Experimental quantum teleportation and multiphoton entanglement via interfering narrowband photon sources

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In this paper, 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 techniques 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 multiphoton 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 [5,6]. Since the development of this technique, numerous important advances have been achieved [7–11]. 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 [12,13] with lasers within a single laboratory, 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 quasiphase 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 [15] Halder *et al.* has demonstrated the feasibility to interfere separate sources through time measurement. In their experiment, Bragg gratings were used to filter out narrowband 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 ultralow time jitter was utilized, which is only available for few groups. Recently, we have reported a narrowband entangled photon source with a ~MHz linewidth through cavity-enhanced SPDC [16]. Such a narrowband 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 [15] 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 multiphoton entanglement [17–19], 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 multiphoton entangled states with a quantum memory [21,22]. But previously due to the usage of SPDC sources, the frequency linewidth of these multiphoton entanglement lies on the order of several THz. While the frequency linewidth required by an atomic ensemble based quantum memory [23–26] is on the order of several MHz. This frequency mismatch greatly limits the applications of the broadband multiphoton entangled sources. Therefore, creating a narrowband multiphoton entanglement with linewidth of several MHz becomes an urgent task.

In this paper, 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. Second the same setup enables us to generate a narrowband three-photon entangled state, with a linewidth of several MHz, which matches the requirement of atomic ensemble based quantum memories. Such a narrowband multiphoton source will have applications in some advanced quantum communication protocols [17,27] and LOQC.

The schematic of our experimental setup is shown in Fig. 1. The entangled photon pairs are generated through cavity-enhanced SPDC. Measured linewidth for this source is 9.6 MHz. Single-mode output is realized by setting a cavity length difference between different polarizations, active cavity stabilization and the use of temperature controlled etal-

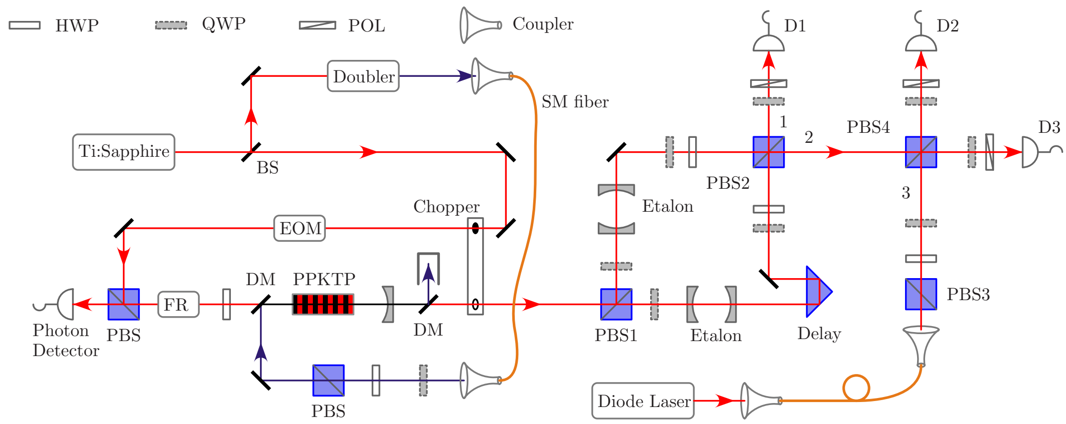

FIG. 1. (Color online) Experimental setup. A continuous-wave Ti:sapphire laser locked to one of the ^{87}Rb D_2 hyperfine transitions is divided into two portions by a beam-splitter (BS). The main portion is up-converted to an ultraviolet (uv) beam (390 nm) through an external-cavity doubler. Then the uv pump beam (about 9 mw) is coupled into the double-resonant cavity which is composed of a PPKTP (from Raicol) and a concave mirror. The PPKTP is type-II configured that one uv photon gives rise to a H polarized photon and a V polarized photon. After separated on polarized beam-splitter 1 (PBS1), an etalon on each arm is used to filter out single longitudinal mode. The quarter-wave plate (QWP) before each etalon is used to form an optical isolator with PBS1 to eliminate the reflection from the etalon. After rotated to $|+\rangle$ polarization with a half-wave plate (HWP) respectively, the two photons get interfered on PBS2. The narrowband entangled photon pair is generated in the case that one photon appears on each output port. The second portion is used to lock the double-resonant cavity actively. A Faraday rotator (FR) and a PBS are utilized to extract the reflected locking beam in order to generate the error signal for the locking. 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.

ons. Detailed description of this narrowband entangled source could be found in a former paper of us [16]. The quantum state of these two photons can be expressed as

$$|\Phi^-\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2 - |V\rangle_1|V\rangle_2), \tag{1}$$

which is one of the four Bell sates, and H represents horizontal polarization, V represents vertical polarization. For a 9 mw input uv power, it is observed that a twofold coincidence rate of about 200 s^{-1} at a coincidence time-window of 16 ns.

The single-photon to be teleported (photon 3 in Fig. 1) is generated by attenuating another completely independent diode laser to an intensity of about 8.0×10^5 s^{-1}. The state to be teleported is prepared with a HWP or a QWP. A partial Bell state measurement (BSM) is realized by sending photon 2 and photon 3 through the 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 σ_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 (20 ns) [5], in our case we choose it to be 3 ns.

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. I. 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

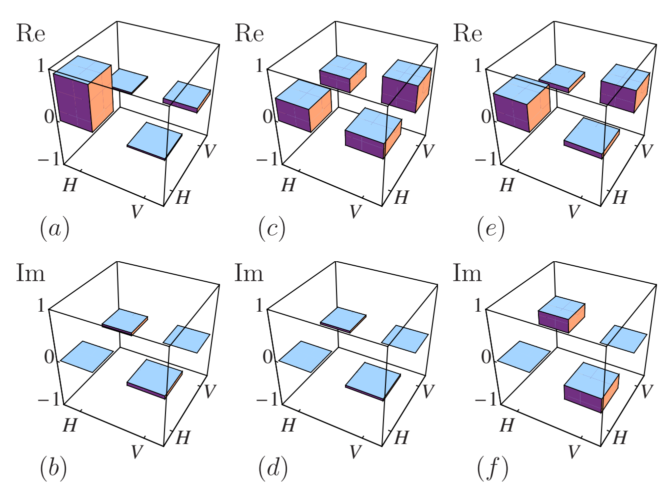

FIG. 2. (Color online) Tomography results for the teleportation of $|H\rangle$, $|+\rangle$, and $|L\rangle$. (a) and (b) are the real and imaginary parts for the teleported state of $|H\rangle$, respectively. (c) and (d) are the real and imaginary parts for the teleported state of $|+\rangle$, respectively. (e) and (f) are the real and imaginary parts for the teleported state of $|L\rangle$, respectively.

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

Polarization	$\|H\rangle$	$\|+\rangle$	$\|L\rangle$
Fidelity	91.0%	79.8%	79.0%

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 narrowband 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 threefold coincidence among the detectors D1, D2, and D3 will lead to a three-photon GHZ state [31],

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

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 threefold 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 threefold components (*HHH* and *VVV*) to any of the six other nondesired ones, is about 7.3:1.

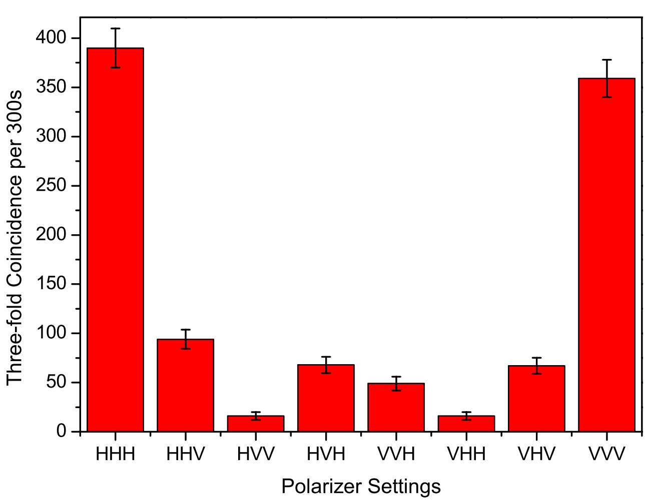

FIG. 3. (Color online) Measured result for the three-photon entangled state in H/V basis. It shows that the signal-to-noise ratio between the desired threefold components to any of the six other nondesired ones, is about 7.3:1, which confirms that *HHH* and *VVV* are the main components of the three-photon state. Error bars represent the statistical errors.

TABLE II. Measured observables of the Mermin inequality [Eq. (3)] for the three-photon entangled state.

Observable	$\sigma_y^1\sigma_y^2\sigma_x^3$	$\sigma_y^1\sigma_x^2\sigma_y^3$	$\sigma_x^1\sigma_y^2\sigma_y^3$	$\sigma_x^1\sigma_x^2\sigma_x^3$
Value	0.64	0.63	0.67	−0.66
Deviation	0.02	0.02	0.02	0.02

To obtain a further characterization of the entanglement, we make a measurement of the Mermin inequality [32]. In our case, the value of A in the inequality is defined as:

$$A = \sigma_y^1\sigma_y^2\sigma_x^3 + \sigma_y^1\sigma_x^2\sigma_y^3 + \sigma_x^1\sigma_y^2\sigma_y^3 - \sigma_x^1\sigma_x^2\sigma_x^3, \qquad (3)$$

where σ_i^j corresponds to the ith Pauli matrix on particle j. Violation of the inequality, that is $|\langle A\rangle| > 2$, proves the nonlocal 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 observable measurements, we can obtain the fidelity between the state generated and the ideal three-photon GHZ state,

$$F(\rho) = \frac{1}{2}({}_{123}\langle HHH|\rho|HHH\rangle_{123} + {}_{123}\langle VVV|\rho|VVV\rangle_{123}) + \frac{1}{8}|\langle A\rangle|. \qquad (4)$$

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 [33]. 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 multiphoton source will have applications in some advanced quantum communication protocols and LOQC.

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