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Polarization entangled photon-pair source based on quantum nonlinear photonics and interferometry

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ABSTRACT

We present a versatile, high-brightness, guided-wave source of polarization entangled photons, emitted at a telecom wavelength. Photon-pairs are generated using an integrated type-0 nonlinear waveguide, and subsequently prepared in a polarization entangled state via a stabilized fiber interferometer. We show that the single photon emission wavelength can be tuned over more than 50 nm, whereas the single photon spectral bandwidth can be chosen at will over more than five orders of magnitude (from 25 MHz to 4 THz). Moreover, by performing entanglement analysis, we demonstrate a high degree of control of the quantum state via the violation of the Bell inequalities by more than 40 standard deviations. This makes this scheme suitable for a wide range of quantum optics experiments, ranging from fundamental research to quantum information applications.

We report on details of the setup, as well as on the characterization of all included components, previously outlined in Kaiser et al. (Laser Phys. Lett. 10 (2013) 045202).

1. Introduction

Quantum communication science has become a very broad and active field of research. On one hand, quantum key distribution (QKD) [1], allowing secure distribution of cryptography ciphers between distant partners, has reached the commercial market as well as high-speed system capabilities [2]. Related networking protocols, such as entanglement based quantum relay operations, are employed as a means for extending the distance of quantum communication links [3,4]. On the other hand, the study of light/matter interaction is a promising approach for implementing quantum storage devices [5]. Those devices are essential elements to achieve quantum repeater scenarios in which entanglement is distributed, stored, and distilled, all in a heralded fashion, making it possible to increase the overall link efficiency [6].

Over the past three decades, entanglement has been widely exploited as a resource in fundamental tests of quantum physics [7,8]. We find, among others, nonlocality tests involving spacelike separated paired photons [9,10], quantum delayed-choice experiments [11–13], and demonstrations of micro–macro entangled states of light [14,15]. Moreover, with the emergence of long-distance quantum communication links working at telecom wavelengths [16–19], new generation sources have been developed, featuring higher brightness, better stability, compactness, and near perfect entanglement fidelities. Photons can now be generated over narrow enough bandwidths (≤ 100 GHz) to avoid both chromatic and polarization mode dispersion along the distribution fibers [20]. More importantly, current light/matter interaction based quantum memories have, depending on both the physical system and the applied storage protocol, acceptance bandwidths ranging from some MHz to several GHz [5]. Consequently, to push long-distance quantum communication one step further, there is a need for implementing versatile solutions so as to benefit from the advantages of different quantum technologies. In this framework, sources based on quantum integrated photonics [21] appear to be natural and very promising candidates, offering the possibility to efficiently create polarization entanglement at wavelengths compatible with standard fiber components [22,23].

In the following, we present the details of a versatile, high-brightness, source of polarization entangled photons, whose main results were first presented in Ref. [24]. Its key features, *i.e.*, the central emission wavelength, the spectral bandwidth, and the quantum state, can be tuned at will and adapted to a broad range of quantum network applications. This is enabled by a pertinent combination of an integrated nonlinear optics photon-pair generator, standard

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telecommunication components, and an entangled state preparation stage based on a stabilized Mach–Zehnder interferometer (MZI). After the presentation of the overall setup and the principle of the source, we will detail all the key elements, namely the integrated nonlinear generator, employed filters, and the quantum state preparation stage. We will then present the entanglement characterization proving the relevance of our approach. Related stabilization schemes and performances in terms of brightness and internal losses will also be outlined. Finally, we will summarize the obtained results, in the perspective of overall performances, and discuss potential improvements.

2. Specifications, setup, and principle of the source

Generation of polarization entanglement has been demonstrated using various strategies based on nonlinear media, such as microstructured fibers [25,26], single pass bulk crystals [27,28], crystals surrounded by a cavity referred to as optical parametric oscillators (OPOs) below the threshold [29–31], or type-II waveguide crystals [22,23]. However, these strategies have all shown relatively low brightness, which becomes an issue when (ultra-)narrowband photons are needed. Other approaches, capable of generating narrowband polarization entangled photons based on quantum dots [32] or cold atomic ensembles [33,34] have recently been demonstrated, albeit showing limited entanglement fidelities.

Our source specifications are outlined in the following. First, the paired photons are emitted at a wavelength lying in the telecom C-band (1530–1565 nm), and further collected using a single mode telecom fiber in order to benefit from both standard components for routing and filtering purposes and low propagation losses in case of distribution over a long distance. Second, the photon bandwidth is made readily adaptable so as to be compatible with a broad variety of applications, ranging from QKD in telecommunication channels to quantum storage device implementations. Third, the coding of quantum information relies on the polarization observable since entanglement correlations can be measured using simple analyzers, being free of interferometric devices as opposed to the case of the time-bin observable [35]. In addition, polarization entanglement can now be distributed over long distances thanks to active compensation systems of fiber birefringence fluctuations [36]. Eventually, and importantly, the key figures of merit are a high rate of available photon-pairs, and a fidelity to the desired entangled state as close to unity as possible.

Based on the experimental setup depicted in Fig. 1, we outline in the following the principles of the main building blocks.

2.1. Photon-pair generation via type-0 spontaneous parametric down-conversion

Light from a continuous-wave (CW) pump laser at 780.24 nm is sent through a type-0 periodically poled lithium niobate waveguide (PPLN/W) in order to generate, via spontaneous parametric down-conversion (SPDC), paired photons around the degenerate wavelength of 1560.48 nm. Using a vertically polarized (V) pump beam, the type-0 interaction permits us to create vertically polarized twin photons, *i.e.*, $|V\rangle_p \overset{type-0}{\longmapsto} |V\rangle_s|V\rangle_i$, where the indices p, s, and i represent the pump, signal and idler modes, respectively. Utilizing the type-0 process presents two main advantages compared to the type-II interaction which produces cross-polarized photons, *i.e.*, in the state $|H\rangle_p \overset{type-II}{\longmapsto} |H\rangle_s|V\rangle_i$, as detailed in [22] and references therein. On one hand, the associated generation efficiency is at least 2 orders of magnitude higher. On the other hand, single photon bandwidth narrow filtering can readily be achieved using fiber filters, without problems with fiber birefringence. However, in contrast to the type-II interaction, where polarization entanglement can be formed by simply splitting the paired photons, the price to pay for using the type-0 process is a more complex experimental arrangement [24].

2.2. Bandwidth filtering stage

In principle, the bandwidth of the paired photons can be adapted at will depending on the desired quantum application. In our case, we work with fiber solutions only, compatible with all other elements of the source. By doing so, we avoid the losses due to in and out fiber coupling, yielding a higher long-term stability. After collection of the paired photons using a single mode fiber, we therefore take advantage of three filtering solutions based on telecom compatible components in order to demonstrate the versatility of our approach:

(a) a standard 100 GHz-spacing dense wavelength division multiplexing (DWDM) filter (AC photonics) compatible with DWDM-QKD protocols [2,22];
(b) a 540 MHz phase shifted fiber Bragg grating filter (PSFBG, from AOS GmbH) compatible with broad acceptance bandwidth quantum memories, based on, *e.g.*, room temperature atomic vapors or ion doped crystals [37–39];
(c) a 25 MHz PSFBG (Teraxion) compatible with the acceptance bandwidth of cold atom, and trapped ion based quantum memories [40,41].

Moreover, to avoid any polarization dependent transmission, and therefore degradation of entanglement, with the narrowband PSFBG filters, those have to be placed in front of the state preparation stage. The polarization state of the photons is adjusted beforehand using a fiber polarization controller (PC$_1$) (see more details below).

2.3. Polarization entanglement preparation stage

To prepare the polarization entangled state, we employ an unbalanced MZI made up of two fiber polarizing beam-splitters (f-PBS) connected by polarization maintaining fibers. This interferometer introduces a delay δt between the two polarization modes H (short arm) and V (long arm). By sending the paired photons prepared in the diagonal (D) state $|D\rangle_s|D\rangle_i$ into this device, the exit states are of the form:

$$|D\rangle_s|D\rangle_i \overset{Prep.}{\mapsto} \frac{1}{2}[|H\rangle_{s,e}|H\rangle_{i,e} + e^{i\phi/2}|H\rangle_{s,e}|V\rangle_{i,l} + e^{i\phi/2}|V\rangle_{s,l}|H\rangle_{i,e} + e^{i\phi}|V\rangle_{s,l}|V\rangle_{i,l}], \qquad (1)$$

where e and l refer to "early" and "late" time bins, respectively. Here, $\phi/2$ represents the phase difference between the short and long paths. Post-selecting only the cases where the two photons exit the interferometer simultaneously reduces the quantum state to $|\psi\rangle_{\text{post}} = \frac{1}{\sqrt{2}}[|H\rangle_{s,e}|H\rangle_{i,e} + e^{i\phi}|V\rangle_{s,l}|V\rangle_{i,l}]$. This time-bin type post-selection constraints δt to be greater than the coherence time of the photon (τ_p) and the detector timing jitters (τ_d). It is important to note that the labels e and l have physical meanings only if the photon-pair creation time is known. In the case of CW SPDC, the creation time uncertainty is directly given by the coherence time of the pump laser (τ_L). In this way, using a laser with a coherence time much greater than δt ensures a constant phase for the two contributions of interest, $|H\rangle_s|H\rangle_i$ and $|V\rangle_s|V\rangle_i$, and therefore allows obtaining polarization entangled states of the form:

$$|\psi\rangle_{\text{post}} = \frac{1}{\sqrt{2}}[|H\rangle_s|H\rangle_i + e^{i\phi}|V\rangle_s|V\rangle_i], \qquad (2)$$

where ϕ represents the phase experienced by the two-photon contribution $|V\rangle_s|V\rangle_i$ in the long arm of the interferometer. To summarize the operation principle described above, the source can produce, together with a proper post-selection, the maximally