Hybrid-cascaded generation of tripartite telecom photons using an atomic ensemble and a nonlinear waveguide: supplementary material

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Coincidence window shift with detuning of pump laser 1

The pump laser with the wavelength of 795 nm is stabilized using the spectrum locking technique. The laser is red-detuned by 1.45 GHz with the ⁸⁷Rb atomic transition of $5S_{1/2}(F=1) \rightarrow 5P_{1/2}(F'=1)$ using a 1.5 GHz acousto-optic modulator. In our experiment, if we change the detuning of the 795-nm laser, then the time-correlation window would shift because of the delay of the 780-nm photon, as shown in Fig. 1S. The reason for this is that the linear susceptibility of the generated 780-nm photon is modulated by the detuning of 795-nm laser; please refer to [1] for a more detailed description of this FWM delay effect. We therefore need to stabilize the 795-nm laser for appropriate experimental performance over long periods.

Fig. S1. The coincidence window is shifted by modulating the detuning of pump laser 1.

Bandwidth of photon pair versus cell temperature

Because of the Doppler effect, the bandwidth of the generated photon is broadened. The bandwidth of the generated photon pair is therefore different at different Rb cell temperatures. We measure the time-width of the coincidence window versus the cell temperature and obtain the relationship between the time-width of the coincidence and temperature. The time-width of the generated photon becomes narrower with increasing temperature in the atomic cell. The recorded results are shown in Fig. S2.

Fig. S2. Measured coincidence window of the signal 1 and signal 2 photons versus cell temperature. In this case, the coincidence window represents the time width of the entire coincidence wave packet.

Proof of extended Cauchy-Schwarz inequality for three variables

We define three unrelated random variables a_i, b_i, c_i ($i=0\sim m$). According to the Cauchy-Schwarz inequality for two variables:

$$\left(\sum_{i=1}^m a_i b_i\right)^2 \leq \sum_{i=1}^m a_i^2 \sum_{i=1}^m b_i^2, \quad (S1)$$

By considering $a_i b_i$ as a variable, we then obtain:

$$\left(\sum_{i=1}^m a_i b_i c_i\right)^2 \leq \sum_{i=1}^m a_i^2 b_i^2 \sum_{i=1}^m c_i^2. \quad (S2)$$

Because $\sum_{i=1}^m a_i^2 b_i^2 \leq \sum_{i=1}^m a_i^2 \sum_{i=1}^m b_i^2$, the final inequality thus can be found as follows:

$$\left(\sum_{i=1}^m a_i b_i c_i\right)^2 \leq \sum_{i=1}^m a_i^2 b_i^2 \sum_{i=1}^m c_i^2 \leq \sum_{i=1}^m a_i^2 \sum_{i=1}^m b_i^2 \sum_{i=1}^m c_i^2. \quad (S3)$$

The extended Cauchy-Schwarz inequality for three variables can thus be written as:

$$\langle uv\kappa \rangle^2 \leq \langle u^2 \rangle \langle v^2 \rangle \langle \kappa^2 \rangle, \quad (S4)$$

where u, v, κ are unrelated random variables.

Estimation of the auto-correlation of the signal 3 and signal 4 photons

We input a weak coherent laser beam at 780 nm into the PPLN waveguide to generate and then measure the auto-correlation of the signal 3 and signal 4 photons for different 780-nm laser input powers. The measured results are shown in Fig. S3. With decreasing 780-nm laser power, the probability of multi-photons from signal 3 and signal 4 decreases. Based on this process, the auto-correlation of signal 3 and signal 4 is estimated to be $g_{s3,s3}^{(2)}(0) = g_{s4,s4}^{(2)}(0) = 1 \pm 0.05$.

Fig. S3. Measured auto-correlation of signal 3 and signal 4 photons versus the power of the 780-nm laser. The error bars indicate the experimental statistics.

REFERENCES

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