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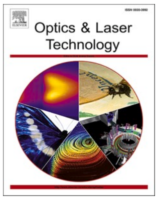

Full length article

On-demand generations of single photons from a DLCZ memory with temporal multiplexing and cavity-enhanced retrieval in a cold atomic ensemble

Haole Jiao [a,b,1], Minjie Wang [a,b,1], Jiajin Lu [a,b], Junjie Zhou [a,b], Jiarun Zhang [a,b], Jiayi Li [a,b], Yafei Wen [c,*], Shujing Li [a,b], Hai Wang [a,b,*]

[a] *State Key Laboratory of Quantum Optics Technologies and Devices, Shanxi University, Taiyuan 030006, China*
[b] *Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan 030006, China*
[c] *Department of Physics, Taiyuan Normal University, Jinzhong 030619, China*

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ABSTRACT

Single photons play an important role in the development of quantum networks using atomic memories as nodes. For performing the task in quantum network with atomic memories being as repeater nodes it is required for single photons to have the frequencies matching to atomic absorption lines and can be generated on demand with higher probabilities. *Here*, we demonstrated on-demand generation of single photons via DLCZ memory in a cold atomic ensemble. A train of write pulses having different wave vectors are directed into the atoms in time, each one can induce spontaneous Raman emissions of Stokes photons in a small probability. The Stokes fields that couple to the mode of a ring cavity is detected by a single-photon detector. One detection event heralds that one spin wave is stored in the atoms. Temporal multiplexing promises us to produce the spin wave with 12-fold increase in the probability compared with single-mode scheme. When a spin wave is heralded, it can be on-demand transformed (retrieved) into a single photon by the application of a read laser pulse. With the ring cavity, the retrieval efficiency is enhanced. In this work, we achieve an intrinsic retrieval efficiency of 70%. The spin wave is stored as magnetic-field-insensitive coherence between Zeeman states, thus, the storage lifetime is up to ∼ 300 μs.

1. Introduction

Single photons [1] are an excellent carrier used in the quantum information process, such as, optical quantum computing [2,3] quantum communication[4] quantum simulation [5], quantum metrology [6], and quantum random number generations [7]. Several strategies that are used for producing single photons have been developed [8]. One is using “single-emitter”, such as, single atom [9], single ion [10], quantum dots [11–15] and color centers in diamond [16,17] to produce deterministic single photons. However, all of them are plagued by different challenges. For example, quantum dots cannot guarantee to produce highly indistinguishable photons from distinct emitters due to the different emitter environment and the inaccuracy of the emitter manufacturing process at the nanoscale [15]. For color centers, the high peak intensities of a pulsed excitation can lead to complex and uncontrollable dark states [1]. The implementation of the single-atom requires sophisticated and expensive setups [9]. Another way is attenuating coherent light sources as a non-deterministic single photon source. However, the output signal-to-noise in this way is fundamentally limited by random photons in the coherence light. Thirdly, the alternative approach is to produce heralded single photons from quantum-correlation photon pairs in spontaneous parametric down conversion SPDC [18–23] or four-wave mixing (FWM) [24] process, which is non-deterministic since the photon pairs are produced in a probabilistic manner. For enhancing the generation probabilities and simultaneously obtaining good non-classical nature of the single photons, multiplexing schemes (spatial, temporal and spectral) have been theoretically proposed and experimentally demonstrated [25–34]. In 2002, Pittman *et al.* utilized time-multiplexing scheme to demonstrate a non-deterministic single-photon source, where, the single photons from SPDC is stored

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* Corresponding authors..
E-mail addresses: 18234061008@163.com (Y. Wen), wanghai@sxu.edu.cn (H. Wang).

[1] These authors contributed equally.

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by using an optical fiber loop with active switching [25]. In 2009, K. T. McCusker *et al.* proposed a novel technique that can efficiently produce a variety of multiphoton states by using time-multiplexing scheme [26]. In 2011, J. Mower *et al.* described a scheme which can generate single-photon states by adopting an active time-multiplexing scheme on a silicon photonic integrated chip [27]. In the same year, Anton Zeilinger group demonstrate a fourfold enhancement of the output photon rate by utilizing a four-photon-pair source, an active feed-forward technique, and an ultra-fast single-photon router [28]. In 2013, J. Eggleton's group experimentally demonstrated heralded single-photon sources by spatially multiplexing two monolithic silicon-based correlated photon pair sources in the telecommunications band [29]. The same group built heralded single photon sources by using active temporal multiplexing scheme based on silicon nanowires [30]. In 2015, P. G. Kwiat's group demonstrated time multiplexing for up to 30 time slots of a periodically pumped heralded single-photon source using a switchable low-loss optical storage cavity [31]. On this basis, the same group demonstrated high-efficiency single-photon generation via large-scale active time multiplexing [32]. In 2017, W. Tittel's group experimentally demonstrated heralded single photons based on spectral multiplexing scheme and feed-forward control [33]. Recently, Q. Zhou's group proposed a 1.5 μm chip-scale heralded single-photon source on lithium niobate on insulator by employing spectral multiplexing and active feedforward spectral manipulating, and demonstrated a proof-of-principle experiment with discrete fiber-based components [34].

To generate heralded single photons with the frequency being matched to atomic absorption lines, an approach based on DLCZ memories, i.e., spontaneous Raman scattering induced by write laser pulse in atomic ensembles, have been developed [1,2]. Such single photons can be on-demand generated from the memories, which can be used for performing the tasks in quantum networks. For example, they can be used for quantum teleportation based on atomic-ensemble memories [35] and for controlled-NOT gates [36]. In the demonstration of a heralded single photon based on DLCZ memory, one will apply write pulses into atoms to produce quantum-correlation pairs of a Stokes photon and a spin wave in probabilistic manners. The detection of a Stokes photon heralds a spin wave stored in the atoms. The spin wave is then transformed (retrieved) into a desired single photon by applying a read pulse into the atoms. Such scheme is based on storage and feedback retrieval and has been experimentally demonstrated in the previous work [37,38]. In those experiments, the probability of generating a spin wave is limited to the storage lifetime, where, the lifetimes are 12 μs in Ref. [37] and ~ 30 μs in Ref. [38]. We noted that the generation probability of a spin wave in Ref. [37] is ~ 6%. Recently, Kuzmich's group experimentally demonstrate single-photon generation from a spin wave with Rydberg atoms [39], where the generation probability (efficiency) of the spin wave is up to 8%, and the storage lifetime is 71(2) μs. So far, the key difficult faced by current single photon sources based on atomic memory is to balance the performance criteria including: (1) high retrieval efficiency, (2) long storage life, and (3) high generation probability at the same time.

Here, we demonstrate an on-demand generation of single photons based on DLCZ memory scheme in a cold atom ensemble. We use the temporal multiplexing storage scheme [40–42] and the cavity-enhanced retrieval [43] to improve the production rate of the single photons. Temporal multiplexing modes, which are achieved by applying a train of write pulses in time that have different wave-vector direction on the atoms, is up to 12. We place a ring cavity around the atom to improve the intrinsic retrieval efficiency to 70%. Meanwhile, we select magnetic insensitive and long-wavelength spin-wave to suppress decoherence due to atomic motion and in-homogeneous broadening of the spin waves, the lifetime of the spin-wave storage is up to 300 μs. The spin wave can be transferred into a single photon on demand within the lifetime. The cavity-enhanced generation temporal multiplexing spin wave provide a high-performance single-photon source for demonstrating the quantum tasks in quantum networks based on atomic ensembles.

2. Experimental setup

The single photon source is mainly formed by a cold atomic ensemble coupled to a ring cavity. The experimental setup for the source is shown in Fig. 1.

The ring cavity is consisted of two lens, three high reflectivity mirror (HR) and a output coupling mirror (OCM). The cavity length is stabilized by a locking beam whose frequency is denuded from the transition $|a\rangle\rightarrow|e_1\rangle$ with 485 MHz. The locking beam is backwards combined along the herald photon channel with a 95% non-polarized beam combiner (NPBS). The output coupling mirror (OCM) has a partial reflection rate of 80%. In order to reduce intracavity losses, all the optical components of the cavity are also anti-reflection coated both sides (include the glass cell, but exclude the cavity mirror). The measured free spectral range (FSR) is about 80 MHz and the finesse is 17 with losses is 13.5%.

An ensemble of ^{87}Rb atom trapped in a magneto-optical trap (MOT) is released for the DLCZ memory. As shown in Fig. 1(b), the atomic ground levels $|a\rangle = |5S_{1/2}, F = 1\rangle$ and $|b\rangle = |5S_{1/2}, F = 2\rangle$ together with the excited level $|e_1\rangle = |5P_{1/2}, F' = 1\rangle$ ($|e_2\rangle = |5P_{1/2}, F' = 2\rangle$) form a $\Lambda-$type system. First, the atoms are prepared in the Zeeman state $|a, m_{F_a} = 0\rangle$, where m_F denotes the magnetic quantum number. The quantum axis is defined by a bias magnetic field ($B = 4G$) applied along z-axis. For generating multiplexing storages, we apply write pulse trains with each containing $m = 12$ pulses in time into the cold atoms. The i-th pulse, which is denoted by $W(t_i)$ (i = 1 to 12)), is applied into the atoms at time t_i. As shown in Fig. 1(c), one write train lasts $\Delta T = 7\mu s$, where, each pulse has a width of 250 ns. The write pulses (w) are σ^+-polarized 795-nm with red-detuned by 110 MHz to the $|a\rangle\rightarrow|e_1\rangle$ transition. The write pulses $w(t_i)$ (i = 1 to 12) goes through the center of the ensemble along the direction of k_W^i(wave-vector). It induces the Raman transition $|a, m_{Fa} = 0\rangle\rightarrow|b, m_{Fb} = 0\rangle$ via $|e_1, m_{Fe} = 1\rangle$, which emit σ^+-polarized Stokes (heralding) photons in space and simultaneously create spin waves non-classically-correlated with the Stokes photons. The spin waves are stored in the clock coherence $|m_a = 0\rangle \leftrightarrow |m_b = 0\rangle$. As shown in Fig. 1, a ring cavity is placed around the atom, which enhances the interaction between the atoms and Stokes filed along z axis (cavity mode). The generation probability (excitation probability χ) of the pair of the spin wave and the Stokes photon along z-axis is small ($\chi << 1$). The σ^+-polarized photon is transformed into *H*-polarized photon by the quarter-wave *QW*2 and goes through a beam displacer (BD). The *H*-polarized Stokes photon is coupled to the cavity mode. It is escaped from the output couple mirror (OCM) of cavity, which is the herald photon. The escaped Stokes photon goes through a set of optical filters, which are used for filting stray light, and is sent to a single photon detector (D1). The detection of a Stokes photon heralds that a spin wave is stored in the atomic ensemble. If the Stokes photon is detected by the D1, a feedforward signal is sent to write pulse controller and the write pulse train sequence is stopped. After a storage time t, the spin wave is retrieved into the heralded single photon.

Additionally, the write pulses will induce the Raman transition $|a, m_{Fa} = 0\rangle\rightarrow|b, m_{Fb} = 2\rangle$ via $|e_1, m_{Fe} = 1\rangle$, which emit σ^--polarized Stokes photons and simultaneously create spin waves associated with the magnetic-field-sensitive coherence $|m_a = 0\rangle \leftrightarrow |m_b = 2\rangle$. However, The σ^-−polarized Stokes photon is transformed into *V*-polarized photon by the *QW2*. The *V*-polarized Stokes photon goes through the BD and is excluded from the cavity mode, which then can't be detected. So, only the spin wave between the clock coherence $|a, m_{Fa} = 0\rangle\rightarrow|b, m_{Fb} = 0\rangle$ is stored.

The i-*th* SW mode M_i *is* defined by the wave-vector $k_M^i = k_W^i - k_S$, where k_S is the wave-vector of the heralding (Stokes) photon. If the heralding photon is detected at the time t_l ($l\subset1$ to $m = 12$), a feedback signal is sent out and the write pulse sequence is stopped. At an on-demand time t (within the storage lifetime), a strong σ^+-polarized read laser pulse along the $k_R^l = -k_W^l$ direction, i.e., opposite to direction of the write pulse $W(t_l)$, is applied time, which transfers the stored spin

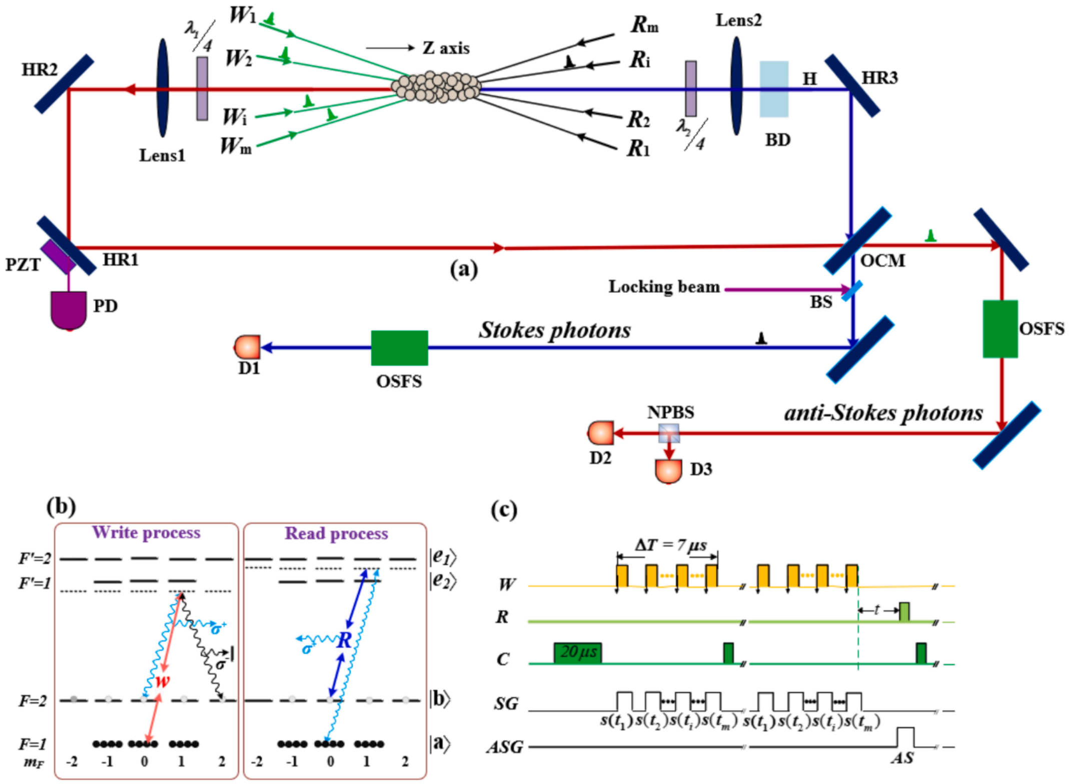

Fig. 1. (a) Experimental setup for m-mode multiplexed sources. The pulse train, containing 12 write pulses labeled as $W(t_1)$, $W(t_2)$, … $W(t_i)$ …,$W(t_{m=12})$), are applied to the ensemble along different directions to generate spin waves, where, for simplicity, we only plot 4 write pulses. The beam displace (BD) is used to exclude the element of V −polarized herald photons, which is transformed from σ^- polarized photon by the QW2. The single-photon detector D1 is used to detect the heralding (Stokes) photon and the detector D2 (D3) is used to detect the heralded single photon. OSFS: optical-spectrum-filter set; NPBS: non-polarization beam splitter; λ/4: λ/4-plate wave. A locking laser pulse is coupled to the cavity through a beam splitter (BS). Leaks of the cavity-locking pulse from HR1 are detected by a fast photodiode (PD) to generate error signals. The error signals are amplified and used to drive a piezoelectric transducer (PZT) to stabilize the cavity length. (b) Relevant atomic levels involved in the write and read processes, respectively, $R(t_1)$, $R(t_2)$, … $R(t_i)$…,$R(t_m)$: read laser pulses. (c) Time sequence of the experimental trials. W, C, R: write, cleaning, and read pulses. SG(t_1), SG(t_2) … SG(t_m) are labeled as the spin wave generated at time t_i. If a Stokes photon is detected by D1 at l-th write pulse in one write sequence, a feed-forward controlled is sent out and the next write-pulse sequence is stopped. After a storage time t, a read pulse propagating along the direction opposite to the l-th write pulse is applied, which transform the spin wave into the single photon.

wave M_l to the anti-Stokes photon. The write-read process is satisfied with phase matching of $k_R^i - k_S = k_W^i - k_S$. Thus the anti-Stokes photon propagates along the −z-axis and is also coupled into the cavity mode. The anti-Stokes photon (heralded single photon) is detected by the detector D2, D3 for the auto-correlation function measurement. The Stokes (herald) photon and the anti-Stokes single photon are both resonated with the cavity.

In current experiment, the anti-Stokes photons retrieved from temporal-multiplexed DLCZ spin-wave memories are served as the single photon. For single-mode storage, the probability of detecting a Stokes, anti-Stokes photon and the coincident probability between the Stokes and anti-Stokes photons can be precisely expressed as:

$$P_S^{(1)} = \chi\eta_S + B\eta_S \tag{1a}$$

$$P_{aS}^{(1)} = \chi\gamma\eta_{aS} + C\eta_{aS} \tag{1b}$$

$$P_{S,aS}^{(1)} = \chi\gamma\eta_{aS}\eta_S + P_S^{(1)}P_{aS}^{(1)}$$

respectively, where, χ is the excitation probability per write pulse, η_S (η_{aS}) is the overall detection efficiency in the Stokes (anti-Stokes) channel, γ is the intrinsic retrieval efficiency, which is a function of the storage time, $B(C)$ is the background noise in the detection channel for Stokes (anti-Stokes) photons, in our presented experiment, the measured $B \approx 0.0004$ per pulse and $C \approx 0.004$ per pulse, For the single mode case, the detection probability of a Stokes (anti-Stokes) photon can be roughly written as $P_S^{(1)} \approx \chi\eta_S$ ($P_{aS}^{(1)} \approx \chi\gamma\eta_{aS}$). For $\chi\eta_S < 1$, the detection probability of a Stokes photon in m temporal multiplexing modes can be written as

$$P_S^{(m)} = 1 - \left(1 - P_S^{(1)}\right)^m \approx mP_S^{(1)}$$

In Eq. (1c), the noise term $P_S^{(1)}P_{aS}^{(1)}$ can be neglected and the coincidence detection probability can be roughly written as $P_{S,aS}^{(1)} = \chi\gamma\eta_{aS}\eta_S$. For the m-mode storages, the coincidence probability can be written as [40]

$$P_{S,aS}^{(m)} \approx mP_{aS,S}^{(1)}$$

For demonstrating the storage capacity of the temporal multiplexing, we measured the detection probability of generating single (anti-Stoke) photon and the probability of coincidence between the Stokes and anti-Stokes photons as a function of the mode number m, which are shown in red square dots in Fig. 2 (a) and red circular dots in Fig. 2 (b), respectively. So, with the temporal multiplexed scheme, the detection probability of a Stokes photon can be linearly increased with the number of modes, which is in agreement the results in Fig. 2 (a). From the measured data in Fig. 2 (a), we have $P_S^{(m=12)}/P_S^{(1)} = 11.6$, which is in agreement with $P_S^{(m)} \approx mP_S^{(1)}$(Eq.(2)).

The measured coincidence probability as a function of mode number m is shown in Fig. 2 (b). From the data, we have $P_{S,aS}^{(m=12)}/P_{S,aS}^{(1)} = 11.6$, which shows that m-mode temporal multiplexed storages give rise to a 11.6 fold increase in the Stokes-anti-Stokes coincident detection rate) compared to the nonmultiplexed scheme.

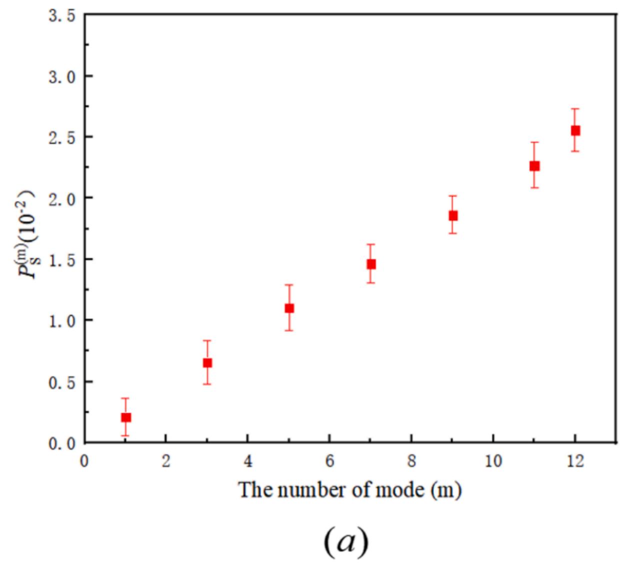

Fig. 2. (a) The measured detection probability of Stokes photon $P_S^{(m)}$ per write train ($7\mu s$) as a function of the mode number m. (b) The measured coincidence probability $P_{S,aS}^{(m)}$ of the Stokes-anti-Stokes photons as a function of mode number m. Error bars represent 1 standard deviation.

From the Eq. (1c)and combining with Eq. (1a), the intrinsic retrieval efficiency γ can be defined as:

$$\gamma = P_{S,\ aS}^{(1)}/(\chi\eta_S)\eta_{aS} \approx P_{S,\ aS}^{(1)}/P_S^{(1)}\eta_{aS}$$

The noise terms ($P_S^{(1)}P_{aS}^{(1)}$) in Eq. (1c) and $B\eta_S$ in Eq. (1a) have been neglected. In the measurement on the intrinsic retrieval efficiency, we use the temporal multiplexed storage scheme, i.e., we measured $P_{S,aS}^{(m)}$ and $P_S^{(m)}$ data. According to $P_{S,aS}^{(m)} \approx m\gamma\eta_{aS}P_S^{(1)}$ and $P_S^{(m)} \approx mP_S^{(1)}$, we can obtain the retrieval efficiency γ according to $\gamma = P_{S,\ aS}^{(m)}/P_S^{(m)}\eta_{aS}$. $P_{S,\ aS}^{(m)}$ is measured as $P_{S,\ aS}^{(m)} = P_{D_1,D_2}^{(m)} + P_{D_1,D_3}^{(m)}$, $P_{D_1,\ D_2}^{(m)}$ ($P_{D_1,\ D_3}^{(m)}$) is the probability of detecting a coincidence between the detectors D_1 and D_2 (D_3) for the DLCZ memory storing m temporal multiplexed modes, the total detection efficiency of the anti-Stokes photon can be written as $\eta_{aS} = \eta_{esp}\eta_t\eta_D$, which includes the efficiency of photon escaping from the ring cavity η_{esp}, the transmission efficiency from the cavity to the detectors η_t, and the detection efficiency of the single-photon detectors η_D.

Fig. 3 plots the measured retrieval efficiency (blue circle dots) as functions of storage time t in the case of m-mode storage case. The solid red curve is the fit to the retrieval efficiency according to the function, which yields retrieval efficiencies, together with a memory lifetime. The retrieval of the single photon from the spin wave can be in the storage time in an on-demand way, which promise one to effectively complete a quantum task involved in multiple photon preparations via synchronization. As shown in Fig. 3, the spin wave decays with the storage time in monotony way. The decoherence of spin wave caused by the two main factors (1) atomic motions [44] (2) inhomogeneous broadening of the spin transition due to inhomogeneity of background magnetic field. [45–47] The experimental result presents monotony, and then is agreement with Markovian dissipative mechanism. We noted that the relevant experiments published in References [48,49] also present exponential decay. We also noted that the articles [50–54] pointed out the impact of non-Markovian environments on quantum system. Such non-Markovian dissipations occur under some special circumstances and may be cause some new phenomenon in the atom-light interfaces, which may be an interesting topic in future.

The auto-correlation function for the single photon retrieved from the memory storing $m = 12$ modes is written as

$$\alpha = P_{D2,D3,D1}^{(m)}/P_{D2,D1}^{(m)}P_{D3,D1}^{(m)}$$

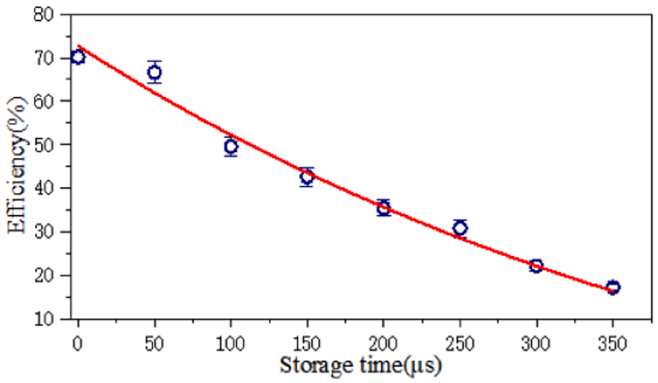

Fig. 3. The measured retrieval efficiency as a function of storage time t for $m = 12$. Error bars represent 1 standard deviation.

where $P_{D2,D3,D1}^{(m)}$ refers to the conditional coincidence probability between the detection *D2, D3*. The value $\alpha = 0$ corresponds to an ideal single photon and $\alpha = 1$ corresponds to classical light.

At first, we measured α as a function of the mode number m. As shown in Fig. 5, α increase with the increase of mode number m, where, $\alpha \approx 0.2$ for $m = 1$, and $\alpha \approx 0.4$ for $m = 12$, showing that the single-

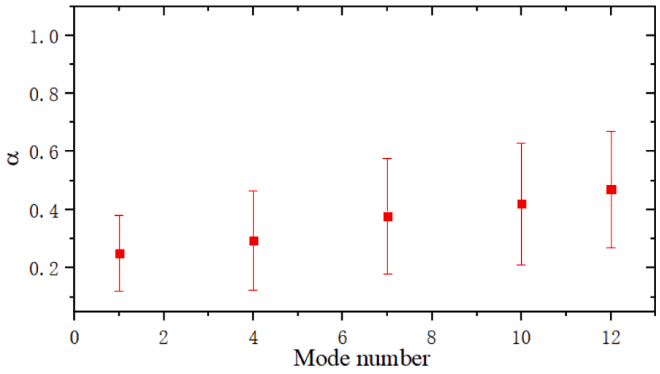

Fig. 4. The auto-correlation α function as a function of mode number m. Error bars represent 1 standard deviation.

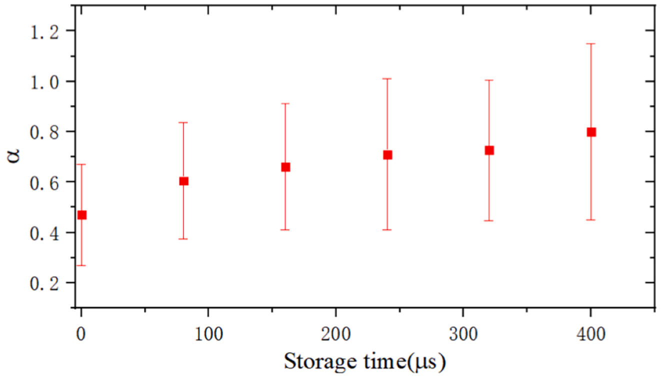

Fig. 5. The second order correlation function depends on the storage time for $m = 12$. Error bars represent 1 standard deviation.

photon quality decrease with m. The reason for this has been briefly explained in the following. When we apply a train containing m write pulses to the atomic ensemble to prepare the temporal-multimode storages, a large number of unwanted spin waves that are associated with undetected Stokes photons are also created. When a read pulse is applied to retrieve the heralded spin wave, the unwanted spin waves may also be converted into anti-Stokes photons, which lead to additional background noise (see Ref. [40] for details). Such noise increases with the mode number [40] and then result in the increase of α in m.

We then measured the auto-correlation function as a function of the storage time t, which are shown in Fig. 4. At 0-delay time, we measured $\alpha \approx 0.4$. When the storage time is 300 μs, we measured $\alpha \approx 0.7$. We noted that the measured α function is not 0 and increases with increasing storage time. This large value α is due to noise including residual leakage of the write and read beams, stray light, and dark counts of the detectors and the signal–noise rate is decreasing with increasing storage time.

Additionally, the excitation probability is set $\chi \approx 1\%$ in the presented experiment. In the future, we can chose a smaller value in order to suppress the two excitations and obtain a high $g^{(2)}$ [55], which then promises us to achieve a smaller α.

3. Conclusion-

In this work, we demonstrated the on-demand generation of single photons from DLCZ spin-wave quantum memory in a cold atomic ensemble. With the temporal multiplexing scheme, the detection probability of generating the spin wave is $\sim$ 5% (Fig. 2a), which is comparable with that (6–8%) of the pervious work [37,38]. However, the lifetime for storing the spin wave in our work is 300 μs, which is 30-fold (4-fold) of that in that work[37]([38]). Additionally, our work uses the cavity-enhanced retrievals, which enable the retrieving efficiency to be up to $\sim$ 70%, far beyond the results [56] ($\sim$25%) without cavity-enhanced retrieval. In the future, the number of storage mode number could be increased by combining the temporal and the spatial [57] multiplexed schemes into a unite DLCZ memory system. We believe that the presented single-photon generation scheme pave a road for performing quantum tasks of quantum networks using atomic-ensemble memories.

CRediT authorship contribution statement

Haole Jiao: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Minjie Wang:** Writing – review & editing, Data curation, Conceptualization. **Jiajin Lu:** Data curation. **Junjie Zhou:** Data curation. **Jiarun Zhang:** Data curation. **Jiayi Li:** Data curation. **Yafei Wen:** Writing – review & editing, Writing – original draft. **Shujing Li:** Writing – review & editing, Writing – original draft, Conceptualization. **Hai Wang:** Writing – review & editing, Writing – original draft, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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