Broadband Source of Polarization-Entangled Photon-Pairs Suitable for Multi-Channel Wavelength-Multiplexed Entanglement Distribution

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Abstract

We demonstrate a broadband source of polarization-entangled photon-pairs suitable for wavelength-multiplexed entanglement distribution over fiber. We show that this source could support up to 44 wavelength channels.

Introduction

It is expected that in future quantum communication applications such as multi-party quantum cryptography [1] and distributed quantum computing [2], application users would need to share and consume quantum entanglement as a resource [3]. However, as entanglement cannot be created by local operations and classical communications (LOCC) [4], it must be physically distributed to users for sharing. While long-distance entanglement distribution is still far from reach due to the difficulty of implementing quantum repeaters [5,6], the concept of a *local-area quantum network*, which involves the generation of entangled photon-pairs via spontaneous parametric down-conversion (SPDC) at a centrally-located service provider, followed by their distribution over optical fiber to application users, seems realizable in the near future.

There have already been several proposals on telecom-band entangled photon-pair sources based on SPDC [7-12] and recently, a few groups have reported entanglement distribution over 100 km of optical fiber, utilizing either polarization-entangled or time-bin-entangled photon-pairs [13-16]. However, most of the sources demonstrated to date have exhibited a relatively narrow bandwidth as compared to the available transmission bandwidth of optical fiber. For fiber-based sources, the bandwidth is seriously limited by spontaneous Raman scattering [17], while sources based on quasi-phase-matched (QPM) crystals or waveguides are usually narrow-band due to long crystal or waveguide lengths and/or operation far from the degeneracy wavelength [10,11].

With narrow-band sources, a service provider would have to wavelength-multiplex a large number of entangled photon-pair sources before transmission in order to fully utilize the available transmission bandwidth, and this is not cost-effective. The concept of a *single* broadband source suitable for wavelength-multiplexed entanglement distribution has not been pursued so far. It is obvious that this source must produce highly-entangled photon-pairs for all wavelength channels *simultaneously*. We emphasize here that this condition is not necessarily satisfied for existing entangled photon-pair sources. For wavelength-demultiplexing, arrayed waveguide gratings (AWGs) can be used, as in conventional wavelength-division-multiplexed (WDM) systems [18]. Figure 1 shows our concept of wavelength-multiplexed entanglement distribution.

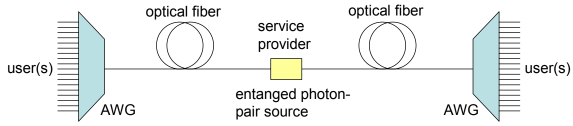

Figure 1: Concept of wavelength-multiplexed entanglement distribution over optical fiber, using a single broadband source of entangled photon-pairs at the service provider. AWG: arrayed waveguide grating.

In this work, we demonstrate for the first time a telecom-band entangled-photon source that is suitable for wavelength-multiplexed entanglement distribution. Our source is specifically based on a very short Type-0 MgO-doped periodically-poled lithium niobate (PPLN) waveguide operating near degeneracy and so it has a very broad SPDC bandwidth. We show that our source is potentially capable of simultaneously supporting up to forty-four independent wavelength channels.

Experiment

Figure 2 shows the experimental setup. The source is based on a 1-mm-long Type-0 MgO-doped PPLN waveguide (HC Photonics) placed at the center of a polarization-diversity loop without temperature control. The polarization-maintaining fiber that forms the polarization diversity loop has a 90-degree-twist so that the same polarization-mode of the PPLN

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waveguide is pumped bi-directionally. The photon-pairs that are produced within the waveguide via SPDC then automatically combine at the polarization beam-splitter resulting in a polarization-entangled state, denoted by $|H\rangle_s|H\rangle_i + e^{i\theta}|V\rangle_s|V\rangle_i$, where the subscripts *s* and *i* denote *signal* and *idler*, respectively, and *H* and *V* denote horizontal and vertical polarization, respectively. θ is an unknown but constant phase, which we compensate using a half-wave plate (HWP) before detection in order to obtain the desired maximally-entangled state $|\Phi^+\rangle \equiv |H\rangle_s|H\rangle_i + |V\rangle_s|V\rangle_i$. It should be noted that the polarization beam-splitter used in this experiment is a custom-made dual-band device that operates at both the pump wavelength and the telecom-band.

Since a single pump photon is split into a pair of telecom-band photons (signal and idler) in the SPDC process, energy conservation requires that the signal and idler be correlated in their wavelengths. We can therefore simply use a dichroic mirror (optically coated for operation from 1500 nm to 1585 nm) with a dividing wavelength at 1550 nm to separate the signal and idler photons. A more detailed description of this source can be found in [19].

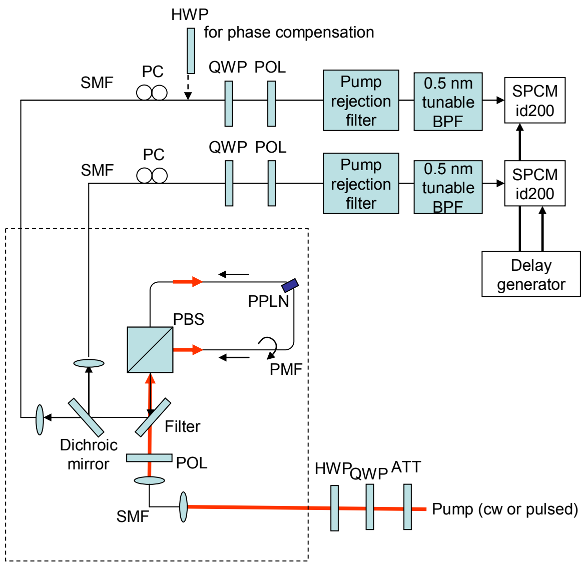

Figure 2: Experimental setup. ATT: attenuator, BPF: band-pass filter, HWP: half-wave plate, PBS: polarization beam-splitter, PC: polarization-controller, PMF: polarization-maintaining fiber, POL: polarizer, QWP: quarter-wave plate, SMF: single-mode fiber, SPCM: single-photon counter module.

The quarter-wave plates and polarizers placed before the two peltier-cooled InGaAs single-photon detectors (id Quantique), as shown in the figure, are used to realize the sixteen polarization-settings needed for quantum state tomography. The single-photon detectors were gated at 4.06 MHz and the gating widths were 2.5 ns. A 10 μs deadtime was also imposed to reduce after-pulses. For reconstruction of the density matrix, we have employed the maximum likelihood method outlined in [20]. Once we have obtained the density matrix, ρ, we can calculate the state purity from $\mathrm{Tr}(\rho^2)$ and the entanglement fidelity from $F(\rho) = \langle\Phi^+|\rho|\Phi^+\rangle$.

In order for the source to be suitable as a wavelength-multiplexed source, entanglement fidelity of the generated photon-pairs must be sufficiently high across the wavelength range of interest. Using two band-pass filters having 60 GHz pass-band and tunable from 1525 to 1580 nm, we can effectively wavelength-demultiplex the generated photon-pairs and measure the entanglement fidelity for the independent wavelength channels. For convenience, we fix Channel 1's signal wavelength to 1525.0 nm. It is then simple to obtain the wavelengths of the other channels since adjacent channels are separated by 60 GHz. Idler wavelengths can be found from energy conservation law as pump wavelength is known.

Results

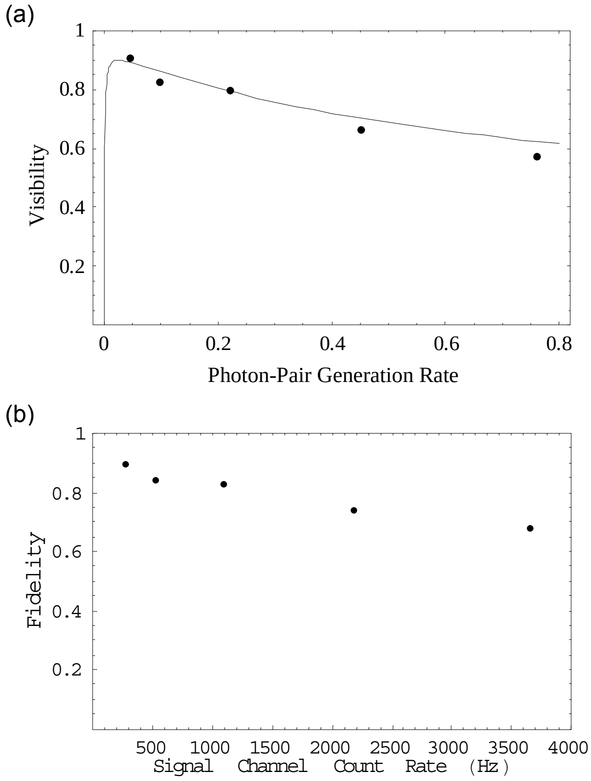

Figure 3: Experimental results for Channel 27. (a) Two-photon interference fringe visibility vs photon-pair generation rate (in units of per pump pulse). The theoretical curve assumes a thermal photon-pair number distribution. (b) Entanglement fidelity vs single-channel count rate. The fidelity is degraded due to emission of multiple-pairs.

First we look at the dependence of entanglement quality on photon-pair generation rate (in unit of *per pump pulse*) and single channel count rate (in unit of per second) when the pump is obtained from a Ti:Sapphire femtosecond laser. Pump pulse width is estimated to be 300 fs. Figure 3 shows data taken for Channel 27 (signal and idler wavelengths are 1537.2 nm and 1567.1 nm, respectively) with a measurement time of 100 seconds for each data point and without subtracting accidental coincidences. As shown in Fig. 3, both the two-photon interference fringe visibility (average value calculated from HH, HV, VH and VV coincidence count rates) and the entanglement fidelity (obtained from reconstructed density matrices) decrease with increasing pump power. This is due to the emission of multiple-pairs which becomes significant at higher pump powers, and this degrades the entanglement quality [19]. For the theoretical curve shown in Fig. 3 (a), we have assumed a thermal distribution of photon-pair number.

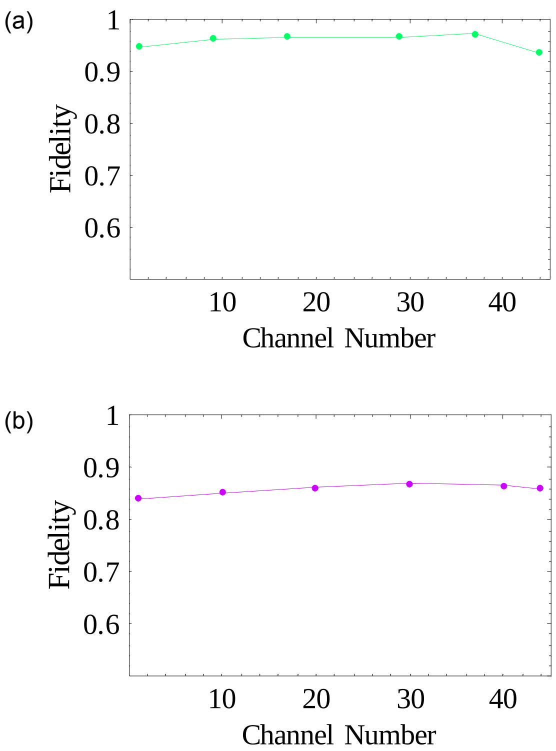

Figure 4: Entanglement fidelity calculated from reconstructed density matrices for selected channels, for (a) cw pumping (center wavelength of the pump is at 775 nm) and (b) pulse pumping (center wavelength of the pump is at 776 nm).

We next compare pulsed and continuous-wave (cw) pumping across the wavelength range of interest. The cw pump is obtained from an external cavity laser and has a wavelength of 775 nm. Figure 4 shows experimental results for selected channels. The source was optimized for one channel and left untouched during measurement of other channels. Our experimental result shows that the entanglement fidelity does not differ much across the wavelength range of interest for both CW pumping (See Fig. 4(a)) and pulse pumping (See Fig. 4(b)). The slight drop in entanglement fidelity observed at Channel 44 is due to slightly higher loss of the dichroic mirror at that wavelength. We also found that for comparable level of coincidence count rates, cw pumping gives much higher entanglement fidelity than pulse pumping.

Discussion

This above result can be understood as follows. The pulsed pump's spectrum is 3 nm, which is much broader than the wavelength demultiplexing filter bandwidth, and this causes a significant fraction of the photon-pairs produced by the broadband pump being filtered by the narrow-band filters into uncorrelated photons. This leads to an increase in the number of accidental coincidence counts and in turn degrades the entanglement fidelity. In contrast, a cw pump does not have this problem. However, it should be noted that in general, pulse pumping is preferred over cw pumping in a practical system because it is easier to synchronize timing for pulse pumping. Our result suggests that the quality of the entangled photon-pairs in our setup could be improved by using wavelength-demultiplexing filters having a broader bandwidth (but this reduces the total number of channels) or by using a narrow-band pulsed laser instead for pumping.

As for the operating bandwidth of the source, we are currently limited by the tunability of the narrowband wavelength-demultiplexing filters. A second limitation would be the optical coating of the dual-band polarization-beam-splitter and the dichroic mirror. Nevertheless, we have proven that the concept of a single broadband source suitable for multiple-channel wavelength-multiplexed entanglement distribution is indeed a feasible one.

Conclusion

In conclusion, we have demonstrated for the first time a broadband source of polarization-entangled photon-pairs in the telecom-band that is well-suited for multi-channel wavelength-multiplexed entanglement distribution over optical fiber. By using a pair of tunable wavelength-demultiplexing filters with a 60 GHz pass-band, we have shown that the proposed source is potentially capable of simultaneously supporting up to forty-four independent wavelength channels. Further improvement to the current setup is possible, and we expect the proposed source to play an important role in future quantum communication fiber networks.

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Acknowledgment

H. C. Lim was on a postgraduate scholarship awarded by DSO National Laboratories in Singapore.

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