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Long-distance quantum teleportation assisted with free-space entanglement distribution*

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Faithful long-distance quantum teleportation necessitates prior entanglement distribution between two communicated locations. The particle carrying on the unknown quantum information is then combined with one particle of the entangled states for Bell-state measurements, which leads to a transfer of the original quantum information onto the other particle of the entangled states. However in most of the implemented teleportation experiments nowadays, the Bell-state measurements are performed even before successful distribution of entanglement. This leads to an instant collapse of the quantum state for the transmitted particle, which is actually a single-particle transmission thereafter. Thus the true distance for quantum teleportation is, in fact, only in a level of meters. In the present experiment we design a novel scheme which has overcome this limit by utilizing fiber as quantum memory. A complete quantum teleportation is achieved upon successful entanglement distribution over 967 meters in public free space. Active feed-forward control techniques are developed for real-time transfer of quantum information. The overall experimental fidelities for teleported states are better than 89.6%, which signify high-quality teleportation.

Keywords: entanglement, teleportation, free space
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1. Introduction

Since quantum teleportation was proposed by Bennett *et al* in 1993,[1] it has become one of the research focuses in the area of quantum information processing.

Quantum teleportation plays a central role in quantum network and universal quantum computation.[2,3] Particularly, it serves as one of the most important parts for a practical quantum a repeater[4] in quantum communication.[5−7]

The experimental implementations of quantum teleportation were first demonstrated in laboratories, simultaneously by the Roman group[8] and the Innsbruck group.[9] The experiment reported by the Roman group could achieve complete Bell state identification based on their proposed two-particle scheme. Inspired by the success of experimental realizations of quantum teleportation, people have realized a series of further demonstrations, such as entanglement swapping,[10] entanglement purification,[11] and so on. Particularly, open-destination teleportation[12] and composite system teleportation[13] were achieved recently. Besides the realization with respect to photonic qubits, quantum teleportation has been further demonstrated between ionic qubits,[14] continuous-variable systems,[15] and more recently, even from light to matter.[16]

A key precondition of quantum teleportation, however, requires prior entanglement shared between the two parties of communication. In most of the performed quantum teleportation experiments, due to the absence of memory for the quantum state, the Bell-state measurements (BSM) are performed even before successful distribution of entanglement. This leads to an instant collapse of the quantum state for the transmitted particle from the entangled states. Therefore,

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it will be only a single-particle transmission for the teleported state thereafter. This would imply that the true distance for quantum teleportation is, in fact, limited to a level of meters only.

No matter how long the quantum channel is, a long-distance quantum teleportation has not really been achieved in previous demonstrations.

In this work, by using single mode fiber as quantum memory[17] we store one of the entangled photon pairs in single-mode fiber and transmit another entangled photon to the receiver site. Once the entangled photon pairs distribution is completed, the transmitter begins to perform Bell-state measurements. In this way we have accomplished a truly long-distance quantum teleportation assisted with free-space entanglement distribution.

2. Scheme and set-up

We choose two separate stations at Badaling of Beijing for two communicated parties of our experiment. The transmitter called Alice located at Rose Valley DaysInn Hotel (40°21′37.62″ N, 115°56′21.89″ E) and the receiver located at Waipao Village (40°21′38.07″ N, 115°55′36.43″ E). A schematic layout of the experiment is shown in Fig.1.

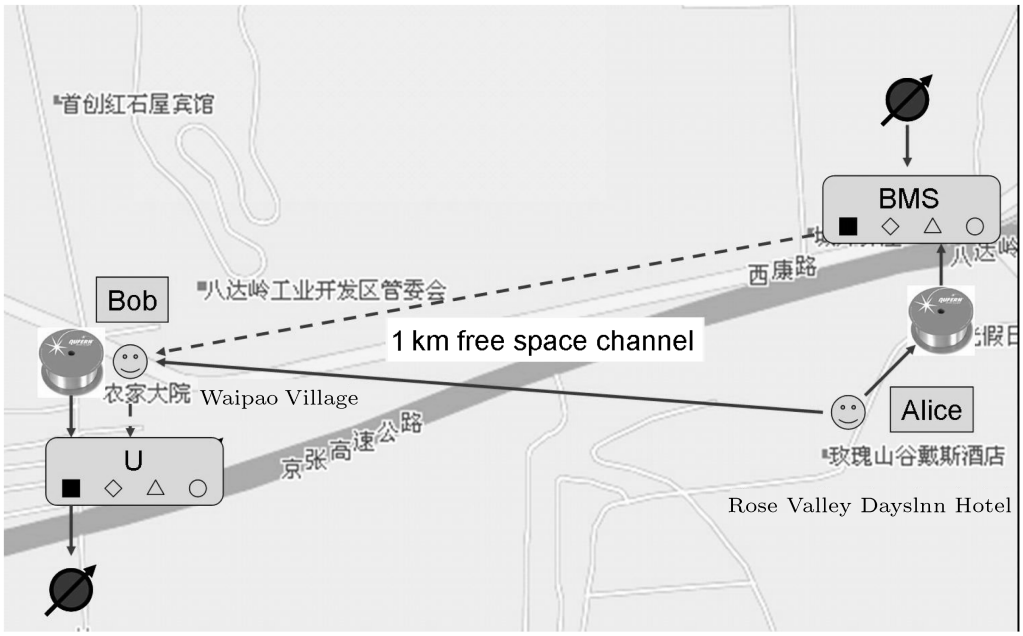


Fig.1. A diagram of the free-space quantum teleportation experiment: Alice is located at Rose Valley DaysInn Hotel and Bob is located at Waipao Village in Beijing. We distribute entangled photon pairs firstly between Alice and Bob. To match the timing for performing truly quantum teleportation, we have managed to design the corresponding optical and electrical delays. Then at Alice's site we perform BSM and transmit the results to Bob. The unitary transformation is imposed accordingly at Bob's site.

In the experiment, a semiconductor blue laser beam (with a power of 34.5 mW, a waist of 100 μm and a central wavelength of 405 nm) incidents on a 2 mm-long beta-barium-borate (β-BBO) crystal to generate the entangled photon pairs at 810 nm via type-II SPDC.[18] Alice transmits one of the entangled photon (called B) to Bob by the 100 mm aperture Galilean telescope system while another entangled photon (called A) is coupled in a spool of single mode fiber (Nufern 780HP) of 645 meters long. This spool serves as a rudimentary quantum memory. When photon A leaves the fiber, photon B will arrive at the receiver site to match the timing. For maintaining the polarization state of photon A, we use a set of wave plates to compensate ofr the birefringence effects of the fiber. Photon B is received by another 100 mm aperture Galilean telescope system. At this stage we have finished a long-distance entangled entanglement distribution. We then construct a Mach–Zehnder interferometer to prepare the teleported state and perform the Bell-state measurements. The BSM results were

encoded on a 638 nm pulse laser (Coherent Cube laser) and transmitted by a telescope system. Once Alice accomplishes BSM, photon B at the receiver will collapse to a single photon state. However Bob does not know the results of BSM at Alice's site, we thus store photon B in a spool single-mode fiber of 800 m long and wait for the result of BSM. When the classical signal carries results of BSM arrives at receiver, photon B just leaves fiber. The BSM results are utilized to trigger a high voltage module to drive fast electro-optical modulators (EOM), which can realize the corresponding unitary transformations on photon B. Therefore truly long-distance quantum teleportation is accomplished after successful distribution entangled state.

2.1. Bell state measurement

One of the key parts in the quantum teleportation experiment is the complete Bell state measurements. In our experiment we adopt the two-photon quantum teleportation scheme proposed by Martini's group.[8] Using the MZ interferometer constructed by two polarization beam splitters, we generate the necessary entangled state between polarization freedom and path freedom in high-dimensional space. We can then distinguish all of the four Bell states by single photon interference in the MZ interferometer.

A schematic layout of the experimental set-up is shown in Fig.2.

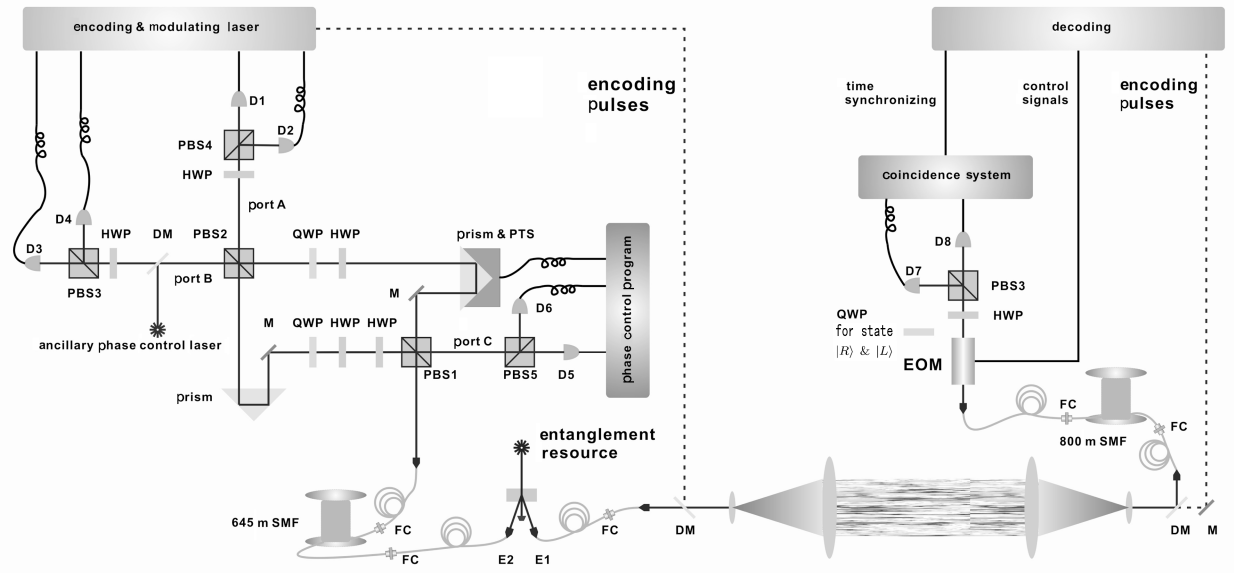


Fig.2. Set-up of the experiment: entangled photon pairs are generated by the type-II SPDC process. Photon A firstly enters the single-mode fiber of 645 meters long while photon B is transmitted by the telescope system. The state to be teleported is prepared by a set of wave planes by using of the MZ interferometer. After BSM, the results will be encoded on an encoding & modulating laser and transmitted to Bob by the telescope system. Photon B is then received by another telescope system in Bob's site and stored in single mode fiber of 800 meters long. When the results of BSM arrive, Bob performs the corresponding unitary transformation (U) and achieves the quantum teleportations.

The polarization entangled photonic source prepared in the experiment can be expressed as follows:

$$\left|\psi^{-}\right\rangle_{AB} = \frac{1}{\sqrt{2}}\left(\left|H\right\rangle_{A}\left|V\right\rangle_{B} - \left|V\right\rangle_{A}\left|H\right\rangle_{B}\right). \tag{1}$$

Here $\left|H\right\rangle_{A}\left|V\right\rangle_{B}$ means that photon A is polarized in the horizontal direction, while photon B is polarized in the vertical direction. There are two spatial modes after photon A passes through the first PBS of the interferometer. We define the transmitted mode as $|T\rangle$, and the reflected mode as $|R\rangle$. Thus the whole quantum state after photon B passing through PBS1 reads

$$\left|\psi\right\rangle_{AB} = \frac{1}{\sqrt{2}}\left(\left|T\right\rangle_{A}\left|H\right\rangle_{A}\left|V\right\rangle_{B} - \left|R\right\rangle_{A}\left|V\right\rangle_{A}\left|H\right\rangle_{B}\right). \tag{2}$$

We set a half wave plane (HWP) oriented in 45° to rotate the polarization of photon A from the vertical to the horizontal direction so that the polarization states of photon A are the same in both spatial modes. Therefore, the polarization of the two modes are both prepared to an arbitrary initial state for teleportation as

$$|\psi\rangle = \alpha\,|H\rangle_A + \beta\,|V\rangle_B\ ,$$

by a combination of a half wave plane (HWP) and a quarter wave plane (QWP), respectively.

We define here a set of two-photon entanglement-like Bell states, which are the maximum entangled state for both the spatial and polarization degree of freedom of single photon

$$\begin{aligned}\left|\psi^{\pm}\right\rangle &= \frac{1}{\sqrt{2}}\left(|T\rangle\,|V\rangle \pm |R\rangle\,|H\rangle\right),\\ \left|\phi^{\pm}\right\rangle &= \frac{1}{\sqrt{2}}\left(|R\rangle\,|H\rangle \pm |T\rangle\,|V\rangle\right).\end{aligned} \tag{3}$$

With this set of Bell states, the quantum state of the entangled photon pairs can be rewritten as

$$\begin{aligned}|\psi\rangle_{AB} = \frac{1}{2}\big[&\left|\psi^{-}\right\rangle_A(-\alpha\,|H\rangle_B - \beta\,|V\rangle_B)\\ &+\left|\psi^{+}\right\rangle_A(-\alpha\,|H\rangle_B + \beta\,|V\rangle_B)\\ &+\left|\phi^{-}\right\rangle_A(\alpha\,|V\rangle_B + \beta\,|H\rangle_B)\\ &+\left|\phi^{+}\right\rangle_A(\alpha\,|V\rangle_B - \beta\,|H\rangle_B)\big].\end{aligned} \tag{4}$$

The above expression indicates that, to achieve a 100% probability of quantum teleportation, one must completely distinguish all of the four single-photon Bell states with maximum entanglement in both the spatial and polarization modes.

To realize the BSM, the two spatial modes of photon A must precisely overlap with each other at the second PBS of the interferometer. This operation will erase the spatial mode information of the photon, and lead to $|\psi^{\pm}\rangle$ and $|\phi^{\pm}\rangle$ output at different ports, and thus be identified. A combination of an HWP and a PBS is sufficient to distinguish $\frac{1}{\sqrt{2}}\left(|H\rangle_A + |V\rangle_A\right)$ from $\frac{1}{\sqrt{2}}\left(|H\rangle_A - |V\rangle_A\right)$, therefore different clicks of the four detectors represent different detections of the four Bell states, respectively.

It should be pointed out that the optical path lengths of the two spatial modes are not exactly the same in the experiment. There is a phase difference between the two modes when they interfere on PBS2, and the difference will change dramatically due to disturbances like airflow and temperature drift. To achieve complete BSM one should fix the phase difference at a wanted point (0, 2π, or their multiples for example) for a successful teleportation experiment.

In the experiment we use a piezoelectric ceramics translation stage (PTS) above which a prism is fixed, to control the optical path length of the transmitted mode with a resolution of several nanometers per step, so the phase difference between the two modes can be controlled precisely. We employ a faint laser to actively stabilize the interferometer. In order to reduce the induced dark counts to the APD, the 45° polarized laser is coupled to the BSM interferometer along the reversed propagating path of photon 1. At the output of PBS1, we analyze the polarization of the photons at a +45°/–45° basis and send the results to our computer control system, in which a program is running to real-time control the PTS to lock the phase difference of the interferometer to be zero. The phase could be locked as long as several hours, or even longer.

2.2. Time synchronization

As the output signal for each of the four APDs corresponds to each of the four Bell states, respectively, a self-designed module will encode the results to a series of TTL signals to modulate the output pulse of a semiconductor laser with a central wavelength of 638 nm. The modulated laser pulse is then coupled with photon B via a dichromatic mirror (DM) and is sent to Bob through the telescope.

At Bob's site, the received beam is filtered by another DM to separate photon B and the encoded pulses. The latter is then detected by a photon-receiver, and the output signals are analyzed by a self-designed decoding module. The main functions of the decoding module include outputting the two control signal for driving the electro-optic modulator (EOM), and a time synchronization signal for coincident measurement with photon B.

The logic of the control signal is shown in Table 1.

Table 1. Logic of the control modules.

	dectect1	dectect2	dectect3	dectect4
control signal 1	0	0	1	1
control signal 2	0	1	0	1
unitary transformation	σ_x	$\widehat{1}$	$\mathrm{i}\,\hat{\sigma}_y$	$\hat{\sigma}_z$

Bob uses the control signal to trigger a high voltage module to drive the fast EOM, such that the following corresponding operation transforms photon B to the desired teleported state $|\psi\rangle$. The time synchronization signal is used to identify whether the detected

photons really come from the other halves of the transmitted parts of the entangled pairs, by means of coincidence measurement. The time sequences of events are sketched in Fig.3.

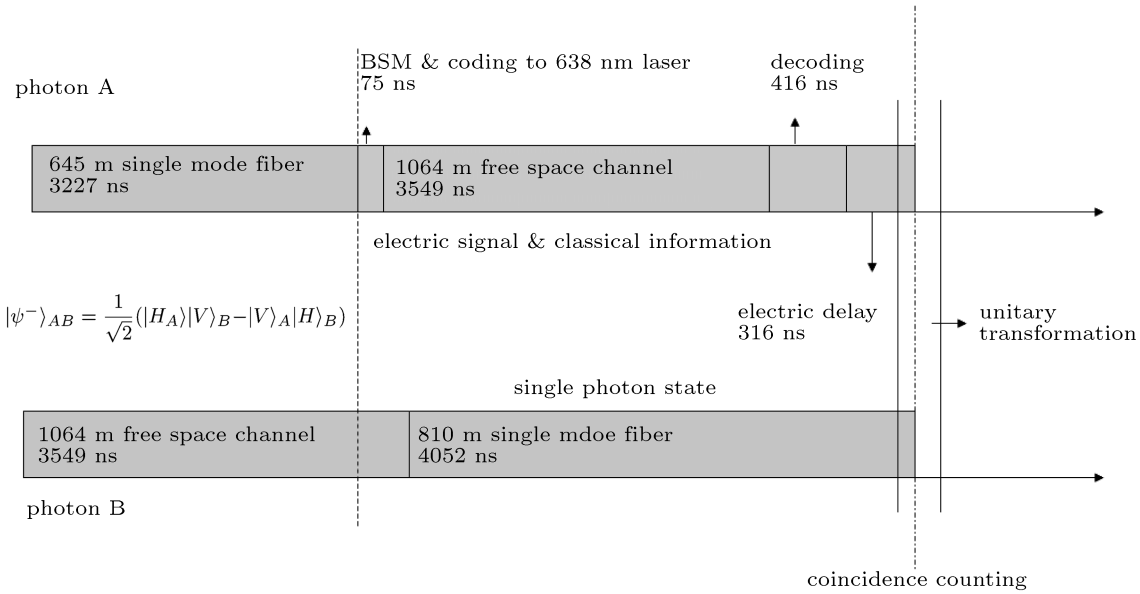


Fig.3. Timing sequential depiction of the experiment.

The measured transmission time of photon A in the 645 m single mode fiber (SMF) is about 3.22 μs; the time spent on BSM and encoding the laser pulses (including the time for transmission on a 5 m and a 10 m single mode fiber used to connect the laser and the telescope) is about 98 ns; the decoding module consumes 416 ns. Photon B is "stored" in a long single mode fiber (800 m, plus two optical patch cables add up to 10 m) before entering the electro-optical modulators, and finally is detected by APD (the transmission time in free space at Bob's site is 3 ns, for photon 2 going through all the optics elements). The coincident window is set to be 4 ns, and we can adjust a self-designed electric delay to manage both the synchronization signals and the APD signals overlapping within the coincident window.

The length of the single mode fiber "storing" photon A is only 645 m, while the corresponding transmitted distance of photon B in free space is about 967 m, which is the actual distance of our teleportation experiment.

3. Results

In the experiment we use a semiconductor blue laser beam (power 34.5 mW, waist 100 μm and central wavelength 405 nm) as the pump laser and it is incident on a 2 mm β-barium-borate (BBO) crystal to generate entangled photonic pairs at 810 nm via type-II spontaneous parametric down conversion. After inserting the bandpass filter (FWHM 4 nm) we achieve a bright entangled resource with a number of counts of 17.8 k/s, the visibility for H/V basis of 100:1(98.2%) and for +/− basis of 20:1(92.4%).

Now we analyze the efficiency of the whole system. Once the photon A is generated, it passes through two FC fiber connectors (with efficiency 60%) and a spool fiber 645 meters long (with efficiency 55%). After BSM, photon A is collected by a single mode fiber (with efficiency 60%) before detected by avalanche diode. The results are then encoded to a semiconductor laser wavelength 638 nm and transmitted to the receiver. The signals will be used for performing coincidence measurement together with photon B. For photon B, it passes through FC fiber connectors and then transmits to the receiver by the telescope sys-

tem. There are atmospheric attenuation (70% transmission rate), geometric attenuation (with efficiency 70%) and optical efficiency of the telescope system. At the receiver site, photon B passes through two FC fiber connectors and a spool fiber 800 meters long (with efficiency 60%). After the unitary transformation is performed by EOM (with a transmission rate of 80%), photon B is collected by a multi-mode fiber and detected by an avalanche diode. The efficiency of the whole system is a product of the efficiency of both photons A and B. Considering atmospheric turbulence and other instability, we get a coincidence counts of 222∼384/min in our experiment.

Table 2. The result of the experiment.

initial states	visibility	fidelity
H	81.4%±1.2%	90.7%±0.6%
V	81.7%±1.2%	90.8%±0.6%
$+$	83.5%±1.1%	91.7%±0.6%
$-$	85.4%±1.0%	92.7%±0.5%
R	82.7%±1.7%	91.4%±0.9%
L	79.2%±1.8%	89.6%±0.9%

To prove the universality for our teleportation set-up, without loss of generality, we select both linear polarization states $|H\rangle$, $|V\rangle$, $\frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$, $\frac{1}{\sqrt{2}}(|H\rangle - |V\rangle)$ and circular polarization states $|R\rangle = \frac{1}{\sqrt{2}}|H + \mathrm{i}\,V\rangle$, $|L\rangle = \frac{1}{\sqrt{2}}|H - \mathrm{i}\,V\rangle$ as initial states to be teleported. The visibility and fidelity of the experiment is shown in Table 2.

The experimental results of teleportation fidelity for different initial states range from 89.6% to 93%.

4. Conclusions

In conclusion, by using single mode fiber as quantum memory we have for the first time accomplished a long-distance quantum teleportation experiment assisted with successful distribution of entanglement. A distance of 967 meters is achieved for free space quantum teleportation. We have performed a complete teleportation since we can distinguish unambiguously all of the four Bell states. At the receiver site we have performed real-time unitary transformation for recovery of the original quantum information by active feedforward. The technology used for accomplishing complete Bell measurement and real-time unitary transformation was achieved in our previous work.[19] The experimental fidelities for teleportation of various initial states are better than 89.6%, which implies the significant high-quality of our demonstration.

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