Compact source of polarization-entangled photon pairs

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Abstract: We present a compact source of polarization-entangled photon pairs at a wavelength of 805 nm using a violet single-mode laser diode as the pump source of type-II spontaneous parametric down-conversion. The source exhibits entanglement and pair-rate comparable to conventional systems utilizing large frame ion lasers thus significantly increases the practicality of novel quantum information or quantum metrology applications.

OCIS codes: (270.0270) Quantum optics; (190.4410) Nonlinear optics, parametric processes

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Entangled states are key elements in the emerging field of quantum information processing such as in quantum computation [1], quantum communication schemes [2], quantum communication complexity [3] or quantum key distribution [4]. These states are also used for the fundamental tests of quantum theory via the violation of Bell inequalities [5]. In recent years, there has been an ongoing experimental effort to produce, manipulate and characterize entangled states. Two-photon polarization entangled states have been used in the implementation of quantum key distribution protocol [6]-[8], quantum teleportation [9], and very recently linear optics quantum computation [10]. In addition, the inherent entanglement of two-photon states is an indispensable resource for a number of different applications, e.g. in quantum metrology [11] or in entangled-photon-pair enhanced microscopy [12].

During the recent decade, type-II spontaneous parametric down-conversion process established itself as the standard method for the generation of polarization-entangled photon pairs [13]. In this process photons of an intense pump beam spontaneously convert in a nonlinear crystal with low probability into pairs of mutually orthogonally polarized photons, conventionally called signal and idler. Energy and momentum conservation in the nonlinear interaction ensures that the emitted photons exhibit nonclassical wavelength and emission direction correlations. When signal and idler photons have the same wavelength, referred to as degenerate case, the photons emerge from the crystal symmetrically to the pump beam along two cones, which intersect for certain orientations of the crystal optic axis. The polarization of each photon collected along the intersection lines is undefined, as it cannot be assigned to one of the two orthogonally polarized cones, but is perfectly anti-correlated with the polarization of the other one. Therefore, the polarization of these photons is entangled.

To ensure the high-level performance of any application using entangled photon pairs the selection of the proper operating wavelength must be done carefully. Generally, for systems utilizing the transport of photons in optical fibres, the most advantageous wavelengths turns out to be at $\lambda = 1.31\ \mu$m and $\lambda = 1.55\ \mu$m, i.e., at the low-absorption spectral windows of fibres. For these wavelengths the efficient laser diode pumped down-conversion sources have been developed [14], [15], however, the only applicable single-photon photodiodes made from germanium or InGaAs/InP semiconductor material show low efficiency and high dark count noise. The other interesting spectral region ranges from $\lambda = 600$ nm to $\lambda = 900$ nm, for which commercially available silicon avalanche photodiodes (Si APDs) show detection efficiencies of up to 70% and very low dark count noise. To generate photon pairs in this spectral region, the pump-beam wavelength for spontaneous parametric down-conversion has to be shorter than 450 nm. This requirement generally led to the use of large-frame ion lasers, which due to their high operating costs are not suitable for practical applications. Hence, a great deal of attention has been recently devoted to replace these cumbersome and expensive lasers. A compact entangled photon pair source was implemented using a frequency doubled red laser diode as a pump source [16], and several groups have also succeeded in building laser diode pumped source in the near-infrared (NIR) region using periodically poled nonlinear crystal, showing high conversion efficiencies, though without the possibility for direct generation of polarization entanglement in crystal [17], [18].

Here, we present a compact, robust and efficient source of polarization-entangled photon pairs in the spectral region around 800 nm using a violet laser diode. Due to optimized coupling the observed photon pair rates are comparable to standard parametric down-conversion sources utilizing powerful ion lasers. Our work represents an important step towards the implementation of many potentially commercial applications in the growing field of quantum information processing, such as in secure communication. Furthermore, the new source may be also employed for quantum metrology [11], precision measurements and for student laboratory courses [19]. The present work was enabled by the recent progress in the area of semiconductor physics, where blue and violet Gallium-Nitride based laser diodes have been developed [20]. With the continuing improvement of beam quality and output power of commercially available laser diodes the source soon will widely replace the large frame ion lasers in current set-ups.

Since in many applications a well-defined spatial mode is highly desirable, in our source single-mode fibres are used for coupling of the down-converted light. To increase a yield of polarization-entangled photon pairs, the method for optimizing their collection was adopted [21]. The leading idea behind this technique is to maximize the overlap between the intensity distribution of the parametric fluorescence light and the distribution of the fundamental transverse mode guided in the single-mode fibre. Similar approach is considered also in [22]. For a given spectral bandwidth of the fluorescence light to be collected, one then has to tilt the crystal optic axis in such a way that the emission cones intersect perpendicularly and use a Gaussian beam of specific waist size as the pump. The considerable merit of this technique is the definition of the spectral bandwidth of the coupled photons by the parameters of the pump beam and the collection optics. Thus, no interference filters are required. This leads furthermore to the advantage that the resultant efficiency of the source is not reduced.

The schematic layout of the source is shown in Fig. 1. As a pump source a single-mode cw laser diode (Nichia, NDHV310ACA) operating at 402.6 nm with a maximum output power of 24 mW at 60 mA driving current is used. The diode together with an aspheric collimation lens (focal length $f = 8$ mm) is mounted in an aluminium housing, which is temperature stabilized with a Peltier element to 20°C. The violet beam is focused to the desired waist size with a Galilean-type telescope, consisting of the collimation lens and a singlet lens ($f = -25$ mm). The elliptical profile of the pump beam is compensated using an additional cylindrical lens ($f = 300$ mm). Aiming for 6 nm spectral bandwidth of fluorescence light to be collected, the optimization method mentioned above determines the pump beam waist radius to be 72 μm. The 2 mm thick BBO ($\beta - \mathrm{BaB_2 0_4}$) crystal, cut for type-II phase matching at $\theta_{pm} = 42.13^\circ$, is placed at the waist position of the pump beam 230 mm behind the housing of the laser diode. For degenerate emission the intersection lines of the emission cones form an angle of 6° and the tangents in the crossing points are perpendicular to each other. The fluorescence light propagating along these lines passes a half-wave plate and additional BBO crystals with a thickness of 1 mm to compensate the transverse and longitudinal walk-off introduced by the birefringence of the conversion crystal. The residual violet light coming from the laser diode is blocked using long-pass filters. The photons are coupled into single-mode fibres at a distance of 365 mm from the emission point. This spacing is determined by the aspheric coupling lenses with focal length of $f = 7.5$ mm, the desired spectral bandwidth and the numerical aperture of

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the optical fibre. To keep the source compact, two mirrors were used to fold the paths of the fluorescence beams.

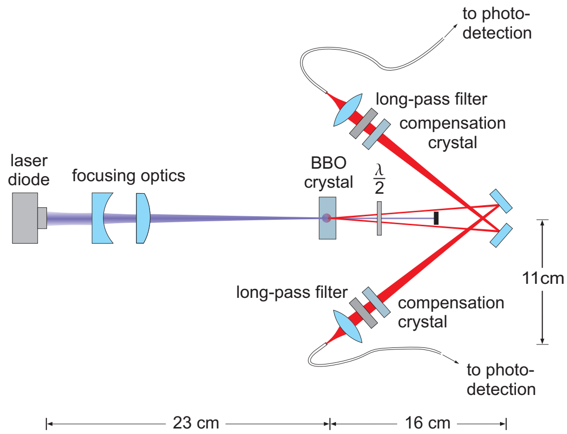

Fig. 1. Schematic set-up of the source. The single-mode cw laser diode operating at 402.6 nm pumps a 2 mm thick BBO crystal and produces polarization-entangled photon pairs at 805.2 nm collected into single-mode fibres. For compensation of the walk-off, two additional BBO crystals preceded by a half-wave retarder are used.

Figure 2 shows the linear dependence of single photon as well as coincidence count rate on the pump power. Using two passively quenched Si APDs (Perkin-Elmer, C30902S) with detection efficiencies of 36%, a slope of 220 coincidences per second and mW in the single-mode fibres was observed. For the maximum laser diode output power of 24 mW, this implies a coincidence count rate of 5200 s^{-1}. The estimated accidental coincidences are negligible for the gate time of $\tau_c = 10$ ns. The coincidence to single count ratio, characterizing the quality of coupling, is 0.19 over the whole range of pump power.

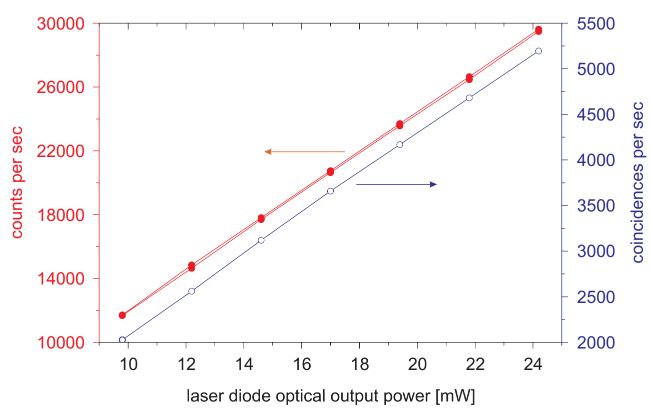

Fig. 2. Single (-•-) and coincidence (-∘-) count rates depending on the pump power measured right behind the violet laser diode.

In order to spectrally analyze the parametric fluorescence light coupled into single-mode fibres, the fibres were individually connected to a grating spectrometer with single-photon sensitivity. As shown in Fig. 3, the measured spectral distributions were mutually separated by only 0.22 nm around the degeneracy wavelength of 805.2 nm. The observed full widths at half

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maxima of 6.03 ± 0.14 nm and 6.24 ± 0.56 nm are in excellent agreement with the design parameters of the coupling-optimization method.

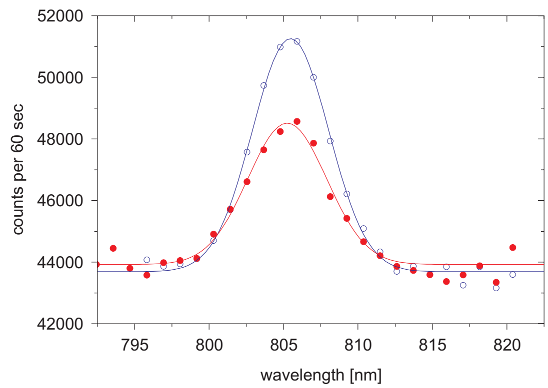

Fig. 3. Spectral distributions of the down-converted light collected into single-mode fibres. Both photons of the pair have nearly the same wavelength with separation only 0.22 nm around the degeneracy wavelength of 805.2 nm. The least-square Gaussian fit (solid lines) to measured data points shows FWHMs of 6.03 ± 0.14 nm (-○-) and 6.24 ± 0.56 (-●-), respectively. The offset of 44000 counts is due to the dark counts of the Si APDs.

To experimentally demonstrate the polarization entanglement of the collected photon pairs, their polarization correlations in two conjugate bases were measured. This was done by directing the down-converted light into adjustable polarization analyzers, each consisting of a polarizing beamsplitter cube preceded by a rotatable half-wave plate. After passing through the analyzers, the light was re-coupled into multi-mode fibres and detected with passively quenched Si APDs. Figure 4 clearly shows the expected $\sin^2$ dependence of the measured coincidence rates on the rotation angle φ_1 of one half-wave plate, while keeping the other one at fixed orientation of $\varphi_2 = 0^\circ$ or $\varphi_2 = 22.5^\circ$, respectively. For the setting of $\varphi_2 = 0^\circ$, corresponding to a detection of photons in H/V linear polarization basis, a visibility of $98.3 \pm 0.1\%$ was observed. For the second investigated setting of $\varphi_2 = 22.5^\circ$, i. e. a detection of photons in $+45^\circ / -45^\circ$ linear polarization basis, we obtained a visibility of $94.3 \pm 0.2\%$.

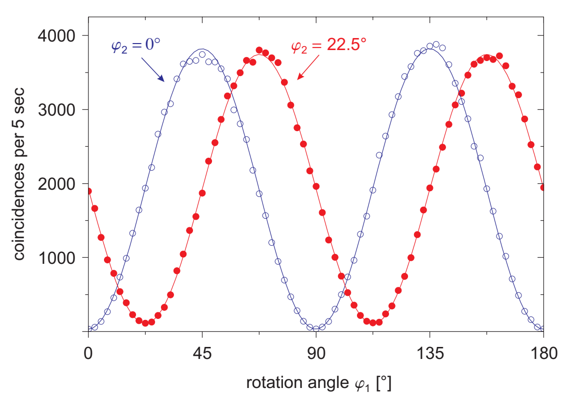

Fig. 4. Polarization correlations between photons of a pair measured in the H/V (-○-) and $+45^\circ / -45^\circ$ (-●-) polarization basis. The visibilities obtained from a $\sin^2$ fit (solid lines) to the measured coincidence count rates are $98.3 \pm 0.1\%$ and $94.3 \pm 0.2\%$, respectively.

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As a final demonstration of the source performance, we accomplished the measurement of a Clauser-Horne-Shimony-Holt (CHSH)-type Bell inequality. For this type of inequality any local hidden-variable model is bound by a correlation coefficient $|S| \leq 2$ whereas the maximum of $|S|$ according to quantum mechanics is $2\sqrt{2}$ [5]. By integrating the whole measurement over 80 s, we obtained the value S = -2.732 ± 0.017, corresponding to a violation of 44 standard deviations.

In summary, a source of polarization-entangled photon pairs in the NIR spectral region using a violet single-mode laser diode was presented. Due to optimized coupling the degree of the entanglement and the photon pair rates are comparable to conventional systems utilizing large-frame ion lasers [6],[7], making the source ideally suited for a variety of experiments or applications in new intriguing fields of quantum optics, where the continuous flux of polarization-entangled photon pairs in the NIR is required. The brightness of the source can be further increased with more powerful blue laser diodes available soon or with resonant enhancement techniques [23]. The performance and robust construction of the source could enable for the first time the outdoor demonstration of various quantum communication schemes, e.g. entanglement-based free-space quantum key distribution [24]. The simplicity of the whole system makes the source a very suitable tool to show practically the intriguing phenomenon of entanglement in undergraduate laboratory courses.

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