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Published in:
Nature Communications

DOI:
10.1038/s41467-020-17603-9

Publication date:
2020

Document version
Publisher's PDF, also known as Version of record

Document license:
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Citation for published version (APA):
Uppu, R., Eriksen, H. T., Thyrrestrup, H., Ugurlu, A. D., Wang, Y., Scholz, S., Wieck, A. D., Ludwig, A., Lobl, M. C., Warburton, R. J., Lodahl, P., Midolo, L., & Schröder, T. (2020). On-chip deterministic operation of quantum dots in dual-mode waveguides for a plug-and-play single-photon source. Nature Communications, 11(1), [3782]. https://doi.org/10.1038/s41467-020-17603-9
On-chip deterministic operation of quantum dots in dual-mode waveguides for a plug-and-play single-photon source

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A deterministic source of coherent single photons is an enabling device for quantum information processing. Quantum dots in nanophotonic structures have been employed as excellent sources of single photons with the promise of scaling up towards multiple photons and emitters. It remains a challenge to implement deterministic resonant optical excitation of the quantum dot required for generating coherent single photons, since residual light from the excitation laser should be suppressed without compromising source efficiency and scalability. Here, we present a planar nanophotonic circuit that enables deterministic pulsed resonant excitation of quantum dots using two orthogonal waveguide modes for separating the laser and the emitted photons. We report a coherent and stable single-photon source that simultaneously achieves high-purity ($g^{(2)}(0) = 0.020 \pm 0.005$), high-indistinguishability ($V = 96 \pm 2\%$), and >80% coupling efficiency into the waveguide. Such ‘plug-and-play’ single-photon source can be integrated with on-chip optical networks implementing photonic quantum processors.

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Photonics quantum information processing encompasses a wide array of emerging quantum technologies including quantum simulators\textsuperscript{1-3}, quantum key distribution\textsuperscript{4,5}, quantum Repeaters\textsuperscript{6,7}, and ultimately a full-fledged quantum Internet\textsuperscript{8,9}. Deterministic generation of coherent single photons is a key building block in realizing these technologies. Quantum dots (QDs) in nanophotonic structures are excellent sources of single photons\textsuperscript{10-12}, and planar waveguides are well suited for scaling up to multiple photons and emitters thanks to near-unity photon-emitter coupling\textsuperscript{15} and advanced on-chip functionalities\textsuperscript{16}. An ideal single-photon source requires suppressing noise and decoherence, which notably has been demonstrated in electrically contacted heterostructures\textsuperscript{17-20} through resonant optical excitation. However, resonant optical excitation is challenging to implement experimentally as it requires suppressing the excitation laser (same frequency as the QD emission) without affecting the source efficiency.

The conventional approach to pulsed resonant excitation of a QD employs a cross-polarized excitation-collection scheme\textsuperscript{10-12}, which inherently limits the collection efficiency of the generated single photons $\leq 50\%$. Recently, elliptical microcavities were proposed and tested to overcome this limit on efficiency\textsuperscript{14}, although this method is complicated by the need of controlling two narrow-band cavity resonances relative to the QD. In comparison, planar nanophotonic waveguides offer broadband and robust operation and are naturally suited for efficient laser suppression since the excitation laser and the collection mode can be spatially separated, allowing to construct devices with near-unity generation efficiency. However, resonant excitation of planar devices has so far relied on coupling the pump laser through leaky radiation mode\textsuperscript{19,21-23}, which results in high alignment sensitivity and possibly uncontrolled specular scattering.

In this work, we demonstrate a tailored nanophotonic circuit that enables resonant pulsed excitation launched through a grating coupler into a waveguide and subsequent out-coupling of highly coherent single photons from the chip with an additional grating coupler. The circuit distributes the excitation laser to the QDs and strongly suppresses the laser in collection, while maintaining $>80\%$ coupling efficiency of single photons. Importantly, as the laser is distributed through the waveguide mode, any QD coupled to the waveguide can be excited by the laser. The circuit realizes an input-output building block that could either be operated as a single-photon source by fiber coupling or integrated as a circuit element in a multiport optical network. The latter is a drop-in replacement of the commonly employed probabilistic photon sources in advanced photonic quantum processors\textsuperscript{3,24}, which will greatly benefit the scaling up towards multiphoton and multimitter quantum information processing\textsuperscript{25,26}.

Results

Operational principle of the single-photon source circuit. The operational principle of the device is presented in Fig. 1a. We design a two-mode nanophotonic waveguide where the embedded QD is efficiently coupled to the fundamental mode and weakly coupled to the first-order mode. The coupling of the QD to a waveguide mode is quantified through the $\beta$-factor. By selectively launching the laser into the first-order mode (excitation mode E), the QD is excited and the single-photon emission collected through the fundamental mode (collection mode C). In order to efficiently collect only the single photons, the residual excitation in laser mode E must be filtered out, while ensuring lossless propagation of mode C. An adiabatically tapered waveguide section is employed to satisfy these demands simultaneously. In the taper section, the E mode becomes leaky and is extinguished by the deliberate introduction of sharp waveguide bends. The adiabatic taper ensures the efficient transfer of the mode C into the single-mode regime that subsequently can be coupled into an optical fiber. We furthermore employ a one-dimensional photonic crystal as a backward reflector for single photons propagating in the mode C to maximize unidirectional out-coupling efficiency. A scanning electron microscopy image of the nanostructured device highlighting the three key elements of the device (photonic crystal, two-mode waveguide with emitters, and waveguide taper-based pump laser filter) is shown in Fig. 1b (see Supplementary Note 1 for the fabrication method). Three high-efficiency ( $>65\%$) grating couplers\textsuperscript{27} are fabricated for in-and out-coupling of light from free-space to the device.

The input excitation grating is connected to a 300-nm-wide single-mode waveguide, followed by a Y-splitter that launches the excitation laser into both the E and C modes of the two-mode waveguide\textsuperscript{28}. The Y-splitter together with the photonic crystal selectively prepares the modes of the excitation pulse (Supplementary Notes 2 and 3). The photonic-crystal section is a key design element of the device serving a dual purpose: (1) as a backward reflector for unidirectional collection of single-photon emission and (2) to selectively prepare the excitation laser in the mode E. It is designed such that it reflects the C mode and transmits the E mode into the emitter section of the waveguide. Figure 1c shows the measured transmission spectrum $T_p(\lambda)$ of the excitation laser through the device, which quantifies how well the residual excitation light can be suppressed. $T_p$ is extracted by comparing the transmitted laser intensity in two nominally similar devices with and without the photonic-crystal section. For reference, the calculated performance for an ideal device without any fabrication imperfections is shown in Fig. 1c, and remarkably ideal performance with $T_p \sim 10^{-5}$ is observed in certain wavelength bands. The minor deviations in the measurements from ideal performance can be attributed to an unintentional disorder in the nanostructured photonic crystal.

Pre-characterization of the device. In order to assess the performance of the device as a single-photon source, the laser suppression $T_p$ should be related to the single-photon emission probability. An essential figure-of-merit is the intensity of the residual pump intensity relative to the intensity of the emitted single-photon signal, i.e., the single-photon impurity $\xi$, which is the ratio of the number of laser photons to the single photons. $\xi$ is related to the measured second-order coherence function through $g^{(2)}(\tau = 0) = 2\xi - \xi^2$\textsuperscript{29}. We relate $\xi$ and $\xi$ as follows: the residual laser intensity at the out-coupling grating is given by $I_\text{p}T_p$, where $I_\text{p}$ is the input pump laser intensity. Under pulsed resonant excitation, we express the single-photon intensity at the collection grating as $I_\text{p} = \beta_\text{p}\beta_\text{c}I_\text{p}/2$, which is a simplified expression for clarity that holds below saturation of the QD and when omitting any effect of dephasing. The factor of 1/2 accounts for the power splitting of the excitation laser into the modes E and C at the Y-splitter. Supplementary Note 8 details the complete theory without these restrictions. $\beta_\text{p}$ and $\beta_\text{c}$ are the photon $\beta$-factors\textsuperscript{15} expressing the probability of the QD to absorb a pump photon and emit a single photon into the waveguide, respectively. Consequently we have

$$\xi = \frac{I_\text{p}T_p}{I_\text{p}} = \frac{2T_p}{\beta_\text{p}\beta_\text{c}}.$$  

(1)

The QD position affects the emitter-photon coupling $\beta_\text{c}$ and $\beta_\text{p}$ and therefore the value of $\xi$. Figure 2 (bottom panel) shows the calculated $\beta$-factors as a function of transverse offset from the waveguide center. A QD positioned exactly at the center of the waveguide maximally couples to $\beta_\text{c}$, but is not pumped by the
excitation laser and the excitation grating and collected at the detection grating.

emitter section within the spectral window where

parameters, (75 nm from the center). Given the spectral inhomogeneity of QDs, even better single-photon purity even when

the position that simultaneously minimizes the photon impurity

ξ

and maintains a high

β

C is seen in Fig. 2 for the measured device parameters, (\(T_p = 2 \cdot 10^{-5}\)). For a QD position where a high single-photon coupling efficiency of \(\beta_C \approx 0.9\) can be reached, we obtain \(\xi \approx 5 \cdot 10^{-4}\), which implies that \(g^{(2)}(0) \approx 10^{-3}\) can be achieved. We note that further reduction in \(T_p\), e.g., by optimizing the filter design or reducing fabrication disorder, could lead to even better single-photon purity even when \(\beta_C\) approaches unity.

From a practical standpoint, the probability of locating well-positioned QDs is dependent on the density of the QDs in the wafer and the length of the emitter section. The wafer employed in our measurements has a QD density of \(\approx 10^{12} \mu m^2\) with emitter section dimensions of 40 \(\mu m \times 0.45 \mu m\). From Fig. 2, we observe that \(\beta_C > 0.5\) requires that the QD is located within an offset of 75 nm from the center. Given the spectral inhomogeneity of QDs, we estimate to find around 10 QDs that are well-positioned in the emitter section within the spectral window where \(T_p < 10^{-4}\) (c.f. Supplementary Note 4 regarding QD selection in two devices).

We carried out resonance-fluorescence measurements on seven devices and found at least one QD per device with \(\beta_C \approx 0.8\).

Pulsed resonant excitation of a quantum dot. Experimental demonstration of waveguide-assisted pulsed resonant excitation of an optimally coupled QD was demonstrated on the device shown in Fig. 1b. Resonance-fluorescence measurement from a neutral exciton under continuous wave excitation is shown in Fig. 3a, which is carried out to identify QD resonances and demonstrate low-noise performance. We observe distinct QD resonances, free of excitation laser background (\(T_p = 2 \cdot 10^{-5}\)), with a linewidth of 800 MHz that tune with the applied bias voltage. The broadening of the QD resonances beyond the natural linewidth (250 MHz, as estimated from lifetime measurement) occurs primarily due to slow spectral diffusion (time scale of 10 ms), which is not relevant for pulsed operation and could be rectified by active feedback\(^{30,31}\). Deterministic pulsed resonant excitation is performed with 26 ps optical pulses tuned to the QD resonance. The observed Rabi oscillations of the detected intensity are shown in Fig. 3b that are modeled as a driven two-level system including minor pure dephasing, see Supplementary Note 8 for details of the model. The single-photon impurity \(\xi\) was extracted at each excitation power by comparing the detected intensity with the QD tuned on- and off-resonance by using the electrical control. The power-dependent \(\xi\) reflects the fact that the QD transition saturates when approaching \(\pi\)-pulse excitation while the residual laser background scales linearly with pump power, and this behavior is fully captured by the theoretical model, cf. Fig. 3b. The coupling efficiency of the QD emission to the waveguide, quantified through \(\beta_C\), is extracted by comparing the measured \(\xi(P \rightarrow 0) = 1.7 \cdot 10^{-3}\) and \(T_p = 2 \cdot 10^{-5}\) values with the calculations in Fig. 2. This comparison results in \(\beta_C = 0.8\), which corresponds to a QD position offset from center of the waveguide by \(\approx 20\) nm. Hence, the device enables 80% collection efficiency of the single photons into the waveguide while ensuring low laser background. At \(\pi\)-pulse, i.e., deterministic QD preparation, we find \(\xi = 0.004 (g^{(2)}(0) = 0.008)\). We detect a single-photon rate of 1.8 MHz, which is primarily limited by the
collection optics in the device characterization setup and can readily be improved further. Supplementary Note 5 presents a detailed description of the observed source efficiency that fully accounts for the independently measured parameters.

Single-photon source purity and indistinguishability. Having demonstrated pulsed resonant excitation through the waveguide mode, we proceed to the characterization of the quality of the single-photon source. Figure 3c shows the intensity-correlation histogram measured at π-pulse excitation using a Hanbury Brown and Twiss interferometer. A clearly suppressed peak at time delay τ = 0 ns is observed that is normalized to the long r limit to extract $g^2(\tau = 0) = 0.020 \pm 0.005$. The observed value of $g^2(\tau) = 0$ is higher than the expected value for the measured device parameters, which can be attributed to the temporal extent of the excitation laser pulses (26 ps) in comparison to the QD decay time (640 ps) that results in non-zero two-photon emission probability. We estimate that excitation laser with <3 ps pulse width would be required to reach $g^2(\tau = 0) = 0$ limited by the device. Even better performance could be achieved by reducing $T_p$ either by design or through an improvement in the fabrication. The current design enables $T_p = 10^{-6}$ (Fig. 1c) corresponding to $g^2(\tau) = 10^{-4}$, which approaches the best reported value in the literature obtained with two-photon resonant excitation, where pump filtering is not a challenge.

Most applications of single photons in quantum information require high indistinguishability of the photons, which we measure in a Hong–Ou–Mandel (HOM) experiment by interfering two subsequently emitted photons in an unbalanced fiber-based Mach–Zehnder interferometer, cf. Fig. 3d. Figure 3e shows the recorded correlation histogram between the two detectors, where the strong suppression of coincidences for zero detector time delay testifies the high degree of indistinguishability of the emitted photons. By controlling the polarization of the incoming photons, the reference case of fully distinguishable photons (perpendicular polarization case) is recorded and we extract the HOM interference visibility $V$ that quantifies the photon indistinguishability. We measure a raw visibility of $V_{\text{raw}} = (91 \pm 2)\%$, which, after correcting for the finite $g^2(\tau = 0)$ and setup imperfections corresponds to $V = (96 \pm 2)\%$ (see Supplementary Note 6 for details).

The measured indistinguishability is on par with the best reported value with cross-polarized resonant excitation and only superseded by experiments relying on excitation pulse-engineering.

Discussion
In conclusion, we have experimentally demonstrated an efficient waveguide circuit for deterministic pulsed resonant excitation of QDs embedded in planar photonic nanostructures. The circuit enables the realization of an efficient “plug-and-play” single-photon source featuring near-unity single-photon coupling, as well as high purity and indistinguishability. The robust excitation process implies that the device could be operated continuously without any realignment, and as a proof-of-concept we operated the source hands-free for over 110 h with <2% fluctuation in the generation rate (Supplementary Note 7). The circuit will also enable improving the collection efficiency for more advanced excitation schemes relying on dichromatic laser pulses, which are typically limited by low-efficiency spectral filters. Large Purcell enhancement of the radiative decay rate for overcoming residual decoherence and increasing the source repetition rate can also be achieved through a small modification of the circuit. The modified circuit includes an additional photonic crystal (same parameters as the first one) after the emitter section to form a standing-wave cavity for QD emission in mode C. An obvious next step is to implement direct chip-to-fiber coupling thereby circumventing the loss associated with collection, mode matching and subsequent fiber coupling. Another opportunity is to scale-up the circuit so that one excitation pulse could be pumping multiple QDs in parallel. In order to overcome the spectral inhomogeneity of QDs, such a device will require independent tunability of the different QDs to match the frequency of the excitation pulse. With such an approach with the circuit, the benefits of the scalable planar platform will be fully exploited in the ongoing pursuit of scaling up single-photon technology.

Methods
Experimental setup. In order to perform single-photon generation experiments, the sample is cooled to a temperature of 1.6 K in a closed-cycle cryostat with optical and electrical access. The excitation laser and the QD emission are focused and collected at the respective grating outcouplers (Fig. 1b) using a wide field-of-view microscope objective. A 20:80 (reflection:transmission) beam splitter is used to separate the

Fig. 3 Demonstration of pure and indistinguishable single photons by pulsed deterministic resonant excitation. a QD resonance-fluorescence intensity under cw laser excitation at a power of $P = 0.01 \cdot \text{P}_{\text{sat}}$ where $P_{\text{sat}}$ is the saturation power. b Power dependence of the resonance-fluorescence intensity and the photon impurity. The Rabi oscillations (red curve) of the two-level system are modeled including a pure dephasing rate of $\gamma_d = 0.2 \text{ ns}^{-1}$. c The intensity-correlation histogram in a Hanbury Brown and Twiss experiment for $\pi$ – pulse excitation. The second-order correlation function $g^2(0) = 0.020 \pm 0.005$ is extracted from the fitted amplitude of the central peak relative to the fitted amplitude for peaks at a time delay of 50 μs (dashed line). The inset shows $g^2(\tau)$ measured by integrating the coincidences under the peak over the 50 μs time span. d Schematic of the Hong–Ou–Mandel interferometer used for measuring the indistinguishability of two subsequent photons delayed by the laser pulse separation of 13.7 ns. e Coincidence counts after the Hong–Ou–Mandel interferometer when the input photons are co-polarized (blue) and cross-polarized (red).
excitation and collection into separate optical paths, with the high-efficiency path used for collection. The collected single-photon emission is coupled into a single-mode optical fiber and sent through a spectral filter constituting of an etalon (linewidth = 3 GHz; free spectral range = 100 GHz). The spectrally filtered single-photon stream can be directed to either a compact fiber-based unbalanced Mach–Zehnder for measuring two-photon interference or directly to a superconducting nanowire single-photon detector (SNSPD). The gate voltage across the QD is tuned using a low-noise voltage source with an RMS noise <0.1 μV, which corresponds to <0.1f, where Γ is the linewidth of the QD.

Samples. A scanning electron microscope image of the nanofabricated device with a footprint of 50 × 45 μm² is shown in Fig. 1b. The photonic-crystal section is a one-dimensional lattice of 40 air holes with radius of 70 nm and lattice spacing of 210 nm. The emitter section (450-nm-wide and 170-nm-thin suspended GaAs nanobeam waveguide) supports the two propagating modes E and C. Self-assembled indium arsenide (InAs) QDs, embedded in a p-i-n diode (see Supplementary Fig. 1 for details), are randomly located across the waveguide with an average density of 10^9 cm⁻². This density is high enough to comfortably find several QDs within the best laser suppression windows in all 20 fabricated devices. The suspended waveguide is electrically contacted (contacts not shown in the figure) to tune the QDs and to suppress noise leading to spectral drift. The pump laser filter is a 5-μm-long linear taper, which gradually reduces the waveguide width from 450 to 200 nm. Two consecutive 90° waveguide bends are introduced to further extinguish the weakly-guided E mode. These shallow-etched grating couplers are fabricated for in- and out-coupling of light from free-space to the waveguides. These gratings enable >65% collection efficiency of light in the C mode from the waveguide into a single-mode optical fiber27.

Data availability
The data are available from the corresponding authors upon reasonable request.

Code availability
COMSOL Multiphysics was used for designing the nanostucture. Data analysis was performed using MATLAB. The scripts are available from the corresponding authors upon reasonable request. Received: 25 April 2020; Accepted: 9 July 2020; Published online: 29 July 2020

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Acknowledgements
We gratefully acknowledge financial support from Danmarks Grundforskningsfond (DNRF) (Center for Hybrid Quantum Networks (Hy-Q)); H2020 European Research Council (ERC) (SCALE), Styrelsen for Forskning og Innovation (FI) (5072-00016B QUANTECH), Bundesministerium für Bildung und Forschung (BMBF) (16KIS0867, Q.Link.X), and Deutsche Forschungsgemeinschaft (DFG) (TRR 160).

Author contributions
R.U., H.A.E., and A.D.U. performed the experiments. H.T. and L.M. performed the numerical calculations for device design. Y.W. fabricated the device. A.L. and S.S. performed the heterostructure wafer growth with input from M.C.L., A.D.W., and R.J.W. R.U. and H.T analyzed the data. R.U., H.T., L.M., and P.I. wrote the manuscript with input from all co-authors. L.M., P.I., A.D.W., and R.J.W. supervised the project.

Competing interests
The authors declared a patent application related to this work (patent applicant: University of Copenhagen). Inventors: Leonardo Solmi, Ravi Lo Uppu, Henri Timmers, and Peter Lodahl; Application number: EP19218224; Status: submitted; the patent covers the method and optical circuit for in-plane waveguide-based resonance fluorescence). P.I. is founder of the company Sparrow Quantum that commercializes single-photon sources.
