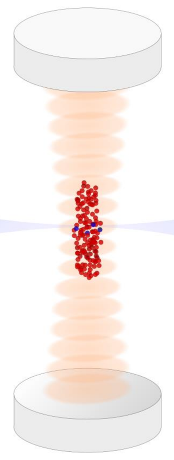

All-Optical Switch and Transistor Gated by One Stored Photon

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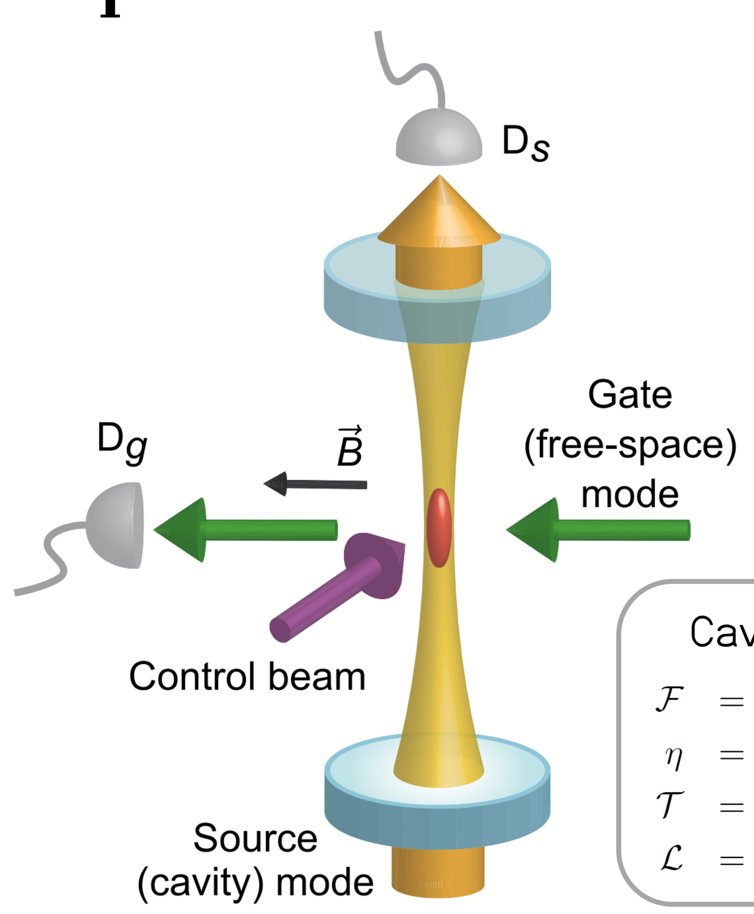
Overview

An all-optical transistor where one 'gate' photon controls the propagation of a 'source' light beam, is a long-standing goal in optics. By reversibly stopping a light pulse in an atomic ensemble contained inside an optical resonator, we realize a device in which one stored gate photon controls the resonator transmission of subsequently applied source photons. With improved storage and retrieval efficiency, our work may enable various new applications, including photonic quantum gates, and deterministic multiphoton entanglement.

Experimental setup



Cavity parameters

$\mathcal{F}$	=	$(7.71 \pm 0.05) \times 10^4$
η	=	$4g^2/\kappa\Gamma = 4.3 \pm 0.2$
$\mathcal{T}$	=	27 ppm
$\mathcal{L}$	=	14 ppm

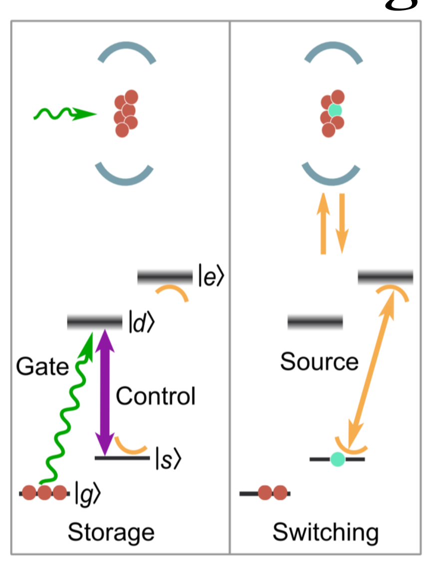
Preparation:

We prepare several hundred ^{133}Cs atoms in the TEM00 mode of a high finesse optical cavity by loading from a MOT into a dipole trap formed along the cavity axis by a strong off-resonant beam. We can efficiently address the atoms using a tightly focused gate beam, for which the ensemble has optical density ≥ 0.9. We remove atoms outside this beam. Remaining atoms are optically pumped into state $|g\rangle = |6S_{1/2}, F=3, m_F=3\rangle$.

Mechanism:

Our scheme is a cavity QED version of an optical switch based on EIT in a four-level system [1] where the collective atomic excitation associated with the storage of one gate photon blocks the resonator transmission.

Large $\langle n_g \rangle$ operation

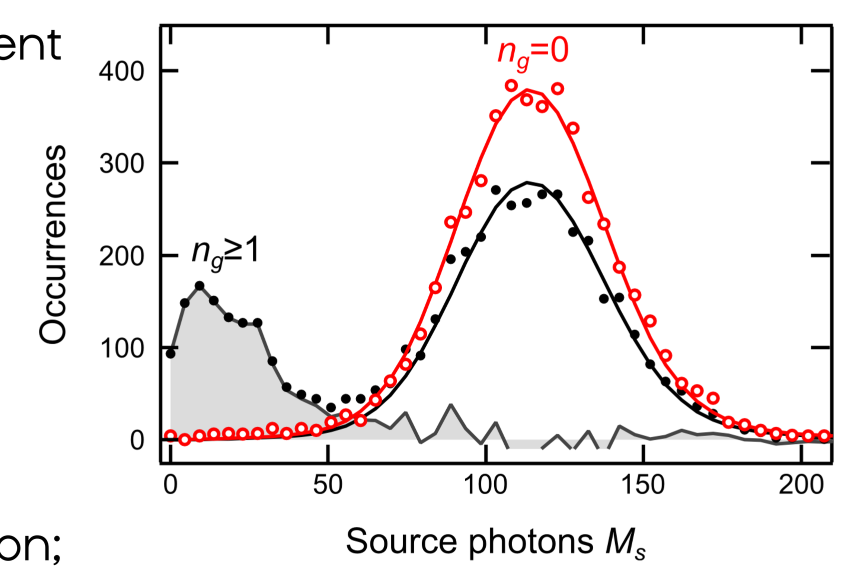


$|g\rangle = |6S_{1/2}, F=3, m_F=3\rangle$
$|d\rangle = |6P_{3/2}, 4, 4\rangle$
$|s\rangle = |6S_{1/2}, 4, 4\rangle$
$|e\rangle = |6P_{3/2}, 5, 5\rangle$

We first store a weak gate pulse inside the atomic ensemble. (Only one out of 5 to 10 incident gate photons is stored.) Then, we apply a source beam for up to 50μs. The atomic population in state |s⟩ associated with one stored gate photon blocks the transmission of the source pulse through the cavity by a factor of $(1+\eta)^2$ [2]. We measure transmission reduction by a factor of up to 11.

Cavity transmission

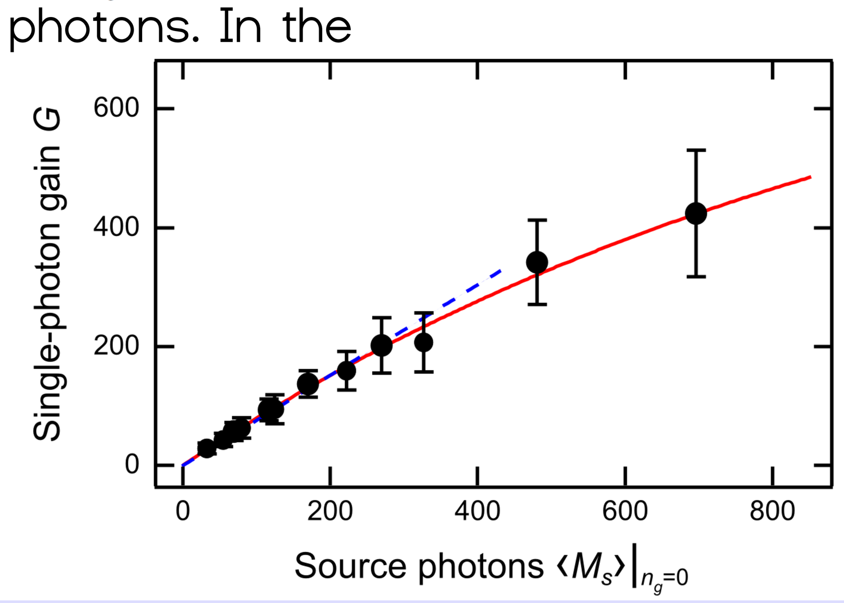
A weak coherent pulse has 0- and 1- photon components. These two separate components are visible in the transmission; individual measurements show either high or low transmission, but not intermediate values.



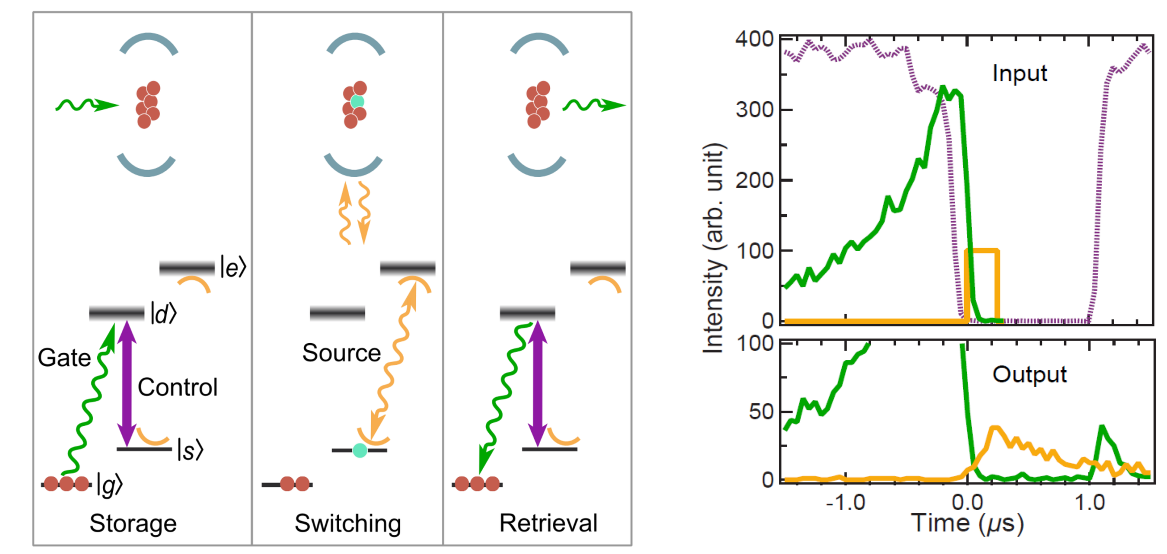
Classical gain

For the all-optical transistor, the gain is the difference in transmitted source photons in the cavity per stored gate photon

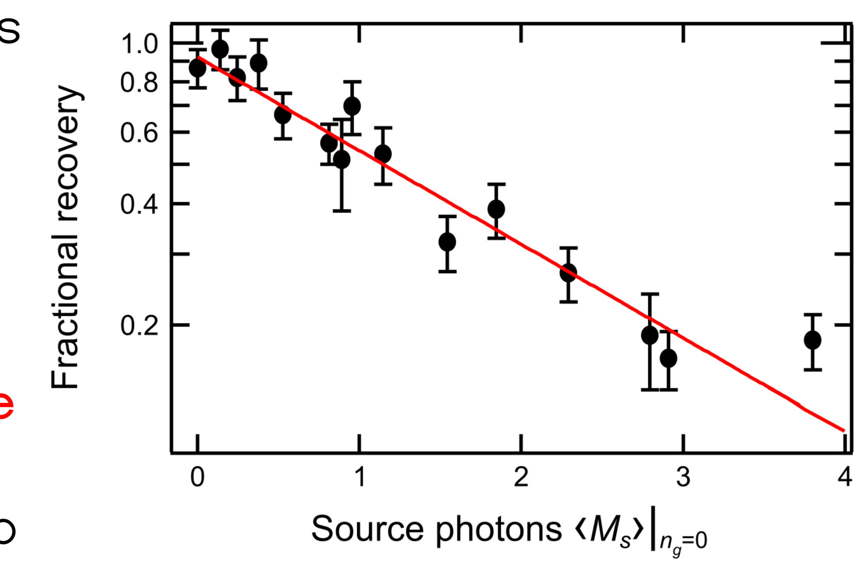
$G = \langle M_s \rangle|_{n_g=0} - \langle M_s \rangle|_{n_g=1}$ as determined by histograms of transmitted photons. In the classical regime, we observe gains higher than 500, limited by depolarization of the sample.



Operation with retrieval



When the source integration time is shorter than the stored gate photon lifetime of (2.1 ± 0.1) μs, we can recover the gate photon into the original mode by reading out the stored photon by adiabatically re-applying the control beam. The gate photon is stored as a collective excitation [3], which is maintained until a source photon is scattered into free space, collapsing the collective excitation to a single-atom excitation in state |s⟩. The scattering probability per source photon is $2\eta/(1+\eta)^2$ [2]. The measured fractional recovery of the gate photon drops to 1/e at $\langle M_s \rangle|_{ng=0}$=1.9±0.1 (2.8±0.2 without cavity outcoupling loss).



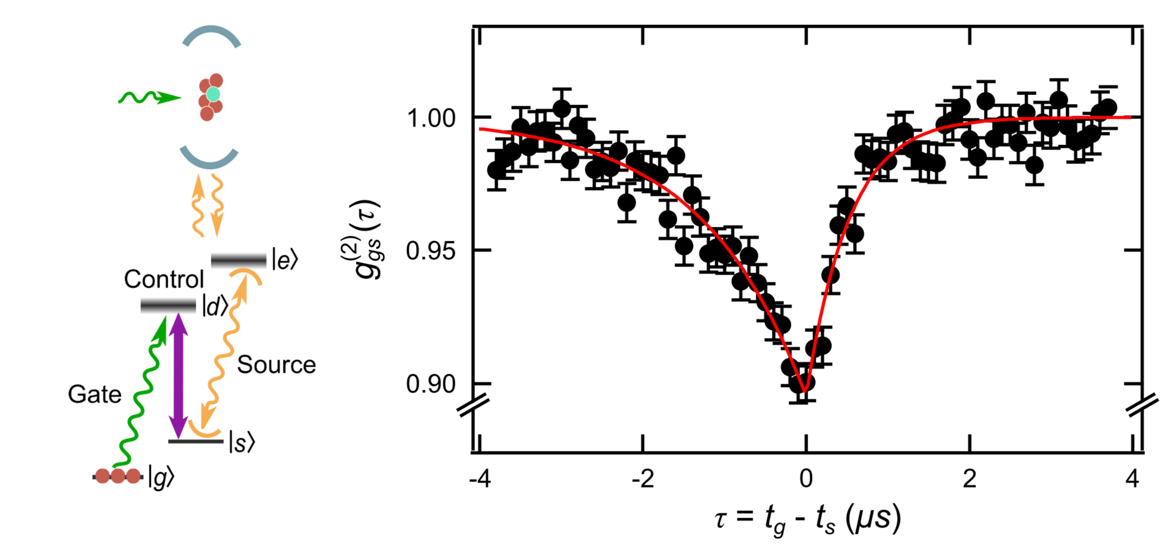
Anticorrelation of output

With low average photon numbers in both the gate and source paths, we can directly measure the cavity transmission conditioned on the presence of a gate photon through the gate-source cross-correlation function, $g^{(2)}_{gs} = \langle n_g n_s \rangle / (\langle n_g \rangle \langle n_s \rangle)$. The measured $g^{(2)}_{gs}$ is 0.29±0.09; after correcting for backgrounds, $\bar{g}^{(2)}_{gs}$ is 0.17±0.08.

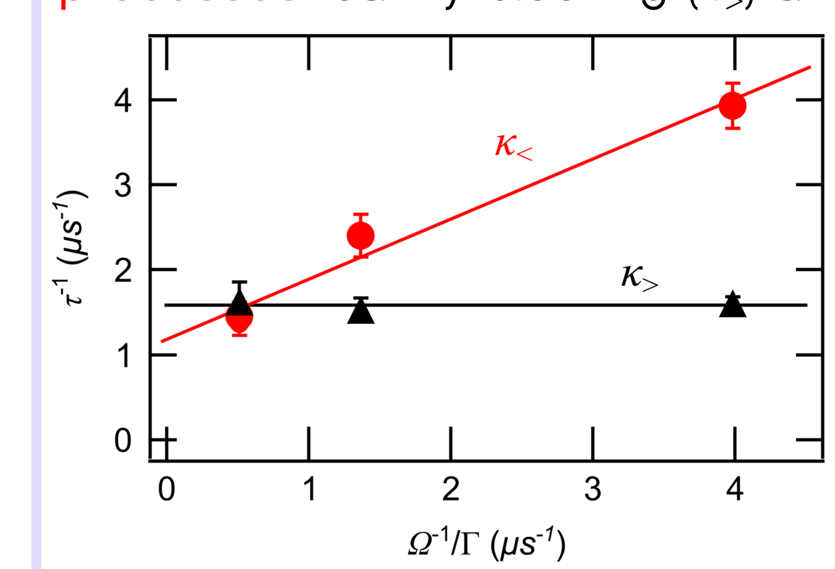
Retrieval gain

At the 1/e photon number, the gain with retrieval is 1.4±0.1 (2.2±0.2 without outcoupling loss).

Continuous operation



In continuous operation, both the source and gate photons are applied simultaneously. Here, we measure the anticorrelation the system produces in the originally uncorrelated beams as a function of the time separation between of output photons, τ. This anticorrelation is due to two separate processes: cavity blocking ($\kappa_>$) and decoherence of the polariton by the cavity field ($\kappa_<$). This second time constant can be changed experimentally by the control beam power.



Outlook

This all-optical transistor opens new possibilities for all-optical processing and non-classical state generation. Future directions include:

- Improving system incoupling and outcoupling efficiencies will make a transistor that is gated by one input photon (as opposed to one stored photon).
- Retrieval gain allows for the investigation of all-optical quantum circuits with feedback and gain, non-destructive single photon detection for optical photons and the creation of two-mode entangled states of many photons.

[1] H. Schmidt, A. Imamoğlu, *Opt. Lett.* **21**, 1936 (1996); A. Imamoğlu, H. Schmidt, G. Woods, M. Deutsch, *Phys. Rev. Lett.* **79**, 1467 (1997); S. Harris, Y. Yamamoto, *Phys. Rev. Lett.* **81**, 3611 (1998).
[2] H. Tanji-Suzuki, *et al.*, *Adv. At. Mol Opt.* **60**, 201 (2011).
[3] M. Fleischhauer, M. D. Lukin, *Phys. Rev. Lett.* **84**, 5094 (2000).