FrPD2 1515-1530 ECIO 2010, Cambridge, 7 - 9 April 2010 LR1

High-quality polarization entangled photon pair source based on a type-II PPLN waveguide

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***Abstract*—We realized a novel polarization entangled photon-pair source at 1310 nm based on a birefringent titanium in-diffused waveguide integrated on periodically poled lithium niobate. Using an original setup, we characterized the quantum properties of the pairs by measuring two-photon interference patterns in both Hong-Ou-Mandel and Bell inequality configurations. We obtained interference net visibilities of 99%, which represent the best results ever reported for similar configurations.**

Non-linear integrated Optics; Entanglement generation.

I. INTRODUCTION

Quantum communication relies on the use of single quantum systems, such as photons, to carry the quantum analog of bits, usually called qubits. Individual photons merely serve as carriers and quantum information is encoded on their quantum properties, such as the polarization observable [1]. Selecting two orthogonal states spanning the Hilbert space, for instance horizontal ($|H\rangle$) and vertical ($|V\rangle$) polarization modes, quantum superposition makes it possible to create states of the form $|\varphi\rangle = \alpha|H\rangle + \beta|V\rangle$, with proper normalization $|\alpha|^2 + |\beta|^2 = 1$.

Entanglement is a generalization of the superposition principle applied to multiparticle systems. Pairs of polarization entangled photons can be described by states of the form $|\psi\rangle = 1/\sqrt{2}[|H\rangle_a|V\rangle_b + |V\rangle_a|H\rangle_b]$, where a and b label the two photons. The interesting property, having no classical analog, is that neither of the two qubits carries a definite value. But as soon as one of them is measured, the associated result being random, the other one will be found to carry the opposite value.

Regarding quantum communication experiments over long distance, spontaneous parametric down-conversion (SPDC) is the common way to produce polarization entangled photons. However, today's high-end experiments require brighter sources emitting photons at a telecom wavelength, associated with narrower bandwidths in a compact design.

The aim of this work is to gather all of the above mentioned features in a single source based on a titanium indiffused periodically poled lithium niobate waveguide (PPLN/W) [2]. In the following, we first describe the essential aspects of the source, and then depict how we analyze the quantum properties of paired photons using two complementary quantum tests, namely Hong-Ou-Mandel (HOM) [3,4] and Bell inequality-type measurements [5]. For both types of tests, we achieved unprecedented two-photon interference visibilities compared to earlier reported works based on guided-wave schemes, proving the relevance of our approach.

II. PRINCIPLE OF THE SOURCE

The source is based on Ti-indiffusion technology for waveguide fabrication so as the device supports both V and H polarization modes. A type-II SPDC process can therefore take place, exploiting the d_{24} non-linear coefficient of the material [2]. Starting from H-polarized pump photons at 655 nm this quasi-phased matched process leads to the generation of paired photons at 1310 nm, having strictly identical properties, but with orthogonal polarizations. The associated brightness was measured to be to $3{\cdot}10^5$ pairs created per s, per GHz of bandwidth, and per mW of pump power at the direct output of the waveguide.

As depicted in Fig. 1, if the paired photons are indistinguishable for all their degrees of freedom but the polarization, and actually separated at a 50/50 beam splitter (*BS*), whose outputs are labeled *a* (Alice) and *b* (Bob), then the two possible outputs, $|H\rangle_a|V\rangle_b$ and $|V\rangle_a|H\rangle_b$, have equal probabilities leading to the entangled state $1/\sqrt{2}\,[|H\rangle_a|V\rangle_b + |V\rangle_a|H\rangle_b]$. Here, in order to make the paired photons indistinguishable, we have to control their spectral, spatial and temporal properties. First,

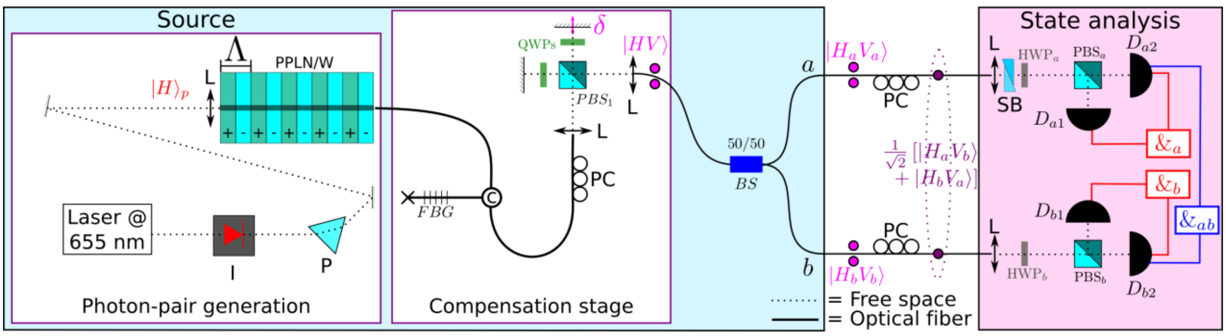

Figure 1. Setup of the source and analysis system. The pairs of circles represent pairs of photons with their associated polarization states, after the birefringence compensation system. The 50/50 beam-splitter (BS) is the ouput of the source. P: prism; I: optical isolator; L: lenses; PPLN/Wg: periodically poled lithium niobate waveguide; FBG: fiber Bragg grating filter (λ_0 = 1310 nm, $\Delta\lambda$ = 0.5 nm); C: fiber optical circulator; PC: polarization controllers; PBS: polarization beam-splitters; HWP/QWP: half/quarter wave-plates; D: single photon detectors; &: AND-gate.

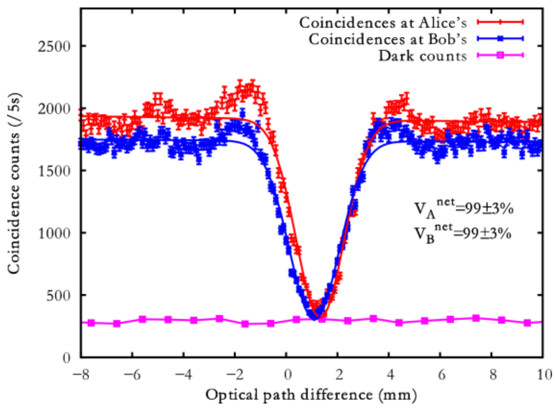

Figure 3. Results for the HOM-type measurement obtained at the two users locations. We obtained net (raw) visibilities of 99±3% (83±2%).

birefringence in the crystal gives rise to two different transverse spatial modes at 1310 nm for H and V polarizations. To erase this spatial mismatch, we collect the photon pairs in a standard single-mode fiber. Second, the spectrum of the emitted photon pairs two some polluting sidebands, each associated with one polarization mode, and therefore leading to distinguishability. The natural emission bandwidth being 0.7 nm, we used a fiber Bragg grating filter having a FWHM of 0.5 nm to remove these sidebands. Third, birefringence also leads to a time delay between the two outgoing photons since H and V modes are associated with different group velocities. To compensate for this temporal distinguishability, we designed and added on the path of the paired photons an adjustable polarization-sensitive birefringence compensator which has an arrangement comparable to that of a Michelson interferometer.

III. QUANTUM CHARACTERIZATION

We can perform two different quantum tests, namely two-photon interference experiments using either a HOM configuration when the photons are not separated at the BS, or a Bell inequality configuration when they are actually separated. The first permits determining the indistinguishability of the paired photons, and the second the quality of entanglement.

To perform the quantum measurements, Alice and Bob have each an adjustable polarization analyzer made of a HWP, a PBS to project the incoming state onto any linear polarization basis, and two detectors. In order to maximize the potential amount of entanglement, the HOM-like two-photon interference takes advantage of non separated pairs at the BS. This amounts to optimizing the photons indistinguishability in terms of spatial, temporal, and spectral overlaps by analyzing the state $|HV\rangle_j$ ($j=a,b$) in the $\{D,A\}$ basis, for diagonal and anti-diagonal polarization, respectively. In this basis two indistinguishable photons are projected onto a coherent superposition of states in which they always have the same polarization. As a consequence, they always exit through the same output port of the PBS. This leads to a HOM dip in the coincidence counts recorded between the considered pair of detectors (D_{j1} and D_{j2}) at a given location (*a* or *b*). In Fig. 2 we show the obtained dips at both locations, when we adjust the temporal overlap with the moving arm of the birefringence compensator. They show each a net (raw) visibility of 99±3% (83±2%).

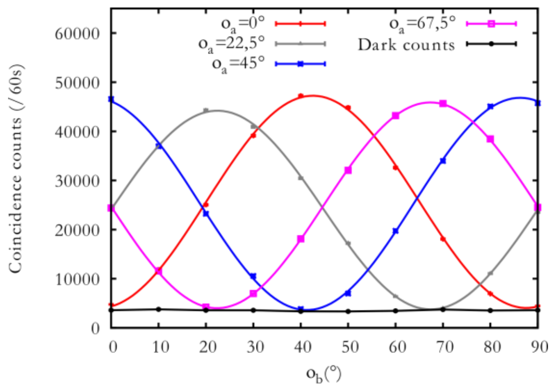

Figure 2. Results for a standard entanglement measurement in the $\{\boldsymbol{H},\boldsymbol{V}\}$ and $\{\boldsymbol{D},\boldsymbol{A}\}$ basis. We obtained net (raw) visibilities of 99±2% (83±1%).

For actual entanglement estimation regarding pairs that are actually separates at the BS, we have to study the visibility of the coincidence rate between the users (D_{a2} and D_{b2}) as a function of the relative angle between their analyzers. Four necessary settings were used for HWP_a, namely 0° and 45° (H and V states), and 22.5° and 67.5° (D and A states), while HWP_b is rotated. The visibilities of these curves are related to the quality of both the optical setup ($\{H,V\}$ basis) and the entanglement ($\{D,A\}$ basis), respectively. In Fig. 3 we show the four raw coincidence rates obtained in these basis. They show net (raw) visibilities of 99±2% (83±1%).

IV. CONCLUSION

We have demonstrated a narrow-band source of polarization entangled photon-pairs at 1310 nm based on a type-II PPLN/W. The obtained near perfect quality of entanglement, which corresponds to the best value ever reported for guided-wave schemes [3-6], associated with high brightness, stability and practicality, makes this source a promising element for long-distance quantum communication protocols, and highlights the potential of non-linear integrated optics in this field.

ACKNOWLEDGMENT

We acknowledge the European ERA-SPOT program "WASPS", the CNRS, the Conseil Regional PACA, and the University of Nice - Sophia Antipolis for financial supports.

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