Quantum Teleportation over 100 km of Fiber using MoSi Superconducting Nanowire Single-Photon Detectors

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Abstract: Using high-efficiency superconducting nanowire single-photon detectors based on MoSi, we successfully achieved quantum teleportation of weak coherent states over 100 km of fiber with an average fidelity of $82.9 \pm 1.7\%$ for six distinct input states.

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Quantum teleportation is an essential component of scalable quantum communications based on quantum repeaters. Several long-distance quantum teleportation experiments over >100 km have already been reported using free-space transmission channels [1,2]. However, the number of reports of quantum teleportation over optical fiber has been relatively limited [3,4], mainly because multi-fold coincidence detection has been difficult due to the relatively low detection efficiency (DE) of typical telecom-band single-photon detectors. So far, the record distance of quantum teleportation over fiber is 25 km [4]. Here we report efficient quantum teleportation over optical fiber using four high DE (80-86%) MoSi superconducting nanowire single photon detectors (SNSPDs) [5]. These detectors enabled highly efficient multi-photon coincidence measurements, allowing us to confirm that quantum states of attenuated laser light were successfully teleported over 100 km of fiber.

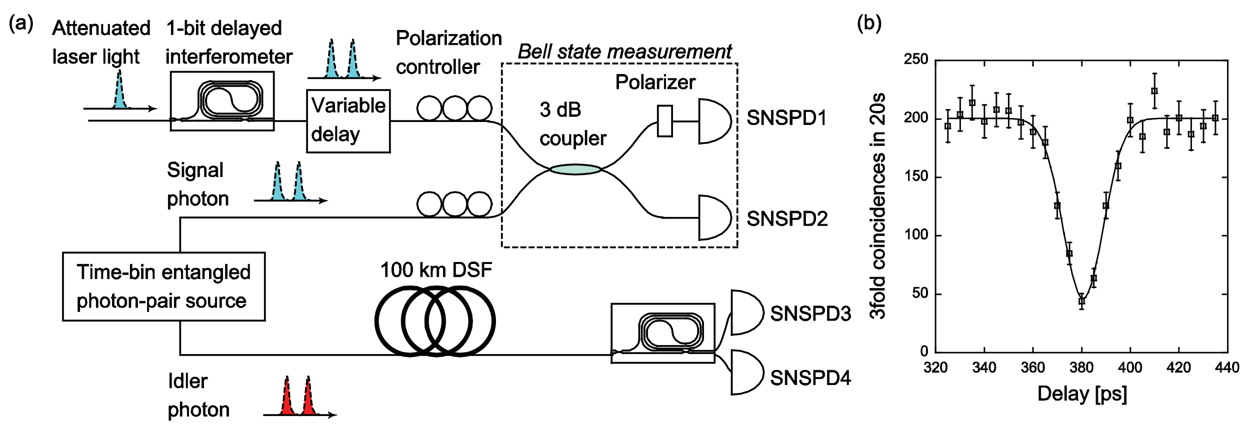

Fig. 1: (a) Experimental setup (b) Hong-Ou-Mandel (HOM) measurement result.

Figure 1 (a) shows the experimental setup. A pulsed, entangled photon pair source based on spontaneous parametric downconversion (SPDC) in a periodically-poled lithium niobate (PPLN) waveguide generates time-bin entangled photon pairs whose wavelengths are 1546.2 and 1555.8 nm for signal and idler channels, respectively. The bandwidth of signal and idler photons was reduced to 20 GHz using narrowband filters, to suppress the temporal waveform broadening caused by higher-order dispersion in fiber. A portion of the coherent pulses from the mode-locked laser, which is used to generate pump pulses for the SPDC via second harmonic generation in another PPLN waveguide, is spectrally filtered to generate a coherent pulse whose wavelength and bandwidth match those of the signal photon. The filtered coherent pulses are then attenuated and input into a 1-bit delayed Mach-Zehnder interferometer to generate a time-bin qubit used as an input photon. The input and signal photons are passed through polarization controllers and launched into a 3-dB coupler followed by SNSPD1 and 2. Here, the temporal distinguishability between the two qubits is erased by adjusting the temporal position of the input photon using a variable delay line, while the polarization distinguishability is eliminated by placing a polarizer in front of SNSPD1 and adjusting the polarization state of the two photons to maximize the count rate at SNSPD1. We can project the two photons into the singlet state by conditioning on events where both SNSPD1 and 2 detect photons, but in different time slots [3]. The idler photon from the entangled photon-pair source is transmitted through 102-km of dispersion shifted fiber (DSF) and received by another 1-bit delayed interferometer whose two output ports are connected to SNSPD3 and 4. By conditioning the detection events at SNSPD3 or 4 on the successful projection to singlet state, we can teleport the quantum state of the input photon to that of the idler photon with pre-determined unitary transformation. The average photon number per pulse for the entangled photon pairs and the attenuated coherent state was set at 0.016. The DEs were ~80% for SNSPD1 and 4 and ~86% for SNSPD2 and 3. The background count rate on each SNSPD was ~100 Hz.

To confirm the indistinguishability of input and signal photons, we eliminated the 1-bit delayed interferometers and the 100 km DSF from the setup and performed Hong-Ou-Mandel (HOM) interference between the attenuated laser light and the heralded single photons [6]. The result is shown in Fig. 1 (b). We observed a clear HOM dip with a visibility of $76.9 \pm 3.4\%$, which significantly exceeds the classical limit of HOM visibility (50%).

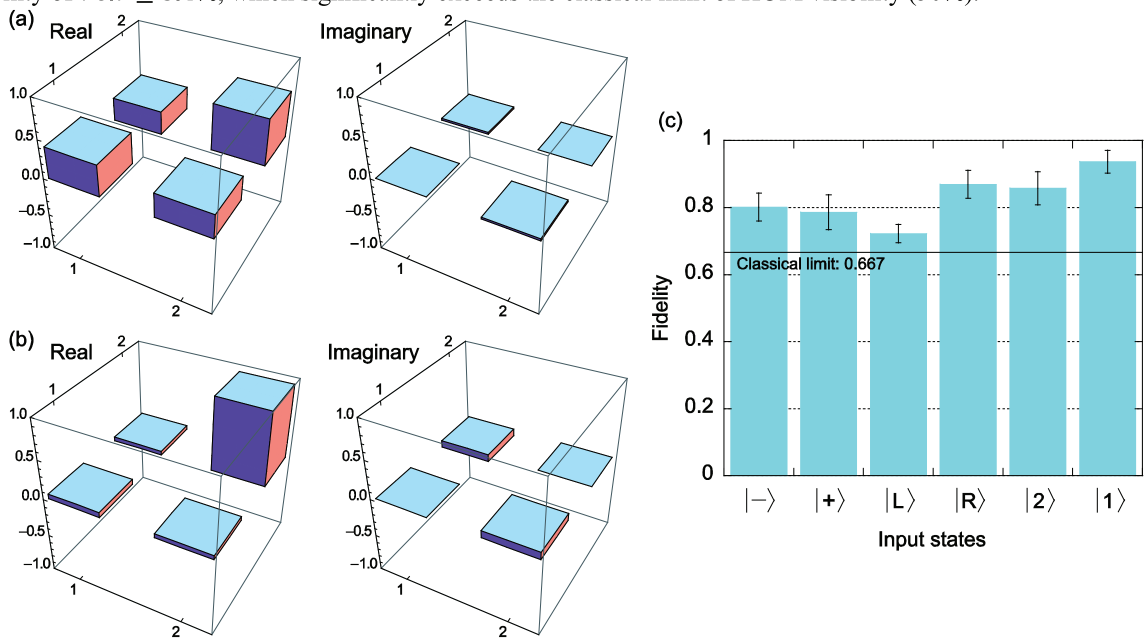

Fig. 2: Examples of density matrices reconstructed by quantum state tomography for target states (a) $|+\rangle$ and (b) $|2\rangle$. (c) Experimentally-obtained fidelities for 6 distinct input states

We then performed quantum teleportation over 100 km of DSF for six input states. We prepared the states $|\pm\rangle = (|1\rangle \pm |2\rangle)/\sqrt{2}$, $|L\rangle = (|1\rangle + i|2\rangle)/\sqrt{2}$, and $|R\rangle = (|1\rangle - i|2\rangle)/\sqrt{2}$ by changing the phase of the delayed interferometer for the state preparation, while $|1\rangle$ and $|2\rangle$ were generated by eliminating the interferometer for input state preparation and adjusting the temporal position of the attenuated laser pulse with the variable delay line. We performed the quantum state tomography (QST) [7] on the teleported state to obtain the density matrices. We performed four projection measurements of the idler photons onto states $|\pm\rangle$, $|L\rangle$ and $|1\rangle$. Since we could simultaneously implement two measurement bases with a delayed interferometer followed by two detectors [3], we did the four projections with only two measurements, with the idler interferometer phase set at 0 and $\pi/2$. The acquisition time for each measurement was 6000 s, so the total QST measurement time for each input state was 12000 s. The average number of 3-fold coincidences for each basis was ~170. The reconstructed density matrices for the target states $|+\rangle$and $|2\rangle$ are shown in Fig. 2 (a) and (b), respectively. We did not subtract any accidental coincidences or background counts. We also performed maximum likelihood estimation to obtain physically legitimate matrices [7]. Using the reconstructed density matrices, we calculated the fidelity for each input state. Results are shown in Fig. 2 (c). We obtained an average fidelity of $82.9 \pm 1.7\%$ for the six distinct input states, and observed a clear violation of the classical limit (66.7%) by at least 2 standard deviations for each of the six states. Thus, we confirmed the successful teleportation of the quantum states of telecom-band photons over 100 km of fiber.

References

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