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Fiber-Coupled Cavity-QED Source of Identical Single Photons
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A fiber coupled cavity QED source of identical single photons


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We present a fully fiber coupled source of high-fidelity single photons. This is achieved by embedding an InGaAs semiconductor quantum dot in an optical Fabry-Perot micro cavity with robust design and rigidly attached single mode fibers which enables through-fiber cross polarized resonant laser excitation and photon extraction. Even without spectral filtering, we observe that the incident coherent light pulses are transformed into a stream of single photons with high purity (97%) and indistinguishability (90%), which is measured at an in-fiber brightness of 5% with an excellent cavity mode to fiber coupling efficiency of 85%. Our results pave the way for fully fiber integrated photonic quantum networks, further, our method is equally applicable for fiber coupled solid-state cavity-QED based photonic quantum gates.

Every isolated two-level quantum system such as an atom, ion, color center or quantum dot, can in principle be turned in a bright single photon source [1, 2]. Ideally, such a source produces a stream of single photons, never more or less than one photon per time bin, and all having the same Fourier limited spectrum and timing. Such a source would be essential for exploration of numerous quantum technologies such as optical quantum computing [3–6] and simulation [7]. Further, the reduced fluctuations of such single-photon light would enable exciting opportunities everywhere where noise is a limiting factor, in fields from metrology to microscopy.

However, only very recently, high-fidelity single photon sources have been demonstrated [8–13] that simultaneously fulfill the key requirements: near-unity single-photon purity and indistinguishability of consecutively emitted photons, and a high brightness. For a single photon source, high brightness and on-demand availability is crucial for efficient implementation of quantum photonic protocols. Additionally, to exploit the power of quantum interference, consecutively produced photons need to be indistinguishable, meaning that their wave functions must overlap well. Until recently, heralded spontaneous parametric down conversion sources [14] were the state of the art for single photon sources (SPS) [15], with which most quantum communication and optical quantum computing protocols have been demonstrated [16]. The main problem of these sources is that the Poissonian statistics of the generated twin photons will always result in a trade-off between single-photon purity (the absence of N>1 photon number states) and brightness (the probability to obtain a photon per time slot).

One way to deterministically produce single photons is to use trapped atoms [17], where single photon rates up to around 100 kHz have been obtained recently [18]. In order to enable integration and increasing the photon rate, solid-state systems have been investigated, in particular promising are semiconductor quantum dots (QDs) [1, 19, 20]. QDs have nanosecond-lifetime transitions that enable GHz rate production of single photons as required for numerous quantum technologies. Compared to other solid state emitters such as NV centers, nanowire QDs, excitons in carbon nanotubes or two-dimensional materials [21, 22], self-assembled QDs in cavities can show almost perfect purity and indistinguishability [9]. A challenging task is to couple the quantum emitter to propagating optical modes with near-unity efficiency. This can be achieved by placing them in optical micro cavities, which additionally increases the emission rate by cavity-QED Purcell enhancement, such as micropillar cavities [1, 23], photonic crystal cavities [24], or ring resonators [25].

For the next major step in implementing quantum dot single photon sources in complex photonic quantum networks, coupling to a single mode optical fiber is essential. Several challenges are connected to this: cryogenic compatibility [26], resonant optical pumping, high coupling efficiency and robust and stable polarization control. Only recently, a first study on a nonresonantly pumped multi mode fiber coupled device appeared [27]. Another approach is to employ fiber-tip micro cavities but the photon collection efficiency is limited to about 10% to date [28, 29].

Here, we show a prototype of a fully fiber coupled solid-state resonantly pumped and transmission-based source of identical photons. Our fiber coupled single photon device is sketched in Fig. 1: The device consists of a layer of self-assembled InAs/GaAs QDs embedded in a micropillar Fabry–Perot cavity (maximum Purcell factor $F_p = 11.2$) grown by molecular beam epitaxy [30]. The QD layer is embedded in a P–I–N junction, separated by a 27 nm thick tunnel barrier from the electron reser-
voir to enable tuning of the QD resonance frequency by
the quantum-confined Stark effect. Since we do not use
air-guided micropillars but an oxide aperture for 3D con-
finement [31, 32], the device is very robust and the optical
or quantum dot properties do not degrade by attachment
of the fibers. It also allows for precise alignment of the
fibers, and therefore the use of single-mode fibers. This is
essential not only for integration in larger quantum net-
works, but also to enable high-fidelity polarization control
as we show here.

Single-mode fibers are attached to the front and back of
the sample using a UV-curable Norland optical adhesive
81. The collection fiber is aligned to the cavity mode by
making use of an inverted microscope. The sample is im-
age by sending through the fiber light from a Superlum
471-HP2 superluminescent diode with a broad (900-980
nm) spectrum. The micropillar trenches are observed with
a CCD camera allowing for coarse alignment of the fiber
to the center of the micropillar. Fine alignment is
done by bringing the fiber closer to the sample and
detecting the resonantly transmitted light with a 1 m
grating spectrometer. The optimal position is found by
maximizing the fundamental mode of the cavity and re-
ducing the transmission of the higher order modes. After
UV curing the optical adhesive at the fiber tip, the fiber
is attached to the copper mount with Stycast for stabil-
ity. The excitation fiber is aligned by sending broadband
light through the cavity via the now-attached collection
fiber, and by maximizing the signal (see Supplemental
Material [33] Section 7), confirming the high performance
of the fiber attachment method. The fiber at the back of the sample has a reduced incoupling ef-
iciency of 0.6% due to the thick GaAs substrate. For
operation of our single photon source this reduced cou-
pling efficiency is irrelevant because we excite the system
from the back where the coupling efficiency only affects
the required excitation laser power.

Now, we discuss the optical properties of the device, in
every experiments presented here we investigate resonance
fluorescence at a temperature of 5 K. The fundamental
mode is split in two linearly polarized modes, the
H and V mode, induced by a small ellipticity of the cav-
ity cross-section and material birefringence. Similarly,
the neutral exciton transition of the QD is split in two
linearly polarized transitions by the fine structure ex-
change interaction. Fig. 2a shows a false color plot of
the transmission as a function of the applied bias volt-
age and laser frequency. Using a free-space polarizer and
a fiber polarization controller, the input polarization is
set along the H cavity polarization axes. The transmit-
ted light is sent to a single photon detector. The two
fine structure split QD transitions are clearly visible as
dips in the transmission spectrum that shift as a func-
tion of the applied electric field. A cross sectional plot of
Fig. 2a (grey line) is shown in Fig. 2c (red line). The
depth of the dips indicate that the “X” QD transition
couples more efficiently to the H cavity mode than the
“Y” QD transition. This is confirmed by comparison to
a numerical model[35, 36] taking all relevant cavity-QED
and polarization effects into account (Supplemental Ma-
terial [33] Section 3). From this model we also determine
the angle $\theta$ between the X QD axis and the H cavity
mode axis to be $\theta = 17^\circ$, and the polarization splitting
of the fundamental cavity mode (18 GHz).

Fig. 2b and c (blue line) show single photons that are
filtered from the transmitted light with a combination of
a fiber polarization controller and a free-space optical po-
larizer set to extinguish the transmitted laser light (cross
polarization). We excite the system along the H cavity
mode polarization but detect only photons emitted from
the V-polarized cavity mode. This is ideal for efficient
collection of the single photons that are coherently scat-
tered from the Y-transition of the QD, as is seen in Fig.
2b. This is a workable scheme because for excitation of
the QD-cavity system, we can simply remedy the reduced

$$
\eta = \left( \frac{2\omega_{\text{fiber}} \omega_{\text{front}}}{\omega_{\text{fiber}}^2 + \omega_{\text{front}}^2} \right)^2 \exp \left( -\frac{2u^2}{\omega_{\text{fiber}}^2 + \omega_{\text{front}}^2} \right).
$$

Here, $u$ is the transverse misalignment. Setting $u = 0$
we obtain an optimal efficiency of $\eta_{\text{front}} = 90\% \pm 7.6\%$.
Experimentally, we obtain for our device a coupling effi-
 ciency that is very close to this value (85\%\%, see Sup-
plemental Material [33] Section 7), confirming the high
performance of the fiber attachment method. The fiber
at the back of the sample has a reduced incoupling ef-
iciency of 0.6% due to the thick GaAs substrate. For
operation of our single photon source this reduced cou-
pling efficiency is irrelevant because we excite the system
from the back where the coupling efficiency only affects
the required excitation laser power.

![Figure 1. Sketch of the micro-cavity quantum dot device with attached fibers from bottom (excitation fiber) and top (single photon collection fiber). The trenches are used for wet-chemical oxidation of a sacrificial AlAs layer to form an intra-cavity lens or aperture that leads to transverse confinement of the optical cavity mode.](image-url)
coupling of the Y QD transition to the H-polarized cavity mode by increasing the laser power, while the emitted single photons are efficiently collected by the V-polarized cavity mode. This also means that the Y QD transition is well suited to be used as a single photon source if it is resonantly excited, and, since the X transition can be neglected due to sufficient QD fine structure splitting, it resembles a nearly perfect two-level system.

We now investigate the dependency between maximum single photon rate and single photon purity that is achievable with the present device. For this, we first perform continuous-wave resonant spectroscopy experiments with a single frequency diode laser. We measure the second order correlation $g^2(\Delta \tau = 0)$ and the flux of emitted photons as a function of the incident laser power (Fig. 3a & b). In the correlation measurements, we observe a lower limit of $g^2(0) \approx 0.3$, which is due to limited timing accuracy due to detector jitter; this is confirmed by comparing to reference measurements using short laser pulses (see Supplemental Material [33] Section 4 for details). Further, we observe an increase in $g^2(0)$ with increasing laser power. Two-photon emission from a single quantum system should in principle be absent if it is excited with laser pulses much shorter than its lifetime. We suspect imperfect laser extinction, which should also be visible in the detected photon count rate, shown in Fig. 3b: instead of a simple saturation behavior of the count rate as a function of input laser power $P$, we observe an additional linear background. We find that the photon rate can very well be fitted (red line) by $96.0 \text{MHz}/(1 + 0.26 \text{nW}/P) + 3.39 \text{MHz} \cdot \text{nW}^{-1} \times P$, where the first part describes standard two-level system saturation [37] and is plotted separately with the grey line in Fig. 3b, and the saturation power agrees well to previous results on similar devices [38]. The power-linear term is most likely due to imperfect polarization extinction of the exciting laser light. These measurements show that good single-photon performance is expected for an input power well below a nW.

For quantum photonic applications, single photons are required on-demand with precise timing. We realize this using a resonant (around 932.58 nm) pulsed laser with
Figure 4. Photon correlations of the QD transition under pulsed excitation. (a): second-order correlation measurement, where $g^2(0) = 0.037$ is obtained from the integrated photon counts in the zero time delay peak divided by the average of the adjacent four peaks. (b): Photon indistinguishability measurement for consecutive photons 5.2 apart. A magnified view around $\Delta \tau = 0$ and a double exponential fit of this data is shown in (c). Taking into account $g^2(0) = 0.037$, we obtain a measured indistinguishability of $M = 0.90$. Measurement time: 600 s (a), 1200 s (b, c).

In conclusion, we have shown a prototype of a fully fiber coupled solid-state single photon source that produces on-demand single photons with a purity of $0.96 \pm 0.01$, indistinguishability of $0.90 \pm 0.05$ and a brightness of $0.05 \pm 0.01$, with fiber coupling efficiency of $0.85 \pm 0.11$. These figures are already promising for exploring small optical fiber based quantum networks such as for boson sampling. From another point of view, we have demonstrated a first all-fiber integrated cavity-QED based photonic quantum gate that filters out single photons from pulses of coherent laser light. A next step is charging...
of the QD with a single electron or hole spin to create a quantum memory [39] which makes the device usable as a quantum node for remote entanglement generation, quantum key distribution, and distributed quantum computation.

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[28] Muller, A., Flagg, E. B., Metcalfe, M., Lawall, J. & Solomon, G. S. Coupling an epistable quantum dot to


[33] See Supplemental Material at [URL will be inserted by publisher] for extended analysis.


