Trapping a Free-propagating Single-photon into an Atomic Ensemble as a Quantum Stationary Light Pulse

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Abstract: We report the first experimental demonstration of trapping a free-propagating single-photon into a cold atomic ensemble. Also, we observe that the quantum properties of the single-photon state are preserved during the trapping process. © 2024 The Author(s)

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Efficient photon-photon interactions have remained one of the foremost challenges in quantum information processing since photons do not interact directly. Thus, an atomic medium is required to mediate the photon-photon interaction. Since the number of the photons is limited to few photons at a quantized regime, one should enhance the atom-photon coupling strength or the interaction time long enough for the quantum applications. In recent, leading approaches have been reported from the enlarged atom-photon coupling strength, such as the cavity-quantum electromagnetic dynamics (QED) or the Rydberg atom system.

In this regard, the stationary light pulse (SLP) suggests a new approach which provides an enhanced interaction time between the photons inside the atomic medium. While the electromagnetically induced transparency (EIT) storage process has been studied to enhance the interaction time as it offers the slow and stopped light effects [1], the quantum memory effect via the EIT storage process fully maps the photons into an atomic state inside the atomic medium, failing to enhance the interaction time between the photons [2]. In contrast, the SLP process traps the photons into an atomic ensemble with a group velocity reduced to zero while still retaining the nature of the electromagnetic field. As a result, the SLP process provides a long interaction time to the trapped photons inside the atomic ensemble at a quantized regime, leading to the efficient photon-photon interaction [3, 4]. Experimentally, the SLP process for classical light pulse has been demonstrated in both a hot and cold atomic ensemble [5, 6]. The SLP process for quantum light, the quantum SLP (QSLP) process, has been demonstrated in a recent study [7]. However, this work is also limited in the sense that no free-propagating photon generated from the outside of the atomic ensemble has been trapped via the QSLP process, which is required for quantum non-linear optics.

Here, we report the first experimental demonstration of trapping a free-propagating single-photon into an atomic ensemble via the QSLP process [8]. The formation of the stationary single-photon state, i.e., quantum stationary light pulse, from the free-propagating single-photon is verified by its suppressed and delayed release.

FIG. 1. (a) Experimental schematics for heralded single-photon generation, stationary single-photon formation, and quantum correlation measurement. (b) The normalized TCSPC histogram for the 2 μs EIT storage process. Blue dots correspond to experimental data, and solid blue line corresponds to fitting curve. (c) The normalized TCSPC histogram for the additional 1 μs QSLP process. Red dots correspond to experimental data, and solid red line corresponds to fitting curve.
during the QSLP process compared to the EIT storage process. We further demonstrate that the cross-correlation of the entangled photon pair and the conditional self-correlation of the heralded single-photon are preserved in the quantum regime even after the QSLP process.

Figure 1(a) shows our experimental schematics. The $^{87}$Rb magneto-optical trap (MOT) 1 serves as the heralded single-photon source in our experiment. The heralded single-photon is generated via the double-$\Lambda$ type spontaneous four-wave mixing (SFWM) process where the counter-propagating pump and coupling beams create energy-time entangled photon pairs. While the Stokes photon is directly detected, the anti-Stokes photon is delivered to another cold atomic ensemble, MOT 2, via a single-mode optical fiber. Then, the heralded single-photon is trapped in the cold atomic ensemble via the QSLP process. The Rb atoms in MOT 2 are dressed by the counter-propagating forward coupling (FWC) and backward coupling (BWC) beams. When the heralded anti-Stokes single-photon arrives at MOT 2, it is mapped into the stationary single-photon state via the QSLP process.

Figure 1(b) and (c) show our experimental results for the normalized TCSPC histogram for the EIT storage and the QSLP process, respectively. Figure 1(b) corresponds to the 2 µs EIT storage process controlled only by FWC. During the 2 µs time window where FWC is turned off, the heralded single-photon is fully mapped into the collective atomic state (green area). Then, the collective atomic state is retrieved to the free-propagating photonic state when FWC is turned on again (blue area). Figure 1(c) corresponds to the additional 1 µs QSLP process. In Fig. 1(c), in contrast to Fig. 1(b), we observe that the release from the QSLP trapping within MOT 2 is suppressed while FWC and BWC are simultaneously turned on for the 1 µs (purple area) after the 2 µs EIT storage process. The released heralded single-photon shows a delayed arrival time due to the 1 µs of QSLP process (red area) compared to the EIT storage process. The suppressed emission during the QSLP process and delayed release time after the QSLP process compared to the EIT process verifies the formation of the stationary single-photon state while the FWC and BWC are simultaneously turned on.

Further, the normalized cross-correlation between Stokes and anti-Stokes photon and conditional self-correlation of anti-Stokes photon after the EIT storage and QSLP process are measured from the TCSPC module. The normalized cross-correlation after the QSLP process is measured to be 7.00±0.12 while the cross-correlation after the EIT storage process is measured to be 7.06±0.14 in noise-subtracted data. We observe that the QSLP process preserves the quantum correlation between the entangled photon pair. Also, the normalized self-correlation after the QSLP process is calculated to be 0.53±0.03 while the self-correlation after the EIT storage process is calculated to be the same. Here again, the QSLP process preserves the anti-bunching feature of the heralded single-photon compared to the EIT storage process. Thus, we verify that the QSLP process traps the free-propagating single-photon as the stationary single-photon and releases again without losing its quantum properties.

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