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Integrated optical source of polarization entangled photons at 1310 nm

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Abstract *- We report the realization of a new polarization entangled photon-pair source based on a titanium-indiffused waveguide on periodically poled lithium niobate. The paired photons are emitted at the telecom wavelength of 1310 nm within a bandwidth of less than 1 nm. The related quantum properties are demonstrated to be of high quality.*

Introduction

Quantum communication often relies on the use of single quantum systems, such as photons, to carry the quantum analog of bits, usually called *qubits*. To do so, individual photons merely serve as carriers and quantum information is encoded on their quantum properties, like polarization or time-bins of arrival [1]. Selecting two orthogonal states spanning the Hilbert space, for instance $|H\rangle$ and $|V\rangle$ when polarization is used, allows encoding the 0 and 1 values of the qubit, and quantum superposition makes it possible to create any state $|\psi\rangle = \alpha|0\rangle + e^{i\phi}\beta|1\rangle$, provided the normalization rule $|\alpha|^2 + |\beta|^2 = 1$ is fulfilled. Entanglement is a generalization of the superposition principle to multiparticle systems. Polarization entangled photon-pairs can be described by states of the form

$$|\psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left[|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2\right], \qquad (1)$$

where the indices 1 and 2 label the two photons, respectively. The interesting property is that neither of the two qubits carries a definite value. But as soon as one of them is measured, the associated result being completely random, the other one will be found to carry the opposite value. There is no classical analog to this purely quantum feature [2].

In today's quantum communication experiments, spontaneous parametric down-conversion (SPDC) in non-linear bulk crystals is the common way to produce polarization entangled photons [3]. However, since such experiments are getting more and more complicated, they require more and more efficient sources together with narrower photon bandwidths [4, 5]. In addition, as soon as long-distance quantum communication is concerned, the paired photons have to be emitted within one of the telecom windows.

The aim of this work is to gather all of the above mentioned features in a single source based on a titanium (Ti) indiffused periodically poled lithium niobate (PPLN) waveguide. We report for the first time the efficient emission of narrowband polarization entangled photons at 1310 *nm*, showing the best quality of two-photon quantum interference ever reported for a similar configuration [6, 7]. In the following, we will first describe the essential aspects of the source. Then, we will focus on classical characterization enabling the choice of the desired SPDC interaction. Finally, we will move on to an interferometric setup designed to evaluate the quantum quality of the source and discuss the results.

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Principle of the entangled photon-pair source

To date, the creation of entangled photon-pairs is usually ensured by SPDC in non-linear bulk or waveguide crystals [1]. In this case, the interaction of a pump field (p) with a $\chi^{(2)}$ non-linear medium leads, with a small probability, to the conversion of a pump photon into so-called signal (s) and idler (i) photons. Naturally, this process is subjected to conservation of energy $\omega_p = \omega_s + \omega_i$ and momentum $\vec{k}_p = \vec{k}_s + \vec{k}_i + \frac{2\pi}{\Lambda} \cdot \vec{u}$, where Λ represents, in the case of a PPLN waveguide, the poling period. Note that the latter equation is also known as quasi-phase matching (QPM). In our case, we choose this condition such that, starting with a pump laser at 655 nm, we expect the generation of pairs of photons centered at the telecom wavelength of 1310 nm.

From the quantum side, since we want to generate cross-polarized entangled photons, the waveguide device has to support both vertical and horizontal polarization modes. Therefore, the well-established Ti-indiffusion technology can be applied for waveguide fabrication and a type-II SPDC process, taking advantage of the non-linear coefficient d_{24} of the material, can be used [6]. This leads, at degeneracy, to the generation of paired photons having strictly identical properties, but showing orthogonal polarizations. As depicted in FIG. 1, the paired photons are emitted simultaneously and, after filtering out the remaining pump photons, separated at a 50/50 beam splitter (BS) whose outputs are labelled a and b. At this stage, when the pairs are actually separated, the two possible outputs, $|H\rangle_a |V\rangle_b$ et $|V\rangle_a |H\rangle_b$, have equal probabilities. Furthermore, provided the two photons are indistinguishable for any observable but the polarization, it is possible to describe them by the entangled state of equation Eq. 1. Two steps are therefore cascaded for obtaining such a state configuration, $|H\rangle_p \xmapsto{NLO} \eta |H\rangle_s |V\rangle_i \xmapsto{BS} \eta^\star \frac{1}{\sqrt{2}} [|H\rangle_a |V\rangle_b + |V\rangle_a |H\rangle_b]$, where η and η^* stand for the efficiencies of the non-linear process and of the entire source, respectively.

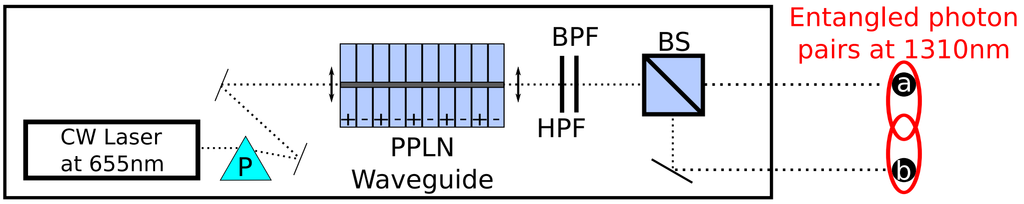
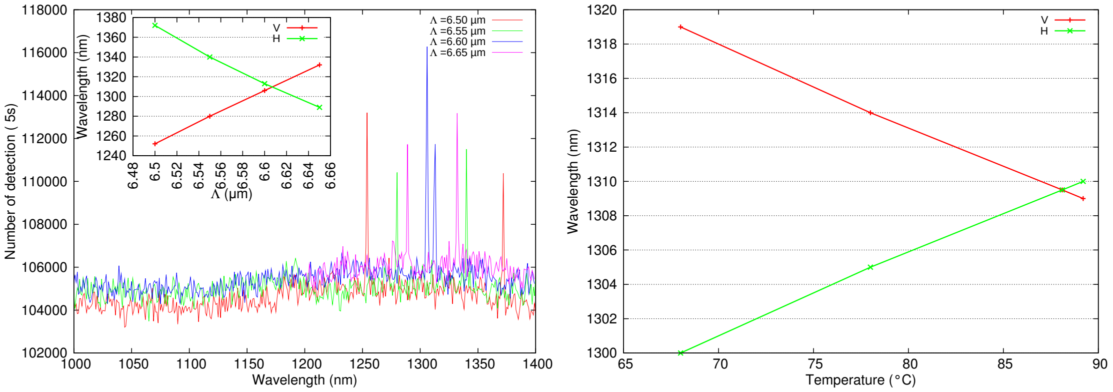


FIG. 1: Schematic of polarization entangled photon-pair source based on an H-polarized CW laser at 655 nm pumping a titanium-indiffused PPLN waveguide; A prism (P) is used to remove the infrared light coming from the laser. The association of a high-pass filter (HPF, cut-off at 1000 nm) and a bandpass filter (BPF, 1310 nm, $\Delta\lambda = 10\,nm$) allows removing the residual pump photons; Finally, a 50/50 beam-splitter (BS) is employed to separate the paired photons, revealing entanglement when coincidences are regarded.

Fabrication and classical characterization of the PPLN waveguide

The required poling period for the generation of photon-pairs at the degenerate wavelength of 1310 nm was calculated to be around 6.6 μm. Therefore, we fabricated a sample containing various waveguides widths (5, 6, and 7 μm) together with different poling periods (6.50 to 6.65 μm with a step of 0.05 μm). Experimentally, we got near-degeneracy photon-pair emission for a temperature of 80° in a 6 μm-wide waveguide for the predicted period. A fine tuning of the temperature up to 88° allowed us to get exactly both signal and idler photons at the degenerate wavelength of 1310 nm, as shown on FIG. 2. The measured bandwidth of those photons is less that 1 nm for a 3.6 cm-long sample. Note here that the measured value of the bandwidth is very close to the resolution of our optical spectrum analyzer. The theoretical value has been estimated to be $0.6\,nm$ which corresponds to a coherence length of about $2.8\,mm$.



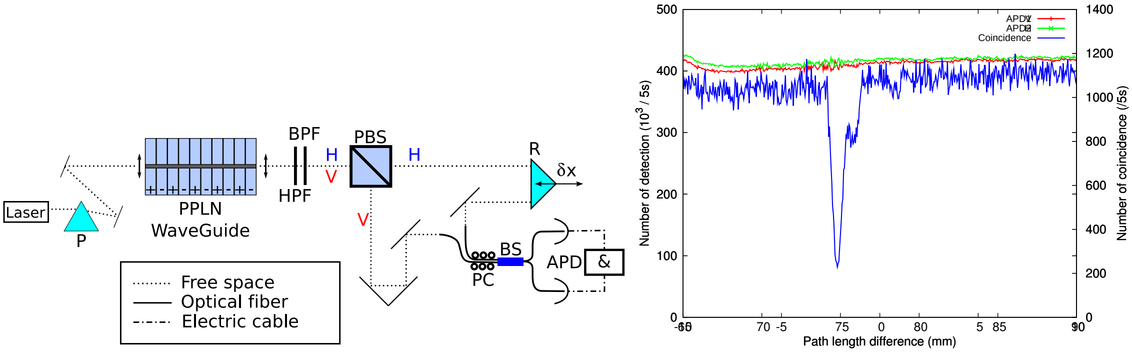
(a) (b)

FIG. 2: (a) Fluorescence spectra, obtained in the single photon counting regime, for various poling periods associated with a $6\,\mu m$-wide waveguide heated to $80°C$ when pumped at $655\,nm$. (b) QPM curve as function of the temperature for $\Lambda = 6.60\,\mu m$; The degeneracy point can be reached by fine tuning of the temperature up to $88°C$.

Quantum characterization of the source

Obtaining polarization entangled photon-pairs (see Eq. 1) requires these two photons to be indistinguishable for any degree of freedom, but the polarization, before they reach the beam-splitter of FIG. 1. To demonstrate the indistinguishability, we performed a non-classical two-photon interference experiment. Contrary to FIG. 1, this now consists of separating the paired photons into two spatial modes regarding their polarization state (H,V) using a polarization beam-splitter (PBS), and then recombining them at a standard fiber optic 50/50 BS. This interferometric apparatus, depicted in FIG. 3-a, permits characterizing the quantum properties of the pairs. Since photons are bosons, and provided the two photons are strictly indistinguishable, we expect them to exit the BS through the same output arm, leading to a dip in the coincidence rate, when two detectors are placed at each output. Such a destructive interference effect, first demonstrated by Hong, Ou, and Mandel (HOM) requires, in our case, to rotate one of the photon polarization states. This is ensured by the polarization controllers placed before the BS. Therefore, indistinguishability means in this case that the two photons have to show the same wavelength, bandwidth, polarization state, spatial mode, and time of arrival for obtaining a perfect overlap at the BS where the interference occurs [8]. Changing the path length difference of the two arms allows scanning over the coherence length of the single photons and leads to the so-called HOM-dip in the coincidence rate. The more indistinguishable the photons are, the better the visibility of the dip is. This figure of merit allows inferring the quality of the entangled state produced by the source (see FIG. 1 and related text).

FIG. 3-b exhibits the coincidence rate as a function of the path length difference between the two arms and shows the obtained HOM interference while single photon detection remains constant in both APDs. In our case, the associated net visibility and FWHM are of about 84% and $1.5\,mm$, respectively. Work is in progress towards understanding the origin of the reduction of visibility. Energy-time entanglement or other phase-matched



(a) (b)

FIG. 3: (a) Two-photon interference experiment. PBS: polarizing cube; R: retroreflector; PC: polarization controller; BS: fiber optics 50/50 beam-splitter; APD: avalanche photodiode; &: coincidence analyzer. (b) Coincidence rate at the output of the 50/50 beam-splitter as function of the relative length of the two arms. The width of the dip is related to the coherence length of the single photons.

interactions, such as Cerenkov, in our non-linear waveguide can be seen as sources of visibility degradation. In any case, the obtained visibility is, to our knowledge, the best ever reported in a similar configuration, i.e. cross-polarized photons at telecom wavelength generated by a Ti-indiffused PPLN waveguide. This is also a clear signature that a high quality of entanglement can be expected from the setup of Fig. 1.

Conclusion

Using a type-II PPLN waveguide, we have demonstrated a narrowband and bright source of cross-polarized paired photons since we estimated the production rate to be on the order of $10^5\,/s/GHz/mW$, which is one of the best ever reported in such a configuration [6, 7]. Using a HOM-type setup, we obtained an anti-coincidence visibility of 84% indicating a good level of photon indistinguishability. These preliminary results permits expecting our source to be an efficient, compact, and reliable key element providing narrow and high-quality polarization entangled photon-pairs for the first time at $1310\,nm$. Finally, this work clearly highlights the potential of integrated optics for long-distance quantum communication protocols.

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