Coherent Logic Gate for Light Pulses Based on Storage in a Bose-Einstein Condensate

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A classical logic gate connecting input and output light pulses is demonstrated. The gate operation is based on three steps: First, two incoming light pulses are stored in a Bose-Einstein condensate; second, atomic four-wave mixing generates a new matter wave; and third, the light pulses are retrieved. In the presence of the new matter wave, the retrieval generates a new optical wave. The latter will only be generated if both input light pulses are applied, thus realizing an AND gate. Finally, we show that the gate operation is phase coherent, an essential prerequisite for a quantum logic gate.

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Single photons are well suited for quantum communication over long distances. To perform quantum information processing with single photons, however, one must find a physical process in which a single photon drastically alters some property of another single photon. This is a major challenge because in traditional nonlinear optical media the nonlinearities are much too weak to generate an appreciable effect on the single-photon level. Several techniques for addressing this problem have been proposed and are being pursued experimentally, namely, the use of atoms in optical resonators [1–3], the use of additional light to drive Raman transitions in atoms [3–5], and the use of the dipole-dipole interaction between Rydberg atoms [6–8].

Here we present a first experiment that explores the avenue of generating a logic gate for classical light pulses by temporarily converting the light pulses into atomic excitations in a Bose-Einstein condensate (BEC) and using s-wave collisions between pairs of ground-state atoms. These collisions are responsible for the appearance of the nonlinear term in the Gross-Pitaevskii (GP) equation. In the context of quantum information processing, they have been used to generate massive entanglement between many atoms [9] but not to generate a logic gate for light pulses. In addition, we demonstrate that the gate operation is phase coherent, an essential prerequisite for a quantum logic gate.

We use a geometry in which the nonlinearity of the GP equation creates a new atomic momentum component by four-wave mixing (FWM) of matter waves [10–13] involving two spin states [14,15]. Upon mapping the new atomic momentum component back onto light, it creates population in a new optical momentum component. This light emission process is accompanied by Raman amplification of matter waves (AMW) [16,17]. The light emitted during Raman AMW and the phase coherence of this light have never been studied experimentally, despite related work in atomic FWM [18], Rayleigh AMW [19,20], and superradiant light scattering [21,22].

A scheme of our experiment is shown in Fig. 1. The ^{87}Rb hyperfine states $|1\rangle = |F = 1\rangle$ and $|2\rangle = |F = 2\rangle$ of the $5S_{1/2}$ ground state together with the $|e\rangle = |5P_{1/2}\rangle$ excited state, each with $m_F = -1$, form a Λ scheme in which Raman transitions are driven. More precisely, the Raman light fields are tuned to the two-photon resonance with the single-photon detuning chosen exactly midway between the $|1'\rangle = |F' = 1\rangle$ and $|2'\rangle = |F' = 2\rangle$ components of the excited state $|e\rangle$.

Initially, a BEC with $N \sim 1.5 \times 10^6$ atoms is prepared in an optical dipole trap with measured trap frequencies of $(\omega_x, \omega_y, \omega_z) = 2\pi \times (70, 20, 20)$ Hz, in internal state $|1\rangle$, and at zero momentum, which we denote as $|1, 0\rangle$. A magnetic hold field of $\sim$1 G is applied along the z axis (orthogonal to the plane shown in Fig. 1) to preserve the atomic spin orientation. All light fields applied in the experiment drive π transitions.

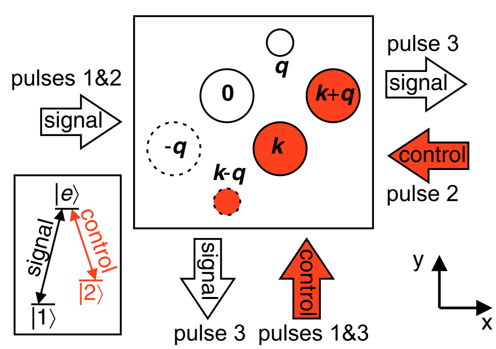

FIG. 1 (color online). Scheme of the experimental procedure. Two Raman pulses are applied, preparing three BECs with momenta $\mathbf{0}$, $\boldsymbol{k}$, and $\boldsymbol{k} + \boldsymbol{q}$. During a subsequent dark time, atomic FWM creates a BEC with momentum $\boldsymbol{q}$. Arrows show the propagation directions of the light beams. Circles represent atomic momentum components. The internal state is color coded: white denotes $|1\rangle$, gray (red) denotes $|2\rangle$. A third light pulse with only control light applied retrieves the signal light. The retrieved light will have a component propagating downward only if signal light is applied during both Raman pulses, thus realizing an AND gate. A modified state preparation can additionally populate the momentum component $-\boldsymbol{q}$ so that atomic FWM also populates $\boldsymbol{k} - \boldsymbol{q}$. This extended scheme, in which the dashed circles are populated, generates a time-dependent interference pattern in the retrieved light.

After preparation, the BEC is illuminated by a Raman pulse, consisting of signal light with wave vector $\boldsymbol{k}_s$, propagating rightward in Fig. 1, and control light with wave vector $\boldsymbol{k}_{c1}$, propagating upward. Signal light is absorbed and coherently stored in the atomic state $|2, \boldsymbol{k}\rangle$ with internal state $|2\rangle$ and wave vector $\boldsymbol{k} = \boldsymbol{k}_s - \boldsymbol{k}_{c1}$. The pulse area of the Raman pulse is chosen such that $\sim 1/3$ of the atomic population is transferred to state $|2, \boldsymbol{k}\rangle$.

Immediately thereafter, a second Raman pulse is applied with the direction of the signal light as before, but now with the control light propagating leftward with wave vector $\boldsymbol{k}_{c2}$. During this pulse, signal photons are absorbed and stored in state $|2, \boldsymbol{k} + \boldsymbol{q}\rangle$ with $\boldsymbol{q} = \boldsymbol{k}_s - \boldsymbol{k}_{c2} - \boldsymbol{k}$ [23]. This Raman pulse has a duration of ~ 100 μs. The pulse area of $\sim \pi/2$ yields equal populations of states $|1, 0\rangle$, $|2, \boldsymbol{k}\rangle$, and $|2, \boldsymbol{k} + \boldsymbol{q}\rangle$.

In principle, the second Raman pulse could simultaneously drive a second process in which population is transferred from state $|2, \boldsymbol{k}\rangle$ to state $|1, -\boldsymbol{q}\rangle$. In practice, however, the nonzero initial momentum creates a Doppler shift for the resonance frequency of this process. By fine-tuning the two-photon detuning we resonantly drive the $|1, 0\rangle \rightarrow |2, \boldsymbol{k} + \boldsymbol{q}\rangle$ processes and drastically suppress the $|2, \boldsymbol{k}\rangle \rightarrow |1, -\boldsymbol{q}\rangle$ process. The pulse is long enough to make interaction-time broadening small compared to the energy splitting between the two resonances frequencies.

During the following dark time, with duration t_{FWM}, atomic FWM with two internal states populates the state $|1, \boldsymbol{q}\rangle$. The FWM can be understood intuitively as an atomic scattering process. An atom in state $|1, 0\rangle$ collides with an atom in state $|2, \boldsymbol{k} + \boldsymbol{q}\rangle$. The existing BEC in state $|2, \boldsymbol{k}\rangle$ creates bosonic enhancement for one atom to emerge in this state. Conservation of momentum and of the internal-state energy makes the other atom appear in state $|1, \boldsymbol{q}\rangle$. In addition, conservation of kinetic energy requires $\boldsymbol{k} \cdot \boldsymbol{q} \sim 0$ [11,12]. Note that the FWM process in our experiment is clearly distinguishable from spin exchange, unlike the only previous experiment on atomic FWM with two internal states [15]. The Bose-enhanced creation of other atomic momentum components $|1, n\boldsymbol{q}\rangle$ and $|2, \boldsymbol{k} + n\boldsymbol{q}\rangle$ with integer n would conserve momentum but not kinetic energy and is therefore negligible. The FWM occurs inside the optical dipole trap in order to avoid a slowdown of the FWM due to the reduced density in a mean-field-driven expansion.

To test whether atomic FWM occurs in our experiment, we study time-of-flight absorption images. The inset in Fig. 2 shows such an image. Four atomic momentum components are clearly distinguishable. The additional tiny signal in the bottom left corner shows that the process populating state $|1, -\boldsymbol{q}\rangle$ during the second Raman pulse is suppressed drastically but not completely.

To confirm that the atom number N_q in the momentum component $|1, \boldsymbol{q}\rangle$ is actually generated by FWM, we study its temporal growth. To avoid FWM during the time of flight, we abort the FWM by applying an 8 μs pulse of depletion light [23], 65 MHz blue detuned from the $|2\rangle \leftrightarrow |1'\rangle$ transition, immediately before release from the dipole trap. The atom number N_q extracted from time-of-flight images taken after applying depletion light is shown in Fig. 2. For short times, N_q displays a quadratic growth with time, as expected for FWM. For longer times, N_q saturates because the different momentum components no longer overlap spatially. The line shows a fit to the data, where the observed time scales for the initial growth and for the saturation agree fairly well with theory [23].

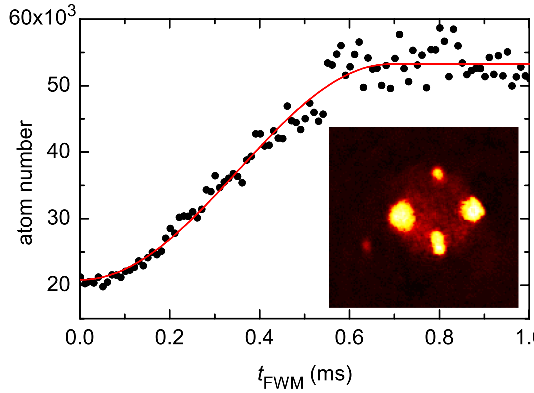

FIG. 2 (color online). Atomic four-wave mixing. The atom number N_q in the atomic momentum component $\boldsymbol{q}$ is extracted from time-of-flight absorption images. N_q depends on the four-wave mixing time. At short times, this dependence is quadratic. Inset: An image oriented as Fig. 1, taken for $t_{\mathrm{FWM}} = 1.8$ ms without applying depletion light.

After confirming that N_q is actually generated by FWM, we now map the atomic states back onto the light field. To this end, the BEC in the trap is illuminated by a third light pulse, the retrieval pulse, during which a control beam propagating upward is applied, whereas no signal light is applied. We use a detuning of 300 MHz red from the $|2\rangle \leftrightarrow |2'\rangle$ transition because we find experimentally that this maximizes the retrieved photon number propagating downward. Using control light with an intensity of roughly 100 mW/cm^2, we find that the retrieved light emerges in less than 5 μs. Each atom in internal state $|2\rangle$ is transferred back into internal state $|1\rangle$ in a Raman process under emission of a signal photon. These Raman processes are bosonically stimulated by the two BECs in states $|1, 0\rangle$ and $|1, \boldsymbol{q}\rangle$. The stimulated growth of atomic population in these two BECs is called Raman AMW. Along with the population growth in states $|1, 0\rangle$ and $|1, \boldsymbol{q}\rangle$, signal light with two momentum components is emitted, one propagating downward, the other rightward.

We concentrate on the downward propagating component with wave vector $\boldsymbol{k}_s - \boldsymbol{q}$. It is created when atoms are transferred from state $|2, \boldsymbol{k}\rangle$ to $|1, \boldsymbol{q}\rangle$. This will only be possible if atomic FWM occurs because otherwise $N_q = 0$. FWM, in turn, will occur only if the signal light is applied during both

Raman pulses. We use an electron-multiplying charge-coupled device camera to measure the photon number propagating downward. An iris diaphragm is placed in an intermediate imaging plane to suppress stray light from the control beam. Results for $t_{\mathrm{FWM}} = 0.4$ ms are shown in Fig. 3. They clearly demonstrate an AND gate for the two classical signal light pulses.

The rightward propagating component of the retrieved light is of less interest here. Its existence does not rely on atomic FWM. If the second pulse were omitted completely, there would still be the retrieval of rightward propagating light, well known from experiments on electromagnetically induced transparency [24]. The photon number retrieved in this beam, however, does depend on whether FWM occurred because there is competition between the processes retrieving light propagating downward and rightward.

When considering the perspectives for scaling this gate down to the single-photon level in order to obtain a quantum logic gate, it is crucial whether the gate operation is phase coherent. We will now show experimentally that this is the case for the gate demonstrated here.

From a theoretical point of view [17], Raman AMW is analogous to a usual stimulated Raman process, except that the emission is bosonically stimulated not by application of a second laser beam but by the presence of a second BEC. Effectively, the role of the second laser beam and the second BEC are exchanged. In a usual stimulated Raman process, the atoms are transferred into the initially empty state in a phase coherent way, with the relative phase of the two applied laser beams determining the phase of the transferred atomic amplitude. Similarly, we expect that Raman AMW generates light in a phase coherent way, with the relative phase of the two BECs determining the phase of the emitted light.

To test experimentally whether the emitted light is phase coherent, we shorten the second Raman pulse to $\sim 35\ \mu$s at correspondingly higher light intensities. Interaction-time broadening now makes the Doppler shift for the transfer of population into state $|1, -\boldsymbol{q}\rangle$ irrelevant. We choose pulse areas of $\sim\pi/2$ for both Raman pulses to create four equally populated atomic momentum components $|1, 0\rangle$, $|1, -\boldsymbol{q}\rangle$, $|2, \boldsymbol{k}\rangle$, and $|2, \boldsymbol{k} + \boldsymbol{q}\rangle$. Subsequently, atomic FWM populates the states $|1, \boldsymbol{q}\rangle$ and $|2, \boldsymbol{k} - \boldsymbol{q}\rangle$; see Fig. 1. We refer to this as the extended scheme because it features six atomic momentum components, instead of four. The retrieval pulse, applied as before, again will generate downward propagating signal light only if atomic FWM occurs. But now, two pathways contribute to this signal. The light can be generated by transfer of an atom either from state $|2, \boldsymbol{k}\rangle$ to $|1, \boldsymbol{q}\rangle$ or from $|2, \boldsymbol{k} - \boldsymbol{q}\rangle$ to $|1, 0\rangle$.

The retrieved photon number propagating downward is shown in Fig. 4 as a function of t_{FWM}. It clearly shows a sinusoidal oscillation. To understand the physical origin of this oscillation, we note that during t_{FWM} the atomic components that contribute to the first pathway, $|2, \boldsymbol{k}\rangle \to |1, \boldsymbol{q}\rangle$, differ in kinetic energy by $\Delta E_1 = \hbar^2(k^2 - q^2)/2m$, whereas the components of the second pathway, $|2, \boldsymbol{k} - \boldsymbol{q}\rangle \to |1, 0\rangle$, differ by $\Delta E_2 = \hbar^2(\boldsymbol{k} - \boldsymbol{q})^2/2m$. Here m denotes the atomic mass. During t_{FWM}, these pairs of BECs thus accumulate different relative phases. Upon retrieval, these relative phases of the pairs of BECs are mapped onto the phases of the retrieved signal light, as discussed above. Eventually, the amplitudes associated with the two pathways create an interference signal on the detector. An independent measurement of our beam geometry yields $q^2 = 2.08k_s^2$ and $\boldsymbol{q} \cdot \boldsymbol{k} = -0.037k_s^2$. With $2\pi/k_s = 794.979$ nm, we expect an angular frequency $\omega = (\Delta E_2 - \Delta E_1)/\hbar = 2\pi \times 15.4$ kHz for the oscillation. If the beams pointed exactly along the

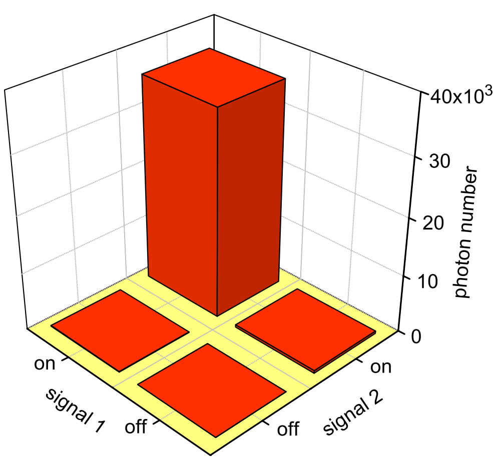

FIG. 3 (color online). Logic gate. The retrieved photon number propagating downward is shown for four different experimental settings, in which the signal beams during Raman pulses 1 and 2 are turned on or off independently. Downward propagating light will only be retrieved if both signal beams are on. This demonstrates an AND gate for classical light pulses based on storage in a BEC and FWM of matter waves.

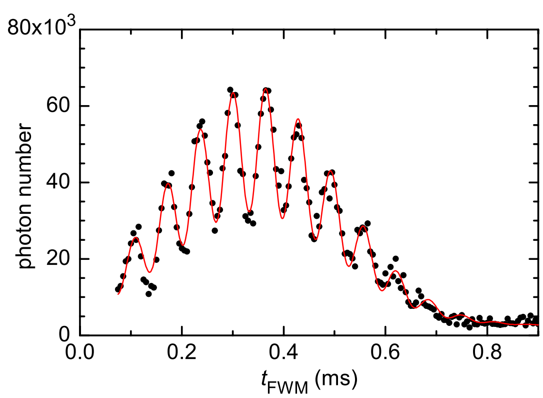

FIG. 4 (color online). Phase coherence. The retrieved photon number propagating downward exhibits a sinusoidal oscillation as a function of the FWM time. The best-fit value for the oscillation frequency is 15.4 kHz. The oscillation occurs because two pathways contribute to this signal in the extended scheme with six momentum components.

coordinate axes, then we would expect $\omega = 4E_{\text{rec}}/\hbar$, where $E_{\text{rec}} = \hbar^2 k_s^2/2m$ is the recoil energy of the signal light.

Two effects contribute to the observed envelope of the oscillation [23]. First, Raman AMW requires spatial overlap of the atomic momentum components. For long times, such overlap is lost and no directed retrieval is obtained. The time scale seen for this effect in Fig. 4 is similar to the time scale of saturation in Fig. 2, as expected. Second, retrieval of downward propagating light requires FWM to occur, so that an increase at short times, as seen in Fig. 2, is also seen in the envelope in Fig. 4.

For simplicity, we fit a sinusoid with a Gaussian envelope and a constant visibility V to the data in Fig. 4. This yields best-fit values of $\omega/2\pi = 15.4 \pm 0.1$ kHz and $V = 0.35 \pm 0.02$. The fact that V is not perfect is theoretically expected [23]. The agreement with the above expectation for ω is excellent. This oscillation is not seen in time-of-flight absorption images, either in Fig. 2 or in similar data that we took for the extended scheme (not shown here). This demonstrates that the retrieval of the light is necessary to make the oscillation appear.

The observed oscillation proves that the complete gate operation is phase coherent. This includes all physical processes involved in the gate, namely, Raman pulses 1 and 2, atomic FWM, and light emission during Raman AMW. The observed phase coherence is a crucial ingredient for a possible extension to a photon-photon quantum logic gate.

It should be noted that an extension of our scheme to the single-photon level is challenging. One possible problem is that smaller photon numbers slow down the atomic FWM so that the spatial overlap of the matter waves might end before achieving enough population transfer. Another possible problem is that the bosonic stimulation caused by a single atom in driving either atomic FWM or Raman AMW is weak so that competing processes might cause problems, e.g., isotropic s-wave scattering or spontaneous photon emission. Working out strategies to solve these problems is beyond the scope of this Letter.

On a more general level, our experiment demonstrates that storage and retrieval of light combined with the nonlinearity of the GP equation can be used to create a phase-coherent gate for two classical light pulses. If the geometry were altered to make all laser beams copropagating, then the nonlinearity of the GP equation would generate a conditional phase shift instead of atomic FWM. A recent theoretical analysis of the single-photon version of that scheme resulted in a detailed proposal for a photon-photon quantum logic gate [25].

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