nature photonics

SUPPLEMENTARY INFORMATION
DOI: 10.1038/NPHOTON.2015.43

Raman Quantum Memory of Photonic Polarized Entanglement

Dong-Sheng Ding, Wei Zhang, Zhi-Yuan Zhou, Shuai Shi, Bao-Sen Shi and Guang-Can Guo

Characterizing the single-photon properties of a heralded single photon

α is a heralded auto-correlation parameter used to characterize the properties of a signal photon. $\alpha = \frac{P_3 P_{123}}{P_{32} P_{31}}$, where P_3 is the Stokes photon count, P_{31} and P_{32} are the twofold coincidence counts between the Stokes photon and the two anti-Stokes photons, separated by a beam splitter, and P_{123} is the threefold coincidence count. For an ideal single-photon state, α tends to zero, for a classical field, $\alpha \geq 1$, based on the Cauchy-Schwarz inequality[1]. A pure single photon has α=0 and a two-photon state has α=0.5. Therefore α<1.0 violates the classical limit and α<0.5 suggests near-single-photon characteristics. In our experiments, α=0.074±0.0012 before storage and α=0.29±0.02 after storage for about 150 ns, confirming that the single-photon nature was preserved during storage[2].

Storing a nanosecond short pulses

The maximum storage bandwidth of our memory was studied. The pulse width of pump 1 laser was changed by using an arbitrary function generator AFG 3252 to change the pulse width of the generated anti-Stokes photons. The pulse widths of the anti-Stokes photons were reduced as much as possible. Because the timing sequence was controlled by the software of card PCI 6602, AOM and AFG 3252, the final width of the anti-Stokes photon at FWHM was about ~7 ns under the limit of our system (see Fig. S1). The results on storing anti-Stokes photons are given in Fig. S2, where Fig. S2(a) is the input signal without a coupling laser and atoms trapped in MOT B, Fig. S2(b) is the storage data and Fig. S2(c) is the recoded noise, where anti-Stokes photons were

DOI: 10.1038/NPHOTON.2015.43

blocked, with an opened coupling laser and atoms trapped in MOT B. The storage efficiency was 10.3%. The measured second-order cross-correlation ($g_{s1,s2}(\tau)$) for the retrieved anti-Stokes and Stokes photons was about 13.6, showing the large nonclassical correlation between them. The practical timing pulse width of the measured cross-correlated function was larger than the timing pulse width of the anti-Stokes photons, because of the influence of the life-time of the atomic level, |4>. The stronger Rabi frequency of the pump 2 laser could be used to reduce the time pulse width of the cross-correlated function[3–5]. If the resolution of the timing controller could be improved, then the system could store a pulse with a smaller timing pulse width (<7 ns) in the quantum regime.

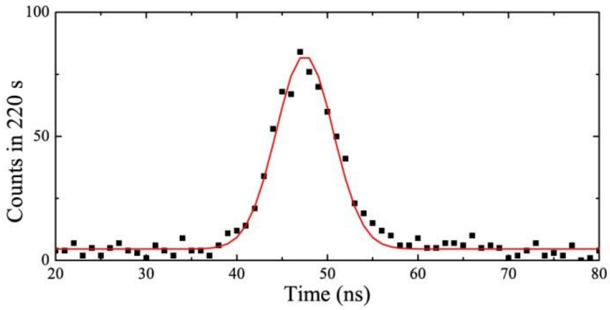
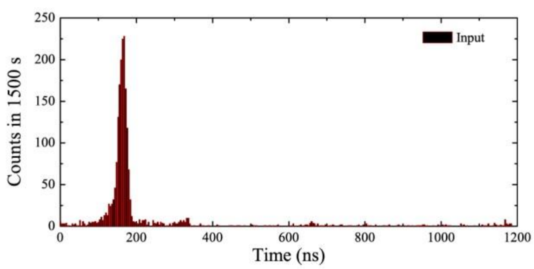
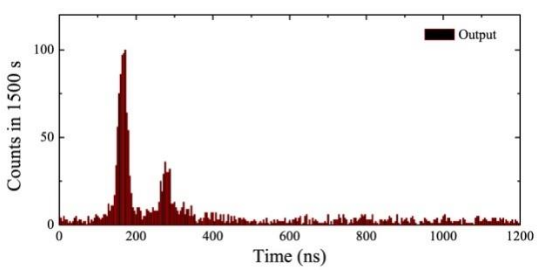


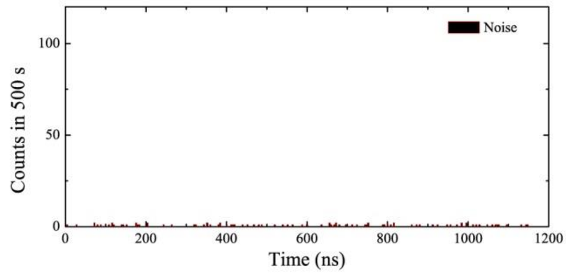
Fig. S1: Measurements of the timing pulse width of the anti-Stokes photons excited by a pump 1 laser. The coincidence counts between the trigger from AFG 3252 and the detection events of the anti-Stokes photons were recorded. The red line is the fitted curve, found using: $y=y_0+A \exp[-2((t-t_c)/w)^2]$, where $w=6.3$; $y_0=4.6$; $t_c=47.5$; and $A=492.9$.



(a)



(**b**)



(c)

Fig. S2: a, Coincidence between the anti-Stokes and Stokes photons without storage. **b**, Coincidence between the Stokes and retrieved anti-Stokes photons. **c**, Coincidence from noise.

Storing a photon under far-off resonance conditions

Here, the memory performance under far-off resonance conditions is further studied. The frequencies of pump 1 and the coupling lasers were changed to make them far-detuned, +200 MHz from the atomic transition of |1>−>|4>. Thus, the generated anti-Stokes photons were also far-detuned by +200 MHz from the atomic transition of |2>−>|4>. The power of the coupling laser was increased as much as possible to perform Raman storage at the single-photon level. With an atomic absorption bandwidth of 5.8 MHz and an almost negligible Doppler linewidth at an atomic temperature of 100 μK, the detuning of the atomic bandwidth ratio was 34.5. During storage, the width of pump 1 laser was 50 ns, the power of the coupling laser was 110 mW with a beam waist of 2 mm, corresponding to a Rabi frequency of 17.6 Γ (where Γ is the decay rate of level |4>). At the same time, a home-made F-P cavity filter was inserted into the filtering system (3 filters were used in the previous experiments). The final extinction ratio of about 10^9:1 was enough to reduce the scattering noise from the coupling laser. The results are shown in Fig. S3. Fig. S3(a) shows the coincidence between the anti-Stokes and Stokes photons without a coupling laser and the trapped atoms in MOT B. Fig. S3(b) shows the storage data and Fig. S3(c) is the recoded coincidence with the anti-Stokes photons blocked, the coupling laser opened and atoms trapped in MOT B. The measured $g_{AS,S}(\tau)$ for the retrieved signal was 5.6. The signal to noise ratio could be improved if more filters were used to reduce the noise. The noise in Fig. S3(b) is Raman scattering from the few atoms in level |2> that were excited by the anti-Stokes photons.

DOI: 10.1038/NPHOTON.2015.43

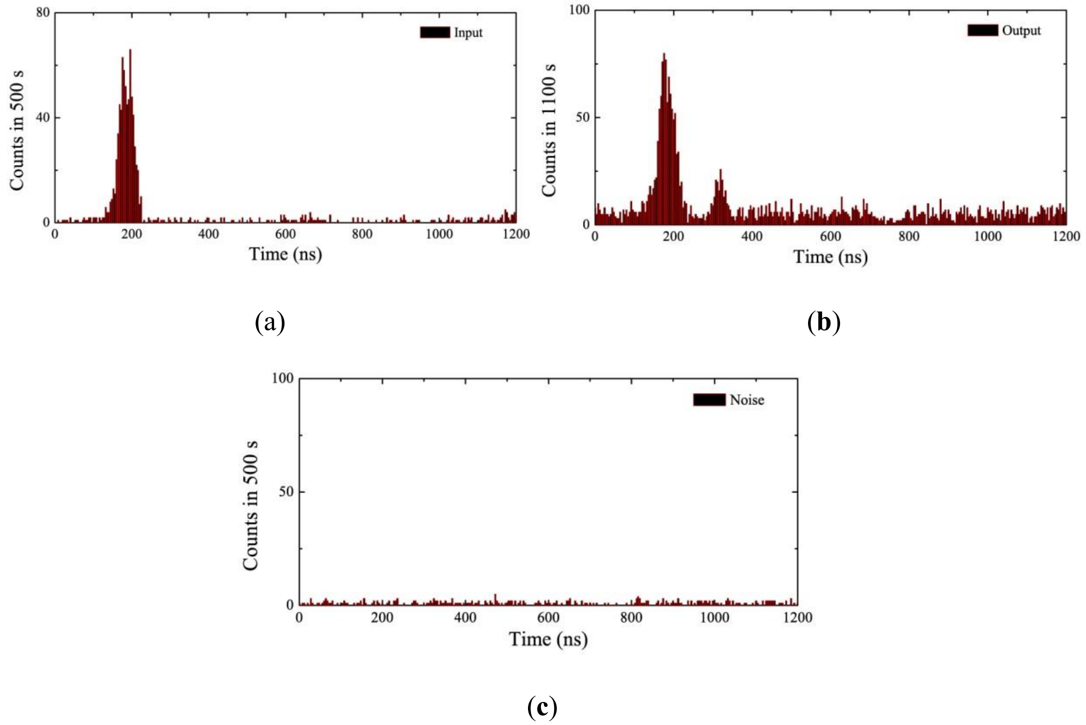


Fig. S3: a/**b**, Coincidence between the anti-Stokes and the Stokes photons with a single photon detuning of +200 MHz before/after storage. **c**, The recorded noise.

References

1. Kuzmich, A., Bowen, W. P., Boozer, A. D., Boca, A., Chou, C. W., Duan, L.-M., and Kimble, H. J., "Generation of nonclassical photon pairs for scalable quantum communication with atomic ensembles," *Nature* **423**(6941), 731–734 (2003).
2. Ding, Dong-Sheng, Zhang, Wei, Zhou, Zhi-Yuan, Shi, Shuai, Xiang, Guo-Yong, Wang, Xi-Shi, Jiang, Yun-Kun, Shi, Bao-Sen, Guo, Guang-Can. Quantum Storage of Orbital Angular Momentum Entanglement in an Atomic Ensemble. *Phys. Rev. Lett.* **114**, 050502 (2015).
3. Liao, Kaiyu, Yan, Hui, He, Junyu, Du, Shengwang, Zhang, Zhi-Ming, Zhu, Shi-Liang, Subnatural-linewidth polarization-entangled photon pairs with controllable temporal length, *Phys. Rev. Lett*. **112**, 243602 (2014).
4. Zhao, Luwei, Guo, Xianxin, Liu, Chang, Sun, Yuan, Loy, M. M. T., and Du, Shengwang, Photon pairs with coherence time exceeding one microsecond, *Optica* **1**, 84 (2014).
5. Du, Shengwang, Kolchin, Pavel, Belthangady, Chinmay, Yin, G.Y., and Harris, S.E., Subnatural linewidth biphotons with controllable temporal length. *Phys. Rev. Lett*. **100**, 183603 (2008).