Wavelength-Multiplexed Entanglement Distribution over 10 km of Fiber

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Abstract

We report the first experimental demonstration of wavelength-multiplexed entanglement distribution. 44 channels of highly-entangled photon-pairs from one single broadband source are distributed over 10 km of fiber.

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Introduction

In future quantum communication applications such as multi-party quantum cryptography [1], quantum secret sharing [2] and distributed quantum computing [3], application users are required to share and consume quantum entanglement as a resource. However, the total amount of shared entanglement cannot be increased via local operations and classical communications (LOCC) [4], and so sharing of entanglement among distantly located users must definitely involve some form of entanglement distribution.

Recently, we have presented the concept of a *local-area entanglement distribution fiber network* [5], in which a centrally located service provider produces highly-entangled photon-pairs via spontaneous parametric down-conversion (SPDC), and distributes these photon-pairs over fiber-optic transmission lines to application users. Experimental progress along this direction includes realizations of high quality telecom-band entangled photon-pair sources [6-10], and demonstrations of entanglement distribution over 100 km of optical fiber [11-14]. However, most of the entangled photon-pair sources demonstrated to date have exhibited a relatively narrow bandwidth as compared to the available transmission bandwidth. To fully utilize the transmission bandwidth of optical fiber, a service provider would have to wavelength-multiplex many such narrowband sources before transmission, and this is not cost-effective.

In another recent paper [15], we have proposed and demonstrated experimentally a *single* broadband source that is well-suited for multi-channel wavelength-multiplexed entanglement distribution. The idea is to employ a 1-mm-long periodically-poled lithium niobate (PPLN) waveguide operating near degeneracy wavelength for SPDC. A simple calculation reveals that the SPDC bandwidth of such a short waveguide could cover hundreds of nm and therefore it is a promising candidate as an ultra-broadband source of entangled photon-pairs. In this work, we demonstrate wavelength-multiplexed entanglement distribution for the first time using the proposed source. Forty-four wavelength channels of highly-entangled photon-pairs are produced from a single source and distributed over 10 km of fiber.
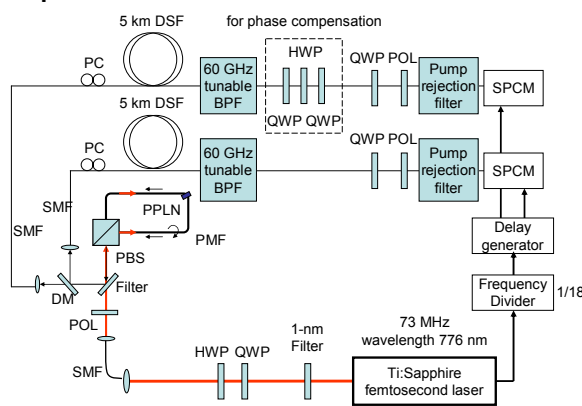
Experiment

Figure 1: Experimental setup. BPF: band-pass filter, DM: dichroic mirror, DSF: dispersion-shifted fiber, HWP: half-wave plate, PBS: polarization beam-splitter, PC: polarization-controller, PMF: polarization-maintaining fiber, POL: polarizer, PPLN: periodically-poled lithium niobate waveguide, QWP: quarter-wave plate, SMF: single-mode fiber, SPCM: single-photon counter module.

Figure 1 shows the experimental setup. The source consists of a 1-mm-long MgO-doped type-0 quasi-phase-matched PPLN waveguide (HC Photonics) placed at the center of a polarization-diversity loop. For a description on the principle of this source, see [10]. The pump laser is a Ti:Sapphire femtosecond laser operating at 776 nm. A 1-nm-bandwidth filter reduces the pump spectral width to about 1 nm. This improves the quality of the output entangled photon-pairs significantly [15]. The photon-pairs produced are entangled in polarization and can be described by $\left|H\right\rangle_s\left|H\right\rangle_i + e^{i\theta}\left|V\right\rangle_s\left|V\right\rangle_i$, where H and V denote horizontal and vertical polarizations, respectively. The subscripts s and i denote signal and idler, respectively, and θ is an unknown but constant phase.
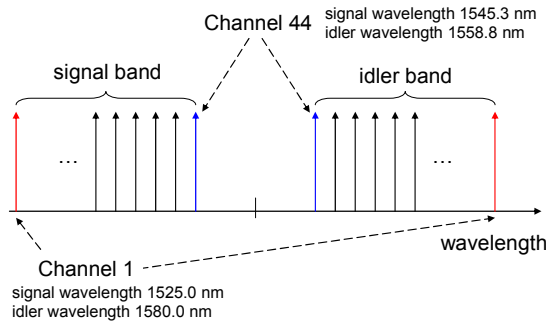
Figure 2: Each channel consists of a signal channel and an idler channel. Channel 1's signal wavelength is 1525.0 nm and channel spacing is 60 GHz.

A dichroic mirror (DM) separates signal and idler photons into two bands, as shown in Fig. 2. Both bands are then sent over 5-km-long dispersion-shifted fibers (DSFs). For wavelength-demultiplexing, we have used a pair of band-pass filters (BPFs, Optoquest) having 60 GHz passband and tunable from 1520 to 1580 nm. In a practical system, arrayed waveguide gratings (AWGs) should be used. Density matrices of the demultiplexed photon-pairs are obtained by quantum state tomography [16]. More details of this experiment can be found in [10].

Although our source can operate without temperature control, we have used a thermo-electric controller to set the waveguide temperature to 20.0 degree Celsius for enhanced stability in this experiment. Two quarter-wave plates (QWPs) and a half-wave plate (HWP) are placed immediately after the BPF of the signal channel for compensating the unknown phase.
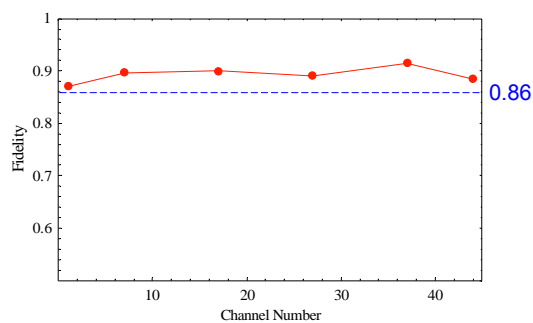
Results and Discussion

Figure 3: Experimental result showing fidelity of distributed entangled photons for selected channels.

Figure 3 shows experimental results. The entanglement fidelities calculated from reconstructed density matrices remain higher than 0.86 for all the selected channels. This shows that the photon-pairs had been successfully distributed. Observed numbers of coincidence counts in 100 seconds (for HH setting) range from 170 at Channel 1 to 250 at Channel 44. Because of randomly varying birefringence of the transmission fiber, we had to use a monitoring laser and polarization controllers to compensate for the polarization drift every few minutes. Polarization

stabilization methods such as those demonstrated in [17, 18] should be incorporated in a practical system. We have also found that θ is wavelength dependent, and so the rotation angle of the HWP must be optimized for every wavelength channel to set θ to 0. The reason for this characteristic is not understood yet, but we suspect that it is due to polarization-mode dispersion (PMD) of the transmission fiber. Nevertheless, as the compensation can be done after demultiplexing, it does not pose a fundamental problem. It should also be mentioned that the source in our experiment was optimized for one channel and left untouched during all subsequent measurements.

Conclusion

In conclusion, we have successfully demonstrated wavelength-multiplexed entanglement distribution over optical fiber using a broadband source of polarization-entangled photon-pairs in the telecom-band. The distribution distance can be extended by replacing the InGaAs single-photon detector modules with super-conducting single-photon detectors [19].

Acknowledgment

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