Bright, Waveguide-based Entanglement Sources for High-rate Quantum Networking

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Abstract: We designed and built two polarization entanglement sources optimized for high-rate quantum networking under pump power constraints. We demonstrated entanglement swapping between the sources.

1. Introduction

Quantum networks use distributed entanglement to achieve enhanced application performance compared to classical analogues. Entanglement swapping is a tool to increase the rate and range of entanglement distribution in multi-span quantum networks. High-fidelity entanglement swapping requires the interacting photons to be indistinguishable in all but the entanglement degree of freedom. The most challenging aspect of this requirement, especially when satellite links are involved, is the need for temporal indistinguishability, i.e., synchronized photon arrivals, at the Bell state measurement (BSM) device. A simple synchronization approach using a forwarded pump signal was recently proposed [1] and demonstrated [2]. To test this approach and other free-space quantum networking concepts, we built two entangled photon pair sources that were designed to output photon pairs with high spectral purity and also to generate a high flux of pairs under the pump power constraints of the forwarded-pump approach. Here, we describe the sources, their feasibility for the forwarded-pump approach, and their use in a tabletop demonstration of entanglement swapping.

2. Bright, waveguide-based entanglement sources

Each entanglement source was based on type-II spontaneous parametric downconversion (SPDC) in a 20-mm-long periodically poled $KTiOPO_4$ (PPKTP) waveguide. PPKTP was selected for the combination of its relatively high nonlinearity and the availability of the group-velocity matching (GVM) condition near the telecom C- and L-bands for type-II phase-matching, enabling spectrally pure photon pairs by matching the pump and phase-matching bandwidths. The waveguide length was chosen to be as long as possible under the constraints of the fabrication process (waveguide design and fabrication was done by AdvR, Inc.), and the corresponding pump pulse duration to achieve spectrally pure photon pairs was $\sim$1–2 ps. The poling periods were uniform, and the phase-matching was designed to convert pump photons around 775 nm to orthogonally polarized, slightly nondegenerate signal and idler photons with wavelengths approximately 7 nm below and above the degenerate wavelength of 1550 nm. The end facets were anti-reflection coated for both the pump and downconversion wavelength bands. To produce polarization-entangled photon pairs, each waveguide was placed in a Sagnac configuration, with bidirectional pumping and collection [3]. Most significantly, waveguides were chosen instead of bulk crystals because SPDC in waveguides can be orders of magnitude more efficient than in bulk crystals, and this was important for the forwarded-pump synchronization approach [2].

The forwarded-pump approach used an erbium-doped fiber amplifier (EDFA) to optically amplify 1550-nm-band pulses, followed by second harmonic generation (SHG) in a periodically poled $LiNO_3$ (PPLN) waveguide to convert the 1550-nm pulses to 775-nm pulses, which then pumped the PPKTP waveguide to produce SPDC. The 775-nm pulses required sufficient power to generate photon pairs at the desired rate (we targeted an average pair generation probability between 1–2% per pulse, and we operated at a 1 GHz pulse repetition rate). The 775-nm pulses were also required to be transform-limited to produce spectrally pure SPDC and have low timing jitter to enable photon synchronization at a BSM; these requirements limited the EDFA gain, since high peak powers can cause pulse distortions due to nonlinearities in fibers. The SHG waveguide needed to have sufficient bandwidth for the pulses, which limited the waveguide length and thus also the SHG efficiency. As a result, the achievable pump power at 775-nm was limited, and this motivated the decision to use waveguides for SPDC. The maximum available power at 775 nm, after fiber

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coupling losses, was 90 mW. The achieved entanglement source brightnesses were 2.8×10^6 pair/s/mW for Source 1 and 4.6×10^5 pairs/s/mW for Source 2; the difference in brightness is attributed to differences in coupling to each waveguide.

3. Interference and entanglement swapping between waveguide-based entanglement sources

Despite recent advances in PPKTP waveguide fabrication, it is currently still a challenge to produce identical waveguides on separate chips. We characterized multiple waveguides on multiple PPKTP chips to select waveguides that produced spectrally overlapping signal photons when pumped by the same 775-nm pulses, as shown in Fig. 1(a). Using only coarse, 10-nm-wide bandpass filters (BPFs) and applying linear polarizers to the signals and idlers, we achieved 75% Hong-Ou-Mandel (HOM) interference visibility between signal photons from different waveguide chips, as shown in Fig. 1(b).

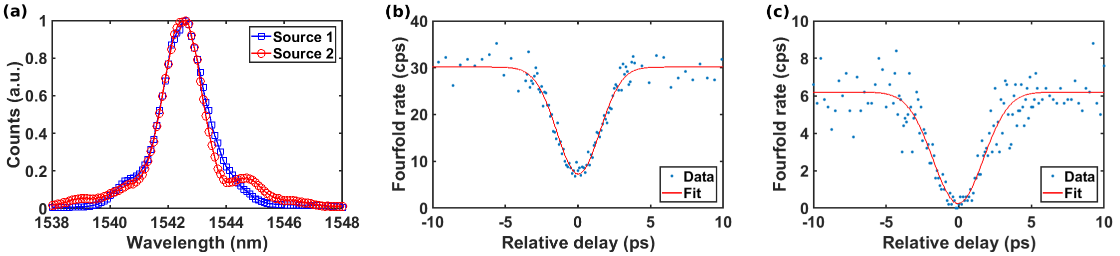

Fig. 1. (a) Spectra of signal photons from different PPKTP waveguides pumped by the same 775-nm pulses. (b) HOM interference between signal photons from different PPKTP waveguides, using only 10-nm BPFs. (c) HOM interference between signal photons from different PPKTP waveguides, adding 2-nm BPFs.

We added 2-nm-wide BPFs to all the signal and idler photons to improve both the HOM visibility and the entangled state quality of each source. With the 2-nm BPFs and linear polarizers applied to all photons, the HOM visibility increased to 96%, shown in Fig. 1(c). Adding the 2-nm BPFs also improved the entangled state fidelity to the Bell state $|\Psi^-\rangle = (|HV\rangle - |VH\rangle)/\sqrt{2}$ from 90.8% to 96.5% for Source 2 and from 77.3% to 93.1% for Source 1. These improvements enabled entanglement swapping between the two sources. In the entanglement swap, the signal photons were projected onto the $|\Psi^-\rangle$ Bell state. The resulting entangled state of the idler photons had 90.2% fidelity to the $|\Psi^-\rangle$ Bell state. Fig. 2 shows polarization correlations measured in multiple bases before and after the entanglement swap.

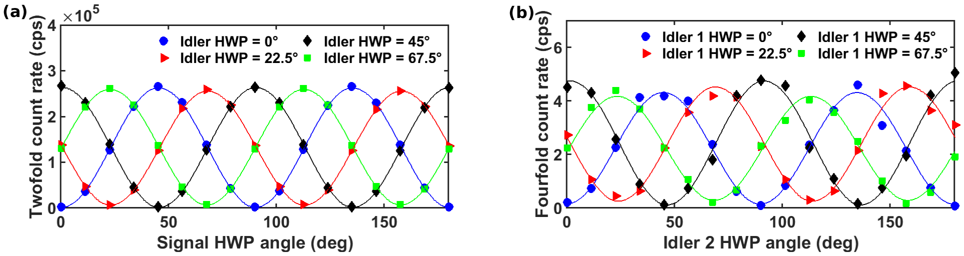

Fig. 2. (a) Polarization correlations of Source 2 before entanglement swap. HWP = Half-wave plate. (b) Polarization correlations between idler photons after entanglement swap.

In summary, we have designed and built two bright polarization entangled photon pair sources based on PPKTP waveguides. Waveguides were specifically chosen to be compatible with the pump-forwarding synchronziation approach. We have demonstrated HOM interference and entanglement swapping between the two waveguide-based sources, indicating their feasibility for future tests of high-rate quantum networking.

References

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