All-Optical Switch and Transistor Gated by One Stored Photon

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The realization of an all-optical transistor, in which one “gate” photon controls a “source” light beam, is a long-standing goal in optics. By stopping a light pulse in an atomic ensemble contained inside an optical resonator, we realized a device in which one stored gate photon controls the resonator transmission of subsequently applied source photons. A weak gate pulse induces bimodal transmission distribution, corresponding to zero and one gate photons. One stored gate photon produces fivefold source attenuation and can be retrieved from the atomic ensemble after switching more than one source photon. Without retrieval, one stored gate photon can switch several hundred source photons. With improved storage and retrieval efficiency, our work may enable various new applications, including photonic quantum gates and deterministic multiphoton entanglement.

Photons are excellent carriers of quantum information, but it is difficult to induce the strong interactions between individual photons that are required for, for example, all-optical quantum information processing. Nevertheless, advances toward such interactions have been made in cavity quantum electrodynamics (QED) systems with atoms (1–6) or artificial atoms (7–11) and in a cavity-free system by using atomic Rydberg states (12, 13) or dye molecules (14). All-optical switching of one beam by another (15) and cross-phase modulation (16) have been demonstrated at the level of a few hundred photons by means of electromagnetically induced transparency (EIT) (17–21). At the few-photon level, nonclassical light has been generated (1, 4, 6–9, 11–13, 22), and optical nonlinearity of 16° in phase shift (23) and up to ∼20% in two-photon attenuation (5, 9, 10) have been observed in cavity QED systems. Although switching of the cavity transmission by a single atom has also been achieved (24), the realization of an optical transistor exhibiting gain with gate signals at the few- or one-photon level (25) remains a challenge.

We demonstrate a cavity QED version (18) of an optical switch (25) based on EIT in a four-level system (17–19) in which the collective atomic excitation associated with the storage of one gate photon (20, 26, 27) blocks the resonator transmission. Our system (5) consists of an ensemble of laser-cooled cesium atoms optically trapped inside a high-finesse optical cavity (Fig. 1A) operating in the strong-coupling regime (1–6) of cavity QED. Each atom has a four-state N-type level structure (|g⟩→|d⟩→|s⟩→|e⟩) with two stable ground states, |g⟩ and |s⟩, and two electronic excited states, |d⟩ and |e⟩ (Fig. 1B). For atoms prepared in state |g⟩, this atomic structure mediates an effective interaction between free-space photons (photons resonant with the |g⟩→|d⟩ transition serving as gate photons) and cavity photons (photons resonant with the |s⟩→|e⟩ transition serving as the source) (17–19). These two transitions are connected via a control laser that addresses the |d⟩→|s⟩ transition and induces transparency (EIT) for the gate photons. By ramping the control laser power down to zero, we stored a weak gate pulse inside the atomic ensemble (Fig. 1B) and retrieved it at a later time by adiabatically reapplying the control beam (Fig. 1D) (20, 26, 27). In between storage and retrieval, we applied a source beam (Fig. 1C). The atomic population in state |s⟩, associated with the stored gate pulse can block the transmission of the source pulse through the cavity (24). Because of the finite optical depth (OD) of the ensemble (OD ≤ 0.9) and suboptimal control waveform (28), 1 out of 5 to 10 incident gate photons is stored.

We first characterized the cavity transmission without gate photon retrieval. To this end, we measured the average cavity transmission spectrum for different mean stored gate photon numbers ⟨n⟩ (Fig. 2). Because the gate pulses are weak classical pulses (coherent states), they are associated with Poissonian distributions in photon number n_{ph}, and there is a finite probability p(0) = e^{-n_{ph}} that the stored gate pulse does not contain any photons. Therefore, even if one photon were to perfectly switch off the source beam, there is a maximum average switching contrast 1 - e^{-n_{ph}} for measurements with coherent states of gate photons (Fig. 2, inset, solid line). The measured data points lie close to the maximum possible switching contrast and within the theoretically expected range (Fig. 2, gray area).

The photon number quantization of the gate pulse and the cavity blocking by just one gate photon are evident when we plot histograms of transmission spectra (Fig. 3) instead of the average transmission. The histogram shows two clearly separated components (Fig. 3B), where the high-transmission component corresponds to n_{ph} = 0, whereas the low-transmission component corresponds to n_{ph} ≥ 1 (mostly n_{ph} = 1 gate photons). The high-to-low peak transmission ratio gives an extinction factor for one stored gate photon of T^{-1} = 11 ± 1.

In order to characterize the optical gain of the system, we measured the distribution of the

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transmitted source photon number, \( M_s = \int_{-\infty}^{\infty} dt \, m_s(t) \) \( \kappa \), on cavity resonance. Here, \( m_s(t) \) is the intracavity photon number at time \( t \), \( \kappa \) is the cavity linewidth, and \( \frac{\kappa}{2T} = 0.66 \) (with cavity mirror transmission \( T \) and mirror loss \( L \)) accounts for the outcoupling efficiency of an intracavity photon. \( M_s \) can be determined from the detected photon number and the independently measured detection-path efficiency \((29)\).

As shown in Fig. 4A, the distribution is double peaked, with the high-transmission peak with the corresponding no gate photon, whereas the gray area responds to the outcoupling efficiency of an intracavity photon. Counts for the outcoupling efficiency of an intracavity photon.

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Fig. 4. Measurement of transistor gain. (A) Histogram of the integrated source photon number $M_s$ in a 50-μs window. The graph shows $M_s$ for no applied gate photon ($n_g = 0$, open red circles) with a Poissonian fit and for a coherent state with $(n_g) = 0.4$ stored gate photons (solid black circles). The gray area indicates the contribution from events with $n_g \geq 1$, with average value denoted by $(M_s | n_g \geq 1)$. (B) Transistor gain $G = (M_s | n_g = 0) - (M_s | n_g \geq 1)$ as a function of source strength $(M_s | n_g \geq 1)$ for integration times of 25 μs (solid black circles) and 50 μs (open red circles), with a linear fit to the first nine data points (black dashed line) and with exponential fit for gain saturation (red line). (C) and (D) Timing sequence for retrieval operation with (C) input pulses and (D) output pulses. (The actual gate, control, and source beam waveforms are shown, but relative powers are not to scale.) First, the control beam is adiabatically ramped down at $t = 0$ in order to store a gate photon in the atomic medium. Then, a source pulse is sent onto the cavity, and its transmission is measured. Subsequently, the control beam is adiabatically ramped up in order to retrieve and detect the gate photon. The combined storage and retrieval efficiency in the absence of source light after a storage time of 1 μs is $(3.0 \pm 0.1)\%$. (E) Measurement of transistor gain in retrieval mode. The average fractional retrieval efficiency of the gate photon after 1 μs is plotted versus $(M_s | n_g = 0)$ with an exponential fit. The fitted source photon number resulting in $e^{-1}$ reduction is $M_{01} = 1.9 \pm 0.1$ outside of the cavity $M_{01} = 2.8 \pm 0.2$ before out-coupling losses, which is in good agreement with the theoretical value $2.8 \pm 0.1$.

The present work opens up new perspectives for all-optical information processing with strong deterministic interactions between initially uncorrelated, distinguishable photons. The gain $G_s > 1$ in operation with gate photon retrieval may enable not only hitherto unexplored all-optical quantum circuits with feedback and gain, but also the nondestructive detection of the gate photon—a feat that has so far only been accomplished for microwave photons confined in a cavity (31). The correlations between one gate and multiple source photons produced by the effective photon-photon interaction can be used to create two-mode entangled states of many photons. Last, cavities with larger cooperativity (1–4) may enable high-fidelity deterministic photonic quantum gates.

References and Notes
29. Materials and methods are available as supplementary materials on Science Online.

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Supplementary Materials www.sciencemag.org/cgi/content/full/science.1238169/DC1 Materials and Methods Supplementary Text Fig. S1 Table S1 References and Notes 22 March 2013; accepted 24 June 2013 Published online 4 July 2013. 10.1126/science.1238169