Noise Reduction in Optically Controlled Quantum Memory

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Abstract

Quantum memory is an essential device for quantum communications systems and quantum computers. An important category of quantum memory, called Optically controlled quantum memory, uses a strong classical beam to control the storage and re-emission of a single photon signal through an atomic ensemble. The residual light from the strong classical control beam can cause severe noise and degrade the system performance significantly. Efficiently suppressing this noise is required for the successful implementation of optically controlled quantum memories. In this paper, we briefly review the latest and most common approaches to quantum memory and discuss the various noise reduction techniques used in implementing them.

Keywords: Noise Reduction, Quantum Memory, Quantum Communication.

1. Introduction

Quantum information is based on the fundamental principles and properties of quantum mechanics, and is believed to be the next generation of information technology. Quantum memory is an indispensable element for quantum information system, such as quantum computers [1-3], quantum communication [4, 5] and may finally facilitate the implementation of a "quantum internet" [6]. The function of quantum memory is to convert a flying qubit into a stationary qubit, to store the quantum state for a time and then revert the stationary qubit back into a flying qubit on demand. When the quantum states are prepared, and manipulated using photons, it is called optical quantum memory. Because most current quantum systems are based on photons, the term "quantum memory" in this paper refers specifically to optical quantum memory.

Quantum memory has many important applications in quantum information science and technology. For example, quantum memory can synchronize operations in linear quantum computing and quantum networks by storing and releasing qubits at a desired time. Another important application example is the implementation of quantum repeaters to extend the distance of quantum communication beyond the loss limitation of optical fibers [7]. Moreover, quantum memory can be operated as an on-demand single photon source by storing and controllably releasing single photons. To date, several comprehensive review articles on quantum memories have been published [8-14].

The main current approaches to quantum memory can be categorized into two schemes: engineered absorption memories and optically controlled memories [12]. Engineered absorption, also called photon echo [15, 16], is based on the engineering of the inhomogeneous broadening of an absorption line to produce the desired absorption and re-emission.

This scheme includes controlled reversible inhomogeneous broadening (CRIB) [17], gradient echo memory (GEM)[18, 19] and atomic frequency combs (AFC) [20], as well as their improved variations using optical control, such as Raman-GEM [19, 21]and Λ-AFC [22, 23]. In the engineered absorption scheme, read-out of quantum information does not occur on demand, and there is no residual control beam emitted along with the single photon in the same time. Therefore, the noise caused by a strong control beam is not a problem.

In contrast, the optically controlled memory approaches use a strong classical optical control beam to induce single photon absorption into (write) and excitation from (read) the storage medium. In this case, single-photon level signals and the residual control beam emerge from the storage medium at the same time, and their optical paths often overlap in space. Additionally, their frequency difference is usually very small. The strong residual light from the classical beam becomes the dominant source of noise and can significantly degrade the performance of the quantum memory. The removal of this residual light from the control beam while preserving the signal is essential to implement high fidelity optically controlled quantum memory. In section 2, we will give a brief overview of the main approaches to optically controlled quantum memory and in section 3 review various techniques to reduce the noise caused by the strong control beam.

2. Overview of optically controlled quantum memory approaches

Currently, the optically controlled scheme has three main approaches: electromagnetically induced transparency (EIT), Raman and Duan-Lukin-Cirac-Zoller (DLCZ).

EIT and Raman are similar approaches and both use a Λ (lambda) type three-energy-level structure (as shown in Fig. 1 (a) and (b)). Two allowed transitions between the two ground levels ($|g\rangle$ and $|s\rangle$) and the excited level ($|e\rangle$) are resonant with the signal and the control light, respectively. The main difference is the frequency detuning, Δ, between the two-photon resonance and the excited level. EIT is an optical phenomenon in atoms that uses quantum interference to induce transparency into an otherwise resonant and opaque medium. The quantum memory based on EIT was first described by Fleischhauer and Lukin in 2000 [24] and has since been demonstrated experimentally with a variety of materials, and has become the most popular approach for implementing quantum memory. In EIT, the detuning, Δ, between the two-photon resonance and the excited level is small (within the linewidth of the excited level). Therefore, since the control and signal beams are on the resonant atomic transitions, the control beam does not require very high power (an advantage with this approach) but its usable storage bandwidth is limited to sub-MHz (for warm atomic vapor) or tens of MHz (for a laser trapped cold atom). Raman quantum memory was first proposed in 2000 [25] and uses a much larger detuning, Δ, between the two-photon resonance and the excited level. Since Raman-quantum-memory approach uses the off-resonant Raman interaction and does not rely on the EIT effect, it requires a much higher power control beam but achieves a much larger operational bandwidth than EIT. Experiments in Raman have demonstrated over GHz storage bandwidth over a THz range. Therefore, Raman quantum memory can store a temporally short pulse which necessarily comprises a large range of frequencies, and so is suitable for high-speed quantum memory [26]. Fig.1 (c) shows the storage and retrieval process of EIT and Raman quantum memories.

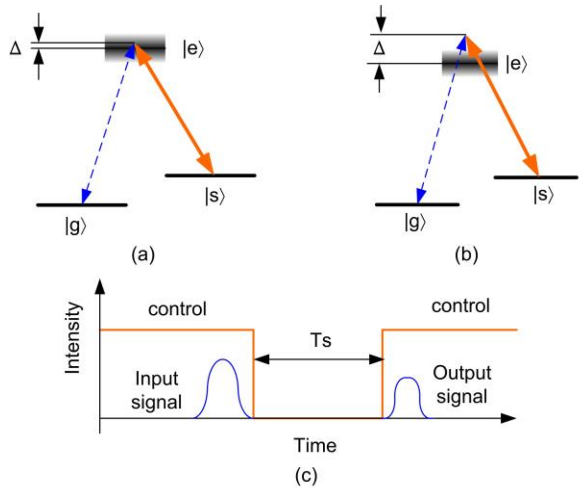

Figure 1. Optically controlled scheme (a) energy level structure of EIT approach, (b) energy level structure of Raman approach, (c) storage and retrieval process of EIT and Raman quantum memory. Ts: storage time

The DLCZ protocol was proposed by Duan, Lukin, Cirac and Zoller in 2001 [27] originally for implementing a quantum repeater. In the DLCZ protocol, quantum states can be transferred between atoms and photons, and then stored in atomic ensembles for long periods. Like EIT and Raman, the DLCZ protocol is also based on atomic ensembles with a lambda configuration. The protocol begins by preparing all atoms in the ground state. As shown in Fig. 2 (a), a weak write pulse illuminates an atomic ensemble and induces a Raman transition ($|g\rangle \rightarrow |e\rangle$) with a probability of $\ll 1$. Afterwards, it decays to the $|s\rangle$ ground state and emits a Raman scattered photon, called a stokes photon. If two atomic ensembles are simultaneously illuminated by write pulses and the emission paths are combined at a beamsplitter, then when a single photon is detected, it is impossible to tell which one of the two ensembles has emitted the photon, and the state of the two ensembles becomes an entangled superposition. Later, a relatively strong read pulse is used to convert the stored atomic excitation into an idler field, as shown in Fig. 2(b). This is a measure-induced protocol, and the entanglement of atomic ensembles can be transferred to photonic modes on demand, which is similar to the function of an optical quantum memory. The main difference between the DLCZ optical quantum memory to other types of optical quantum memories is that the DLCZ building block, shown in Fig. 2(c), does not store external photons, but instead generates photons within the atomic ensemble itself. However, the write and read process is similar to other optically controlled quantum memory protocols, i.e. the signal photons are emitted with a strong classical control beam (called write and read beam in the DLCZ protocol). Therefore, the DLCZ building block is usually considered as an optically controlled quantum memory.

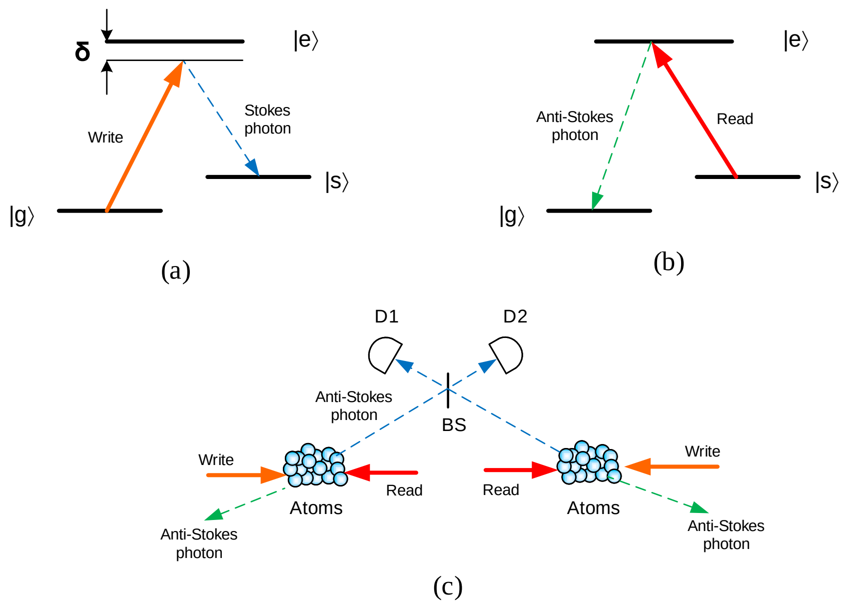

Figure 2. The DLCZ protocol. (a) and (b) The energy levels associated to write and read process in DLCZ; (c) Process in DLCZ protocol

3. Key technologies to noise reduction

In optically controlled quantum memories, the strong classical beam, called the "control beam" or "coupling beam" in EIT, the "control beam" in Raman, and the "write beam" and "read beam" in DLCZ, is much stronger than single photon level signal and usually requires over 100 dB (10 orders of magnitude) suppression to satisfy the fidelity requirement. In this section, we discuss the key technologies that are used for the noise reduction.

3.1. Polarization filter

In optically controlled quantum memories that have an input signal, such as the EIT and Raman protocols, the polarization states of the signal and the control beam can be perpendicular, and can be separated with a polarization filter. The typical configuration is shown in Fig. 3. The suppression ability of polarization is dependent on the polarization purity of the control beam, the extinction ratio of the polarizers, and the birefringence of the optical elements used in the quantum memory. Because the polarization of a control beam can be purified by a polarizer, these first two factors are ultimately determined by the polarizer. Currently, the highest extinction ratio of a high quality commercial polarizer, such as a Glan polarizer, can reach as high as 10^7. Considering the imperfect birefringence of optical elements, the practical noise suppression of polarization filtering can reach approximately 60 dB. The polarization filtering technique has been extensively used in almost all EIT and Raman quantum memory configurations.

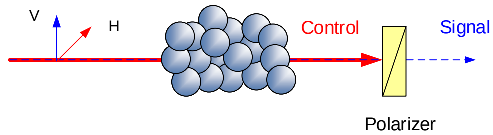

Figure 3. Polarization filter application in EIT or Raman quantum memory

One issue is that quantum memory with a polarization filter can only operate with photons on a certain polarization state. However, in practice, the single photons carry quantum information that is encoded as the superposition of a two-dimensional degree of freedom to form a qubit. For polarization encoding, the quantum memory must store and retrieve photons with arbitrary polarization states. In this case, two spatially separated atomic ensembles can be used to implement quantum memory for storing polarization encoded qubits. An arbitrary photonic polarization qubit can be expressed as:

$$|\psi_{in}\rangle = \cos\theta|H\rangle + e^{i\phi}\sin\theta\,|V\rangle \tag{1}$$

where $|H\rangle$ and $|V\rangle$ refer to horizontal and vertical polarization states, respectively. Each of the polarization basis states can be mapped into the corresponding atomic ensemble with a polarization filter. The state of the two atomic ensembles after a storage process can be considered as an atomic polarization state and the state can be mapped back to the photonic polarization qubit by turning on the control beam. A typical configuration is shown in Fig. 4. Quantum memory for a photonic polarization qubit has been demonstrated by two spatially separated atomic ensembles in magneto optical trapping (MOT) [28, 29] and in a warm atomic cell [30, 31], and has also been demonstrated with two spatially overlapped cold atomic ensembles in an optical cavity [32].

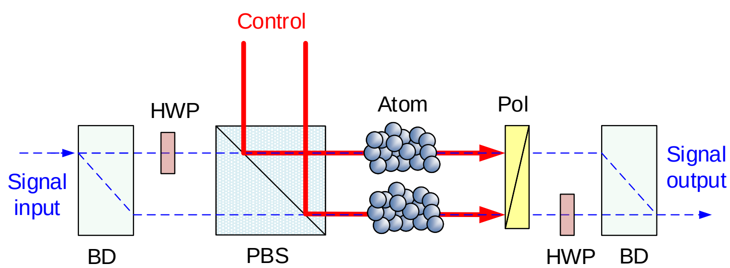

Figure 4. Quantum memory configuration for polarization qubit. BD: Beam displacer; HWP: Half-wave plate; PBS: Polarizing beam splitter.

Although DLCZ-type optical quantum memory does not have input photons, polarization filters are also used. Fig. 5 shows the experimental configuration of the first demonstrated DLCZ type memory in Ref. [33]. The write and read beams are in different polarization states. The PBS on the left combines the read and write beam and guides them into the atomic ensemble, which is based on cold atoms trapped in a MOT. Stokes and anti-stokes photons are generated and emitted with write and read pulses respectively, and are collected on the same axis (in a collinear geometry). The second PBS on the right works as a polarization filter to separate the read and write beams. After further filtering by atomic filters (see details below), the write beam and anti-stokes photons go to Detector 1, and the read beam and stokes photons go to Detector 2. For each detector, the arrival time of the classical beam pulse and the single-photon signal is different, therefore, an electronic timing gate can be used to block the classical pulse, but allow the single-photon signal to be detected. For a polarization encoded system, the DLCZ type of quantum memory uses two atomic ensembles to generate horizontal and vertical polarization states which are later combined [34].

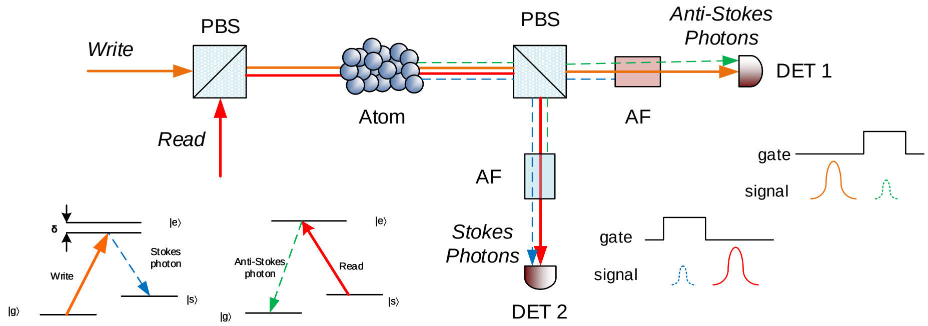

Figure 5. DLCZ type memory in collinear geometry. PBS: Polarizing beam splitter; AF: atomic filter; DET: single photon detector

3.2. Spatial filter

In most optically controlled quantum memory schemes, including EIT, Raman and DLCZ, the control beams are typically required to co-propagate along with the single-photon-level signal. In some quantum memories based on atomic ensembles, however, such as the cold atoms in a MOT, the atoms hardly move, and are almost rigid, permitting a very small angle (usually 2-3 degree) difference between signal photons and the control beam without significant performance degradation. In this case, the control beam can be suppressed in a slightly off-axis configuration referred to as a spatial filter.

For DLCZ, in the earlier experiments based on a collinear geometry [33], as shown in Fig. 5, only polarization and spectral filters were used and the single-photon signal was significantly contaminated by noise from the residual write and read beams. In the experimental configuration of DLCZ memory in Ref. [35], the write and read beams propagate with a small angle difference. However, the photon collection remains on the axis, and the photons cannot be separated from the strong classical beams spatially. The first experiment with an off-axis spatial filter was reported in the classical regime in 2004 [36], followed by a report in the quantum regime in 2005 [37]. Since then, more off-axis spatial filtering experiments have been reported [38-40] and the technique has become a mainstream configuration for DLCZ type quantum memories based on cold atoms [41-46]. A typical off-axis spatial filter for DLCZ quantum memory [38] is shown in Fig. 6. The write and read beams are in different polarization states and counter-propagated into the atomic ensemble. The stokes and anti-stokes photons are collected at a direction deflected 3° angle from the common axis defined by the write and read beams. This small angle allows for efficient noise suppression. With this spatial filter in combination with a polarization filter and a spectral filter (atomic filter), this configuration achieved a much higher photon heralding rate than a collinear geometry of the DLCZ memory implemented by the same research group.

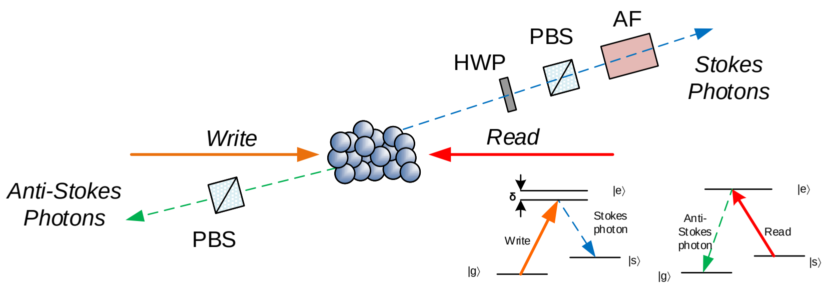

Figure 6. DLCZ type of memory in counter-propagation and off-axis configuration. PBS: Polarizing beam splitter; AF: Atomic filter; HWP: Half-wave plate.

Spatial filtering has also been applied to EIT [29, 43, 47-51] and Raman [52, 53] memories. As shown in Fig. 7, the path of the signal photons is a few degrees off the control beam. After they interact in the atomic ensemble, the control beam can be blocked spatially. The effectiveness of a spatial filter is limited by the scattering of the control beam from the inner surfaces of the container of the atomic ensemble. In a carefully arranged experiment, a noise suppression of 40-50 dB can be achieved.

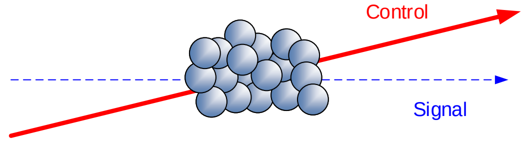

Figure 7. Spatial filter application in EIT or Raman quantum memory

It is worth noting that the spatial filters are typically only suitable for optically controlled quantum memory based on cold atoms, and not for quantum memories based on a warm atomic ensemble where collinear propagation of the signal and control beams is required to avoid large Doppler broadening [54]. However, recently, a new protocol of optically controlled quantum memory, called off-resonant cascaded absorption (ORCA), has been reported [67, 68]. Different from other previous protocols based on the Λ energy structure, the ORCA protocol uses a ladder energy structure, as shown in Fig. 8 (a) and (b). Because of the ladder energy structure, the classical control beam counter-propagates with the signal photon beam, as shown in Fig. 8 (c), which allows them to be spatially separated resulting in low noise.

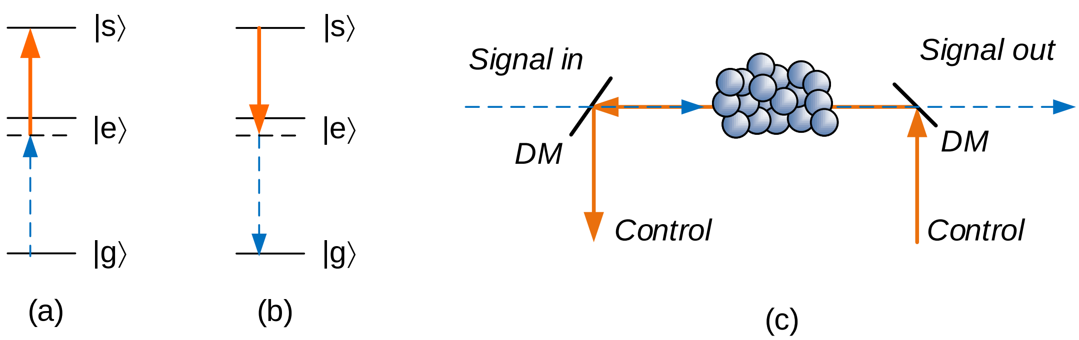

Figure 8. ORCA protocol. (a) energy level structure of writing process in ORCA protocol. (b) energy level structure of reading process in ORCA protocol (c) the experimental schematic of ORCA protocol.   DM: Dichroic Mirror

Since the frequencies of control beam and signal photons are slightly different, spectral filters can be used to further suppress the residual control beam. The frequency difference between control and signal beams is usually the hyperfine splitting of the atomic ground level, which is very small, for example, 9.2 GHz for the Cs atom, 6.8 GHz for the ^{87}Rb and 3.0 GHz for the ^{85}Rb. Traditional dispersive elements and interference filters are not suitable due to the small frequency difference of just a few GHz. In that case, Fabry-Perot (FP) etalons and atomic filters can be used.

A FP etalon consists of two parallel reflecting surfaces forming a resonator. Its spectral response is based on interference between the light launched into and the light circulating in the resonator. When a frequency is resonant with an etalon mode, constructive interference occurs and light can pass through the etalon while other frequencies are blocked. Therefore, a FP etalon can work as a very narrow bandpass spectral filter. The free spectral range (FSR) of FP etalon is determined by the distance between the two reflecting surfaces (d) and the refractive index of the material between the two surfaces (n).

$$FSR = \frac{c}{2 \cdot n \cdot d} \tag{2}$$

where c is the speed of light in vacuum. In an ideal condition, the transmittance of a FP etalon can be calculated by

$$T = \frac{1}{1 + F\sin^2(\frac{\phi}{2})} \tag{3}$$

where T is the transmission of an FP etalon, F is the coefficient of finesse, $F = \frac{4R}{(1-R)^2}$, R is the reflectivity of the reflecting surface, ϕ is the phase difference and it is determined by $\phi = \frac{4\pi nd}{c}\delta\nu$, $\delta\nu$ is the difference between the light frequency and the resonant frequency of the FP etalon. When $\phi = 0$, the light frequency is in phase and is resonant with the FP etalon, so light will pass through the FP etalon ($T = 1$). When $\phi = \pi$, the light frequency is fully out of phase, and the light is suppressed by a maximum value ($T = \frac{1}{1+F}$). The out-of-phase frequency is centered between resonant modes, so to realize the optimal performance of a FP etalon in optically controlled quantum memories, the FSR should be twice the frequency difference between signal and control beams. In that case, the signal photon is resonant with the etalon and can pass through while the control beam is suppressed by the maximum value, shown as in Fig. 9. For example, for a Cs based memory system, the frequency difference between the signal and control beams is 9.2 GHz, and the corresponding free spectral range should be 18.4 GHz.

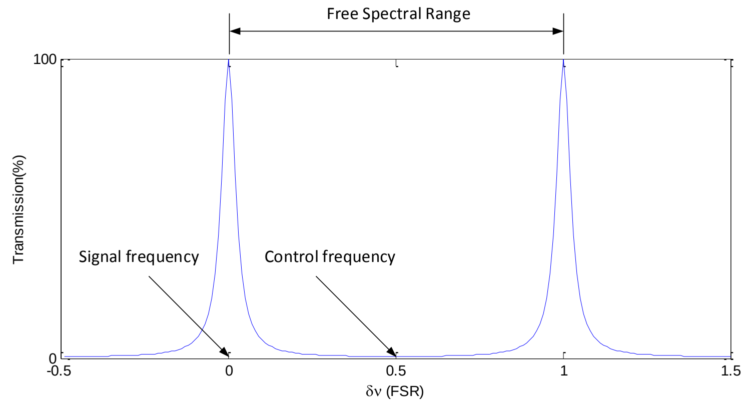

Figure 9. The signal and control frequency in the

Another important parameter of an FP etalon is finesse ($\mathcal{F}$)

$$\mathcal{F} = \frac{FSR}{\delta\nu_{FWHM}} = \frac{\pi}{2\arcsin(\frac{1}{\sqrt{F}})} \approx \frac{\pi\sqrt{F}}{2} \tag{4}$$

where the $\delta\nu_{FWHM}$ is the bandwidth of the FP etalon. From the Eq. (3) and (4), the suppression ratio of a FP etalon is dependent on the finesse. In theory, the higher the reflectivity (R), the higher finesse and the larger the suppression. However, due to irregularities in the reflecting surfaces, imperfect parallelism of two reflecting surfaces, absorption and scattering of light in the substrate, and scattering at the coating layer, it is very challenging to obtain FP etalons with the maximum transmission and finesse. In practice, approximately 90 % transmission for the signal and 20 dB suppression for control beam are typical. Also, using several FP etalons in series or multi-pass FP etalons can achieve sufficient suppression in optical quantum memories. Ref. [55] reported such a multi-pass FP etalon, in which two retroreflectors placed above and below the etalon are used to direct the beams back through the etalon three times at different locations along the etalon surfaces. Combining a multi-pass FP etalon with a Glan polarizer, the authors demonstrated an EIT quantum memory based on warm Cs atoms at a single-photon power level. The multi-pass etalon achieved 46 dB of control beam suppression and 65 % of signal beam transmission.

Atomic filters are another type of spectral filter with a suitably narrow bandwidth for optical quantum memory. Specifically, atomic resonance absorption filters and Faraday atomic filters have been implemented for noise suppression in optical quantum memory.

An atomic resonance absorption filter uses an atomic vapor that absorbs light components whose frequencies are resonant with the allowed electronic transitions of the atom. The absorbance rate and bandwidth are determined by the cell temperature. The higher the cell temperature, the higher absorbance and broadener bandwidth. In addition, the absorption frequencies and bandwidth also can be slightly adjusted by applying a magnetic field that is perpendicular to the direction of the light propagation.

In an optically controlled quantum memory, both the signal and control beams are close to the allowed transitions. If the same atom is used in the quantum memory as the atomic filter, both signal and control beams would be absorbed. To avoid this, different elements or isotopes with transitions to absorb the control frequency but transmit the signal frequency are used. For example, in natural rubidium there are two isotopes, ^{85}Rb and ^{87}Rb. The two isotopes have nearly degenerate transition lines (in the D1 line, ^{85}Rb $5^2S_{1/2}$ F=3 $\rightarrow$ $5^2P_{1/2}$ F'=3 and ^{87}Rb $5^2S_{1/2}$ F=2 $\rightarrow$ $5^2P_{1/2}$ F'=1, and in the D2 line, ^{85}Rb $5^2S_{1/2}$ F=3 $\rightarrow$ $5^2P_{3/2}$ F'=3 and ^{87}Rb $5^2S_{1/2}$ F=2 $\rightarrow$ $5^2P_{3/2}$ F'=1.) When the nearly degenerate transition frequency is used for control light, the control light is absorbed in an allowed transition of the filtering isotope. Meanwhile, there is no allowed transition at the signal frequency in the filtering isotope and it is transmitted [56, 57]. To date, many EIT and DLCZ quantum memory experiments have used ^{87}Rb as a memory medium and ^{85}Rb as an atomic resonance absorption filter [50, 56-59].

However, unlike Rb, most other commonly used elements, including Cs, do not have suitable isotopes for this application. To implement an atomic absorption filter for quantum memories based on Cs atoms, an additional optical pump is needed to reduce or eliminate the absorption at the signal frequency. We have developed such an optically pumped atomic resonance absorption filter and have used it in our EIT quantum memory based on Cs atoms. The configuration of the filter is shown in Fig. 10 (a). A Cs cell is magnetically shielded and mounted in a temperature controlled oven. The partial energy level diagram of cesium is shown in Fig. 10 (b). The four wavelengths contained in the allowed D1 transition of Cs atoms, including the wavelengths of the control and signal beams (solid red lines, $6^2S_{1/2}$ F=3 $\rightarrow$ $6^2P_{1/2}$ F'=4 and $6^2S_{1/2}$ F=4 $\rightarrow$ $6^2P_{1/2}$ F'=4) in our quantum memory. In other words, both the control and signal beams could be blocked. Since there is no suitable isotope in natural cesium that can be used for this purpose, a strong pump beam is used to make the Cs atoms transparent to the signal photons. A strong pump beam at the wavelength near 852 nm in the D2 transition is used to excite the Cs atoms from $6^2S_{1/2}$ F=4 to $6^2P_{3/2}$ F'=3 which then decay to the lowest hyperfine splitting of the ground state $6^2S_{1/2}$ F=3 (solid black lines). If this pump is strong enough, the atoms in the cell can be prepared at the lowest ground energy level of $6^2S_{1/2}$ F=3, while the population of the other higher ground state $6^2S_{1/2}$ F=4 approaches zero. Therefore, two allowed transitions (dotted red lines) become unable, and the atoms are then transparent to the signal photons. Fig 10 (c) and (d) show the absorption spectra of the filter without and with the pump, respectively. The optically pumped atomic resonance absorption filter can pass the signal photons and absorb the control beams. Such filters have been extensively used in Cs-based EIT quantum memory and DLCZ quantum memory [33, 59] .

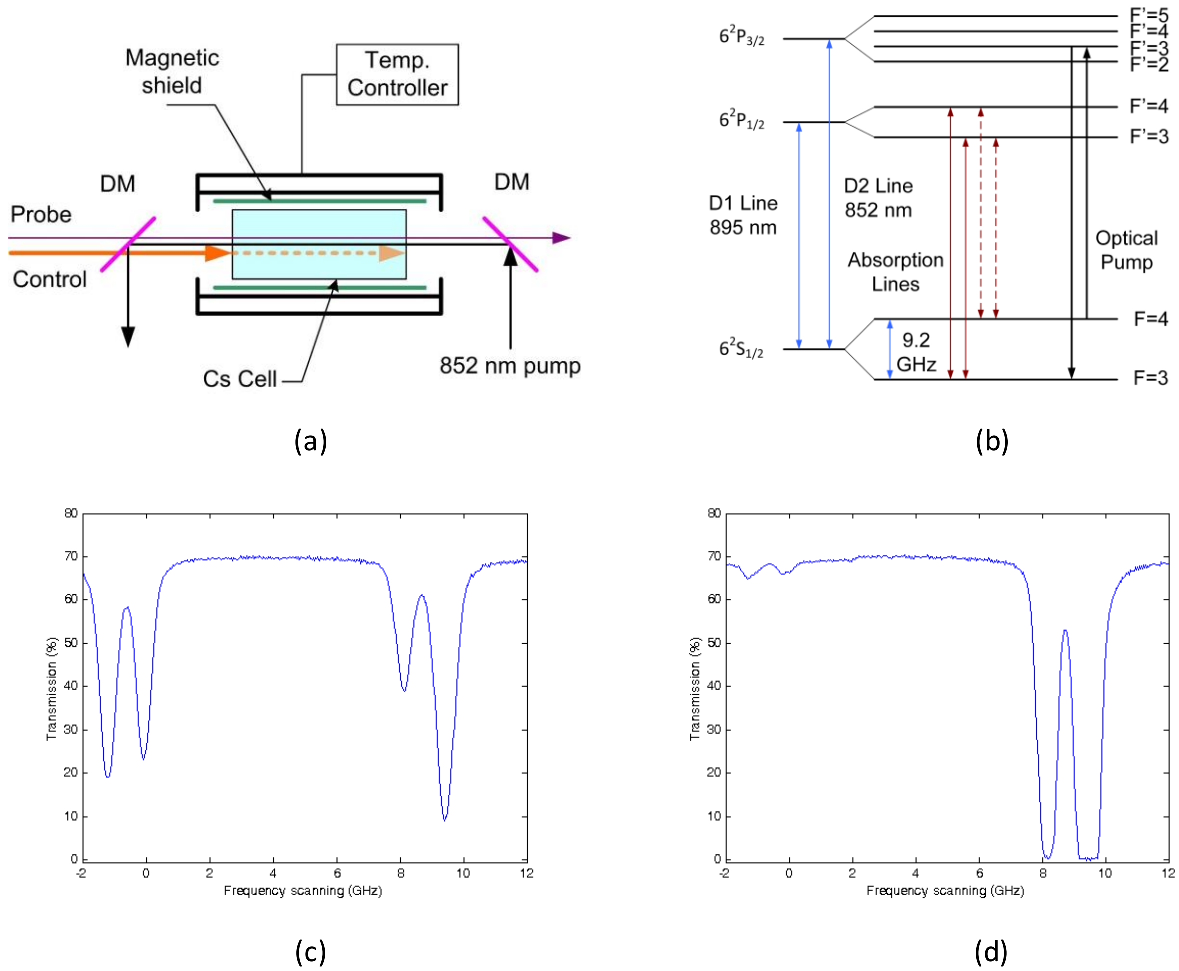

Figure 10. Optically pumped atomic resonance absorption filter based on Cs atom (a) filter configuration (b) Partial energy level diagram of Cs atom: the absorption wavelengths in D1 lines and optical pump (c) absorption spectrum without pump (d) absorption spectrum with pump

The Faraday atomic filter, also known as magneto-optical filter or Faraday anomalous dispersion optical filter (FADOF) is based on the Faraday effect and anomalous dispersion near the atomic absorption lines [60-62]. This filter consists of an atomic vapor cell positioned between a pair of crossed optical polarizers. A magnetic field along the light propagation direction is applied to the atomic cell. It is well known that linearly polarized light can be decomposed to left- and right-circularly polarized components. Due to the resonant Faraday effect, when a near-resonance linearly polarized light passes the first polarizer and propagates through the atomic cell, the left- and right-circularly polarized components experience a different phase delay that results in a polarization rotation. When the rotation is 90°, the light can pass through the second polarizer. Therefore, only the frequency components near the atomic resonance can transmit through the filter. The Faraday atomic filter is a bandpass filter with very narrow bandwidth around the atomic absorption lines, and is perfectly suitable to be used in optically controlled quantum memories for suppressing a strong noise background from a weak optical signal. If a polarization filter is used in the quantum memory system, then the signal photons are already in a pure polarization state. In this case, the first polarizer is not needed.

Like the atomic resonance absorption filter, the Rb based Faraday atomic filter can also take advantage of two isotopes, while the Cs based filter can use an optical pump to avoid unwanted transparent windows. Fig. 11 (a) shows a Faraday atomic filter developed in our laboratory, and Fig. 11 (b) is the corresponding diagram of the Cs energy levels. Fig. 11 (c) and (d) show the absorption spectrum of the filter without and with pump, respectively. The Faraday atomic filter has also been used in quantum memory for noise suppression [63].

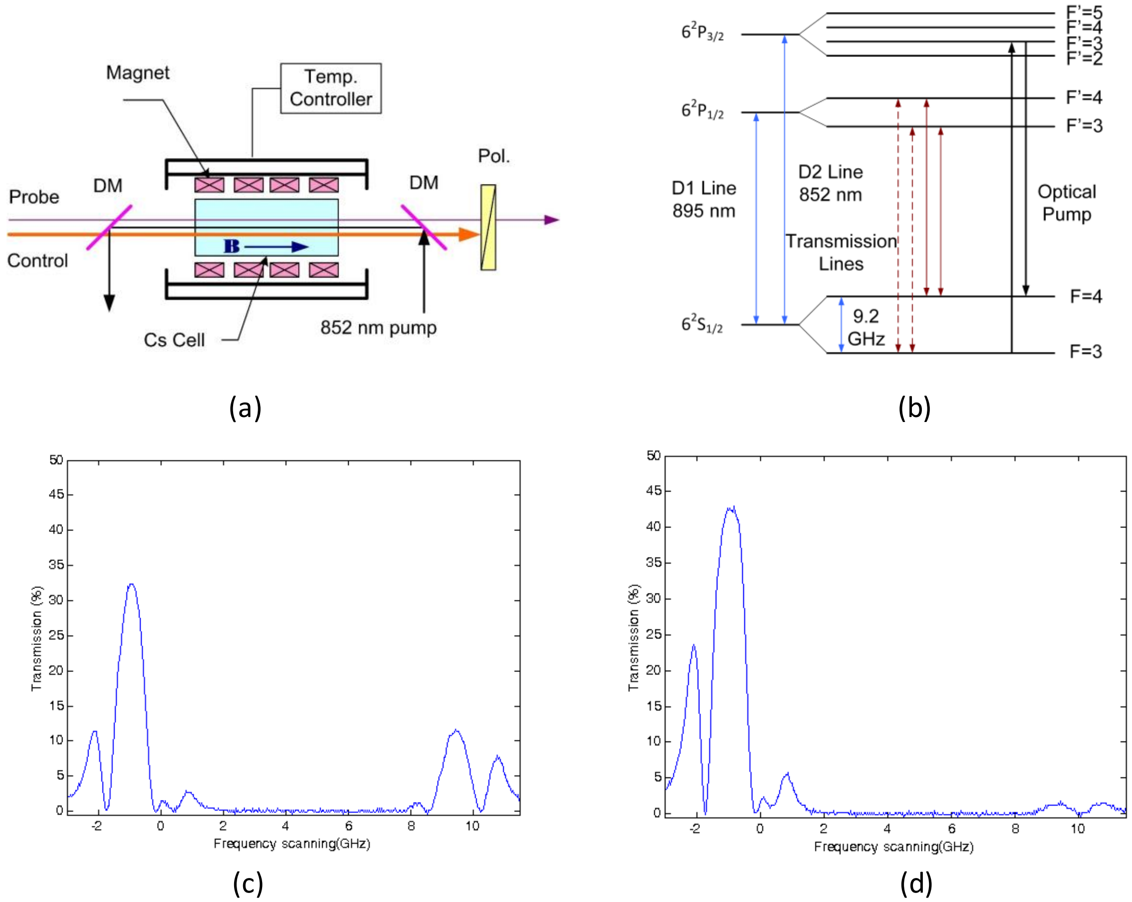

Figure 11. Optically pumped Faraday atomic filter based on Cs atom (a) filter configuration (b) Partial energy level diagram of Cs atom: the resonance wavelengths in D1 lines and optical pump (c) absorption spectrum without pump (d) absorption spectrum with pump

4. Summary

Optically controlled quantum memory is an important category to storing quantum information and includes EIT, Raman and DLCZ approaches. In these approaches, a strong classical optical beam (control beam in EIT and Raman, write and read beams in DLCZ) is used to control the storage and re-emission of a single-photon-level signal. This strong classical control beam overlaps with the single-photon signal in time, co-propagates along the same direction as the signal photons, and has frequencies that are very close to the signal photon. To efficiently suppress the noise caused by the control beam is a key process in such types of quantum memories. Currently, polarization filters, spatial filters and spectral filters, including cascade or multi-pass FP etalons, atomic resonance absorption filters and Faraday atomic filters, have been used in optically controlled quantum memories. With various combinations of these filters, the noise caused by the residual control beam is greatly suppressed, and many optically controlled quantum memories have been demonstrated. It is worth noting that although the residual control beam is the dominant noise source in optically controlled quantum memory, other noise photons exist including from spontaneous emission of thermally excited atoms, collision-induced fluorescence [64, 65], and spontaneous four-wave-mixing caused by the strong control beam [66]. With sufficient noise suppression, many high fidelity optically controlled quantum memory experiments have been demonstrated.

References

[1] E. Knill, R. Laflamme, and G. J. Milburn, "A scheme for efficient quantum computation with linear optics," *nature,* vol. 409, pp. 46-52, 2001.

[2] P. Kok, W. J. Munro, K. Nemoto, T. C. Ralph, J. P. Dowling, and G. J. Milburn, "Linear optical quantum computing with photonic qubits," *Reviews of Modern Physics,* vol. 79, p. 135, 2007.

[3] R. Raussendorf and H. J. Briegel, "A one-way quantum computer," *Physical Review Letters,* vol. 86, p. 5188, 2001.

[4] N. Gisin and R. Thew, "Quantum communication," *Nature Photonics,* vol. 1, pp. 165-171, Mar 2007.

[5] H. Weinfurter and A. Zeilinger, "Quantum communication," *Quantum Information,* vol. 173, pp. 58-95, 2001.

[6] H. J. Kimble, "The quantum internet," *Nature,* vol. 453, pp. 1023-1030, 2008.

[7] N. Sangouard, C. Simon, H. de Riedmatten, and N. Gisin, "Quantum repeaters based on atomic ensembles and linear optics," *Reviews of Modern Physics,* vol. 83, pp. 33-80, Mar 21 2011.

[8] A. I. Lvovsky, B. C. Sanders, and W. Tittel, "Optical quantum memory," *Nature Photonics,* vol. 3, pp. 706-714, 2009.

[9] C. Simon, M. Afzelius, J. r. Appel, A. B. de La Giroday, S. J. Dewhurst, N. Gisin, *et al.*, "Quantum memories," *The European Physical Journal D,* vol. 58, pp. 1-22, 2010.

[10] K. Hammerer, A. S. Sørensen, and E. S. Polzik, "Quantum interface between light and atomic ensembles," *Reviews of Modern Physics,* vol. 82, p. 1041, 2010.

[11] F. Bussières, N. Sangouard, M. Afzelius, H. de Riedmatten, C. Simon, and W. Tittel, "Prospective applications of optical quantum memories," *Journal of Modern Optics,* vol. 60, pp. 1519-1537, 2013.

[12] K. Heshami, D. G. England, P. C. Humphreys, P. J. Bustard, V. M. Acosta, J. Nunn, *et al.*, "Quantum memories: emerging applications and recent advances," *Journal of Modern Optics,* vol. 63, pp. 2005-2028, 2016.

[13] M. Afzelius, N. Gisin, and H. d. Riedmatten, "Quantum memory for photons," *Physics Today,* vol. 68, p. 6, 2015.

[14] L. Ma, O. Slattery, and X. Tang, "Optical quantum memory based on electromagnetically induced transparency," *Journal of Optics,* vol. 19, p. 043001, 2017.

[15] N. Kurnit, I. Abella, and S. Hartmann, "Observation of a photon echo," *Physical Review Letters,* vol. 13, p. 567, 1964.

[16] I. Abella, N. Kurnit, and S. Hartmann, "Photon echoes," *Physical review,* vol. 141, p. 391, 1966.

[17] S. Moiseev and S. Kröll, "Complete reconstruction of the quantum state of a single-photon wave packet absorbed by a Doppler-broadened transition," *Physical review letters,* vol. 87, pp. 173601-173604, 2001.

[18] M. Hosseini, B. Sparkes, G. Campbell, P. K. Lam, and B. Buchler, "Storage and manipulation of light using a Raman gradient-echo process," *Journal of Physics B: Atomic, Molecular and Optical Physics,* vol. 45, p. 124004, 2012.

[19] M. Hosseini, B. M. Sparkes, G. Campbell, P. K. Lam, and B. C. Buchler, "High efficiency coherent optical memory with warm rubidium vapour," *Nature communications,* vol. 2, p. 174, 2011.

[20] M. Afzelius, C. Simon, H. De Riedmatten, and N. Gisin, "Multimode quantum memory based on atomic frequency combs," *Physical Review A,* vol. 79, p. 052329, 2009.

[21] Y.-W. Cho, G. Campbell, J. Everett, J. Bernu, D. Higginbottom, M. Cao*, et al.*, "Highly efficient optical quantum memory with long coherence time in cold atoms," *Optica,* vol. 3, pp. 100-107, 2016.

[22] P. Jobez, I. Usmani, N. Timoney, C. Laplane, N. Gisin, and M. Afzelius, "Cavity-enhanced storage in an optical spin-wave memory," *New Journal of Physics,* vol. 16, p. 083005, 2014.

[23] P. Jobez, C. Laplane, N. Timoney, N. Gisin, A. Ferrier, P. Goldner*, et al.*, "Coherent spin control at the quantum level in an ensemble-based optical memory," *Physical review letters,* vol. 114, p. 230502, 2015.

[24] M. Fleischhauer and M. Lukin, "Dark-state polaritons in electromagnetically induced transparency," *Physical Review Letters,* vol. 84, p. 5094, 2000.

[25] A. Kozhekin, K. Mølmer, and E. Polzik, "Quantum memory for light," *Physical Review A,* vol. 62, p. 033809, 2000.

[26] K. F. Reim, J. Nunn, V. O. Lorenz, B. J. Sussman, K. C. Lee, N. K. Langford*, et al.*, "Towards high-speed optical quantum memories," *Nature Photonics,* vol. 4, pp. 218-221, 2010.

[27] L. M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, "Long-distance quantum communication with atomic ensembles and linear optics," *Nature,* vol. 414, pp. 413-418, Nov 22 2001.

[28] D. N. Matsukevich and A. Kuzmich, "Quantum state transfer between matter and light," *Science,* vol. 306, pp. 663-666, Oct 22 2004.

[29] K. S. Choi, H. Deng, J. Laurat, and H. J. Kimble, "Mapping photonic entanglement into and out of a quantum memory," *Nature,* vol. 452, pp. 67-U4, Mar 6 2008.

[30] Y.-W. Cho and Y.-H. Kim, "Atomic vapor quantum memory for a photonic polarization qubit," *arXiv preprint arXiv:1004.1325,* 2010.

[31] C. Kupchak, T. Mittiga, B. Jordaan, M. Namazi, C. Nölleke, and E. Figueroa, "Room-Temperature Single-photon level Memory for Polarization States," *Scientific reports,* vol. 5, 2015.

[32] H. Tanji, S. Ghosh, J. Simon, B. Bloom, and V. Vuletić, "Heralded single-magnon quantum memory for photon polarization states," *Physical review letters,* vol. 103, p. 043601, 2009.

[33] A. Kuzmich, W. Bowen, A. Boozer, A. Boca, C. Chou, L.-M. Duan*, et al.*, "Generation of nonclassical photon pairs for scalable quantum communication with atomic ensembles," *Nature,* vol. 423, pp. 731-734, 2003.

[34] Y. A. Chen, S. Chen, Z. S. Yuan, B. Zhao, C. S. Chuu, J. Schmiedmayer, *et al.*, "Memory-built-in quantum teleportation with photonic and atomic qubits," *Nature Physics,* vol. 4, pp. 103-107, Feb 2008.
[35] C. H. van der Wal, M. D. Eisaman, A. André, R. L. Walsworth, D. F. Phillips, A. S. Zibrov, *et al.*, "Atomic memory for correlated photon states," *Science,* vol. 301, pp. 196-200, 2003.
[36] D. A. Braje, V. Balić, S. Goda, G. Yin, and S. Harris, "Frequency mixing using electromagnetically induced transparency in cold atoms," *Physical review letters,* vol. 93, p. 183601, 2004.
[37] D. Matsukevich, T. Chaneliere, M. Bhattacharya, S.-Y. Lan, S. Jenkins, T. Kennedy*, et al.*, "Entanglement of a photon and a collective atomic excitation," *Physical review letters,* vol. 95, p. 040405, 2005.
[38] J. Laurat, H. de Riedmatten, D. Felinto, C. W. Chou, E. W. Schomburg, and H. J. Kimble, "Efficient retrieval of a single excitation stored in an atomic ensemble," *Optics Express,* vol. 14, pp. 6912-6918, Jul 24 2006.
[39] J. Laurat, C. W. Chou, H. Deng, K. S. Choi, D. Felinto, H. de Riedmatten*, et al.*, "Towards experimental entanglement connection with atomic ensembles in the single excitation regime," *New Journal of Physics,* vol. 9, Jun 29 2007.
[40] J. Laurat, K. Choi, H. Deng, C. Chou, and H. Kimble, "Heralded entanglement between atomic ensembles: preparation, decoherence, and scaling," *Physical review letters,* vol. 99, p. 180504, 2007.
[41] T. Chaneliere, D. Matsukevich, S. Jenkins, S.-Y. Lan, T. Kennedy, and A. Kuzmich, "Storage and retrieval of single photons transmitted between remote quantum memories," *Nature,* vol. 438, pp. 833-836, 2005.
[42] S. Chen, Y. A. Chen, B. Zhao, Z. S. Yuan, J. Schmiedmayer, and J. W. Pan, "Demonstration of a stable atom-photon entanglement source for quantum repeaters," *Phys Rev Lett,* vol. 99, p. 180505, Nov 2 2007.
[43] Y.-H. Chen, M.-J. Lee, I.-C. Wang, S. Du, Y.-F. Chen, Y.-C. Chen*, et al.*, "Coherent optical memory with high storage efficiency and large fractional delay," *Physical review letters,* vol. 110, p. 083601, 2013.
[44] C.-S. Chuu, T. Strassel, B. Zhao, M. Koch, Y.-A. Chen, S. Chen*, et al.*, "Quantum memory with optically trapped atoms," *Physical review letters,* vol. 101, p. 120501, 2008.
[45] A. G. Radnaev, Y. O. Dudin, R. Zhao, H. H. Jen, S. D. Jenkins, A. Kuzmich*, et al.*, "A quantum memory with telecom-wavelength conversion," *Nature Physics,* vol. 6, pp. 894-899, Nov 2010.
[46] B. Zhao, Y. A. Chen, X. H. Bao, T. Strassel, C. S. Chuu, X. M. Jin*, et al.*, "A millisecond quantum memory for scalable quantum networks," *Nature Physics,* vol. 5, pp. 95-99, Feb 2009.
[47] K. Akiba, K. Kashiwagi, M. Arikawa, and M. Kozuma, "Storage and retrieval of nonclassical photon pairs and conditional single photons generated by the parametric down-conversion process," *New Journal of Physics,* vol. 11, p. 013049, 2009.
[48] K. Akiba, K. Kashiwagi, T. Yonehara, and M. Kozuma, "Frequency-filtered storage of parametric fluorescence with electromagnetically induced transparency," *Physical Review A,* vol. 76, p. 023812, 2007.
[49] D. S. Ding, Z. Y. Zhou, B. S. Shi, and G. C. Guo, "Single-photon-level quantum image memory based on cold atomic ensembles," *Nat Commun,* vol. 4, p. 2527, 2013.

[50] H. Zhang, X.-M. Jin, J. Yang, H.-N. Dai, S.-J. Yang, T.-M. Zhao, *et al.*, "Preparation and storage of frequency-uncorrelated entangled photons from cavity-enhanced spontaneous parametric downconversion," *Nature Photonics,* vol. 5, pp. 628-632, 2011.
[51] S. Zhou, S. Zhang, C. Liu, J. Chen, J. Wen, M. Loy, *et al.*, "Optimal storage and retrieval of single-photon waveforms," *Optics express,* vol. 20, pp. 24124-24131, 2012.
[52] D.-S. Ding, W. Zhang, Z.-Y. Zhou, S. Shi, B.-S. Shi, and G.-C. Guo, "Raman quantum memory of photonic polarized entanglement," *Nature Photonics,* vol. 9, pp. 332-338, 2015.
[53] D.-S. Ding, W. Zhang, Z.-Y. Zhou, S. Shi, G.-Y. Xiang, X.-S. Wang, *et al.*, "Quantum storage of orbital angular momentum entanglement in an atomic ensemble," *Physical review letters,* vol. 114, p. 050502, 2015.
[54] I. Novikova, R. L. Walsworth, and Y. Xiao, "Electromagnetically induced transparency‐based slow and stored light in warm atoms," *Laser & Photonics Reviews,* vol. 6, pp. 333-353, 2012.
[55] D. Höckel and O. Benson, "Electromagnetically induced transparency in cesium vapor with probe pulses on the single-photon level," *Physical review letters,* vol. 105, p. 153605, 2010.
[56] A. Heifetz, A. Agarwal, G. C. Cardoso, V. Gopal, P. Kumar, and M. Shahriar, "Super efficient absorption filter for quantum memory using atomic ensembles in a vapor," *Optics Communications,* vol. 232, pp. 289-293, 2004.
[57] D. T. Stack, P. J. Lee, and Q. Quraishi, "Simple and efficient absorption filter for single photons from a cold atom quantum memory," *Optics express,* vol. 23, pp. 6822-6832, 2015.
[58] M. Eisaman, L. Childress, A. André, F. Massou, A. Zibrov, and M. Lukin, "Shaping quantum pulses of light via coherent atomic memory," *Physical review letters,* vol. 93, p. 233602, 2004.
[59] M. Eisaman, A. André, F. Massou, M. Fleischhauer, A. Zibrov, and M. Lukin, "Electromagnetically induced transparency with tunable single-photon pulses," *Nature,* vol. 438, pp. 837-841, 2005.
[60] J. Menders, K. Benson, S. Bloom, C. Liu, and E. Korevaar, "Ultranarrow line filtering using a Cs Faraday filter at 852 nm," *Optics letters,* vol. 16, pp. 846-848, 1991.
[61] Y. Wang, S. Zhang, D. Wang, Z. Tao, Y. Hong, and J. Chen, "Nonlinear optical filter with ultranarrow bandwidth approaching the natural linewidth," *Optics letters,* vol. 37, pp. 4059-4061, 2012.
[62] D. Dick and T. M. Shay, "Ultrahigh-noise rejection optical filter," *Optics letters,* vol. 16, pp. 867-869, 1991.
[63] M. Dąbrowski, R. Chrapkiewicz, and W. Wasilewski, "Magnetically tuned, robust and efficient filtering system for spatially multimode quantum memory in warm atomic vapors," *Journal of Modern Optics,* vol. 63, pp. 2029-2038, 2016.
[64] S. Manz, T. Fernholz, J. Schmiedmayer, and J.-W. Pan, "Collisional decoherence during writing and reading quantum states," *Physical Review A,* vol. 75, p. 040101, 2007.
[65] S. Jiang, X. M. Luo, L. Q. Chen, B. Ning, S. A. Chen, J. Y. Wang, *et al.*, "Observation of prolonged coherence time of the collective spin wave of an atomic ensemble in a paraffin-coated Rb-87 vapor cell," *Physical Review A,* vol. 80, Dec 2009.
[66] M. R. Sprague, D. G. England, A. Abdolvand, J. Nunn, X. M. Jin, W. S. Kolthammer, *et al.*, "Efficient optical pumping and high optical depth in a hollow-core photonic-crystal fibre for a broadband quantum memory," *New Journal of Physics,* vol. 15, May 20 2013.

[67] K. T. Kaczmarek, P. M. Ledingham, B. Brecht, A. Feizpour, G. S. Thekkadath, S. E. Thomas, *et al.*, "A noise-free quantum memory for broadband light at room temperature," in *Quantum Information and Measurement*, 2017, p. QT2A. 4.
[68] K. Kaczmarek, P. Ledingham, B. Brecht, S. Thomas, G. Thekkadath, O. Lazo-Arjona, *et al.*, "A room-temperature noise-free quantum memory for broadband light," *arXiv preprint arXiv:1704.00013*, 2017.