Preservation of spatial coherence of an optical pulse in atomic vapor quantum memory

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We report on the preservation of transverse spatial coherence of an optical pulse stored in atomic vapor quantum memory. The high visibility Young-type spatial fringes formed by interference between the retrieved and the delayed optical pulses clearly demonstrate that the atomic vapor quantum memory based on electromagnetically induced transparency preserves transverse spatial coherence. This demonstration has important implications in quantum imaging and multimode quantum information processing.

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Quantum memory is an essential element in the field of quantum information [1,2], and the optical quantum memory is expected to play an important role in photonic quantum information networks as a synchronization tool to time quantum operations properly [2,3], a quantum repeater permitting long-distance quantum communication [4,5], and a tool to convert heralded single photons to on-demand single photons [2,6,7]. Research on optical quantum memory has attracted considerable interest in recent years, and one of the widely used approaches is the method based on coherent transition between photons and long-lived ground-state atomic coherence of an atomic ensemble by using electromagnetically induced transparency (EIT) [8–10]. EIT-based optical quantum memories are reported to satisfy quantum memory requirements, such as high fidelity, efficiency, and the ability to preserve quantum properties of light, namely, quantum coherence, entanglement, and photon statistics [11–18].

Recently, the spatially multimode capacity of quantum memory drew extensive interest since the increased number of optical modes can be utilized to store optical images or to perform multiplexed information processing for both classical and quantum applications [19–28]. For instance, multiple qubits can be stored in a single atomic memory as a spatial array of photonic qubits in the transverse plane, multimode quantum memory for quantum images, and continuous-variable quantum computation based on transverse spatial degrees of freedom, etc. [29,30]. Clearly, the aforementioned applications require that quantum memory preserves the transverse spatial coherence as well as the longitudinal coherence during the storage and retrieval processes. In Ref. [31], it has been shown that, via a beat-note interferometer, longitudinal phase coherence is preserved during the storage and retrieval processes in atomic vapor quantum memory. Although there are reports indirectly implying that the transverse coherence is maintained during light storage [24–26], no direct measurement on the preservation of transverse spatial coherence has been reported to date.

In this paper, we report a direct demonstration of the preservation of transverse spatial coherence of an optical pulse during the storage and retrieval processes in an EIT-based rubidium vapor quantum memory. The high-visibility Young-type spatial interference between the retrieved and the delayed pulses clearly and directly demonstrates that transverse spatial coherence of an optical pulse is preserved during the dynamic storage and retrieval processes.

Let us first describe the schematic of the experimental setup shown in Fig. 1. In short, a probe pulse is split into two at a balanced FBS—one is sent to a Rb cell for EIT storage and retrieval, and the other is sent to an optical delay line consisting of several single-mode fiber (SMF) spools. Young-type interference between the retrieved and the delayed optical pulses are then observed at the CCD.

For the dynamic storage and retrieval of the probe pulse, we make use of the Λ-type EIT scheme for ^{87}Rb D_1 lines. The strong coupling beam (vertically polarized) is prepared such that it is 60-MHz frequency upshifted to the ^{87}Rb D_1 line, $5\,^2S_{1/2}F = 2 \rightarrow 5\,^2P_{1/2}F = 2$. The weak probe beam (horizontally polarized) is then prepared by 6.8-GHz frequency upshifting a small portion of the coupling beam by using an electro-optic modulator and an etalon filter (not shown in Fig. 1) so that it is coupled to the $5\,^2S_{1/2}F = 1 \rightarrow 5\,^2P_{1/2}F = 2$ transition, completing the Λ-type EIT scheme. The probe pulse is then split at the FBS: one for the storage and retrieval and the other for the delay. At the output ports of the SMFs, QWPs and HWPs are used to fully compensate the polarization rotation in the SMFs. The polarizers are used to make the polarizations of the two beams equal. By rotating the HWP before the polarizer, it is possible to control the intensity of each beam without changing its polarization.

For the EIT storage, the probe pulse at the upper path (see Fig. 1) is spatially overlapped with the strong coupling beam at the PBS and is sent into the Rb cell (75-mm long antireflection-coated ^{87}Rb with 10-Torr Ne buffer gas). The temperature of the Rb cell is maintained at 55 °C so that the number density is approximately $2 \times 10^{11}/\text{cm}^3$. The optical powers of the probe beam and the coupling beam at the entrance of the Rb cell were 40 μW and 7 mW, respectively. The EIT bandwidth at this condition was about 300 kHz. After interacting at the Rb cell, the vertically polarized coupling beam is filtered out by using a PBS and an additional polarizer (Pol) so that only the retrieved probe pulse reaches the CCD (JAI CM-030; 7.4-μm-square pixels).

The retrieved probe pulse from the EIT medium is then made to interfere with the delayed probe pulse in the Young-type two-beam interferometer, formed with a BS and a lens. Due to nonperfect retrieval of the probe pulse in the EIT-storage and retrieval process, to match the intensities of the retrieved and the delayed beams, the delayed optical pulse

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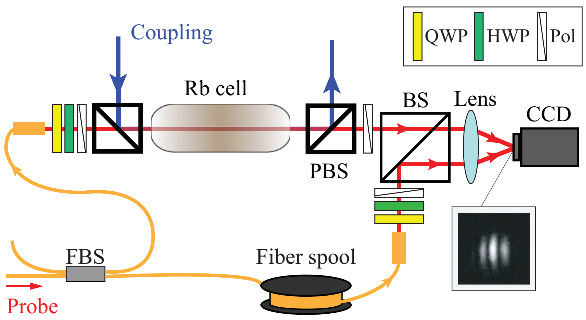

FIG. 1. (Color online) Experimental schematic. The probe pulse is split into two at a fiber beam splitter (FBS)—one is sent to the EIT medium, and the other is sent to an optical delay line. The retrieved and the delayed probe pulses are then made to interfere at the CCD in a Young-type two-beam interferometer formed with a lens. QWP: quarter-wave plate, HWP: half-wave plate, Pol: polarizer, PBS: polarizing beam splitter.

needed to be attenuated with wave plates (QWP and HWP) and a Pol. The CCD located at the focus of the lens then records the Young's interference fringe.

Since the EIT-based storage using hot atomic vapor cannot completely store (both the storage efficiency and the pulse shape) an optical pulse due to the lack of optical depth, it is essential to synchronize the coupling and probe beams and the CCD gating times, see Fig. 2, to observe the Young's interference fringe. The probe pulse was shaped to a Gaussian pulse of 3.1 μs at full width at half maximum by using an acousto-optic modulator. Once the probe pulse enters the Rb cell and gets compressed due to the EIT-slow light effect, the coupling beam is turned off at $t_{\rm off}$ so that the probe pulse is stored as spin excitations of the EIT medium. Then, after some storage time t_s, the coupling beam is turned back on to retrieve the probe pulse. Since the probe pulse is partially stored into and retrieved from the EIT medium, the retrieved probe pulse has the shape shown as the shaded area in Fig. 2. The delayed

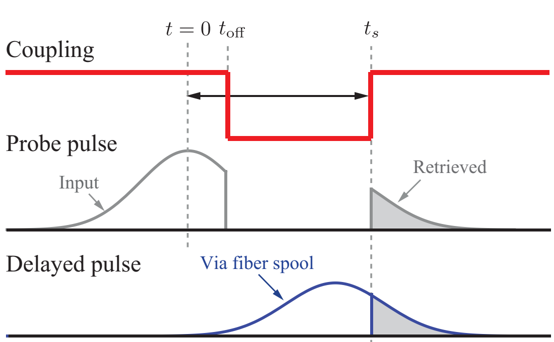

FIG. 2. (Color online) Coupling, probe, and CCD timing sequence. Once the probe beam enters the Rb cell, the coupling beam is turned off to store the probe pulse as dark-state polaritons. When the coupling beam is turned on again at a later time, the probe pulse (shaded area) is retrieved from the Rb cell. The delayed pulse maintains the original pulse shape which is much longer than the retrieved pulse, and this will decrease interference visibility. To account for this pulse-shape mismatch, the delayed pulse is first precisely timed for the delay. We then make sure that only the shaded areas of the optical pulses are detected by electronically gating the CCD.

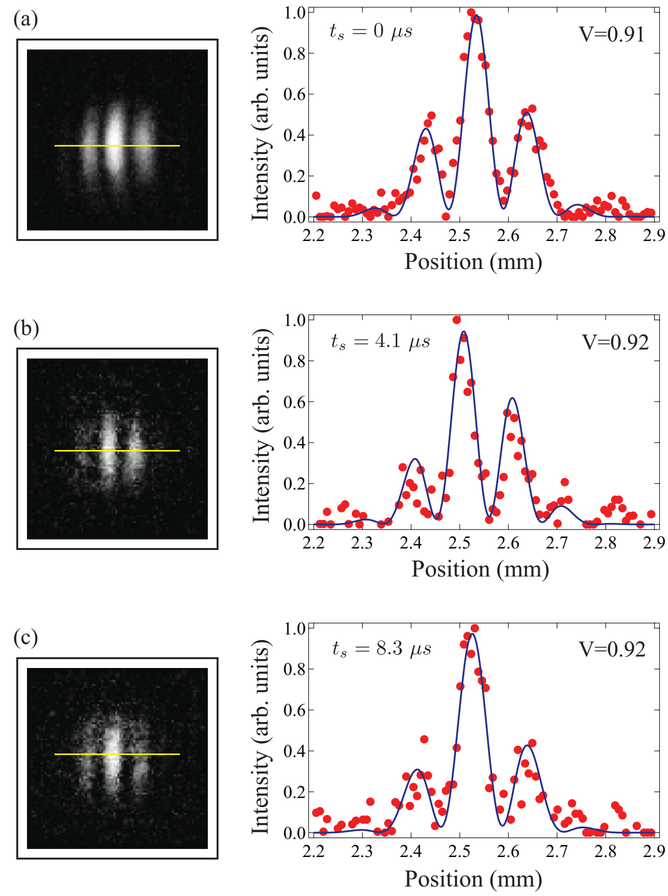

FIG. 3. (Color online) Young-type spatial interference between the retrieved and the delayed optical pulses. (a) No storage ($t_s = 0\ \mu$s), (b) storage time is $t_s = 4.1\ \mu$s, and (c) storage time is $t_s = 8.3\ \mu$s. CCD images are shown at the left and, at the right, the cross-sectional intensity distributions (corresponding to the yellow horizontal lines on the CCD images) are shown. Solid lines represent the theoretical double-slit interference fringes. Preservation of transverse spatial coherence in the EIT-storage and retrieval processes is clearly demonstrated.

pulse maintains the original pulse shape, so it is essential to account for the pulse-shape mismatch to observe interference between the retrieved and the delayed pulses. To match the temporal mode, the two pulses are picked off before the lens and are monitored with an oscilloscope. The leading edges of the retrieved and delayed pulses are made to overlap in time by slightly adjusting the EIT-storage time. Then, the CCD, which is synchronized to the probe-pulse generating acousto-optic modulator, is electronically gated to turn on only for the time duration to fully detect the retrieved pulse. This way, we make sure that only the shaded areas of the retrieved and delayed probe pulses are detected, hence, maximizing the interference visibility, see Fig. 2.

The experimental data, exhibiting the Young-type spatial interference fringes between the retrieved and the delayed optical pulses are shown in Fig. 3. The CCD images are analyzed by calculating the interference visibility at the cross-sectional intensity distribution (at the yellow horizontal lines in Fig. 3). The fitting curves are Gaussian envelops multiplied by a raised sine curve, and the visibility is

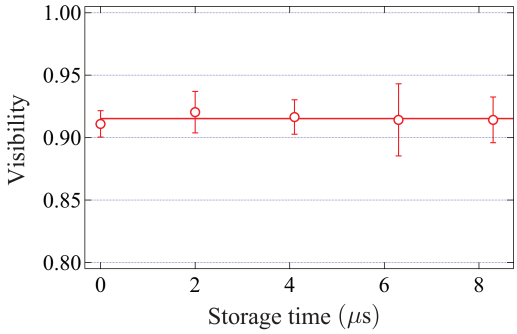

FIG. 4. (Color online) Young-type interference visibility with different storage times. The error bars denote the statistical error of one standard deviation. The red solid line is the average visibility.

calculated from the offset and amplitude of the sinusoidal modulation [32]. The visibility of the spatial interference fringes with different storage times is shown in Fig. 4. The maximum storage time of 8.3 μs was limited by the length of the fiber spool delay line, which was about 1.6 km. The experimental data show that the interference visibility V is maintained high (>0.9) during the light storage, and they also clearly demonstrate that the EIT-storage and retrieval process preserves the transverse spatial coherence of an optical pulse. In the gaseous atomic medium, the atomic motional diffusion results in the spreading of the stored light field. Considering the image storage experiments, it is generally true that the image quality gets worse as the storage duration gets larger. Therefore, one might intuitively consider that the degree of spatial coherence is also significantly affected by the storage duration. However, generally, the diffusion of the dark-state polariton is coherence preserving [33]. The atomic motional diffusion in the light storage does give a spread in the stored and retrieved beam profile. However, the spatial coherence is well maintained as indirect evidences of which are reported in [24–26]. In our paper, we have directly shown the preservation of spatial coherence. The interference visibility V is less than unity mainly due to the fact that the detector has a rather large pixel size and the small difference in the intensities between the retrieved and delayed pulses. Note that the constant background noise from the CCD, originating from nonperfect removal of the coupling beam, has been independently measured and has been subtracted from the data for each measurement setting.

To summarize, we have reported, to the best of our knowledge, a direct experimental demonstration of the preservation of transverse spatial coherence of an optical pulse during the EIT-storage and retrieval processes in hot atomic vapor. The experimental data clearly show that not only the transverse spatial coherence is well preserved during the EIT-storage and retrieval processes, but also the transverse spatial coherence is hardly affected by the storage duration. Although our work is demonstrated with classical light pulses, our scheme, based on a hot vapor cell, can be extended to the quantum regime with optimized storage efficiency and proper narrow-band probe filtering [34,35]. We believe that this result has important implications in quantum imaging and multimode quantum information processing.

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