University Research Highlights

Faithful Quantum Communication Over Noisy Environment

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Abstract

Quantum communication allows secure transfer of classical messages by means of quantum key distribution, and faithful transfer of unknown quantum states between distant sites by quantum teleportation. At the heart of these tasks lies the manipulation of entanglement and faithful node-to-node transmission of quantum information carriers, qubits. During the process, qubits will unavoidably interact with environment which induces decoherence and reduces the purity of the states. This letter highlights the recent theoretical and experimental work performed in our group to overcome such problems.

Introduction

Quantum information science has increasingly been attracting interest since the beginning of the last decade from different disciplines ranging from physics to mathematics, engineering and computer science. It differs from classical information science in its handling of quantum mechanical properties such as entanglement and superposition for information processing which includes its generation, distribution, manipulation and storage. These non-classical properties enable tasks such as teleportation [1], dense coding [2], and quantum key distribution [3], which cannot be otherwise realized. It is also this toolbox that allows massive parallelism for quantum computing [4].

The photonic quantum bits (qubits) based on polarization or spatial degrees of freedom of optical modes are a promising candidate for long distance communication due to their easy manipulation and measurement as well as possibility of communicating over comparatively long distances. However, fragility of those qubits poses challenges and requires careful handling to protect them against photon loss and decoherence, which reduces information exponentially.

Given the importance of entanglement in quantum information science and the fact that it cannot be generated by classical communication and local operations (LOCC) between distant parties, faithful distribution of entangled photons among the nodes of a communication network is crucial. Quantum repeater [5], which aims to establish high-quality long-distance entanglement among the users of a communication network by using entanglement swapping [6], purification protocols [7, 8] and quantum memory [9], is a sophisticated architecture proposed as a remedy. Entanglement purification and distribution of qubits are important steps for realizing quantum repeaters. Several schemes have been proposed to extract

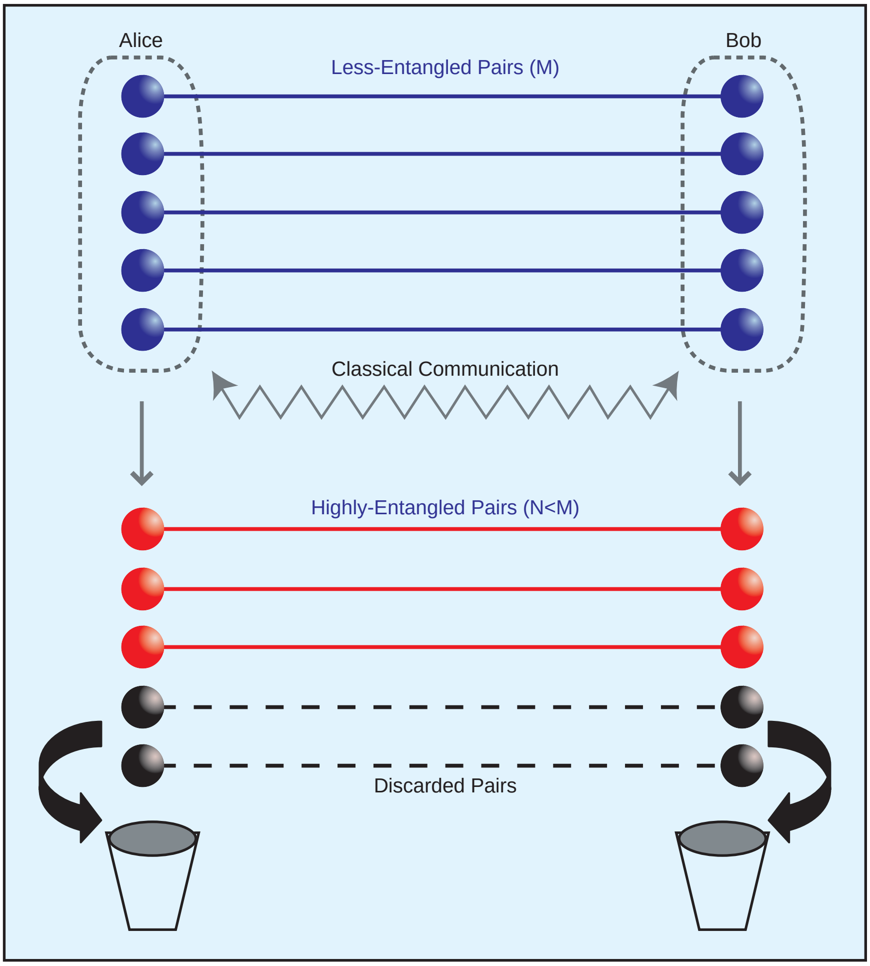

Figure 1 Extracting highly-entangled photon pairs from less- entangled pairs by local operation and classical communication (LOCC).

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photon pairs with higher degree of entanglement from less-entangled pairs by LOCC [10, 11] (see Fig. 1), and a number of experiments have been realized [12–14].

In photonic qubit transmission, the main source of decoherence is due to fluctuations which tends to be correlated within a short period, such as fluctuations in the birefringence of optical fiber and rotations of reference frame in free-space communications via satellite relay. This feature is fully utilized in Reference [13], which gives a highly practical version of entanglement purification. Recently, however, it became clear that we could go further, i.e., it is possible to construct simple and stable ways of faithful transmission of arbitrary qubit states [15, 16], which, of course, include the entanglement purification as a special case. In the following section, we review the basic principles of our schemes and highlight experimental results.

Extracting a Highly-Entangled Photon Pair from Two Less-Entangled Pairs

Here we show how Alice and Bob can extract a maximally entangled state (MES), $|\Phi\rangle \equiv (|H\rangle_a|H\rangle_b + |V\rangle_a|V\rangle_b)/\sqrt{2}$ from two partially entangled states $|\psi\rangle_{12} \equiv (\alpha|H\rangle_1|H\rangle_2 + \beta|V\rangle_1|V\rangle_2)$ and $|\psi\rangle_{34} \equiv (\alpha|H\rangle_3|H\rangle_4 + \beta|V\rangle_3|V\rangle_4)$ where α and β are complex numbers satisfying $|\alpha|^2 + |\beta|^2 = 1$ [10, 13]. Modes (1&3) and (2&4) belong to Alice and Bob, respectively (Fig. 2), and $|H\rangle$ and $|V\rangle$ represent horizontal and vertical polarization states. Note that the whole state $|\psi\rangle_{12} \otimes |\psi\rangle_{34}$ has a less-entangled part $\alpha^2|H\rangle_1|H\rangle_3|H\rangle_2|H\rangle_4 + \beta^2|V\rangle_1|V\rangle|V\rangle_2|V\rangle_4$ and a maximally entangled part $\alpha\beta(|H\rangle_1|V\rangle_3|H\rangle_2|V\rangle_4 + |V\rangle_1|H\rangle_3|V\rangle_2|H\rangle)_4$. Then the task is to discard the first part and extract a maximally entangled pair from the latter using LOCC.

With a quantum non-demolition (QND) measurement, it would be enough for Alice to count the number of V-polarized photons: If the outcome is one, she communicates the result to Bob and they keep the second part from which they can obtain $|\Phi\rangle$ by local unitary operations. However, QND measurement is technically challenging. Instead, Alice and Bob can perform quantum parity checking (QPC) (Fig. 3) using linear optics and destructive measurement with photon counters in our scheme (Fig. 2): (1) Alice rotates the polarization of the photon in mode 3 by $\pi/2$ using HWP_3 and then sends it to an input port of PBS_1. She sends the photon in mode 1 to the other input of PBS_1. This transforms the less-entangled part of the whole state into $\alpha^2|H\rangle_6|V\rangle_6|H\rangle_2|H\rangle_4 + \beta^2|V\rangle_5|H\rangle_5|V\rangle_2|V\rangle_4$, and the maximally entangled part into $\alpha\beta(|H\rangle_5|H\rangle_6|H\rangle_2|V\rangle_4 + |V\rangle_5|V\rangle_6|V\rangle_2|H\rangle)_4$. (2) The photons in modes 2 and 6 of the latter is in the form of $|\Phi\rangle$ which can

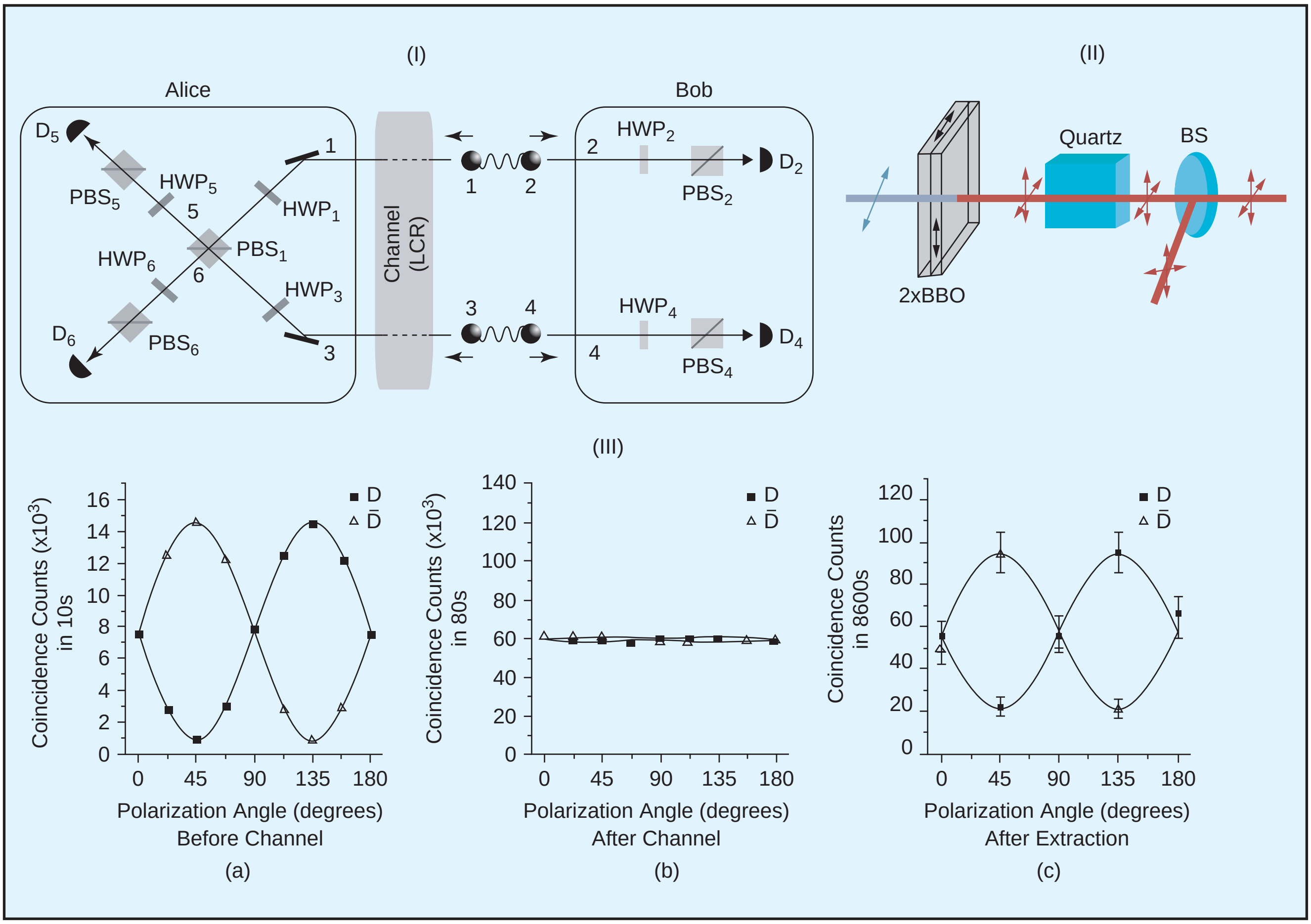

Figure 2 Implementation of a quantum parity check (QPC) [17] using polarizing beam splitters (PBS), polarization rotators (R) and photon detectors. In QPC, the incoming photons in modes 1 and 3 are mixed at the first PBS, and the output in mode 6 is accepted only for the cases in which one and only one photon is detected by the detectors placed after the second PBS. This may only happen if the two photons in modes 1 and 3 have opposite polarization (polarization of the photon in mode 3 is rotated by π/2)

be extracted by quantum parity checking on Alice's side, and by detecting the photons on the diagonal basis $\{|D\rangle_4, |\bar{D}\rangle_4\}$ where $|\mathrm{D}\rangle = (|\mathrm{H}\rangle + |\mathrm{V}\rangle)/\sqrt{2}$ and $|\bar{\mathrm{D}}\rangle = (|\mathrm{H}\rangle - |\mathrm{V}\rangle)/\sqrt{2}$ on Bob's side. (3) Alice and Bob communicate their results via classical communication channel, and perform local operations to obtain the MES $|\Phi\rangle$ in the modes 2 and 6. In QPC, Alice performs $\{|\mathrm{D}\rangle_5, |\bar{\mathrm{D}}\rangle_5\}$ measurement to preserve the coherence of $\alpha\beta(|\mathrm{H}\rangle_5|\mathrm{H}\rangle_6|\mathrm{H}\rangle_2|\mathrm{V}\rangle_4 + |\mathrm{V}\rangle_5|\mathrm{V}\rangle_6|\mathrm{V}\rangle_2|\mathrm{H}\rangle)_4$.

The method works equally well for channels with correlated phase fluctuations. In this scenario, Bob prepares the MES, $|\Phi\rangle_{12}$, and sends the photon in mode 1 through the channel which induces a time-varying random phase ϕ. Bob then prepares another MES, $|\Phi\rangle_{34}$, and launches the photon in mode 3 into the same channel within the correlation time of the phase fluctuations in order to ensure that both photons are affected with identical phase fluctuations. The state $|\Phi\rangle_{12} \otimes |\Phi\rangle_{34}$ after the channel becomes $(|\mathrm{HH}\rangle_{12} + e^{i\phi}|\mathrm{VV}\rangle_{12}) \otimes (|\mathrm{HH}\rangle_{34} + e^{i\phi}|\mathrm{VV}\rangle_{34})/2$. Since ϕ is unknown, the state of each pair is found by averaging over all possible phases which results in the mixed states $\rho_{12} = (|\mathrm{HH}\rangle_{12}\langle\mathrm{HH}| + |\mathrm{VV}\rangle_{12}\langle\mathrm{VV}|)/2$ and $\rho_{34} = (|\mathrm{HH}\rangle_{34}\langle\mathrm{HH}| + |\mathrm{VV}\rangle_{34}\langle\mathrm{VV}|)/2$. Each pair is no longer entangled. On the other hand, when both pairs are considered together there is still some entanglement in the whole state, which is a mixture of the separable states, $|\mathrm{HH}\rangle_{13}|\mathrm{HH}\rangle_{24}$ and $|\mathrm{VV}\rangle_{13}|\mathrm{VV}\rangle_{24}$, and the entangled part $e^{i\phi}(|\mathrm{HV}\rangle_{13}|\mathrm{HV}\rangle_{24} + |\mathrm{VH}\rangle_{13}|\mathrm{VH}\rangle_{24})$. From the entangled part, the desired state $|\Phi\rangle$ is extracted as described above.

In the experiments [13], we measured the correlations between the polarizations of photons in each pair separately, both before and after the phase fluctuations are induced in the channel, which was realized by a liquid crystal retarder (LCR). Polarization correlations were probed by two-fold coincidence measurements. For example, for the photon pair in modes 3 and 4, coincidence counts at detectors D_4 and D_5 were recorded for various angles of HWP_3 and HWP_4 while the photons in modes 1 and 2 were blocked and the HWP_5 was adjusted so that it does not rotate the polarization. The coherence between $|\mathrm{HH}\rangle_{34}$ and $|\mathrm{VV}\rangle_{34}$ was observed as an interference fringe in the count rate of D_4 when HWP_4 was rotated on the condition that a photon in $|\mathrm{D}\rangle$ (or $|\bar{\mathrm{D}}\rangle$) was detected by D_3. The visibility of the interference curve was 0.89 before the LCR was modulated (no phase fluctuation) implying the presence of highly entangled photon pairs (Fig. 2A). When the phase fluctuations are introduced by modulating the LCR, the visibility of the interference curve became less than 0.03, which is a sign of the loss of coherence (Fig. 2B). Using state tomography, we reconstructed the density matrix for the decohered pair and calculated the entanglement of formation to be very small $\sim$0.0018. Similar measurements were performed for the photon pair in modes 1 and 2. After the extraction process explained above, we performed four-fold coincidence measurements at detectors D_2, D_4, D_5 and D_6 in order to probe the polarization correlation of the photons in modes 2 and 6. The interference fringe showed a visibility of 0.63, which is above the classical limit of 0.5 and is a good sign of the presence of entanglement in the extracted pair (Fig. 2C). The lower bounds for the fidelity of the extracted entangled state to a MES and for its entanglement of formation are calculated as 0.78 ± 0.05 and 0.42 ± 0.12, respectively. The visibility of the interference curve and the amount of entanglement extracted in this experiment is limited mainly due to residual temporal and spatial mode mismatch between the photons belonging to different pairs [18, 19].

Faithful Transmission of Unknown Photonic Qubit

A conceptually similar method to that of the previous section can be employed for faithful transmission of an unknown photonic qubit with the help of an ancillary (reference) qubit prepared in a fixed state [15, 16]. The unknown photonic qubit may be stand-alone or a part of a multipartite entangled system. Suppose Alice wants to transmit an unknown photonic qubit (signal) in the state $|\varphi\rangle = \alpha|\mathrm{H}\rangle + \beta/\mathrm{V}\rangle$ through a noisy channel with correlated phase fluctuations. Alice prepares the ancillary qubit in the fixed state $|\mathrm{D}\rangle = (|\mathrm{H}\rangle + |\mathrm{V}\rangle)/\sqrt{2}$ and launches both the signal and reference qubits into the same channel one after another within the correlation time of the channel noise. The noisy channel will induce the phase shifts ϕ_H and ϕ_V on the photons in H- and V-polarization states, respectively. The two-photon state at Bob's side after the channels becomes an equal superposition of two terms: $e^{i2\phi_H}\alpha|\mathrm{HH}\rangle + e^{i2\phi_V}\beta|\mathrm{VV}\rangle$ and $e^{i(\phi_H+\phi_V)}(\alpha|\mathrm{VH}\rangle + \beta|\mathrm{HV}\rangle)$. Note that the latter is invariant with respect to phase fluctuations, and Bob can decode it into the desired state,

$\alpha|\mathrm{H}\rangle + \beta|\mathrm{V}\rangle$, by quantum parity checking (QPC) and post-selection.

The experimental scheme utilizes two interferometers, one on each side of Alice and Bob (Fig. 4A). Alice prepares two photons in H-polarization by type-I SPDC and sends them in two arms of the interferometer. The polarization of the photon launched into the short arm of the interferometer is rotated by $\pi/4$ to prepare the reference signal, and the photon in the long arm is used to prepare the unknown signal state by rotating its polarization with an HWP and adding a relative phase by an LCR. The time-delay between the two arms is Δt_A. The photons from both arms are combined at the $\mathrm{BS_A}$ and launched into the channel, which induces phase fluctuations (Fig. 4B). For decoding, Bob splits the photons from the channel into the short (Σ) and long (Λ) arms of an interferometer by the $\mathrm{BS_B}$ and then performs QPC (Fig. 2). The time delay between the two arms is Δt_B. The successful event occurs with a probability of 1/4 when the signal and reference photons go to the short and long arms of Bob's interferometer, respectively. In this case, the state before the QPC is the mixture of $e^{i2\phi_H}\alpha|\mathrm{HH}\rangle_{\mathrm{LS}} + e^{i2\phi_V}\beta|\mathrm{VV}\rangle_{\mathrm{LS}}$ and $e^{i(\phi_H+\phi_V)}(\alpha|\mathrm{VH}\rangle_{\mathrm{LS}} + \beta|\mathrm{HV}\rangle_{\mathrm{LS}})$, and the desired state $\alpha|\mathrm{H}\rangle + \beta|\mathrm{V}\rangle$ appears at mode-Y after the QPC. The successful events are post-selected by discriminating the arrival time delay of the photons between the detectors $\mathrm{D_X}$ and $\mathrm{D_Y}$ using the time resolving coincidence detection.

The coherence of the output state was probed by looking at the interference fringe of two-fold coincidence detection between the detectors $\mathrm{D_X}$ and $\mathrm{D_Y}$ while the optical delay Δt_B was varied for the signal state $|\mathrm{D}\rangle$ (Fig. 4). The full-width at half-maximum (FWHM) of the interference fringes, which corresponds to the coherence length of the photons, was 75 μm. This value is roughly 100 times larger than the photon wavelength implying robustness of the scheme against path-length mismatch or fluctuations up to order of many wavelengths. To verify the output, state tomography was performed by recording coincidence counts on four different settings of $\mathrm{HWP_Y}$ and $\mathrm{QWP_Y}$ within 100s for signal states prepared in $|\mathrm{H}\rangle$, $|\mathrm{V}\rangle$, $|\mathrm{D}\rangle$, and $|\mathrm{L}\rangle = (|\mathrm{H}\rangle + i|\mathrm{V}\rangle)/\sqrt{2}$. The fidelity of the extracted state for all of these inputs was calculated to be around 0.99 from the reconstructed density matrices of the corresponding output states. The overall extraction process can be interpreted as the preparation of a noiseless transmission channel with the help of a reference and quantum parity check. The fidelity of the effective channel prepared in the experiment to a noiseless one was calculated as 0.972 ± 0.022. This implies that the effective channel in the experiment is very close to a noiseless one.

Conclusion

A key pre-requisite for implementation of communication and computation protocols in a quantum network is the faithful node-to-node transmission of arbitrary qubit states among the distantly located participants. The transmission scheme in the quantum network should achieve faithful transmission equally well for all quantum states regardless of whether they are known, unknown or entangled to other states in the network, and should allow easy connectivity to the network nodes without the need for stabilization and calibration tasks among distantly located users.

In this letter, we reviewed two experiments which are designed to overcome decoherence to provide faithful transmission in long distance quantum communication networks. In the first experiment, we have shown that a highly entangled pair can be extracted from two identically decohered pairs. In the second one, we demonstrate that to protect a photonic qubit against channel noise, it is enough to send a photon in a fixed known state within the correlation time of the noise. Both experiments utilize collective operation on two photons using quantum parity checking which is an important building block of quantum information processing with linear optics. The first scheme gives a practical way of entanglement distribution over realistic channels with phase noise. The second scheme enjoys the unique advantage

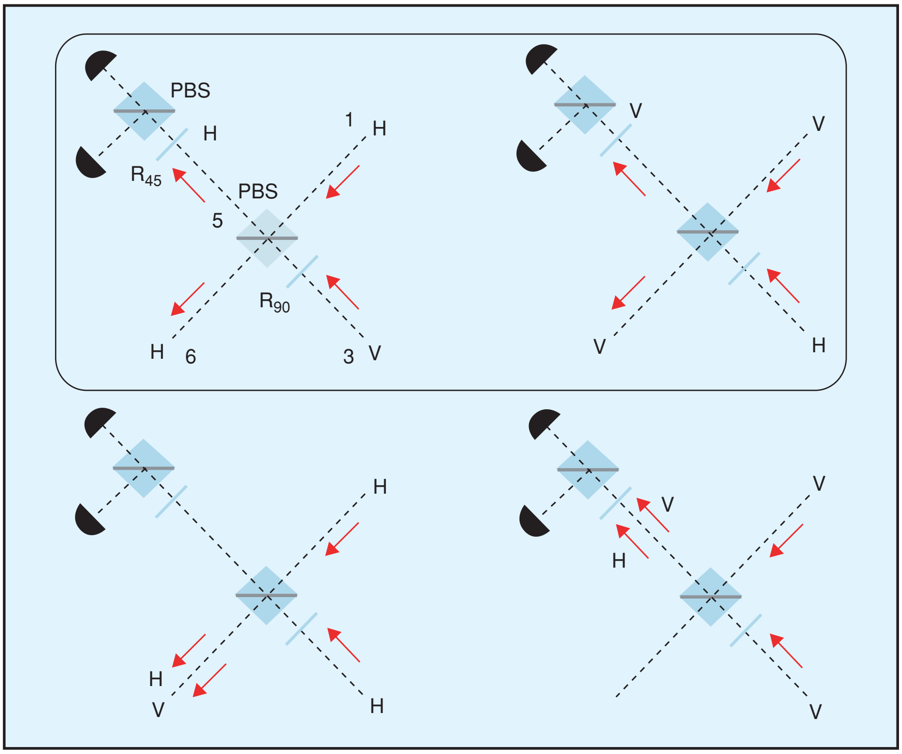

Figure 3 (I) Schematic diagram of the experimental setup for entanglement extraction from two identically decohered photon pairs. The channel realized by a liquid crystal retarder (LCR) is a phase damping channel, which gives identical phase fluctuations to photons in mode 1 and 3. (II) Polarization-entangled photon-pair source using spontaneous parametric down-conversion (SPDC) from two adjacent Type I phase matched β-barium borate (BBO) crystals in collinear configuration. The pump beam is obtained from a frequency doubled mode-locked Ti:sapphire laser (wavelength: 790nm, pulse width: 80fs, repetition rate: 82MHz). (III) Results of interference experiments.

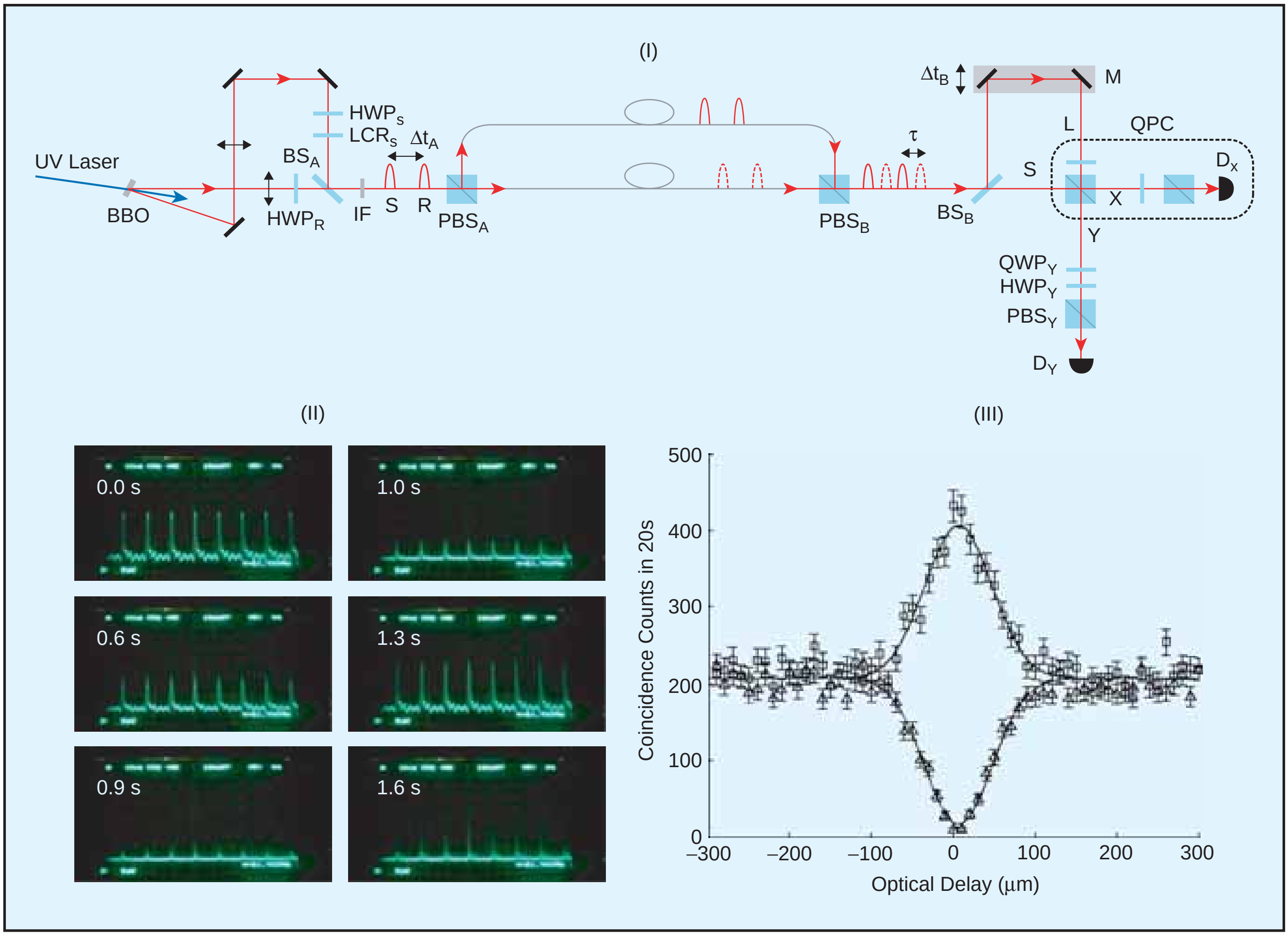

Figure 4 (I) Experimental setup for faithful photonic qubit transmission. (II) oscilloscope traces showing phase fluctuations in the transmission channel. (III) observed two-photon interference fringes after quantum parity checking.

of being robust against path-length mismatches among the network nodes and relaxes the strict requirements of phase stabilization in long-distance quantum communication. These results open up an exciting possibility and shed light on realistic long distance quantum communication.

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