Experimental Quantum Teleportation and Multi-Photon Entanglement via Interfering Narrowband Photon Sources

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In this letter, we report a realization of synchronization-free quantum teleportation and narrowband three-photon entanglement through interfering narrowband photon sources. Since both the single-photon and the entangled photon pair utilized are completely autonomous, it removes the requirement of high demanding synchronization technique in long-distance quantum communication with pulsed spontaneous parametric down-conversion sources. The frequency linewidth of the three-photon entanglement realized is on the order of several MHz, which matches the requirement of atomic ensemble based quantum memories. Such a narrowband multi-photon source will have applications in some advanced quantum communication protocols and linear optical quantum computation.

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Quantum teleportation [1] is a process to transfer a quantum state of a photon without transferring the state carrier itself, which plays a central role in quantum communication [2]. It necessitates the interference of a single-photon and an entangled photon pair. Since spontaneous parametric down-conversion (SPDC) is the main method to generate entangled photons [3], typically with a frequency linewidth of several THz. To interfere independent sources, the resolution time of the photon detectors has to be much smaller than the coherence time (< 1 ps) [4], which is still not available until today. This problem was later solved by utilizing a femtosecond pumping laser and frequency filtering [3, 5]. Since the development of this technique, numerous important advances have been achieved [5-7, 8, 9, 10, 11, 12]. But in this pulsed regime, interference of independent sources requires a synchronization precision of several hundred fs for the pumping lasers. Even though there are some experimental investigations with lasers within a single lab, when one wants to build entanglement over several hundred kilometers, it will become rather challenging.

While in the continuous-wave regime, with the development of the quasi-phase matching technique, it is now possible to narrow the frequency bandwidth for SPDC sources to several tens GHz [14], lowering down the requirement for photon detectors. In [13] Halder et al. has demonstrated the feasibility to interfere separate sources through time measurement. In their experiment, Bragg gratings were used to filter out narrow-band photons from a SPDC source, increasing the coherence time to several hundred ps. In order to interfere such entangled sources, a high-demanding superconducting detector with ultra-low time jitter was utilized, which is only available for few groups. Recently, we have reported a narrow-band entangled photon source with a ~MHz linewidth through cavity-enhanced SPDC [16]. Such a narrow-band source will enable the possibility to interfere separate sources with the widely used commercial sub-ns photon detectors. Also the tolerance of length fluctuations for the quantum communication link will improve from several centimeters in [13] to several meters, which means we can realize quantum teleportation for longer distance, larger time scale, and worse weather condition.

Interference of independent sources is also the main method to generate multi-photon entanglement [17, 18, 19], which is the main resource for linear optical quantum computation (LOQC) [20]. To efficiently build large entangled states for LOQC, it is required to store the intermediate multi-photon entangled states with a quantum memory [21, 22]. But previously due to the usage of SPDC sources, the frequency linewidth of these multi-photon entanglement lies on the order of several THz. While the frequency linewidth required by an atomic ensemble based quantum memory [23, 24, 25, 26] is on the order of several MHz. This frequency mismatch greatly limits the applications of the broadband multi-photon entangled sources. Therefore, creating a narrowband multi-photon entanglement with linewidth of several MHz becomes an urgent task.

In this Letter, we experimentally investigate the interference of a single-photon and an entangled photon pair, both of which are continuous-wave and narrowband (~MHz). Through this interference, first we realize a synchronization-free quantum teleportation. Since both for the single-photon and the entangled photon pair utilized are completely autonomous, it removes the requirement of high demanding synchronization technique for the case of pulsed SPDC sources, enabling the possibility to teleport a photonic state between distant locations. Secondly the same setup enables us to generate a narrowband three-photon entangled state, with a linewidth of
The quantum state of these photons can be found by using temperature controlled etalons. Detailed description of this narrow-band entangled source could be found in a former paper of us [16]. The linewidth for this source is 9.6 MHz. Single-mode output is generated through cavity-enhanced SPDC. Measured fold coincidence rate of about 200 s$^{-1}$ is shown in Fig. 1. The entangled photon pairs $(|H\rangle_1|V\rangle_2+|V\rangle_1|H\rangle_2)$ are generated through cavity-enhanced SPDC. The optical chopper is utilized to switch between the locking and the detecting process. The beam from another completely independent diode laser (locked to the same atomic transition line as the Ti:Sapphire laser) is attenuated to an intensity of about $8.0 \times 10^5$ s$^{-1}$ as the single-photon source to be teleported. A partial Bell state measurement (BSM) of photon 2 and photon 3 is realized with PBS4 and the following polarization analyzers. When a coincidence of $|+\rangle_2|+\rangle_3$ ($(|\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle \pm |V\rangle))$ clicks between detector D2 and D3, the two photons are projected into the state of $|\Phi^+\rangle_{23} = 1/\sqrt{2}(|H\rangle_2|H\rangle_3 + |V\rangle_2|V\rangle_3)$. Then after a local operation of $\sigma_z$ on photon 1, the teleportation from photon 3 to photon 1 is finished. In order to get a high-visibility interference on PBS4 between the single-photon and the entangled pair, the coincidence time window between photon 2 and photon 3 should be much smaller than the correlation time between photon 1 and photon 2 (20ns) [3], in our case we choose it to be 3 ns.

**TABLE I:** Fidelities for the teleportation experiment. All the fidelities of the teleportation are well above the classical limit of 2/3.

| Polarization | \(|H\rangle\) | \(|+\rangle\) | \(|L\rangle\) |
|--------------|-------------|-------------|-------------|
| Fidelity     | 91.0%       | 79.8%       | 79.0%       |

For the states to be teleported of photon 3, we choose three states, namely, $|H\rangle$, $|+\rangle$, and left-handed $|L\rangle$ circular polarization states $\frac{1}{\sqrt{2}}(|H\rangle - i|V\rangle)$. In order to evaluate the performance for the teleportation process, we make a quantum tomography [28] for all the teleported states, with results shown in Fig. 2 and fidelities shown in Table. 1. It shows that the fidelities of the six states are well above the classical limit of 2/3 [29]. Thus the success of quantum teleportation is proved.
A great advantage to use continuous-wave sources for quantum teleportation and entanglement connection is that the two sources can be completely autonomous. In our experiment, for a 3 ns coincident time window, which is much smaller than the coherent time of the input photons, a perfect overlap between photon 2 and photon 3 at PBS4 is always guaranteed. It removes the high-demanding synchronization technique and provides a much easier way to generate entanglement by using completely independent sources over a large distance.

With similar setup [30], it is now possible to generate the first narrow-band three-photon entanglement. By preparing photon 3 in the state of $|+\rangle$ and photon 1 and 2 in the entangled state of $|\Phi^-\rangle$, the three-fold coincidence among the detector D1, D2 and D3 will lead to a three-photon GHZ state [31]:

$$|\Phi\rangle_{123} = \frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2|H\rangle_3 - |V\rangle_1|V\rangle_2|V\rangle_3).$$

To experimentally verify that the desired state of Eq. 2 has been successfully generated, we first characterize the components of the three-photon state corresponding to such a three-fold coincidence. This was done by measuring each photon in the $H/V$ basis. The result is shown in Fig. 3. The signal-to-noise ratio, which is defined as the ratio of any of the desired three-fold components $(HHH$ and $VVV)$ to any of the 6 other non-desired ones, is about 7:3:1, which confirms that $HHH$ and $VVV$ are the main components of the three-photon state. Error bars represent the statistical errors.

![Figure 2: Tomography results for the teleportation of $|H\rangle$, $|+\rangle$ and $|L\rangle$. (a) and (b) are the real and imaginary parts for the teleported state of $|H\rangle$ respectively. (c) and (d) are the real and imaginary parts for the teleported state of $|+\rangle$ respectively. (e) and (f) are the real and imaginary parts for the teleported state of $|L\rangle$ respectively.](image)

![Figure 3: Measured result for the three-photon entangled state in $H/V$ basis. It shows that the signal-to-noise ratio between the desired three-fold components to any of the 6 other non-desired ones, is about 7.3:1, which confirms that $HHH$ and $VVV$ are the main components of the three-photon state. Error bars represent the statistical errors.](image)

![Figure 4: Measured observables of the Mermin inequality (Eq. 3) for the three-photon entangled state.](image)

| Observable     | $\sigma_1^x\sigma_2^y\sigma_3^z$ | $\sigma_1^y\sigma_2^x\sigma_3^z$ | $\sigma_1^z\sigma_2^y\sigma_3^x$ | $\sigma_1^x\sigma_2^z\sigma_3^y$ |
|----------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Value          | 0.64                             | 0.63                             | 0.67                             | -0.66                            |
| Deviation      | 0.02                             | 0.02                             | 0.02                             | 0.02                             |

where $\sigma_j^i$ corresponds to the $i$ th Pauli matrix on particle $j$. Violation of the inequality, that is $|\langle A \rangle| > 2$, proves the non-local property of the three photon state. The measured value of the observables are shown in Table. II With simple calculation, it is obtained that $|\langle A \rangle| = 2.59 \pm 0.05$, which violates the inequality by 12 standard deviations. Combining the results of components and Mermin observables measurements, we can obtain the fidelity between the state generated and the ideal three-photon GHZ state:

$$F(\rho) = \frac{1}{2} \langle 123 (HHH |\rho| HHH)_{123} + 123 (VVV |\rho| VVV)_{123} \rangle + \frac{1}{8} |\langle A \rangle|$$

Our result is $F(\rho) = 0.68 \pm 0.01$, which is well above the boundary of 1/2, and thus a proof of true three-photon entanglement [32]. As the linewidth of entangled three-photon is of several MHz, it may have broad application in future LOQC together with atomic quantum memory, especially for the generation of large cluster states [21] that are storable.

In summary, a realization of synchronization-free quantum teleportation and narrowband three-photon entanglement through interfering continuous-wave narrowband sources is reported. Since both for the single-photon and the entangled photon pair utilized are completely autonomous, it removes the requirement of high...
demanding synchronization technique for the case of pulsed SPDC sources, enabling the possibility to teleport a photonic state between distant locations. The frequency linewidth of the narrowband three-photon entanglement realized is on the order of several MHz, which matches the requirement of atomic ensemble based quantum memories. Such a narrowband multi-photon source will have applications in some advanced quantum communication protocols and LOQC.

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