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Simple, pulsed, polarization entangled photon pair source

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ABSTRACT

We report the realization of a fibred polarization entangled photon-pair source at 1560 nm based on a type-II nonlinear interaction and working in the picosecond regime. By taking advantage of a set of fibre filters, we deterministically separate the photons and project them into wavelength separable states. A standard entanglement measurement with a net interference visibility close to 1 proves the relevance of our approach as an enabling technology for entanglement-based quantum communication.

1. Introduction

Entanglement is a fundamental resource in quantum information science and sources of photonic entanglement are key enabling technologies for quantum communication [1]. Entangled photons can be generated from a wide range of single- or heralded-photon sources [2], or directly via interactions in materials with nonlinear optical susceptibility, such as spontaneous parametric down conversion (SPDC). A simple way to generate polarization entangled photon pairs consists in employing a nonlinear crystal with type-II phase-matching conditions [3], which allows one to generate pairs of photons with orthogonal polarization and to exploit the conservation of energy and momentum to produce entanglement.

However, a constraint arises when we want to use a collinear configuration or waveguide crystals [4], for example, to increase the source brightness. The simplest approach is to use a balanced beam splitter, in which case the two photons take different paths half of the times. Hence, one immediately has only 50% efficiency and the scheme only works in post-selection. We can no longer deterministically separate the entangled photons to obtain polarization entangled pairs, as they are indistinguishable in all the other degrees of freedom [5,6]. A solution to this can be found by engineering two different type II phase matching conditions, for non-degenerate pairs of photons, in the same crystal [7,8]. In addition, it is possible to engineer geometries that allow one to produce polarization entanglement without post compensation or manipulation in fiber based setups [9] or on chip [10,11].

In this work, we report on an extension of a scheme proposed in Ref. [12], which exploits energy conservation and degenerate photon pairs in SPDC along with readily available fiber components such as dense wavelength division multiplexer (DWDM) filters. However, in our case, the picosecond pulsed regime allows one to generate narrowband photons and overcome synchronization problems associated with distributed systems. We can also adapt the filtering bandwidth to obtain spectrally separable [13] photons that are a requirement for more complex quantum communication tasks.

2. Principle

In the present work, the realization of the entangled photon pair is based on a type II spontaneous parametric down conversion (SPDC) process in a nonlinear crystal. As proposed in Ref. [12], in order to generate entangled photon pairs with minimal losses (*i.e.* the collinear photons are deterministically separated), it is necessary to be in a degenerated configuration. A filtering stage with wavelengths slightly detuned from the central one, like a dense wavelength division multiplexer (DWDM) [12], has the role of separating the photons. At the two outputs, labeled *a* (Alice) and *b* (Bob), if all the distinguishabilities between the H and V polarized photons are erased, we obtain an entangled state of the form:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}[|H_{+\delta\omega_f}\rangle_a |V_{-\delta\omega_f}\rangle_b + |V_{+\delta\omega_f}\rangle_a |H_{-\delta\omega_f}\rangle_b] \quad (1)$$

where $\delta\omega_f$ represents the detuning between the central filter frequency and the degeneracy frequency of the photon pairs.

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Parametric down conversion processes in nonlinear crystals are governed by energy and momentum conservation laws:

$$\omega_p = \omega_i + \omega_s; \quad \vec{k}_p = \vec{k}_i + \vec{k}_s + \frac{2\pi}{\Lambda}\vec{z} \tag{2}$$

where ω and $\vec{k}$ represent respectively the frequency and the wavenumber for the pump (p), signal (s), and idler (i) photons [14]. Λ is the crystal poling period employed to compensate the crystal dispersion. It was chosen to produce degenerate photon pairs at 1560 nm. This nonlinear process is governed by the Hamiltonian:

$$H = c\int d\omega_s\, d\omega_i\; \epsilon(\omega_s,\omega_i)\; \varphi(\omega_s,\omega_i)\; a^\dagger(\omega_s)\; a^\dagger(\omega_i) + \text{h.c.} \tag{3}$$

$\epsilon(\omega_s,\omega_i)$ and $\phi(\omega_s,\omega_i)$ are the pump pulse envelope and the phase matching function, respectively, which fix the energy conservation and the phase matching conditions. If the pump pulse is Gaussian, the first factor is given by $\epsilon(\omega_s,\omega_i) = \exp[-(\omega_i+\omega_s-\omega_p)^2/4\Delta\omega_p^2]$, with $\Delta\omega_p$ the pump frequency bandwidth. The second factor, for a crystal of a length L, is given by: $\varphi(\omega_s,\omega_i) = \text{sinc}(L(k_i+k_s+2\pi/\Lambda-k_p))$.

Fig. 1 represents the joint spectral intensity (JSI) ($J(\omega_s,\omega_i) = |\epsilon(\omega_s,\omega_i)\;\varphi(\omega_s,\omega_i)|^2$) corresponding to our experimental configuration. From Fig. 1 it is possible to observe a correlation in wavelength: indeed in this case the state of the two photons at the output of the crystal is not separable in frequency. This state can be made spectrally separable by filtering one photon down to 200 pm [13].

If we include the action of such a filter in the JSI function, we can define the wavelength distribution of Bob's photons that are correlated with the photons sent to Alice. Fig. 2a gives an example of this distribution. H and V polarized photons are spectrally distinguishable, which will clearly reduce the entanglement visibility [15]. The visibility in the diagonal basis is given directly by the overlap in frequency of the two polarization modes. Fig. 2b shows this overlap as a function of the relative position of the filter compared to the degeneracy wavelength.

This distinguishability is not observed in the CW regime [12], due to perfect spectral correlation between the photons. In the pulsed regime the JSI contour is no longer an ellipse at 45° (see Fig. 1). The "tilt" angle θ of the phase matching function is given by

$$\tan\,\theta = -\frac{k_p' - k_s'}{k_p' - k_i'} \tag{4}$$

where $k' = dk/d\omega$ is the first derivative of the wavenumber, which in this case corresponds to a $\theta = 59.96°$. To avoid this distinguishability it is necessary to add a second filter on Bob's arm, with a bandwidth adapted to select the part of the spectrum where the two photons, H and V, overlap.

3. Experimental realization

A scheme of the experimental setup is depicted in Fig. 3. The two photons are generated via SPDC in a 2 cm-long PPLN bulk crystal (Covesion), pumped by a 2 ps pulsed laser at 780 nm with a repetition rate of 76 MHz (Coherent Mira 900). Type II quasi-phase matching generates two orthogonally polarized photons.

A birefringent medium, e.g. a polarization maintaining single mode fiber (PMF) is used to compensate the temporal walk-off introduced by the LN birefringence between the two orthogonally polarized photons. The photon pairs are directly coupled into the PMF with an efficiency of 50%, the slow and fast axis as well as the length of the fibre (1.44 m) are adapted to compensate the temporal walk-off introduced by the crystal. To separate the two photons, a circulator is placed at the output of the PMF and a fiber

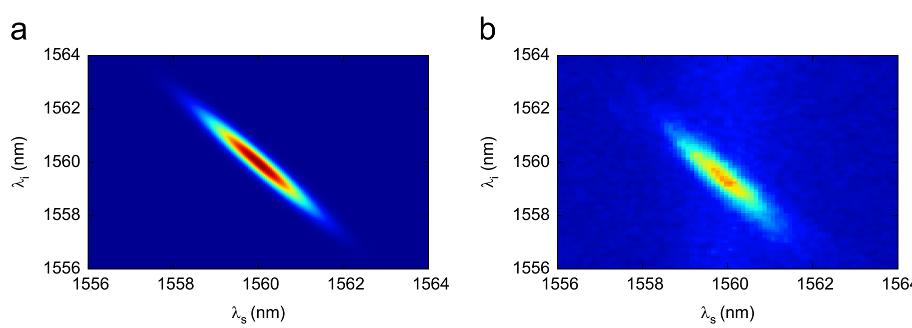

Fig. 1. (a) Numerical simulation of the joint spectral intensity for a 2 cm-long type II periodically poled Lithium Niobate (PPLN) crystal pumped by a 2 ps pulsed laser and (b) corresponding measurement realized scanning two tunable filters with a bandwidth of 200 pm and counting the coincidences between signal and idler photons. Note that signal and idler are associated to H and V polarization, respectively.

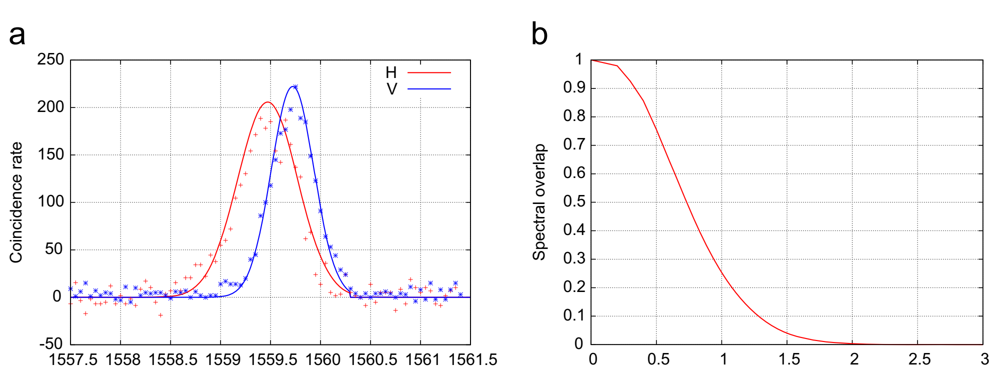

Fig. 2. (a) Coincidence spectrum heralded by the photon passing the 0.2 nm filter. The lines and the points represent respectively the theoretical prediction and the experimental results and (b) overlap in frequency between the two polarization modes as a function of $\delta\lambda$ the difference between the degeneracy wavelength and the central wavelength of the 0.2 nm filter.