Generation of Polarization-Entangled Photons in a Standard Polarization-Maintaining Fiber

V. O. Lorenz, Bin Fang, Offir Cohen

Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA

Present address: Joint Quantum Institute, National Institute of Standards and Technology & University of Maryland, Gaithersburg, MD 20849

E-mail: vlorenz@udel.edu

Abstract. We demonstrate the capability of standard, commercially available polarization-maintaining fibers (PMFs) to generate polarization-entangled photon-pairs by inserting a PMF source into a Sagnac interferometer. We perform a quantum state tomography to reconstruct the density matrix, yielding, without background subtraction or spectral filtering, a polarization-entangled photon-pair state with \(92.37 \pm 0.14\%\) fidelity to the maximally entangled Bell state. With its high coupling efficiency into SMFs and ability to produce spectrally uncorrelated photons, we expect this source to be useful for free-space and fiber-based quantum information protocols.

1. Introduction

Entangled photon pairs are an important resource for many applications such as quantum communication protocols [1], quantum computation schemes [2] and fundamental tests of quantum mechanics [3]. Many of these applications often require the distribution or processing of entangled photons through single-mode fiber (SMF) networks. However, coupling into SMFs has been a challenge due to the spatial mode mismatch between the created photons and the guided mode in the SMF. Recently, it was demonstrated that efficient generation of photon-pairs at visible wavelengths is possible using standard, commercially available polarization-maintaining fibers (PMFs) [4] by employing the so-called birefringent phase-matching, in which the photons are produced with polarization orthogonal to the pump beam. Also, it was demonstrated that such a source can generate the photons with no spectral correlations between them, and that the coupling efficiency of the generated photons into single-mode fiber networks was as high as 85% [5]. Here we demonstrate the capability of the source to generate polarization-entangled photon-pairs by inserting a PMF source into a Sagnac interferometer.

2. Experiment

The experimental setup is shown in Fig. 1(a). An 80 MHz Ti:sapphire femtosecond laser provides pump pulses at 708 nm central wavelength with 6 nm full-width at half-maximum (FWHM) bandwidth. A bandpass filter (BPF1) (Semrock FF01-692/40) cleans up the spectrum and a half-wave-plate (HWP1) sets the polarization of the pump at 45°. The horizontal and vertical polarization components of the pump are then coupled into opposite ends of a 20 cm-long PMF (Nufern PM630-HP), which is angle-cleaved to reduce back-reflections. Inside the Sagnac loop,
two sideband photons are created through spontaneous four-wave mixing. In the spontaneous four-wave mixing process, two pump photons at angular frequency $\omega_p$ are annihilated by a $\chi^{(3)}$ medium to generate two side-band photons at angular frequencies $\omega_s$ and $\omega_i$, denoted as signal and idler, respectively ($\omega_s > \omega_i$). Energy conservation and phase-matching result in the conditions, assuming self- and cross-phase modulation are negligible, \[ 2\omega_p = \omega_s + \omega_i, \] \[ \Delta k = 2k(\omega_p) - k(\omega_s) - k(\omega_i) + 2\Delta n \frac{\omega_p}{c} = 0, \] where $\omega_{p,s,i}$ are the angular frequencies of the pump, signal, and idler, respectively, $k(\omega)$ is the wave vector of the angular frequency $\omega$ given by the dispersion of pure silica glass, $\Delta k$ is the phase mismatch and $\Delta n$ is the birefringence of the PMF. For our experiment these conditions result in the signal at 620 nm and the idler at 825 nm. As shown in Fig. 1(b), the pump propagates on the slow axis of the fiber ($\Delta n > 0$), and signal/idler photons are created with polarization orthogonal to the pump, traveling on the fast axis of the fiber. The fiber is twisted by 90° such that an entangled state is generated at the output port of PBS1. For an ideally symmetric Sagnac loop, the outputs of the two counter-propagating paths are spatially and temporally indistinguishable such that the polarization-entangled state $|\Psi\rangle = (|H_s\rangle |H_i\rangle + e^{i\phi} |V_s\rangle |V_i\rangle)/\sqrt{2}$ is created. A dichroic mirror (DM) (Semrock FF685-Di02) then splits the signal and idler photons into two arms to perform joint polarization measurements. Bandpass filters (BPF2,3) (Semrock FF01-609/54, FF01-832/37) suppress the pump and other background. Each arm has a polarization analyzer composed of a quarter-wave-plate (QWP), a half-wave-plate (HWP) and a PBS. The transmitted photons are coupled into SMFs connected to silicon-based avalanche photodiodes (APDs) that...
detect the photons (Excelitas SPCM AQ4C). The electronic output of the APDs is analyzed by a field-programmable gate array (FPGA) [6] coincidence counter connected to a personal computer.

Any source of distinguishability of the two pathways through the source can result in degradation of the entanglement. For femtosecond sources, small temporal differences in the two paths is a particular issue [7] as the photons’ coherence time is short. As will be explained in more detail in the next section, in this experiment we find that a temporal difference may arise due to the fact that one pathway is reflected twice from the PBS, while the other is transmitted twice, meaning that a small separation between the two reflective surfaces in the PBS may impose a temporal mismatch between the two pathways. One way to address temporal distinguishability is to filter the photons through a narrow bandpass filter, thus imposing temporal and spectral matching between the $H$ and $V$ photons that pass through. However, the filtering technique degrades both the efficiency and reliability of the source. Instead, we pre-compensate for the presence of temporal delay between the two paths by inserting a quartz plate to delay one of the pump’s polarizations with respect to the other. This method is preferable to the use of spectral filtering as it does not result in loss of photons and allows for loop-hole free tests of Bell’s inequality.

3. Results and Discussion

To characterize the photon-pair state we perform a quantum state tomography [8] through 36 different settings of HWP2, HWP3, QWP1 and QWP2 that project the photons onto different joint combinations of the \{H, V\}: \{D = (H + V)/\sqrt{2}, A = (H - V)/\sqrt{2}\}; and \{L = (H - iV)/\sqrt{2}, R = (H + iV)/\sqrt{2}\} bases and obtain coincidences statistics. We count coincidences for 25 seconds for each setting of the wave-plates. We reconstruct the density matrix of the state using the maximum likelihood method and determine the tangle and linear entropy.

![Figure 2](image_url)  
**Figure 2.** Tangle (black dots) versus delay imposed on the vertical polarization of the pump relative to the horizontal polarization. Error bars are estimated assuming Poissonian statistics of the counts. The FWHM of the Gaussian fit (solid red) is $\Delta \tau_{FWHM} \approx 120$ nm.

To determine the degree to which the entanglement is degraded by the presence of temporal distinguishability, we measure the tangle for various combinations of three quartz crystals which produce 13, 41, and 68 fs delays between orthogonal polarizations of the pump. As shown in Fig. 2, we achieve the highest tangle $T_{max} = 0.7362 \pm 0.0049$ when the vertically polarized pump is delayed by 28 fs with respect to the horizontally-polarized pump (all errors are estimated...
assuming Poissonian statistics of the counts). For this case we also obtain the lowest linear entropy $L_{\text{min}} = 0.1791 \pm 0.0034$. For comparison, without any delay compensation we find tangle and linear entropy $T = 0.6010 \pm 0.0032$ and $L = 0.2710 \pm 0.0023$, respectively. These results suggest that, without quartz crystals, the optical path along which the vertically polarized photons are created is shorter than the path in which the horizontally polarized photons are created.

![Figure 3](image1.png)

**Figure 3.** Real and imaginary parts of the reconstructed density matrix with 28 fs temporal compensation. Without any corrections or background subtractions the fidelity to the Bell state $|\Phi^+\rangle = (|H_sH_i\rangle + |V_sV_i\rangle)/\sqrt{2}$ is calculated as 92.37 ± 0.14%

![Figure 4](image2.png)

**Figure 4.** Quantum interference visibility in the H/V (red triangles) and D/A (black circles) bases. $\theta_{\text{signal}}$ is the angle by which the signal arm polarization is rotated.

For the setup with maximal tangle, we tilt one of the quartz crystals to control and set the phase to $\varphi = 0$. Using 30 mW total pump power, we obtain $\sim 9,000$ coincidences/s. The reconstructed density matrix, shown in Fig. 3, suggests a 92.37±0.14% fidelity with the Bell state $(|H_sH_i\rangle + |V_sV_i\rangle)/\sqrt{2}$. We validate the generated state by an independent quantum-interference visibility measurement, in which QWP1 and QWP2 are set to 0° so that they do not affect the photons, and HWP3 is fixed at either 0° for the H/V basis or 22.5° for the D/A basis interference measurement. Coincidences between signal and idler are recorded as a function of the rotation angle $\theta$ of the signal polarization, controlled using HWP2. The results, shown in Fig. 4, show a visibility of 95.00 ± 1.16% in the H/V basis and 88.21 ± 0.80% in the D/A basis (again, without any corrections or background subtractions). This result agrees with the expected visibilities given the density matrix in Fig. 3, which are 94.31% and 89.04%, respectively.
4. Conclusion
In summary, we have presented a polarization-entangled photon pair source based on standard polarization-maintaining fiber and have shown that entanglement was created with quality comparable to other demonstrated sources. Due to the large birefringence of the fiber, the photons are far-detuned from the pump, practically eliminating Raman contamination even at room temperature. We showed that temporal distinguishability can be compensated without the use of spectral filters, avoiding photon loss and allowing for loop-hole free tests of Bell's inequality. With its capabilities for spatial mode-matching, the creation of spectrally-uncorrelated photons [5], low cost, and high wavelength tunability [4] we expect such a source to be useful for free-space and fiber-network-based quantum information protocols.

Acknowledgements
This work was supported in part by the University of Delaware Research Foundation and the NSF Physics Division, Grant No. 1205812.

References
[1] Ekert A K 1991 Phys. Rev. Lett. 67(6) 661–663 URL http://link.aps.org/doi/10.1103/PhysRevLett.67.661
[2] Pellizzari T, Gardiner S A, Cirac J I and Zoller P 1995 Phys. Rev. Lett. 75(21) 3788–3791 URL http://link.aps.org/doi/10.1103/PhysRevLett.75.3788
[3] Tittel W and Weihs G 2001 Quantum Information & Computation 1 3–56
[4] Smith B J, Mahou P, Cohen O, Lundeen J S and Walmsley I A 2009 Opt. Express 17 23589–23602 URL http://www.opticsexpress.org/abstract.cfm?URI=oe-17-26-23589
[5] Söller C, Cohen O, Smith B J, Walmsley I A and Silberhorn C 2011 Phys. Rev. A 83(3) 031806 URL http://link.aps.org/doi/10.1103/PhysRevA.83.031806
[6] Fabricated based on a design by the group of A. Steinberg, University of Toronto URL http://www.physics.utoronto.ca/~astummer/pub/mirror/Projects/Archives/2008%20Coincidence%20Counter/Coincidence%20Counter.html
[7] Kim Y H, Kulik S P and Shih Y 2000 Phys. Rev. A 62(1) 011802 URL http://link.aps.org/doi/10.1103/PhysRevA.62.011802
[8] James D F V, Kwiat P G, Munro W J and White A G 2001 Phys. Rev. A 64(5) 052312 URL http://link.aps.org/doi/10.1103/PhysRevA.64.052312