (b) Same plot as (a) with a magnified vertical axis.

we also calculate the coupling efficiencies for nanofibers with hemispherically shaped tips. Note that we have demonstrated fabricating nanofibers with hemispherical tips recently⁵¹. 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 sub-wavelength waist having a transmission in excess of 99.95% has been realized³⁴. 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 field⁴³, 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

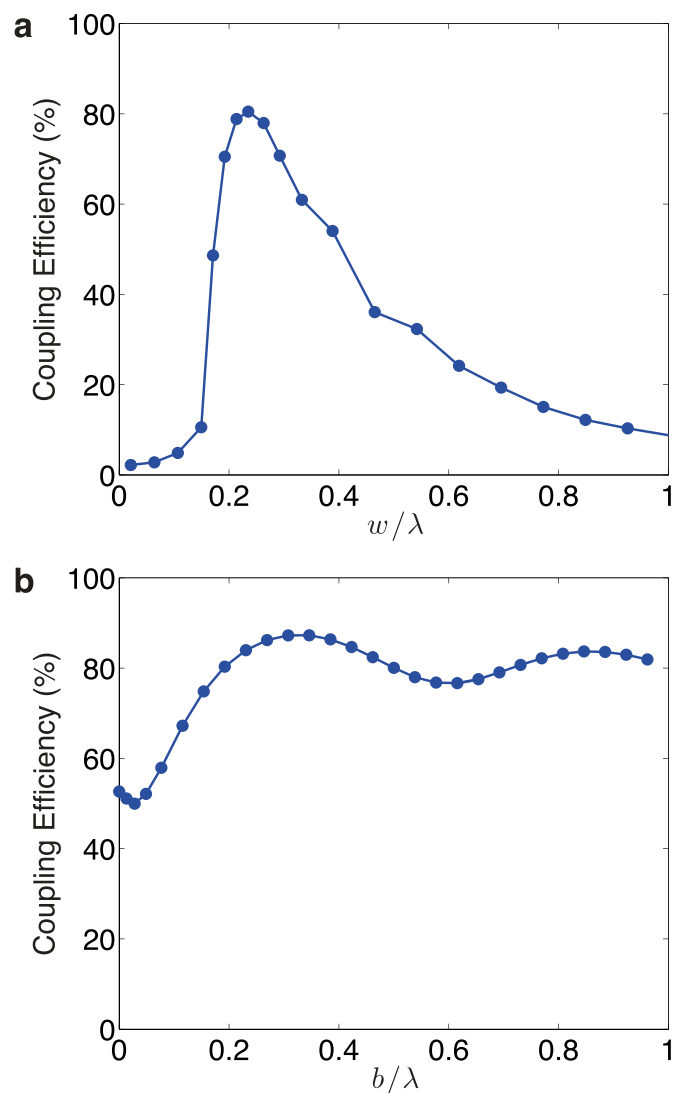


Figure 7 | Coupling efficiency of radiation from a point dipole source to the fundamental guided mode of the silicon waveguide with a square cross-section. a, Dependence of the coupling efficiency on the waveguide width w when the source is attached to the center of the waveguide tip surface. b, Dependence of the coupling efficiency on the tip-mirror distance b when the waveguide width of $w = 0.235\lambda$ and the source is attached to the center of the waveguide tip surface.



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 $w = 0.235\lambda$. 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 losses⁵².

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 method⁵³ for the simulations. Figure 1b is a schematic of the simulation geometry. We consider a silica nanofiber of radius a and refractive index $n = 1.46$, with one end cut flat along 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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