Single-Photon-Level Quantum Image Memory Based on Cold Atomic Ensembles

Dong-Sheng Ding*, Zhi-Yuan Zhou, Bao-Sen Shi†,and Guang-Can Guo

Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei 230026, China

Abstract. Quantum memory is a key component for quantum networks. Successful development enabling the distribution of quantum information requires storing single-photon light. Encoding photon with spatial shape through higher-dimensional states significantly increases their information-carrying capability and network capacity. Constructing such quantum memory, though, is a big challenge. In this work, we report the first experimental realisation where a true single photon carrying orbital angular momentum is stored via electromagnetically induced transparency in a cold atomic ensemble. Experiments show that the non-classical pair correlation between trigger photon and retrieved photon is retained, and the spatial structure of input and retrieved photons exhibit strong similarity. More importantly, single-photon coherence is preserved during storage as demonstrated. The ability to store spatial structure at the single-photon-level opens the possibility for high-dimensional quantum memory.

Keywords: Image, EIT

Here, we report on the first experimental realisation of a multimode optical memory at true single-photon levels via EIT. In our experiment, we prepare non-classical correlated photon pairs using spontaneous four-wave mixing (SFWM) via a double lambda configuration in a cold Rb85 atomic ensemble. One photon of each pair is used as a trigger; the other is mapped and stored in a second cold atomic ensemble via EIT. Each photon to be stored carries one OAM unit per photon (in units of $\hbar$). After a programmed storage time, the photon can be retrieved. We not only prove experimentally that the non-classical correlation between the trigger photon and the retrieved photon is kept, but also demonstrate that the spatial structure of the photon is also very well preserved during storage. More important, we show with the aid of a Sagnac interferometer that coherence of the single photon is also preserved. Combining these results with the recent important progress made in quantum repeaters, we can expect the development of a high-dimensional quantum network in the near future.

Very recently, work has begun storing such light at near single-photon levels [1,2], but still the light is a strongly attenuated laser, not a true single photon. So far, there is no report on imaging at a true single-photon level. In quantum information science, essential is the reversible transfer of a quantum state between a true single photon and matter, a crucial resource in operating quantum repeaters, having the potential solution in overcoming distance limitations of quantum communication schemes through transmission losses.

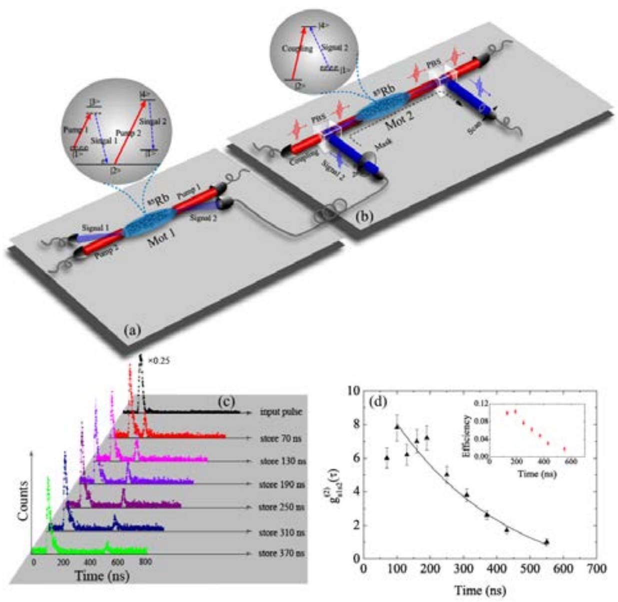

FIG. 1 (a) Simplified diagram depicting the generation of non-classical photon correlations using SFWM. MOT:

*dds@mail.ustc.edu.cn
†drshi@ustc.edu.cn

magneto-optical trap; (b) Photon storage diagram. PBS: Glan-Taylor polarisation beam splitter with the extinction ratio of 10^5:1; (c) Coincidence counts between the retrieved signal and the trigger as a function of storage time. (d) Cross-correlation function $g_{s1,s2}(\tau)$ between the retrieved signal and the trigger photons against the storage time. The solid line is the exponential fit $Ae^{-\tau/T}+g_0$ to $g^{(2)}_{s1s2}(\tau)$ (where A=13.3,T=348, g_0=-1.89). The inset shows the efficiency function against storage time.

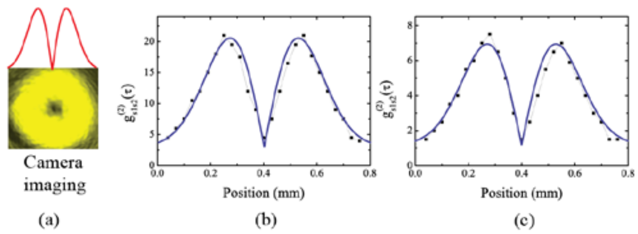

FIG. 2 (a) Image of a laser beam after traversing the spiral phase plate; (b) cross-correlation between input signal and trigger photons, obtained by scanning the transverse position of the input signal; (c) cross-correlation function between retrieved signal and the trigger photons. The solid lines are theoretical fits.

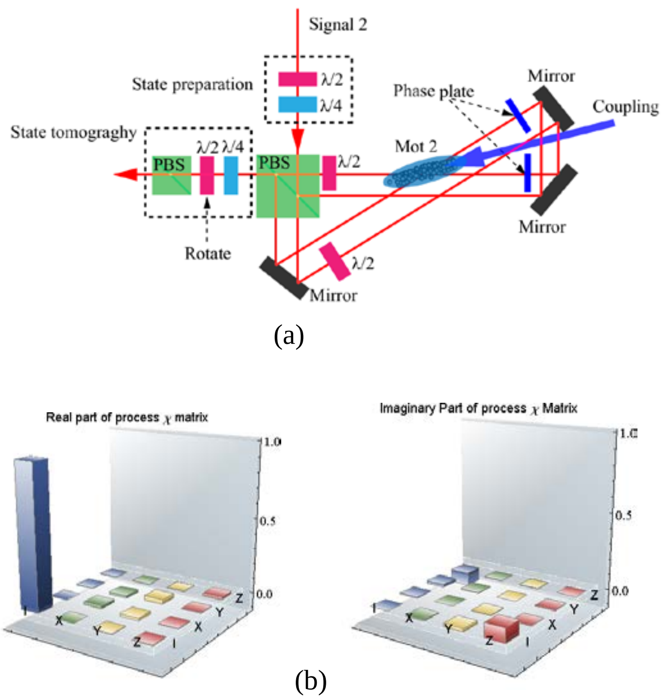

FIG. 3 (a) Schematic of the simplified experimental setup demonstrating coherence of a single photon; (b) Calculated real and imaginary parts of the storage process matrix obtained from experimental data.

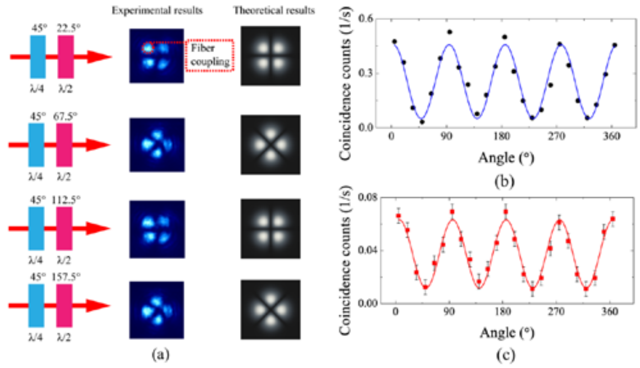

FIG. 4 (a) Rotated interference patterns at different angle settings of the half-wave plate (see the Movie); (b) interference pattern of the input signal photon as a function of plate angle; (c) interference of retrieved signal with plate angle. Blue and red lines are fits of the sinusoid $sin(4\theta)$.

In this work, we provided the first evidence of the storage in a cold atomic ensemble of a true single photon carrying spatial structure. Our work makes an important step towards realizing high-dimensional quantum memory. It accompanies recent progress in infrared-to-visible wavelength conversion [3] and long-distance fiber transmission of photons encoded in high-dimensional states [4], as well as the significant advances in quantum key distribution transmission between ground and air [5, 6]. Our results could lay the foundation in establishing a high-dimensional quantum network in the future.

References

1. Dong-Sheng Ding, *et al*. Multimode image memory based on a cold atomic ensemble.*Phys. Rev. A*.**87**, 013835 (2013).

2. L. Veissier, *et al*., A reversible optical memory for twisted photons, *Opt. Lett*.**38**, 712 (2013).

3. Ding, D.-S. *et al*., Image transfer through two sequential four-wave-mixing processes in hot atomic vapor, Phys. Rev. A.**85**, 053815 (2012).

4. Loffler, W. *et al*., Fiber Transport of Spatially Entangled Photons, Phys. Rev. Lett.**106**, 240505 (2011).

5. Jian-Yu Wang, *et al*. Direct and full-scale experimental verifications towards ground–satellite quantum key distribution, Nat. Photons.**7**, 387-393 (2013).

6. Sebastian Nauerth, *et al*. Air-to-ground quantum communication, *Nat. Photonics*. **7**. 382-386 (2013).

7. Dong-Sheng Ding, *et al*. Single-Photon-Level Quantum Image Memory Based on Cold Atomic Ensembles. arXiv:1305.2675.