Ultrafast all-optical switching by single photons

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An as yet outstanding goal in quantum optics is the realization of fast optical nonlinearities at the single-photon level. This would allow for the implementation of optical devices with new functionalities such as single-photon switches/transistors or controlled-phase gates. Although nonlinear optics effects at the single-emitter level have been demonstrated in a number of systems, none of these experiments showed single-photon switching on ultrafast timescales. Here, we perform pulsed two-colour spectroscopy and demonstrate that, in a strongly coupled quantum dot–cavity system, the presence of a single photon on one of the fundamental polariton transitions can turn on light scattering on a transition from the first to the second Jaynes–Cummings manifold. The overall switching time of this single-photon all-optical switch is ~50 ps. In addition, we use the single-photon nonlinearity to implement a pulse correlator. Our quantum dot–cavity system could form the building block of future high-bandwidth photonic networks.

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 durations. The difference signal is displayed in Fig. 2b as blue filled circles. Subtracting the two nonlinear responses in Fig. 2b from one another yields the fast nonlinear optical response from the strongly coupled QD–cavity system, as presented in Fig. 2c. The data show that the largest nonlinear effect occurs at the spectral position of the polaritons (vertical blue lines). Here, the change in the scattering rate induced by the control laser is negative (−15%) due to saturation of the corresponding transitions. At the transition wavelength from the first to the second manifold (vertical red line), this change is positive (−6%), because the absorption of the control photon enables the subsequent scattering of a signal photon. The relative increase in reflection signal is rather moderate due to the presence of the uncoupled cavity peak. In the absence of blinking and background laser light, we theoretically expect a switching contrast of 110%. In addition to the contribution from the transition of interest, we also observe a non-negligible positive response at slightly positive detunings, which we attribute to pure exciton dephasing (see section ‘Pure exciton dephasing’ in the Supplementary Information). To compare our experimental data with theoretical expectations, we performed numerical simulations based on a Monte Carlo wavefunction (MCWF) approach, with the experimental parameters as input and only the absolute amplitude of the nonlinear signal determined from a least-squares fit to the data (see section ‘Calculation of the optical non-linearity’ in the Supplementary Information). The excellent agreement between theory (black line) and experiment clearly demonstrates that the observed positive nonlinearity is indeed due to the two-colour transition to the second Jaynes–Cummings manifold, ensuring the single-photon nature of the observed nonlinearities. We emphasize here that, because of the finite linewidth of the coupled-system eigenstates as well as the finite bandwidth of the laser pulses, there is some overlap between transitions from the first to the second and from the second to the third manifold, and so forth. Hence, we expect a non-negligible contribution to the nonlinear signal stemming from states higher up in the Jaynes–Cummings ladder.

To demonstrate ultrafast switching by single photons—that is, conditional scattering of signal photons on ultrafast timescales—we varied the delay between control and signal pulses while recording the (positive) nonlinearity for fixed laser-detections. As depicted in Fig. 1b, the control pulse was chosen to be resonant with the fundamental upper polariton transition and the signal pulse to be

Figure 1 | A single-photon all-optical switch. a, A single control photon incident on the QD– cavity device determines whether a signal photon of different colour is scattered. b, Energy-level diagram of the strongly coupled QD– cavity system up to the second manifold of the anharmonic Jaynes–Cummings ladder. A single control photon on the upper polariton transition (UP) to the first manifold (|g⟩→|1, +⟩) changes the scattering rate of a second signal photon resonant with a transition from the first to the second manifold (|1, +⟩→|2, +⟩). c, Set-up for the demonstration of ultrafast single-photon-switch operation. The relative delay between signal and control pulses is adjusted by a continuous delay stage. In addition, a discrete delay line, corresponding to a time delay of ~5 ns, can be added to the path of the signal pulse using a fibre switch. The photons back-scattered from the QD–cavity system are detected by an avalanche photodiode (APD) in single-photon counting mode.

Figure 2 | Two-colour spectroscopy of the strongly coupled QD–cavity device. a, System response with (filled circles) and without (open circles) control laser present when scanning the signal laser across the QD–cavity spectrum for a cavity detuning of ~0.1ωcav. Pulse durations of both control and signal laser pulses were 86 ps. b, Nonlinear behaviour is observed for a time delay of 5 ns (blue filled circles) and 25 ps (red filled circles) between the control and signal pulses. c, Subtracting the red and blue data points of b from one another, we obtain the system nonlinearity due to the Jaynes–Cummings dynamics, which is taking place on ultrashort timescales. The red vertical line indicates the transition from the first to the second manifold (|1, +⟩→|2, +⟩). The positions of the fundamental polaritons are marked by blue vertical lines. In b and c, three adjacent data points were averaged. The black curve in c was obtained from a MCWF simulation of the system dynamics with the experimental parameters as input.
For average powers larger than 1 nW, the photon switch. As the data show, our single-photon switch combines both ultrafast turn-on and turn-off times, a combination that is typically hard to achieve in other quantum emitter–cavity systems. The strong nonlinearity of the QD–cavity system can be applied to measuring the number of signal photons scattered from the system as a function of input power of the control pulse. As expected, we observe an initial linear increase with control laser power, and then saturation of the polariton transition corresponding to a mean intracavity average photon (polariton) number of \( \approx 0.25 \) (0.5).

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At delay times longer than \( \approx 30 \) ps, the nonlinear signal of Fig. 3a exhibits a fast decay with a \( 1/e \) time of \( \approx 30 \) ps, close to the polariton lifetime of 25 ps, which in turn sets the fundamental limit for the turn-off time of our device. The asymmetry in the pulse-delay dependence is a direct consequence of the cascaded nature of the underlying two-photon transition (Fig. 1b) and is most pronounced for pulse durations on the order of the polariton lifetime.

As well as the switching speed, a quantity of interest is the transfer characteristic, that is, the output signal as a function of control power, which is plotted in Fig. 3b. Here, we recorded the number of signal photons scattered from the system as a function of input power of the control pulse. As expected, we observe an initial linear increase with control laser power, and then saturation of the polariton transition corresponding to a mean intracavity average photon (polariton) number of \( \approx 0.25 \) (0.5).

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pulse durations of ultrafast optical pulses down to the single-photon level. Pulse-correlator operation is demonstrated in Fig. 4, where the nonlinear system response is mapped as a function of pulse delay for pulse durations of 51 ps and 86 ps. Because the pulse durations are significantly longer than the polaron lifetime of 25 ps, the system response is more symmetric than was the case for the 33 ps pulses of Fig. 3a. We find good agreement between the pulse-delay–dependent nonlinearity and the numerical convolutions of the independently obtained streak camera images (red lines).

Figure 4c compares the full-width at half-maximum (FWHM) obtained from Monte Carlo simulations of the nonlinear system response with the FWHM of the incident (Gaussian) laser pulses. The red dashed line corresponds to the correlator width of the pulses. Above 50 ps, the deviation of the simulated width from this line is less than 5%, so in this range our device works nicely as a pulse correlator. Finally, we remark that single-photon switch and/or pulse-correlator operation can also be realized by centring the signal pulse on the other (lower) polaron transition, which yields a larger magnitude for the nonlinearity (Fig. 2c; see section ‘Cross-correlations of upper and lower polaritons’ in the Supplementary Information).

A natural extension of our work would be the realization of a single-photon transistor, in which the presence of a single control photon ($N_c = 1$) enables the scattering of $N_s \geq 2$ signal photons$^{1,2}$. A simple calculation shows that if pure dephasing was absent (see section ‘Transistor operation’ in the Supplementary Information), our QD-cavity device would exhibit a modest gain of $G = N_s/N_c > 2$. While increasing the ratio $g/\kappa$ will already increase $G$, high-gain ($G \gg 1$) transistors may be realized in combination with electromagnetically induced transparency (EIT) schemes$^{26–29}$. Finally, combining our device with state-of-the-art waveguide technology$^{30–38}$ and implementing QD charge control using p–i–n structures$^{39}$ to suppress blinking would enable high-contrast all-optical switching of single-photon pulses. This might enable the demonstration of the preservation of quantum coherence during the nonlinear interaction, which in turn could pave the way for the realization of an ultrafast controlled-phase gate between two single-photon pulses$^\circ$

After submission of this work, we became aware of two recent papers reporting on related experiments$^{31,32}$.

Methods

Pulse preparation. Both control and signal laser pulses were derived from the same mode-locked Ti:sapphire laser with a pulse repetition rate of 76.3 MHz and an intrinsic pulse width of a few picoseconds. The laser pulses were sent through a grating spectrometer for frequency filtering and split by a 50/50 beamsplitter. Both beams were then coupled into single-mode optical fibres. The resulting spectral width of the pulses could be adjusted from 0.04 nm to 0.015 nm by an additional slit in front of the spectrometer that determines the effective numerical aperture of the spectrometer. The pulses were nearly Fourier-limited, so we could adjust the pulse duration from ~33 ps to 86 ps. The central frequency of the signal pulse was mechanically tuned using a piezo-driven mirror holder in front of the fibre coupler, enabling coupling of different parts of the spectrum into the fibre. The central frequency of the pulse was monitored using a wavemeter, and a computer-controlled feedback loop allowed tuning. The average power of both control and signal laser beams was stabilized using acousto-optical modulators. The relative delay of the two pulses was adjusted using a motorized delay stage. Pulse shapes and delays were monitored by sending the light reflected from the sample surface to a streak camera with a time resolution of ~4 ps.

Extraction of the optical nonlinearity. When applying both a control pulse at time $t$ and a signal pulse at time $t + \tau$ to the system, the time-integrated response can be written as $N_{\text{signal}}(\tau) = N_{\text{control}} + N_{\text{signal}} + N_{\text{blinking}}$, where $N_{\text{control}}$ and $N_{\text{signal}}$ denote the number of scattered photons when only a control or signal laser, respectively, are applied. $N_{\text{blinking}}$ is the total optical nonlinearity, quantified as the number of additional scattered photons. Its origin is twofold—a fast (approximately picosecond) contribution arising from the anharmonicity of the Jaynes–Cummings ladder (JC) and a slow (approximately microsecond) contribution stemming from charge blinking—so $N_{\text{blinking}} = N_{\text{JC}}(\tau) + N_{\text{blinking}}(\tau)$. If we choose an intermediate timescale $\tau_{\text{int}}$ on the order of nanoseconds, such that $ps \ll \tau_{\text{int}} \ll \mu s$, then $N_{\text{JC}}(\tau_{\text{int}}) = 0$. For $\tau \gg \mu s$, $N_{\text{blinking}}(\tau_{\text{int}})$ and

$$N_{\text{blinking}}(\tau) = N_s(\tau) - N_{\text{control}}(\tau)$$

where

$$N_{\text{control}}(\tau) = N_{\text{both}}(\tau) - N_{\text{signal}}$$

To determine $N_{\text{blinking}}(\tau)$, we chose $\tau_{\text{int}} \approx 5 \text{ ns}$ by switching an additional delay line into the path of the signal laser. To eliminate long-time drifts we simultaneously measured $N_{\text{both}}(\tau)$, $N_{\text{control}}$ and $N_{\text{signal}}$ by switching the control and signal lasers on and off at 5 kHz and 10 kHz, respectively, and sorting the output photons accordingly.

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Author contributions
T.V. and A.R. conducted the experiments, analysed the data and performed the simulations. M.W. made essential contributions to the experiment in its early stages. A.B., K.J.H. and E.L.H. fabricated the structure that ensures maximal dot cavity coupling. T.V., A.R. and A.I. conceived the experiment, discussed the results and wrote the manuscript.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permission information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to T.V. and A.I.

Competing financial interests
The authors declare no competing financial interests.