A millisecond quantum memory for scalable quantum networks

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(Dated: July 31, 2008)

Scalable quantum information processing critically depends on the capability of storage of a quantum state.1, 2 In particular, a long-lived storable and retrievable quantum memory for single excitations is of crucial importance to the atomic-ensemble-based long-distance quantum communication3, 4, 5, 6, 7. Although atomic memories for classical lights8 and continuous variables9 have been demonstrated with milliseconds storage time, there is no equal advance in the development of quantum memory for single excitations, where only around 10 µs storage time was achieved10, 11, 12, 13. Here we report our experimental investigations on extending the storage time of quantum memory for single excitations. We isolate and identify distinct mechanisms for the decoherence of spin wave (SW) in atomic ensemble quantum memories. By exploiting the magnetic field insensitive state, “clock state”, and generating a long-wavelength SW to suppress the dephasing, we succeed in extending the storage time of the quantum memory to 1 ms. Our result represents a substantial progress towards long-distance quantum communication and enables a realistic avenue for large-scale quantum information processing.

PACS numbers: 03.67.Hk, 03.67.Pp, 32.80.Qk

Quantum repeater with atomic ensembles and linear optics has attracted broad interest in recently years, since it holds the promise to implement long-distance quantum communication and distribution of entanglement over quantum networks. Following the protocol proposed by Duan et al.3 and the subsequent improved schemes4, 5, 6, 7, significant progresses have been accomplished, including coherent manipulation of the stored excitation in one atomic ensemble14, 15, and two atomic ensembles16, demonstration of memory-built-in quantum teleportation17, and realization of a building block of the quantum repeater13, 18. In these experiments, the atomic ensembles serve as the storable and retrievable quantum memory for single excitations.

Despite the advances achieved in manipulating atomic ensembles, long-distance quantum communication with atomic ensembles remains challenging due to the short coherence time of the quantum memory for single excitations. For example, to directly establish entanglement between two memory qubits over a few hundred kilometers, one needs a memory with a storage time of a few hundred microseconds. However, the longest storage time reported so far is only on the order of 10 µs10, 11, 12, 13.

It is long believed that the short coherence time is mainly caused by the residual magnetic field19, 20. Thereby, storing the collective state in the superposition of the first-order magnetic-field-insensitive states19, i.e. the “clock state”, is suggested to inhibit this decoherence mechanism19. A numerical calculation shows that the lifetime of the collective excitation stored in the “clock state” is on the order of seconds.

Here we report our investigation on prolonging the storage time of the quantum memory for single excitations. In the experiment, we find that only using the “clock state” is not sufficient to obtain the expected long storage time. We further analyze, isolate and identify the distinct decoherence mechanisms, and thoroughly investigate the dephasing of the spin wave (SW) by varying its wavelength. We find that the dephasing of SW is extremely sensitive to the angle between the write beam and detection mode, especially for small angles. Based on this finding, by exploiting the “clock state” and increasing the wavelength of the SW to suppress the dephasing, we succeed in extending the storage time from 10 µs to 1 ms, which for the first time allows for the quantum memory of single excitations to persist for times comparable to the propagation of light over 100 kilometers. Our work has opened the door to the first steps in building a quantum repeater, and thus provides an essential tool for long-distance quantum communication.

The architecture of our experiment is depicted in Fig. 1a and 1b. A cold 87Rb atomic ensemble in a magneto-optical trap (MOT) at a temperature of about 100 µK serves as the quantum memory. The two ground states |g⟩ and |s⟩, together with the excited state |e⟩ form a Λ-type system. A bias magnetic field of about 3.2 G is applied along the axial direction to define the quantization axis. Note that there are three pairs of “clock states” for the ground states of 87Rb atom, i.e. (|j⟩, |e⟩), (|1⟩, |2⟩), (|0⟩, |0⟩), (|0⟩, |0⟩), and (|j⟩, |j⟩), where we have defined |i⟩ = |S⟩/2, F = i, m_F = j⟩. In a timescale of milliseconds, we can use any of them to store the collective excitation, because the decoherence of the “clock
states” caused by magnetic field is negligible. In our experiment, we prepare the atoms in $|1,0\rangle$ to exploit the clock state $(|g\rangle = |1,0\rangle, |s\rangle = |2,0\rangle)$. An off-resonant $\sigma^-$ polarized write pulse with wave vector $k_W$ is applied to the atomic ensemble along the axial direction, inducing spontaneous Raman scattering. The Stokes photon with $\sigma^-$ polarization and wave vector $k_s$ is collected at an angle of $\theta = 3^\circ$ relative to the write beam, as in most of the previous experiments\cite{10, 13, 14, 15, 16, 21, 22}. The beam waist of the detection mode is about 100 $\mu$m in the atomic ensemble. To detect a Stokes photon, a collective excited state or a SW is imprinted in the atomic ensemble\cite{2}, described by

$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_j e^{i\Delta k \cdot r_j} |g...s...g\rangle,$$

with $\Delta k = k_W - k_s$ the wave vector of the SW, and $r_j$ the coordinate of the $j$-th atom. After a controllable delay $\delta t$, a strong $\sigma^+$ polarized read light, counter-propagating with the write light, converts the collective excitation into an anti-Stokes photon, which is $\sigma^+$ polarized and spatially mode-matched with the Stokes photon from the opposite direction. The Stokes (anti-Stokes) photon and the write (read) light are spatially separated.

The quality of the quantum memory can be well characterized by the cross correlation $g_{S,AS} = p_{S,AS}/(p_S \cdot p_{AS})$ (See Methods), with $p_S$ ($p_{AS}$) the probability of detecting a Stokes (anti-Stokes) photon and $p_{S,AS}$ the coincident probability between the Stokes and anti-Stokes channels. The larger the cross correlation is, the higher-quality single photon source\cite{10, 14, 21} or atom-entanglement source\cite{18, 22} we can acquire. In the experiment, to evaluate the coherence time of the quantum memory, we measure the cross correlation as a function of the time delay, described as \cite{11} (See Methods)

$$g_{S,AS}(\delta t) = 1 + C\gamma(\delta t),$$

with $C$ a fitting parameter, and $\gamma(\delta t)$ the time dependent retrieval efficiency. Note that $g_{S,AS} > 2$ means that the Stokes and anti-Stokes photons are nonclassically correlated\cite{19, 22}.

The experimental result is given in Fig. 2. Our data shows that the lifetime is a little bit longer than our previous results\cite{11}, where the lifetime is mainly limited by the residual magnetic field, but far from the theoretical prediction for the “clock state”. From this result, we infer the “clock state” can really help to improve the lifetime. But more importantly, it indicates that, in our experiment, there is another decoherence mechanism, which dominates when the decoherence due to magnetic field is suppressed.

We carefully analyze the decoherence mechanism of the quantum memory and find that the short lifetime could be explained by the dephasing of the SW induced by atomic random motion\cite{12, 24}. This decoherence mechanism plays an important role in many previous experiments\cite{10, 13, 14, 15, 16, 21, 22}, but it has not attracted sufficient attention.

The dephasing can be understood as follows. As shown in Fig. 1c, assume a SW is stored in the atomic ensemble and will be retrieved out after a time delay $\delta t$. In this interval, each atom randomly moves from one point to another along the wave vector direction. The internal states or the spin of the atoms are conserved since collisions can be safely neglected at a low temperature and density. However, the atomic motion leads to a perturbation on the phase of the SW. Consequently, the projection of the perturbed SW on the original one gradually decreases as the delay of the retrieve becomes longer. In other words, the atomic random motion leads to a random phase fluctuation in the SW and thus causes decoherence. The timescale of the dephasing can be estimated by calculating the average time needed for the atoms to cross $\frac{1}{\lambda}$ of the wavelength of the SW, giving a lifetime of $\tau_0 \sim \frac{\lambda}{v_s}$, with $v_s = \sqrt{\frac{\Delta k}{\lambda}}$ the one dimensional average speed and $\lambda = \frac{2\pi}{\lambda}$ the wavelength of the SW. A more detailed calculation gives $\gamma(\delta t) \sim e^{-\delta t^2/\tau^2}$, with the lifetime $\tau_0 = \frac{\lambda}{v_s\Delta k}$ (see Methods). In our case, there is an angle $\theta$ between $k_W$ and $k_s$, and thus we have $\Delta k = |k_W - k_s| \approx k_W \sin \theta$. For $\theta = 3^\circ$, a simple calculation gives $\lambda = 15 \mu$m and then $\tau_0 = 25 \mu$s. By fitting the data in Fig. 2 with $g_{S,AS}(\delta t) = 1 + C \exp(-\delta t^2/\tau^2)$, we obtain a lifetime of $\tau_0 = 25 \pm 1 \mu$s, which is consistent with the theoretical calculation. Note that besides the atomic random motion, the collisions between atoms may also affect the phase of the SW. While in our experiment, the effect of collisions is negligible. The collisions rate can be estimated by $\Gamma \sim n v_s \sigma \approx 1$ Hz, where the atomic density $n = 10^{10}/\text{cm}^3$, the $s$-wave scattering cross section $\sigma = 8\pi a^2$ with the scattering length $a = 6 \text{ nm}$. Thereby, in the time scale of milliseconds, the collisions can be safely neglected.

To further confirm that the decoherence is mainly caused by the dephasing induced by atomic motion, we increase the wavelength of the SW by decreasing the detection angle (see Fig. 1d). In this way, according to the above model, the dephasing is suppressed and the storage time will be extended. In our experiment, we reduce the angle by choosing $\theta = 1.5^\circ, 0.6^\circ$, and $0.2^\circ$ and measure the lifetime of the quantum memory for each configuration. Note that, for $\theta = 0.2^\circ$, the two beams with the same polarization can not be spatially separated, and thereby we use another “clock state” $(|g\rangle = |1,1\rangle, |s\rangle = |2,-1\rangle)$ by preparing the atoms in $|1,1\rangle$. In this case, the Stokes (anti-Stokes) photon is $\sigma^+$ ($\sigma^-$) polarized. The write (read) and Stokes (anti-Stokes) lights have orthogonal polarizations and are separated by a Glan-Laser prism.

The experimental results are displayed in Fig. 3a-3c. As expected, the dephasing of the SW dominates,
when the effect of magnetic field is inhibited by using the “clock state”. The lifetime increases from 25 µs to 283 µs by reducing θ or, in other words, increasing the wavelength of SW. Our results clearly show that the dephasing of the SW is extremely sensitive to the small angle between the write beam and Stokes modes, and that the long-wavelength SW is robust against the dephasing induced by atomic random motion. Note that, for θ = 0.2°, the data are fitted by taking into account the effect of loss of atoms. The measured lifetime τD is shown in Fig. 3d as a function of angle θ. The solid line is the theoretical curve τD = Δθ/vs, with vs = 0.1 m/s corresponding to a temperature of T = 100 µK. The good agreements between theory and experiment imply that our work provides an alternative approach to measure the temperature of an atomic ensemble. Moreover, since the lifetime is only sensitive to the velocity of the atoms in the interaction region, which is determined by the waist of the detection mode and is controllable, one can also use our method to measure the velocity distribution of the atomic ensemble by performing measurement in different regions.

To further suppress the dephasing and achieve a longer storage time, we use the collinear configuration (θ = 0°), where we have the maximum wavelength of the SW λ ≈ 4.4 cm and thus τD ≈ 72 ms. In this case, the decoherence due to loss of atoms, which usually gives a lifetime of a few hundred microseconds, is isolated as the principal decoherence mechanism. This mechanism can be estimated by calculating the average time for the atoms flying out of the pencil shaped interaction region, where the thermal motion in radial direction dominates. At temperature T, an atomic cloud with a cross section radius r0 expands according to r2(δt) = r20 + v2r/2δt2, with the average speed in radial direction vr = \sqrt{\frac{2k_{B}T}{m}}. The retrieval efficiency can be given by γ(δt) = r2/v2(δt + 1/2r20δt2). Thereby, when γ(τL) = 1/e, only 1/e of the atoms remain in the interaction region, giving a lifetime of τL = 1/(1 + r20/v2). For r0 = 100 µm as the waist of the detection mode and T = 100 µK, a direct calculation gives τL = 950 µs, which is much smaller than the dephasing due to atomic motion and decoherence induced by the magnetic field. The experimental result is shown in Fig. 4, where the “clock state” (|1, 1⟩, |2, −1⟩) is also used. Our data give a lifetime of τL = 1.0 ± 0.1 ms, when the retrieval efficiency has dropped to 1/e. The experiment result is in good agreement with the theoretical estimation.

In our experiment, we have isolated and identified different decoherence mechanisms of the quantum memory for single excitations and thoroughly investigated the dephasing of stored SW by varying its wavelength. Moreover, we have successfully realized a long-lived quantum memory for single collective excitation by exploiting the “clock state” and long-wavelength SW. The storage time of 1 ms is 30 times longer than the best result reported so far[10], and is long enough for photons transmission over 100 kilometers. In our experiment, the coherence time of the quantum memory is limited by the decoherence due to loss of atoms, which can be suppressed by lowering the temperature via optical molasses. A storage time of 3 ms is achievable by reducing the temperature to 10 µK. This will be the upper limit for the atomic memory in MOT, since longer storage time is prohibited by the free falling of the atoms under gravity. Further improvement might be achieved by trapping the atoms in an optical dipole trap[19, 23], where the decoherence due to loss of atoms and the dephasing induced by atomic random motion can both be suppressed. In this case, the principal decoherence mechanism is the diffusion caused by collisions, which will give a lifetime of a few tens of milliseconds. To inhibit the collision-induced diffusion, one has to trap the atoms in a deep optical lattice[20] or use solid state system[27], where each atom is tightly confined in a single site and collisions are avoided. The optical lattice has the potential to store the collective excitation for a few tens of seconds, which will reach the requirement in the storage time for a robust and efficient quantum repeater with atomic ensembles[28]. The idea presented in this work can also be applied to the quantum memory based on electromagnetically induced transparency[20, 21, 30]. By using the same method as in our experiment, a storage time of a few hundred microseconds can be expected.

Our work opens up the exciting possibility to implement many tasks of quantum information processing. Combined with the techniques developed in recent years, one can implement a high-quality on-demand single-photon source, deterministic preparation of multi-qubit entanglement, generation of entanglement between two remote atomic memory qubits over a few hundred kilometers, and even construction of long-lived quantum nodes for quantum repeater. More generally, our work presents an experimental investigation on the decoherence of the SW at single quanta level. It is clearly shown that a long-wavelength SW is robust against dephasing. Besides, our work also provides an approach to measure the temperature or the velocity distribution of an atomic ensemble. Furthermore, since the decoherence of the SW is controllable, one can measure certain important physical quantities by introducing additional physical mechanisms. For example, when performing experiments in optical dipole trap, the lifetime is determined by collision between atoms[24]. Thereby, the s-wave scattering cross section or scattering length might be measured using our approach.

We acknowledge M. Fleischhauer and Y. J. Deng for useful discussions. This work was supported by the Deutsche Forschungsgemeinschaft (DFG), the Alexander von Humboldt Foundation, the European Commission through the Marie Curie Excellence Grant, the ERC Grant, the National Fundamental Research Program (Grant No.2006CB921900), the CAS, and the NNSFC.
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Fig. 1. (a) Schematic view of the experiment. The atoms are initially prepared in $|g\rangle$. A weak $\sigma^+$ polarized write pulse is applied to generate the SW and Stokes photon via spontaneous Raman transition $|g\rangle \rightarrow |e\rangle \rightarrow |s\rangle$. The Stokes photon are detected at an angle of $\theta$ relative to the write beam. After a controllable delay, a strong $\sigma^+$ polarized read light induces the transition $|s\rangle \rightarrow |e\rangle \rightarrow |g\rangle$, converting the SW into an anti-Stokes photon. (b) The structure of atomic transitions ($^{87}$Rb) under a weak magnetic field. The left panel corresponds to the experiment with $(|1,0\rangle, |2,0\rangle)$. The right one corresponds to the experiment with $(|1,1\rangle, |2,-1\rangle)$. The photons emitted in undesired transitions are filtered by polarization filter and filter cell. (c) Illustration of the SW dephasing induced by atomic random motion. The blue curve represents the SW initially stored in the quantum memory. The atoms randomly move along the wave vector direction, resulting in a phase fluctuation. The perturbed SW is represented by the red curve. (d) The wavelength of the SW can be controlled by changing the detection configuration. In the collinear case, we have the maximum wavelength.

Fig. 2. The cross correlation $g_{S,AS}$ versus the storage time $\delta t$ for $(|1,0\rangle, |2,0\rangle)$ at $\theta = 3^\circ$. The data are fitted by using $g_{S,AS}(\delta t) = 1 + C \exp(-\delta t^2/\tau_D^2)$. Our data give a lifetime of $\tau_D = 25 \pm 1 \mu s$, which is much less than the theoretical estimation for the “clock state”. Error bars represent statistical errors.

Fig. 3. The cross correlation $g_{S,AS}$ versus the storage time $\delta t$ for different angles (a)-(c) and the measured lifetime $\tau_D$ as a function of detection angle $\theta$. Panels (a) and (b) are for $(|1,0\rangle, |2,0\rangle)$ at $\theta = 1.5^\circ$ and $0.6^\circ$, respectively. The data are fitted by using $g_{S,AS}(\delta t) = 1 + C \exp(-\delta t^2/\tau_D^2)$, where $\tau_D$ is the lifetime due to dephasing. Panel (c) is for $(|1,1\rangle, |2,-1\rangle)$ at $\theta = 0.2^\circ$. In this case we take into account the effect of loss of atoms and fit the data by using $g_{S,AS}(\delta t) = 1 + C \exp(-\delta t^2/\tau_D^2)/(1 + A\delta t^2)$, with $A$ the fitting parameter obtained from the collinear configuration. The fitted lifetime for each case is: (a) $\tau_D = 61 \pm 2 \mu s$, (b) $\tau_D = 144 \pm 9 \mu s$, (c) $\tau_D = 283 \pm 18 \mu s$. The first data are a little bit higher than the fitted curves, which might be caused by the imperfection in the pumping process. By reducing the angle, the lifetime is increased from 25 $\mu s$ to 283 $\mu s$, which implies the decoherence is mainly caused by the dephasing induced by atomic random motion. Panels (d) depicts the measured lifetime $\tau_D$ as a function of detection angle $\theta$, where the horizontal error bars indicate measurement errors in the angles. The solid line is the theoretical curve with $T \simeq 100 \mu K$. The experimental results are in good agreement with the theoretical predications. The vertical error bars indicate statistical errors.

Fig. 4. The cross correlation $g_{S,AS}$ versus the storage time $\delta t$ for $\theta = 0^\circ$ and $(|1,1\rangle, |2,-1\rangle)$. The data are fitted by using $g_{S,AS}(\delta t) = 1 + \frac{C}{1 + A\delta t^2}$, with $A$ the fitting parameter. Our data give a lifetime of $\tau_L = 1.0 \pm 0.1$ ms, when the retrieval efficiency $\gamma(\delta t) = \frac{1}{1 + A\delta t^2}$ has dropped to $1/e$. Error bars represent statistical errors.
FIG. 1:
FIG. 2:
FIG. 3:
FIG. 4:
Methods

Dephasing of Spin Wave Induced by Atomic Random Motion. Assume the \( j \)-th atom moves to \( \mathbf{r}_j(\delta t) = \mathbf{r}_j + \mathbf{v}_j \delta t \) after a storage time of \( \delta t \). The collective state or spin wave (SW) freely evolves to
\[
|\psi_D\rangle = \frac{1}{\sqrt{N}} \sum_j e^{i \Delta k \cdot \mathbf{r}_j(\delta t)} |g_s g_s g_s \ldots g_s g_s g_s \rangle,
\]
where we have neglected the effect of magnetic field for simplicity. The retrieval efficiency is given by the overlap between the original SW and the perturbed one,
\[
\gamma(\delta t) \sim |\langle \psi | \psi_D \rangle|^2 = \frac{1}{N} \sum_j e^{i \Delta k \cdot \mathbf{v}_j \delta t} = \left| \int f(\mathbf{v}) e^{i \Delta k \cdot \mathbf{v} \delta t} dv \right|^2
\]
with \( f(\mathbf{v}) \) the velocity distribution. Assume \( f(\mathbf{v}) \sim e^{-\frac{m v^2}{2\tau_T}} \) is a Boltzmann distribution at temperature \( T \). Integrating over all possible velocity, we obtain \( \gamma(\delta t) \sim e^{-\delta t^2/2\tau_T} \), with the lifetime \( \tau_T = \frac{1}{\Delta \omega_c} \).

Cross Correlation Function. The quality of the quantum memory can be well characterized by the cross correlation \( g_{S,AS} = p_{S,AS}/(p_S \cdot p_{AS}) \). For \( g_{S,AS} \gg 1 \), when the atomic ensemble is used as a single photon source \cite{11,11}, the autocorrelation of the heralded single photons can be estimated by \( \alpha \approx 4/(g_{S,AS} - 1) \). When the atomic ensemble is used to prepare atom-photon entanglement source \cite{18,22}, the violation of the CHSH-type Bell inequality can be approximated by \( S \approx 2\sqrt{2} (g_{S,AS} - 1)/(g_{S,AS} + 1) \). Thereby, a large cross correlation function indicates a high-quality quantum memory. The nonclassical correlation between Stokes and anti-Stokes fields is characterized by the violation of Cauchy-Schwarz inequality \( g_{S,AS} \leq g_{S,S} g_{AS,AS} \), with \( g_{S,S} \) and \( g_{AS,AS} \) are the autocorrelation of Stokes and anti-Stokes field. In ideal case, \( g_{S,S} = g_{AS,AS} = 2 \), and in practice, they are usually smaller than 2 due to the back ground noise \cite{23}. Thereby, one can infer when \( g_{S,AS} > 2 \), the Stokes and anti-Stokes field are nonclassically correlated \cite{15}. In the experiment, we measure the decay of the cross correlation to evaluate the lifetime of the quantum memory. By neglecting the noise in Stokes channel, we have \cite{11}
\[
\begin{align*}
p_S &= \chi \eta_S, \\
p_{AS} &= \chi \gamma(\delta t) \eta_S + B \eta_{AS}, \\
p_{S,AS} &= \chi \gamma(\delta t) \eta_S \eta_{AS} + p_S p_{AS},
\end{align*}
\]
with \( \chi \) the excitation probability, \( \gamma(\delta t) \) the time dependent retrieval efficiency, \( \eta_S(\eta_{AS}) \) the overall detection efficiencies in the Stokes (anti-Stokes) channel, and \( B \) the background noise in anti-Stokes channel. Thereby the decay of the cross correlation function can be approximated by,
\[
g_{S,AS}(\delta t) = 1 + \frac{\gamma(\delta t)}{\chi \gamma(\delta t) + B} \approx 1 + C \gamma(\delta t),
\]
where \( C \) is a fitting parameter. In our experiment, \( p_S \approx 0.003 \) and the cross correlation is comparable with previous works \cite{11}. For small angles and in the collinear regime, the cross correlation is lower because of the relatively large background noise due to the write and read beams. Note that by reducing the power and waist of write and read beams, and improving the filtering techniques, a high cross correlation of about 100 can be achieved in the collinear configuration \cite{11}.

Experimental Details. In the experiment, the MOT is loaded for 20 ms at a repetition rate of 40 Hz. The trapping magnetic field and repumping beams are then quickly switched off. After 0.5 ms, the bias magnetic field is switched on, whereas the cooler beams stay on for another 0.5 ms before being switched off to prepare the atoms in the \( |5S_{1/2}, F = 1 \rangle \) ground state. Then, within another 4 ms, experimental trials (each consisting of pumping, write and read pulses) are repeated with a controllable delay depending on the desired retrieval time. In order to optically pump the atoms to the desired sub-level, we switch on two pumping beams in each experimental trial before write and read process: one couples the transition \( |5S_{1/2}, F = 2 \rangle \rightarrow |5P_{3/2}, F' = 2 \rangle \) with linear polarization for 2 \( \mu s \), and the other couples the transition \( |5S_{1/2}, F = 1 \rangle \rightarrow |5P_{1/2}, F' = 1 \rangle \) for 1.7 \( \mu s \), which is linearly \( (\sigma^+ \) polarized for \( (1, 0) \) \( (1, 1) \)). From the experimental result, we estimate more than 80% of the atoms are prepared to the desired state.

In our experiment, more than \( 10^8 \) \( ^{87} \)Rb atoms are collected by the MOT with an optical depth of about 5 and a temperature of about 100 \( \mu K \). The write pulse with a detuning of \( \Delta = 20 \) MHz and a beam diameter of about 400 \( \mu m \) is applied to generate the SW and the Stokes photon. The Stokes mode is coupled into a single-mode fiber (SMF) and guided to a single-photon detector. After a controllable delay, the strong read pulse with a detuning of \( \Delta = 6 \) MHz is applied to retrieve the SW. The stored SW is converted into the anti-Stokes photon, which is also coupled into a SMF and detected by a single-photon detector.

In the experiment, for \( \theta = 3^\circ, 1.5^\circ \) and \( 0.6^\circ \), the Stokes (anti-Stokes) photon and the write (read) light can be spatially separated and thus we can choose any of the three pairs of “clock states”. Because the retrieval efficiency is proportional to the coupling strength of the transition \( |e \rangle \rightarrow |g \rangle \), we choose the clock state \( (|1, 0\rangle, |2, 0\rangle) \) to get higher retrieval efficiency. While for smaller angles \( \theta = 0.2^\circ \) and \( 0^\circ \), the two beams with the same polarization cannot be spatially separated, and thereby we have to use the other two “clock states”. In this case, we choose the “clock state” \( (|1, 1\rangle, |2, -1\rangle) \), since the energy level \( |1, 1\rangle \) is lower than \( |1, -1\rangle \) under the bias magnetic field and the pumping effect is better. The overall retrieval efficiency, including transmission efficiency of filters and optical components, the coupling efficiency of...
the fiber coupler, and the detector quantum efficiency, are about 2% for \((|1, 0\rangle, |2, 0\rangle)\) at \(\theta = 3^\circ, 1.5^\circ\) and 0.6\(^\circ\), and 1% for \((|1, 1\rangle, |2, -1\rangle)\) at \(\theta = 0.2^\circ\), and 0.8% for \((|1, 1\rangle, |2, -1\rangle)\) at \(\theta = 0^\circ\). The retrieval efficiency at \(\theta = 0^\circ\) is a little bit lower than at \(\theta = 0.2^\circ\), because one more etalon was used to filter the excitation beams. These correspond to 15% and 10% of original retrieval efficiency for \((|1, 0\rangle, |2, 0\rangle)\) and \((|1, 1\rangle, |2, -1\rangle)\), respectively. The low overall retrieval efficiency is caused by the transmission loss, the mode mismatch, the imperfect pumping, and the imperfect polarization of the write and read light.