A Deterministic and Storable Single-Photon Source Based on Quantum Memory

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A single photon source is realized with a cold atomic ensemble ($^{87}$Rb atoms). In the experiment, single photons, which is initially stored in an atomic quantum memory generated by Raman scattering of a laser pulse, can be emitted deterministically at a time-delay in control. It is shown that production rate of single photons can be enhanced by a feedback circuit considerably while the single-photon quality is conserved. Thus our present single-photon source is well suitable for future large-scale realization of quantum communication and linear optical quantum computation.

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Although weak coherent beams can be used as a pseudo single-photon source, the advent of quantum information processing (QIP) has placed stringent requirements on single photons either on demand or heralded. In particular, secure quantum cryptography and linear optical quantum computing depend on the availability of such single-photon sources. Different approaches have been attempted in the last decade to develop the on-demand single-photon source, such as the implementations with quantum dots, single atoms and ions, and color centers. However, all of them are confronted with different challenges. For example, the single-atom implementation provides spectrally narrow single photons with a well defined spatial mode, but the main challenge is the manipulation of single atoms, which requires sophisticated and expensive setups. Although quantum dots present many advantages as potential source of single photons, e.g. high single-photon rate, the requirement of spectral filtering entails inevitable losses. Additionally, it is a major problem for preparing truly identical sources due to inhomogeneities in both the environment of the emitters and the emitters itself. The stability of color centers is excellent, even at room temperature. However, the high peak intensities of a pulsed excitation can lead to complex and uncontrollable dark states. So it has been taken as a formidable task to develop a promising single-photon source.

Moreover, an important challenge in distributed QIP is the controllable transfer of quantum state between flying qubit and macroscopic matter. Remarkably, as shown in a recent proposal for long-distance quantum communication with atomic ensembles, it is possible to implement both a single-photon source on demand and the controllable transfer of quantum state between photonic qubit and macroscopic matter, provided that proper feedback is applied to achieve the classical feed-forward ability. Such feed-forward ability is a crucial requirement in linear optics QIP. In other words, it must be, in principle, possible to detect when an operation has succeeded by performing some appropriate measurement on ancilla photons. This information can then be feed-forwarded for conditional future operations on the photonic qubits to achieve efficient QIP.

Recently, significant experimental progresses have been achieved in demonstration of quantum storage and single-photon sources, and even entanglement between two atomic ensembles has been generated. However, coincidence-based post-selection was used in these experiments. Consequently no feedback could be applied to achieve the feed-forward ability and the requirement of resources will exponentially increase with each new step of operation. This significantly limit the scalability of the schemes.

In this letter, we present an experimental realization of a deterministic and storable single-photon source. Single spin excitations in an atomic ensemble are generated by detecting anti-Stokes photons from spontaneous Raman scattering. This detection allows to implement feed-forward and convert the spin excitations into single photons at a predetermined given time. Moreover, it is shown that the single-photon quality is conserved while the production rate of single photons can be enhanced greatly by the feedback circuit. In principle, the spatial mode, bandwidth, and frequency of single-photon pulses are determined by the spatial mode, intensity and frequency of the retrieve laser. So it is feasible to integrate such a single-photon source with the storage medium, atomic ensembles. Together with the technology developed in previous experiments, our controllable single-photon source potentially paves the way for the construction of scalable quantum communication networks and linear optical quantum computation.

The basic concept of our experiments is shown in Fig. 1. Cold atoms with A-type level configuration (two ground state $|a\rangle$, $|b\rangle$ and an excited state $|e\rangle$) collected by a magneto-optical trap (MOT) are used as the media for quantum memory. The atoms are initially optically pumped to state $|a\rangle$ by a pump laser. Then a weak classical write pulse, with the Rabi frequency $\Omega_w$, close to the resonance of transition $|a\rangle$ to $|e\rangle$ is introduced in the atomic cloud. Due to the spontaneous Raman process, a photon of anti-Stokes field $\hat{a}_{AS}$ is emitted into the forward scattering mode. Simultaneously, a collective spin...
excitation corresponding to the mode of the anti-Stokes field $\tilde{a}_{AS}$ is generated in the atomic ensemble. The state of the field $\tilde{a}_{AS}$ and the collective spin state of the atoms can be expressed by the superposed state

$$\Psi = |0_{AS}0_b\rangle + \sqrt{1-\chi}|1_{AS}1_b\rangle + \chi|2_{AS}2_b\rangle + O(\chi^{3/2}),$$  

where $\chi$ is the excitation probability of one spin flip, $|i_{AS}i_b\rangle$ denotes the $i$-fold excitation of the anti-Stokes field and the collective spin. Ideally, conditioned on detecting one and only one anti-Stokes photon in detector D1, a single spin excitation is generated in the atomic ensemble with certainty. After a controllable time delay $\delta t$ (in the order of the lifetime $\tau_s$ of the spin excitation), another classical read pulse with the Rabi frequency $\Omega_R$, which is on-resonance with the transition from $|b\rangle$ to $|e\rangle$, is applied to retrieve the spin excitation and generate a photon of Stokes field $\tilde{a}_S$.

In our present experiment, more than $10^8$ $^{87}$Rb atoms are collected by the MOT with an optical depth of about 5 and the temperature of about 100 $\mu$K. The earth magnetic field is compensated by three pairs of Helmholz coils. The two ground states $|a\rangle$ and $|b\rangle$ and the excited state $|e\rangle$ in the $\Lambda$-type system are $|5S_{1/2}, F = 2\rangle$, $|5S_{1/2}, F = 1\rangle$, and $|5P_{1/2}, F = 2\rangle$, respectively. The write laser is tuned to the transition from $|5S_{1/2}, F = 2\rangle$ to $|5P_{1/2}, F = 2\rangle$ with detuning of 10 MHz and the read laser is locked on resonance to the transition from $|5S_{1/2}, F = 1\rangle$ to $|5P_{1/2}, F = 2\rangle$. By using orthogonal polarizations, write and read beams are spatially overlapped on a polarized beam splitter (PBS1), and then focused into the cold atoms with the beam waist of 35 $\mu$m. After going through the atomic cloud, the two beams are split by PBS2 which also serves as the first stage of filtering the write (read) beam out from the anti-Stokes (Stokes) field. The leakage of write (read) field from PBS2 propagating with the anti-Stokes (Stokes) field will be further filtered by a thermal cell filled with $^{87}$Rb atoms, in which the rubidium atoms are prepared in state $|5S_{1/2}, F = 2\rangle$ ($|5S_{1/2}, F = 1\rangle$) initially. Coincident measurements among D1, D2 and D3 are performed with a time resolution of 2 ns.

After switching off the trapping laser and the gradient magnetic field of the MOT, the atoms are optically pumped to the initial state $|a\rangle$. The write pulse containing about $10^4$ photons with a duration of 100 ns is applied into the atomic ensemble, to induce the spontaneous Raman scattering via $|a\rangle \rightarrow |e\rangle \rightarrow |b\rangle$. The state of the induced anti-Stokes field and the collective spin in Eq. 4 is generated with a probability $\chi \ll 1$. After a controllable delay of $\delta t$, the read pulse with the duration of 75 ns is applied for converting the collective excitation into the Stokes field. In comparison, the intensity of the read pulse is about 100 times stronger than that of the write one.

Assume the probability to have an anti-Stokes (Stokes) photon is $p_{AS}$ ($p_s$), and the coincident probability between the Stokes and anti-Stokes channels is $p_{AS,s}$, then the intensity correlation function $g^{(2)}_{AS,s} = p_{AS,s}/(p_{AS}p_s) = 1 + 1/\chi$. We measured the variation of $g^{(2)}_{AS,s}$ as a function of $p_{AS}$ shown in Fig. 2(a) with a time delay of $\delta t = 500$ ns. Considering the background in each channel, we obtain

$$p_{AS} = \chi \eta_{AS} + B \eta_{AS},$$  

$$p_s = \chi \eta_s + C \eta_s,$$  

$$p_{AS,s} = \chi^2 \eta_{AS} \eta_s + p_{AS} p_s.$$  

Here, $\eta_{AS}$ and $\eta_s$ are the overall detection efficiencies in
FIG. 2: Intensity correlation function $g^{(2)}_{AS,S}$ along the excitation probability $p_{AS}$ with $\delta t = 500 \text{ ns}$ (a) and along the time delay $\delta t$ between read and write pulses with $p_{AS} = 3 \times 10^{-3}$ (b). The black dots are obtained from current experiment and the curves correspond to a least-square fitting procedure according to Eq. 2 and 3. Here the observed lifetime is $\tau_c = 12.5 \pm 2.6 \text{ ms}$ according to Eq. 3.

The anti-Stokes and Stokes channels respectively, which include the transmission efficiency $\eta_k$ of the filters and optical components, the coupling efficiency $\eta_c$ of the fiber couplers, and the quantum efficiency $\eta_\gamma$ of single photon detectors (there is another spatial mode-match efficiency $\eta_m$ embodied in $\eta_{AS}$) $\gamma$ is the retrieve efficiency which is a time-dependent factor, and $B$ ($C$) is a fitted factor indicating the background in the anti-Stokes (Stokes) channel. The red curve is the least-square fitting result according to Eq. 2, where we assume $B = 0$ for simplicity. The efficiency in the anti-Stokes channel is observed as $\eta_{AS} \sim 0.07$ and the retrieve efficiency $\gamma \sim 0.3$. It can be seen the largest correlation $g^{(2)}_{AS,S}$ (101 ± 6) appears at the lowest excitation probability $p_{AS}$ ($3.5 \times 10^{-4}$).

The finite lifetime of the spin excitation results from the dephasing of the collective state due to the Larmor precession of the collective spin in the residual magnetic field. It can be characterized by the decay of the density of the anti-Stokes channel. Once an anti-Stokes photon is detected by D1, the atomic ensemble will be pumped back to the initial state by a cleaning pulse. The above process will be halted until either an anti-Stokes photon is detected, or the maximum number of trials ($N$) given by the lifetime of the excitation is exceeded. In principle, the production rate of the anti-Stokes photons is enhanced while the single-photon quality is conserved. This can be understood by the new excitation probability $P_{AS} = \sum_{i=0}^{N-1} p_{AS}(1 - p_{AS})^i$.

Our protocol can be executed in two different modes. In the first mode, we fix the retrieving time $\Delta T$. Therefore, the delay $\delta t$ varies because the spin excitation is created randomly in the $N$ write pulses. Single photons could be produced at a certain time with a high probability, ideally approaching unity if $N \gg 1$. Furthermore, the retrieve efficiency can be improved significantly by an increased optical depth of the atomic ensemble and an optimal retrieve protocol [14]. Thus, this mode serves as a deterministic single-photon source. In second mode, we retrieve the single photon with a fixed delay $\Delta t$ after a successful write. Thus the imprinted single photon can be retrieved at any time needed. This is well suited for a quantum repeater [17] when one node is prepared while waiting for the other node.

In the first mode, we fixed $\Delta T = 12.5 \mu s$ and $\delta t_w = 1 \mu s$. Then $N = 12$ write pulses were introduced. The anti-correlation parameter $\alpha$ [20] of field $\hat{a}_s$ characterizes the quality of the single photon source. A 50/50 beam splitter is put in the Stokes channel to measure the auto-correlation of the conditioned Stokes photons. The coincident probability between D1 and D2 (D3) is $p_{2,AS}$ ($p_{3,AS}$) and the three-fold coincident probability in D1, D2 and D3 is $p_{23,AS}$ if we use only one write pulse and retrieve immediately after the write. When we use $N$ write pulses and the feedback protocol, the detection probabilities in D2 and D3 conditioned on a registration of an anti-Stokes photon in D1 are

$$P_{m|AS} = \frac{\sum_{i=0}^{N-1} p_{AS}(1 - p_{AS})^i p_{m|AS}(\Delta T - n \cdot \delta t_w)}{\sum_{i=0}^{N-1} p_{AS}(1 - p_{AS})^i}.$$

where $m = 2, 3, 23$ and $p_{m|AS}(\Delta T - n \cdot \delta t_w)$ is the time-dependent probability conditioning on a click in the anti-Stokes channel. Therefore, the anti-correlation parameter $\alpha = P_{23|AS}/(P_{2|AS} P_{3|AS})$.

In Fig. 2(b), $\alpha$ was measured as a function of the excitation probability $p_{AS}$. The variation of $\alpha$, shown as black dots, is nearly linear in the region of $p_{AS} = 0 \sim 0.006$ when the experiment is performed as each write pulse is followed by one read pulse. The black curve is the fitted result according to Eq. 4 ($N = 1$). When we use 12 successive write pulse, $\alpha$ versus $12 p_{AS}$ is plotted as red dots, which is consistent with the theoretical curve eval-
The delay $\Delta t < \tau \alpha$ background in the black curve. Note that, the value of reversed profile of $g$ the feedback protocol does not suffer from such noises. It can be seen that the single-photon nature is conserved even when we increase the excitation probability $p_{AS}$ by 12 times. The red curve is the theoretical evaluation taking account of the fitted background of the black dots, which are consistent with the measured data. In Fig (b), 12 write pulses were applied in each trial while measuring. When the delay $\Delta t < \tau \alpha$, the value of $\alpha$ keeps at a low level.

\[ \text{FIG. 3: The anti-correlation parameter as a function of } p_{AS} \text{ (a) and } \Delta t \text{ (b). In Fig (a), the data in black correspond to the experiment without feedback circuit, in which each write pulse is followed by one read pulse. Contrastively, the data in red correspond to the experiment with feedback circuit, in which 12 successive write pulses are followed by one read pulse. It can be seen that the single-photon nature is conserved even when we increase the excitation probability } p_{AS} \text{ by 12 times. The red curve is the theoretical evaluation taking account of the fitted background of the black dots, which are consistent with the measured data. In Fig (b), 12 write pulses were applied in each trial while measuring. When the delay } \Delta t < \tau \alpha, \text{ the value of } \alpha \text{ keeps at a low level.} \]

uated from Eq. 4 ($N = 12$) taking account of the fitted background in the black curve. Note that, the value of $\alpha$ is $0.057 \pm 0.028$ when $p_{AS} \rightarrow 0$, which should be 0 in principle. This offset comes from noise including residual leakage of the write and read beams, the stray light, and dark counts of the detectors. However, the advantage of the feedback protocol does not suffer from such noises. It is verified that $\alpha$ is conserved even the excitation probability is much larger. If the lifetime of the spin excitation is long enough to hold many write pulses, the excitation probability can reach unity while the single-photon nature is still conserved. Then the generation efficiency only depends on the retrieve efficiency itself.

In the second mode, $\delta t_w = 1 \mu s$ and $N = 12$. In Fig. 3(b), $\alpha$ was measured as the function of $\Delta t$. For every $\Delta t$, $\Delta T$ vary due to the spin excitation created randomly in the $N$ write pulses. The behavior $\alpha(\Delta t)$ is just like a reversed profile of $g_{AS,S}^{(2)}(\delta t)$ in Fig. 2(b). However, when the delay $\Delta t < \tau \alpha$, the value of $\alpha$ keeps at a low level and varies more slowly compared with $g_{AS,S}^{(2)}$. Even when we extend the delay to $20 \mu s$, $\alpha \sim 0.6$ which is still smaller than 1. Satisfying agreement is observed between the theoretical curve and the experimental data.

As demonstrated in the present work, the lifetime of collective states is important for the quality and production rate of single photons. In the atomic ensemble, the coherence time of the collective state suffers from the residual magnetic field around the MOT and the thermal motion of the atoms. The latter effect is negligible because of the very low temperature of the atomic cloud. Using a better compensation of residual magnetic field (within current technology, below 1 mG) we can greatly increase the lifetime of the collective state. Moreover, by further improving the control circuit, i.e. reducing the period of write pulses, we can apply more write pulses within the lifetime. In particular, in the case with $p_{AS} = 0.003$ and a write period of 300 ns, we can obtain a single-photon source with a probability as high as 95% within a lifetime of 300 $\mu s$.

In conclusion, we have demonstrated an experimental realization of an controllable single-photon source with atomic storage. The lifetime of the collective spin excitation reaches 12.5 $\mu s$. A feedback circuit was constructed to control the generation of the spin excitation and the storage time $\delta t$. Being a key device in the scalable quantum communication network, this circuit also shows a promising performance in the enhancement of the excitation probability while the single-photon quality is conserved. This single-photon source is able to work at either a deterministic mode or a time controllable mode heralded by the feedback circuit. The single-photon source based on atomic ensemble has the advantages of narrow band, high quality and controllable character, which is helpful for the construction of scalable quantum information processing system in the future.

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*Note added.– During the preparation of our manuscript, we are aware of two recently related experiments by A. Kuzmich’s group [21] and H. J. Kimble’s group [22].

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