A single-crystal source of path-polarization entangled photons at non-degenerate wavelengths

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Abstract

We demonstrate a bright, narrowband, compact, quasi-phase-matched single-crystal source generating path-polarization-entangled photon pairs at 810 nm and 1550 nm at a maximum rate of 3×10^6 s^{-1} THz^{-1} mW^{-1} after coupling to single-mode fiber, and with two-photon interference visibility above 90%. While the source can already be used to implement quantum communication protocols such as quantum key distribution, this work is also instrumental for narrowband applications such as entanglement transfer from photonic to atomic qubits, or entanglement of photons from independent sources.

Introduction

Two-photon entangled states constitute an integral resource for the implementation of quantum information protocols, such as quantum key distribution, quantum teleportation, or all-optical quantum computing.

Different approaches can be considered to create entangled photon pairs. Promising networkable sources under development generate photons directly in single-mode fibre or photonic crystal fibre by means of four-wave mixing. Other emerging sources use semiconductor components with the prospect of integration on optical chips. While those sources have the potential of increasing the generation efficiency, the most practical and spectrally bright sources to date are based on SPDC in non-linear dielectric quasi-phase matched (QPM) crystals.

In the case of type-II SPDC, inserting the non-linear crystal inside a Sagnac interferometer provides an intrinsically phase-stable source, because both counter-propagating beams travel the same loop structure, so that any change of path length in the loop is experienced by both beams, resulting in stable interferences. While it was claimed that such a set-up could work with photon pairs created at non-degenerate wavelengths, experimental realizations so far have been limited to operation near degeneracy. In this contribution, we present a type-I QPM single-crystal source of entangled photons operating at non-degenerate wavelengths. Photons are entangled in path and polarization at 810 nm and 1550 nm, respectively. The path-entanglement configuration at 810 nm leads to a very compact set-up, while the use of polarization coding at 1550 nm with only 0.8 nm bandwidth makes the fiber-coupled source potentially suitable for long-distance quantum communication.

Presentation of the source

The source is drawn in Fig. 1. We use a 50 mm-long type-I bulk crystal made of periodically poled (PP) lithium niobate PPLN:MgO. The crystal is pumped by two focused counter-propagating beams driven by a diode laser operating at a wavelength of 532 nm. The pump is focused into the crystal by an achromatic lens and split in two orthogonal beams by a polarizing beam-splitter (PBS). The intensity of the pump along the two arms is balanced by means of a half-wave plate (HWP) set before the PBS. Since the crystal only down-converts pump light having a polarization of the electromagnetic field set along the crystal's optical axis, a second HWP is used along one of the two pump arms in order to undo the polarization rotation induced by the PBS. The signal and idler are generated with vertical (V) polarization.

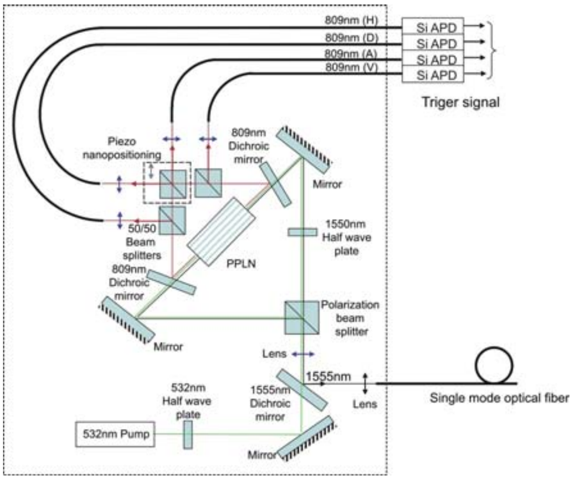

Figure 1: Single crystal source of entangled photons at 810 and 1550 nm.

The two counter-propagating idler beams generated at 1550 nm are recombined at the PBS splitting the pump, after rotation of the polarization in one of the two arms by the same HWP used to adjust the polarization of the pump beam. After the PBS, the idler is separated from pump by means of a dichroic mirror, filtered from residual pump light, coupled to 100 meters of single-mode fiber after which one analyzes the polarization state of the qubit. The bandwidth of the 1550 nm photon after coupling to single mode fiber, as measured by a spectrograph at full pump power without conditional gating, is 0.8 nm FWHM, compatible with 100 GHz wavelength multiplexing.

The two signal beams at 810 nm are separated from the pump beams by dichroic mirrors, and the correlations shared with idler photons are mapped onto the four output ports of three non-polarizing beam-splitters (BS) before coupling to one of four avalanche photo-detectors (Si APD) labeled H, V, D and A, in relation to the horizontal (H), vertical (V), diagonal (D) and anti-diagonal (A) polarization states of the idler qubits measured in the two conjugate basis H/V and D/A, see Fig. 1.

If APD “H” or “V” clicks when detecting a photon at 810 nm, the transmitted qubit at 1550 nm must have H or V polarization, respectively, since the path taken by the 810nm photon determines non-ambiguously the polarization acquired by the corresponding idler photon as it reaches the PBS.

If APD “D” or “A” clicks (corresponding to interference of the two indistinguishable signal paths at the third 50-50 BS), the H and V polarization states at 1550 nm will interfere constructively in the D/A basis, providing that the phase difference φ of the interfering paths at 810 nm is set to -π/2 (thus compensating the π/2 phase shift introduced by the third BS). φ can be controlled by means of a piezo nano-positioning actuator mounted on the corresponding BS.

Apart from the conditions of spectral and spatial indistinguishability, which are fullfilled by bidirectional pumping of the single-crystal and coupling to single-mode fiber, respectively, good quality entanglement also requires temporal indistinguishability. This condition implies that the two idler fields overlap in time relative to the time difference of the two signal fields. This is equivalent to say that the interferometer defined by the PBS and the opposite BS (with respect to the PPLN crystal) is balanced for the pump light. This provides a convenient way to actively stabilize the source against environmental disturbances by monitoring of pump light interferences.

Performances

Fig. 2 illustrates the quantum correlations shared by the entangled pairs after transmission over 100 m of single mode fiber (SMF). Curves were obtained at a pump power of 1.2 mW and single-count rate of 0.3 × 10^6 s^{-1} at 810 nm. The coincidence rate reached 1.1 × 10^4 counts/s^{-1} with a raw visibility of 91% for all output states. We estimated a spectral brightness of 3 × 10^6 s^{-1} THz^{-1} mW^{-1} after coupling to SMF. Using a narrower detection time window (< 1 ns) would reduce the rate of accidental counts and improve the visibility significantly.

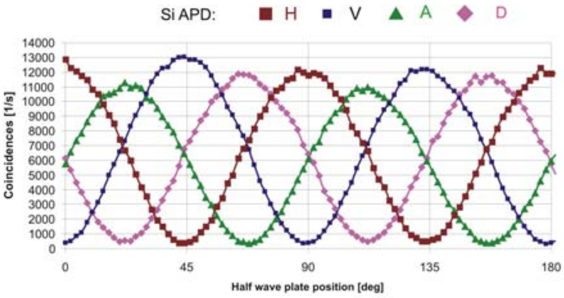

Figure 3: Coincidence rate after 100 m of fiber as a function of idler polarization for each of the four output states detected at 810 nm by the Si avalanche photo diodes (denoted H, V, D and A).

Conclusions

We have demonstrated a compact, narrowband, fiber-coupled source of path-polarization entangled photons at 810 and 1550 nm generated by bidirectional pumping of a 50 mm long PPLN:MgO crystal. The source has a spectral brightness of 3 × 10^6 $s^{-1}THz^{-1}mW^{-1}$ with two-photon interference visibility above 90%. With its small number of components, the source is ideal for table-top experiments. The set-up is compatible with applications requiring cw as well as pulsed operation. With 0.8 nm bandwidth at the telecommunication wavelength, the source can also be bridged over existing optical networks operating with 100GHz (0.8 nm) WDM environment. Moreover, the bandwidth is narrow enough so that real time polarization control of each flying qubit could be implemented with negligible contribution to the quantum bit error rate. By inserting a waveguide in a cavity with the same configuration, the bandwidth of the emitted pairs could be narrowed down to few hundreds of MHz with a coincidence rate still sufficiently high for enabling long distance teleportation schemes in which entanglement is stored in trapped-atom quantum memories, or to entangle photons from two independent sources.

References

1. S. Sauge et al., Optics Express, Volume 16 (2008), page #9701-9707 and references therein.