EIT Quantum Memory with Cs Atomic Vapor for Quantum Communication

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ABSTRACT

Quantum memory is a key device in the implementation of quantum repeaters for quantum communications and quantum networks. We demonstrated a quantum memory based on electromagnetically-induced transparency (EIT) in a warm cesium atomic cell. The quantum memory system can avoid the need for helium temperature apparatus and it is low cost for bulk scalability.

Keywords: Quantum Memory, Quantum Communication, Electromagnetic introduced transparency

1. INTRODUCTION

A Quantum Repeater is an essential element for long distance quantum communications and quantum network systems[1]. The optical propagation of photons in fiber optic cables is subject to losses, which limits the distance that optical qubits can be transferred. Quantum repeaters enable long distance quantum communications beyond the loss limitation by entangling photons at both ends of a communications chain. Quantum repeaters can also be network nodes to connect variety quantum systems forming quantum networks. Currently, most common protocol for quantum repeaters is based on quantum teleportation. In such quantum repeater, it is only possible if quantum memories are used to temporarily store quantum states. Though a new protocol of quantum repeater without quantum memories have recently been proposed [2], as a main stream, quantum teleportation-based quantum repeaters using quantum memories attract lot attentions and seem to be promising.

The technical approaches to quantum memories are quite diverse[3, 4], including Electromagnetic introduced transparency (EIT) based on trapped cold atoms [5-13] or warm atomic vapor[14-18], photon echo (including controlled reversible inhomogeneous broadening (CRIB) [19-21], and atomic frequency combs (AFC) [22, 23], Raman excitation [24-26], NV centers in diamond [27], and quantum dots [28]. Most of these approaches need to cool down the atomic systems. Noticeably, there are two main approaches to implementing quantum memories using warm atomic vapor: EIT and Raman excitation. In comparison to other approaches, the implementation of warm atomic vapor can avoid the need for helium temperature apparatus and it is low cost for bulk scalability. The storage time is limited to a few tens of

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microseconds due to thermal Doppler broadening, but it satisfies the requirement of a high speed quantum communication system. Raman excitation is based on far off-resonant interaction, and therefore needs an extremely strong pump and generates serious noise, which limit its practical implementation. EIT-based quantum memories [29-32] use long-lived atomic states as quantum memory elements by mapping the quantum state of photons onto long-lived atomic states. It uses a strong light (coupling light) to control the propagation of photons (probe light) through a Λ type resonant atomic medium. First EIT based light memory was demonstrated in an atomic vapor in 2001 [33, 34], and since then many groups have successfully implemented quantum memories in atomic vapors [14-18]. So, EIT in atomic vapor is a feasible, inexpensive and scalable approach for quantum memory and suitable for quantum communication systems.

Rubidium (Rb) or Cesium (Cs) atoms are commonly used for EIT-based quantum memories. The operating wavelengths of Rb are 780 nm or 795 nm, and the wavelengths of Cs are 852 and 895 nm. Although many groups focus on Rb-based memory, we believe that the wavelengths of Cs are also suitable for quantum communication systems. The D2 line of Cs atom (852 nm) corresponds to the wavelength of the first generation optical communication systems. The D1 line of Cs atom (895 nm) is in the wavelength regime of fluorescence emission from InAs quantum dots, so it could be a coherent interfaces between atomic and solid-state systems. The D1 line of Cs atom also corresponds to a popular photon pair (895+1310 nm) generated by spontaneous parametric down conversion with a 532 nm pump wavelength. Light near 1310 nm can be operated in any existing 1550 nm optical communication systems. In addition, standard telecom fibers show a zero dispersion in this range so it is a suitable wavelength for long-distance quantum communications. Our group has developed several quantum communication systems based on 1310 nm [35, 36], consisted of the building blocks including up-conversion single photon detectors for 1310 nm [37-41], and a photon pair source at 895 and 1310 nm [42]. The EIT quantum memory with Cs atoms developed in this work will be integrated with these building blocks to implement long distance communication systems. In this paper, we will introduce our research on the EIT quantum memory with warm Cs atomic vapor.

2. SYSTEM CONFIGURATION

The experimental configuration is shown in Fig. 1. A tunable CW diode laser around 895 nm is locked to Cs D1 transition $6^2S_{1/2}$ F=3 → $6^2P_{1/2}$ F'=4. The light was split into two optical paths for coupling and probe lights. The probe light first passes an electro-optic phase modulator (EOM) to generate sidebands at a 9.192 GHz separation corresponding to the hyperfine splitting of the two ground states of Cs. An Etalon selects the red-shifted sideband light, which is corresponding to the transition $6^2S_{1/2}$ F=4 → $6^2P_{1/2}$ F'=4. Two acousto-optic modulators are used in both the coupling and probe lights to blue-detune the light for better transmission, and also modulate the light into pulses. After the EOM and AOMs, the coupling and the probe lights are resonant with $6^2S_{1/2}$ F=3 → $6^2P_{1/2}$ F'=4 and $6^2S_{1/2}$ F=4 → $6^2P_{1/2}$ F'=4 respectively with 40 MHz blue detuning as shown in Fig. 2(a).

The coupling and probe light are then combined with a PBS and sent into a Cs cell. The Cs cell is paraffin-coated and buffer gas free, which can reduce collision-induced florescence background noise and provide longer coherence time. The Cs cell is in a 3-layer μ-metal chamber to block any influence from stray magnetic fields. The temperature of the vapor cell is kept at approximately 55º C. After the cell, a Glan-Thompson polarizer and another Etalon remove the coupling light. The probe light is then detected by an avalanche photodiode (APD) for weak light or a single photon counting module (SPCM) for single photon signal.

A delay generator is used to generate the time sequence for the light storage and retrieval. The time sequence is shown in Fig. 2(b). The probe light is shaped into a rectangular pulse by turning on/off the AOM 1. The coupling light is initially turned on, and after the probe light enters into the Cs Cell, the coupling light is off by turning off the AOM 2. In this case, the probe light is stored in atomic collective excitation modes. After the storage time, the coupling light is turned on to retrieve the probe light. The detectors also can work in gated mode, so that they only detect the retrieved light or photons. The delay generator also provides synchronized signal to a time-correlated single photon counter (TCSPC) for the signal record.

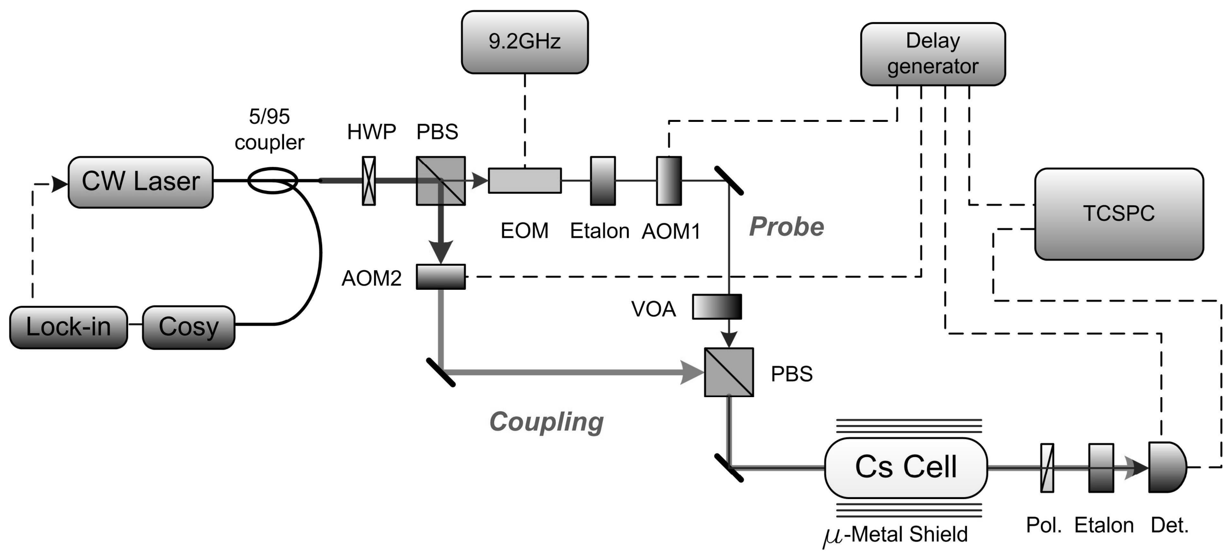

Fig. 1 . System configuration of experiment. EOM: electro-optic modulator; AOM, acousto-optic modulator; HWP: half-wave plate; PBS, polarizing beam splitter; VOA: Variable Optical Attenuator; Pol., Glan-Thompson polarizer; Det. is detector. TCSPC: Time-Correlated Single Photon Counter

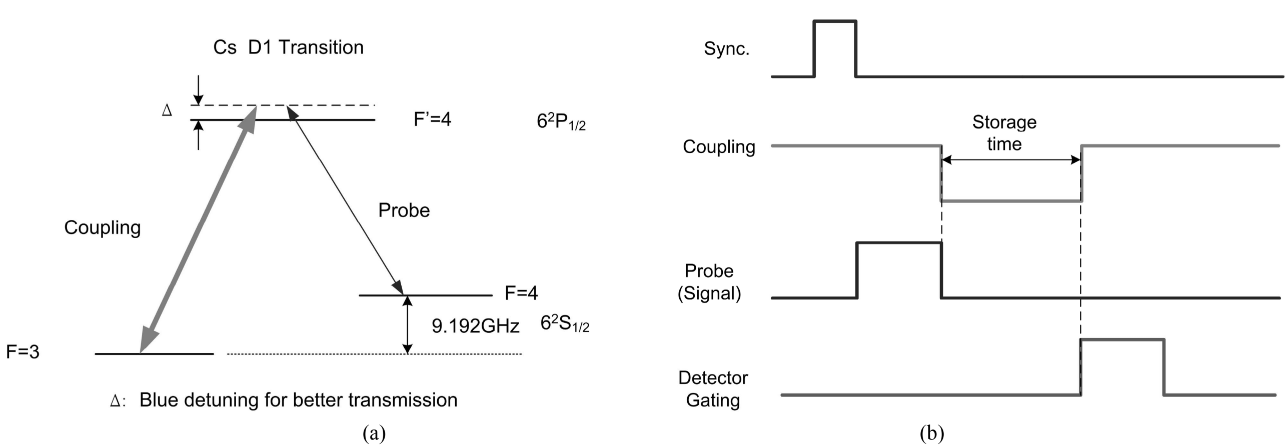

Fig. 2 . (a) The energy level configuration of Cesium D1 transition. (b) Time sequence of sync. signal, coupling, probe and the detector gating signal.

3. EXPERIMENTAL RESULTS

We first optimize the experimental set-up with weak probe light ~ 40 μW. The linewidth of EIT resonance corresponds to the decoherence rate and a narrower linewidth will result in higher retrieval efficiency [43]. The linewidth is influenced by magnetic shield, cell temperature, coupling light power and the angle between probe and coupling light. In our set-up, the cell is already magnetically shielded by a 3-layer μ-metal chamber and we optimize the linewidth by adjusting the temperature, coupling light power and alignment. The full width half maximum (FWHM) linewidth of spectra of the EIT is about 120 KHz, as shown in Fig. 3.

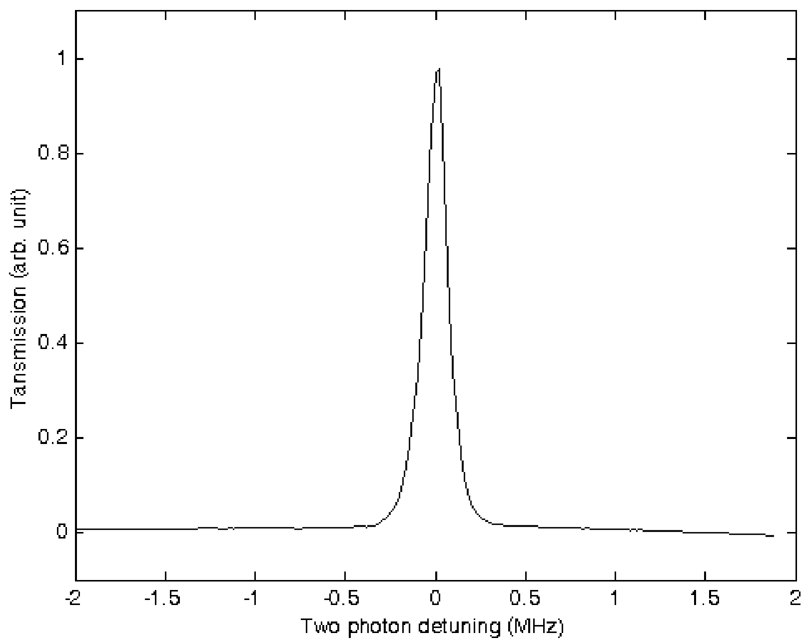

Fig. 3 . . EIT spectra (by tuning coupling frequency)

After optimizing the EIT spectra with weak light, we perform the quantum memory with a single photon level signal. For a single photon level signal, the noise is a key concern in the memory system. Besides the dark counts of detector (in our case, it is about 250 counts/second), the main noise sources for EIT quantum memory with atomic vapor includes residual coupling light, collision induced fluorescence and the spontaneous emission of thermal excited atoms. For removing the coupling light, we use Glan-Thompson polarizer and FP-Etalon, the two sets of filtering can provide extinction ratio of 10^{-11} and reduce the residual coupling light to a level much lower than probe photons. To reduce the collision induced fluorescence, a buffer gas free and paraffin coating cell is used in the experiment as has been adopted in alkali atomic vapor cells in quantum memory [14, 44]. Currently, a new anti-relaxation coating material based on the alkenes is used for alkali atomic vapor cells which further reduces the collision induced fluorescence, providing longer decoherence times [45]. The spontaneous photons of thermal excited atoms emit in all directions. In our experiment, the signal photon was collected into an optical fiber at about 0.5 m away from the cell, so very few spontaneous photons can be collected and detected by the SPCM. In addition, in our experiment, the probe light is generated by a phase EOM from light that have the same wavelength as the coupling light and the same polarization as probe light. The efficiency of phase EOM is about 3%, so the original light is still about two orders of magnitude stronger than the probe light. The light is in the same propagation direction and has the same polarization direction with probe light, so a strong filtration in spectrum is the only way to remove it. Two Etalons are used to greatly suppress the noise in our experiment. After these noise reduction treatments, the total noise count rate is measured about 3×10^4 counts/second when the coupling light is on.

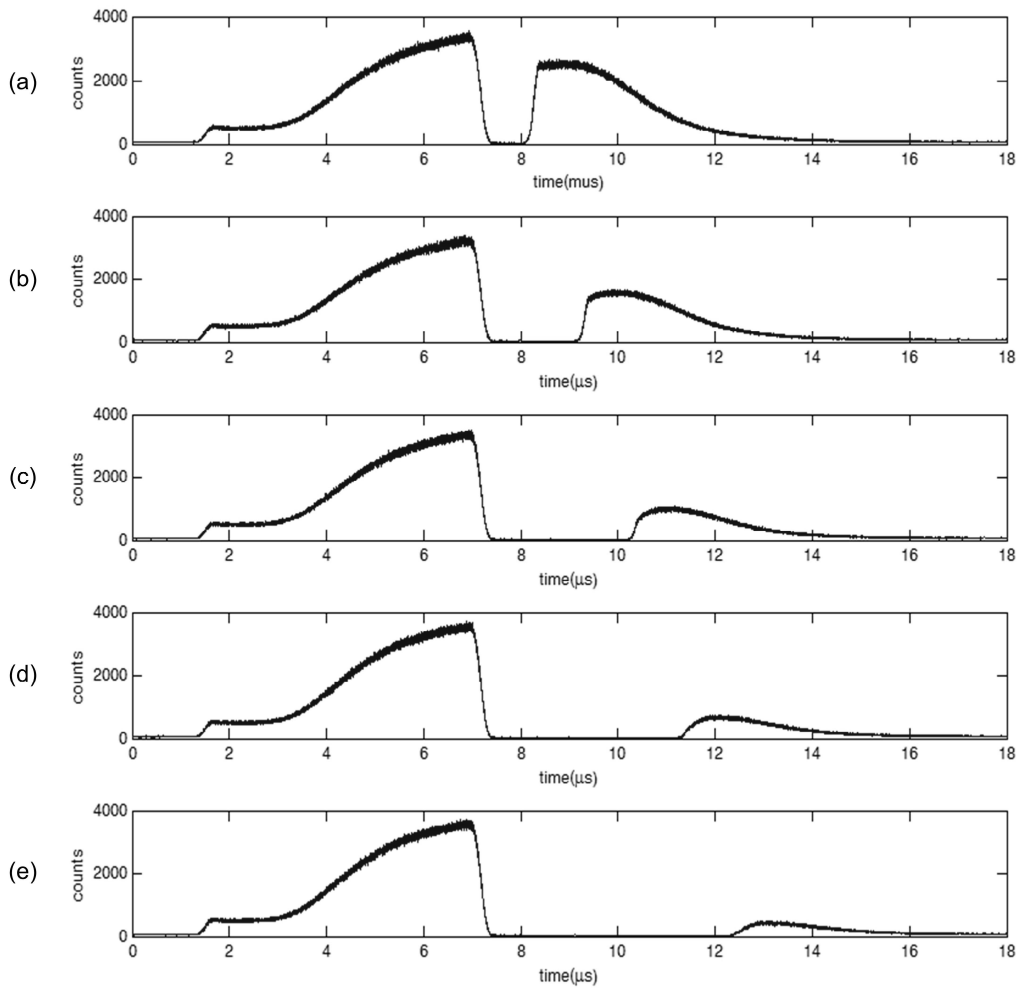

Fig. 4. Storage and retrieval of 5 µs photon pulse with 1-5 µs storage duration. The SPCM is in free running mode and the integration time is 1s.

We further tested the quantum memory system for single photon level signal. The bandwidth of our memory system is about 200 KHz, the corresponding photon source should have similar linewidth. According to the relationship between linewidth and lifetime, the signal pulse duration would be 5 μs. The pulse sequence of the experiment is shown in Fig. 2(b). A synchronized electrical pulse is sent to TCSPC as a start signal. The coupling light is initially turned on, and this prepares the EIT medium. The probe light is shaped to a 5-μs pulse and enters into the Cs Cell.

The group velocity of the probe light will be reduced in the EIT medium. After the probe pulse has completely entered into the cell, the coupling light is turned off, which maps the state of the probe field onto the atomic states. The coupling light is then turned on again after certain storage time, and the stored photons are then retrieved. The retrieved photons are detected by a SPCM and the detected signals are sent to TCSPC as a stop signal. In practical application, the detector will be gated to detect the photons only after they are retrieved. Here, we make the SPCM in a free-running mode, so that we can observe the leaked photons. The measured data are shown in Fig.3. The first peak is corresponding to the leaked photons and the second peak is corresponding to the stored and retrieved photons. From the result, we can see the quantum memory system can store and retrieve photon up to 5 μs with acceptable efficiency. Therefore, such a quantum memory system could work with a quantum communication system at 5 μs clock rate.

4. CONCLUSION

Quantum memory is a key device for implementation of quantum repeaters, which enables long distance quantum communications beyond the photon-loss limitation in transmission. An EIT quantum memory with Cs atomic vapor provides an inexpensive and scalable scheme for quantum repeaters. The Cs D1 line at 895 nm corresponds to photon pairs (895 + 1310 nm) generated by spontaneous parametric down conversion with a 532-nm pump wavelength. We implemented a quantum memory with a paraffin coated Cs atomic vapor Cell. The bandwidth of the memory system is about 200 KHz, and the noise count rate is about 3×10^4 counts/second (when the coupling light is on). We demonstrate the storage and retrieval of single photons with 5-μs pulses in this memory system. Such quantum memory system could be a promising building block for quantum repeaters.

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