Compact all-solid-state source of polarization-entangled photon pairs

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(Received 25 April 2001; accepted for publication 4 June 2001)

A compact source of polarization-entangled photon pairs at a wavelength of 856 nm is realized using a frequency-doubled laser diode as the pump source for cavity-enhanced type-II spontaneous parametric down-conversion. Our setup generates photon pairs with entanglement visibility of ⩾95% and with count rates comparable to those of standard experiments based on large-frame ion lasers. [DOI: 10.1063/1.1389835]

Entangled photons are key elements in the field of quantum information and quantum communication and are required for methods like quantum teleportation and quantum dense coding.[1] Particularly quantum cryptography,[2] which is close to becoming the first practical application of quantum communication, significantly profits when applying entanglement-based schemes.[3,4] In addition, photon pairs are essential for recently proposed methods in quantum metrology[5] and for many investigations of basic quantum effects.

Type-II spontaneous parametric down-conversion (SPDC) has proven to be an effective and experimentally simple process for the creation of entangled photon pairs.[6] In this process, a pump beam is incident on a nonlinear optical crystal, in which pump photons spontaneously "split" with a low probability into two orthogonally polarized photons, usually called signal and idler photons. Energy and momentum conservation require that the wavelengths and emission directions of the down-conversion photons are tightly correlated. They depend on the pump wavelength as well as on the angle between the optical axis of the crystal and the pump beam. For signal and idler photons having the same wavelength (degenerate case), the photons leave the crystal symmetrically with respect to the pump beam along two cones, which intersect for certain orientations of the crystal axis. Photons emerging at these intersection directions cannot be assigned to one of the two orthogonally polarized cones anymore and thus form a polarization-entangled pair.

The performance of any application of quantum communication strongly depends on the single-photon detection efficiency. Silicon avalanche photodiodes (Si APDs) are widely used, because they show low noise and a detection efficiency of up to 70% for $\lambda = 600$–900 nm. To generate photon pairs in this regime, the pump wavelength for SPDC has to be shorter than 450 nm. Since currently no single-mode solid-state laser with an output power of more than a few mW is available for such wavelengths, large-frame ion lasers are usually used as the pump source. Yet, entangled photon pair sources based on ion lasers are large and expensive and not suited for practical applications. Recently, experiments using laser diode pumped down-conversion in periodically poled nonlinear crystals created pair photons in the near-infrared (NIR).[7] However, due to the limitation to collinear emission it is not clear whether the generation of polarization-entangled photons is feasible. The other interesting wavelengths for quantum communication systems are given by the telecom windows of optical fibers at $\lambda = 1.3$ μm and $\lambda = 1.55$ μm. For these wavelengths laser diode pumped down-conversion sources have been developed.[8] However, the only available single-photon detectors for this spectral regime (Ge or InGaAs APDs) exhibit high dark count noise and a very low detection efficiency.

Here, we present an all-solid-state source of entangled photon pairs in the high-efficiency region of Si detectors using a frequency-doubled laser diode as the pump and an optical resonator to enhance the type-II SPDC process. We start with a single-mode cw laser diode (SDL-5431-G1, output power 175 mW) at a wavelength of 856 nm (Fig. 1). The collimated light passes an anamorphic prism pair to compensate the elliptic beam profile and optical isolators with a total isolation of more than 70 dB. To achieve high efficiency of frequency doubling, resonant enhancement of the IR light[9] and the high nonlinearity of a $KNbO_3$ crystal (*a* cut) in a semimonolithic resonator configuration are used.[10] For this purpose, one end face of the crystal is flat and antireflection

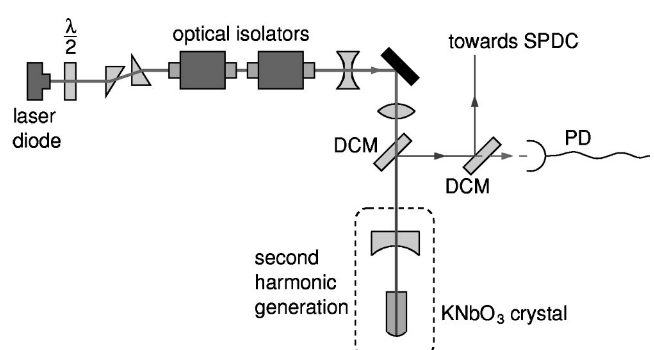

FIG. 1. Schematic setup of the frequency doubler. The light emitted from the laser diode passes an anamorphic prism pair, two optical isolators, and is mode matched to a resonator, where second-harmonic generation takes place. (DCM: dichroic mirror, PD: photo diode, λ/2: half-wave plate at 45°, SPDC: spontaneous parametric down-conversion).

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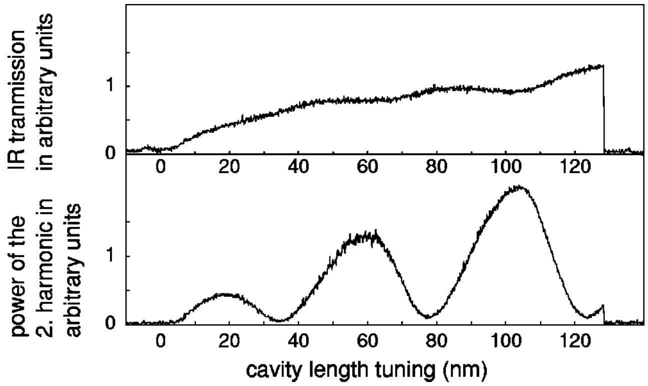

FIG. 2. IR cavity transmission and power of the second harmonic while tuning the cavity length over resonance within a sweep time of 13 s. The transmission shows a broad and asymmetric shape, while the second-harmonic power exhibits strong oscillations.

(AR) coated for the fundamental and second harmonic, while the other end face is curved (radius $r=5$ mm) and highly reflective for both wavelengths. This end face, together with the curved coupling mirror ($r=25$ mm, AR at 428 nm, reflectivity $R=95\%$ at 856 nm), forms the resonator with an optical length of 41.6 mm and a pump waist of 13 μm located inside the crystal. From the finesse $F=80$ of the cavity we derive an enhancement of the pump intensity of 33. To maintain an optimal noncritical phase-matching condition, the temperatures of the crystal and laser diode are stabilized with Peltier elements to 18 and 22 °C, respectively, to an accuracy of better than 0.1 K. A fraction of the back-reflected IR light is used to stabilize the cavity on the laser diode frequency with a Pound–Drever-like scheme with sidebands at 50 MHz obtained by current modulation of the laser diode.[11]

From a power of 125 mW incident on the doubling cavity we obtained up to 12 mW for the second harmonic. Yet, thermal effects occurring along with the generation of the blue light made long-time stable operation difficult. Figure 2 shows the transmission of the doubling cavity and the corresponding power of the second harmonic when slowly increasing the length of the resonator. The IR transmission is strongly asymmetric, slowly increasing towards resonance with a sudden drop to zero from the maximum value. We attribute this to heating of the crystal by the IR pump beam. We avoided this thermal instability by choosing a lock point below maximum transmission for the cavity length control. Furthermore, the power of the generated blue light shows oscillations when varying the cavity length, which are likely due to effects caused by blue enhanced infrared absorption.[12] Similar instabilities in $KNbO_3$ at these particular short wavelengths have been reported previously.[13] Stable operation could be achieved by changing the external crystal temperature 1.5 K below the phase-matching temperature.

The generated second harmonic with $\lambda=428$ nm and a power of about 6 mW is used as the pump light for SPDC, after separating it from the IR light by dichroic mirrors and a bandpass filter. To be competitive with conventional arrangements with typical pump powers of 100–500 mW, significant increase of the photon pair yield is necessary for this source. Thus, the intensity of the second harmonic is enhanced in a second resonator, which has a similar semimonolithic design

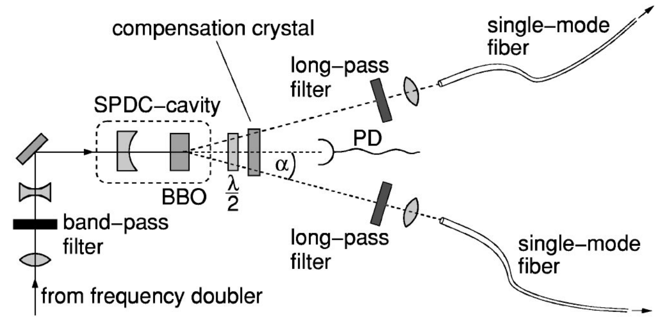

FIG. 3. Schematic view of the setup used to create entangled photon pairs. Blue light is incident on a cavity containing a nonlinear crystal (BBO). The photon pairs generated by SPDC are emitted under $\alpha=4°$. After passing a half-wave plate and the compensation crystal, they are coupled into single-mode optical fibers.

as above and which contains a BBO (β-BaB_2O_4) crystal for SPDC.[14] The frontside of the 2-mm-long crystal (cut for type-II SPDC) is AR coated for both 428 and 856 nm, whereas the backside is AR coated for 856 nm and highly reflective for 428 nm. This backside, together with the curved coupling mirror ($r=300$ mm, $R=97\%$ at 428 nm and AR at 856 nm), forms the cavity for the blue light (Fig. 3). Optimization of the coupling efficiency of the down-converted photons into single-mode fibers[15] determines the geometrical parameters of the cavity to a pump waist of 110 μm in the BBO crystal. The optical length of the resonator is, therefore, fixed to 31 mm. We measured a cavity finesse of $F=67.5$ corresponding to an enhancement of the pump intensity of 13.7. The length of the resonator was stabilized to maximum transmission of the blue light using a dither-lock scheme. Impedance matching of the second cavity is important, because back-coupling of blue light into the frequency doubler leads to further instabilities of the second-harmonic power.

The angle between the extraordinarily polarized pump beam and the optical axis of the BBO crystal is 40.3°, so down-converted photons with twice the pump wavelength leave the crystal under a half-opening angle of $\alpha=4°$. They pass a half-wave plate and a second (1-mm-long) BBO crystal to compensate walk-off,[6] and are coupled into single-mode optical fibers, directing the light to Si APDs for detection. Figure 4 shows single-photon and photon pair count rates measured as a function of SPDC cavity tuning. They exhibit Lorentzian dependency, well according to the fact that SPDC fluorescence is proportional to the circulating

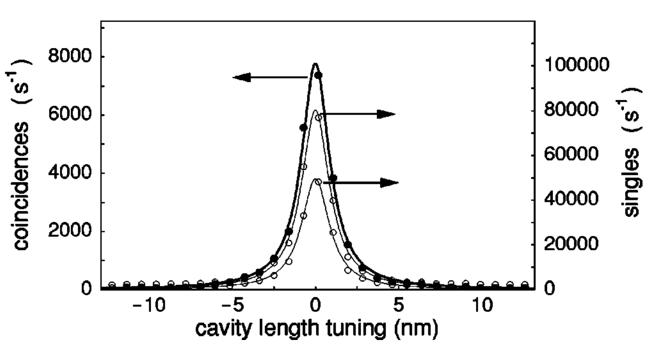

FIG. 4. Single (-○-) and coincidence (-●-) count rates as a function of length tuning of the SPDC resonator (with 5 mW pump power). The solid lines are least-square fits of Lorentzians of the measured data.

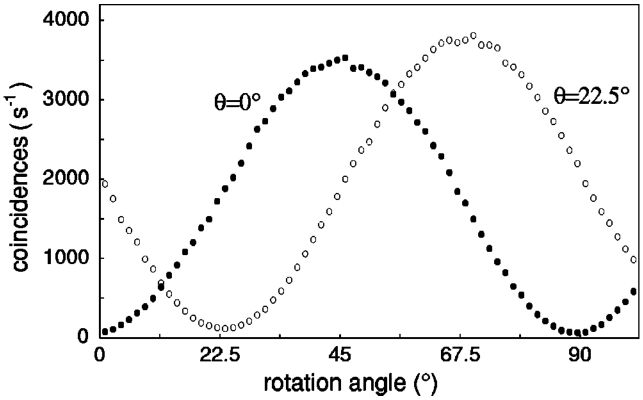

FIG. 5. Coincidence count rates measured when rotating the half-wave plate in front of a polarizer in one arm, while the half-wave plate in front of the other polarizer (selecting the detection base) was fixed to $\theta=0°$ (-●-) and $\theta=22.5°$ (-○-), respectively, showing a visibility of more than 97% ($\theta=0°$) and 95% ($\theta=22.5°$).

power in the cavity. The achieved rates of about 10 000 coincidences per second in single-mode fibers on resonance (with 6.5 mW pump power) are comparable to or better than the count rates of most recent down-conversion experiments,[3,16] all operating with large-frame ion lasers.

The entanglement of the collected photon pairs was determined by measuring their polarization correlation in different bases. For this purpose a half-wave plate and a calcite polarizer were arranged in front of each fiber. Figure 5 shows the measured coincidence rates for different orientations of one half-wave plate, while keeping the other at fixed orientations of $\theta=0°$ and 22.5°, thus setting the detection basis in this arm to H/V or $+45°/-45°$, respectively. Thereby, a visibility of more than 97% in the H/V and 95% in the $+45°/-45°$ basis was observed. This is comparable with other state of the art entangled photon pair sources and well suited for quantum information applications. A further benchmark in the characterization of entanglement of photon pairs is a test of Bell's inequality, e.g., in the Clauser–Horne–Shimony–Holt (CHSH) formulation.[17] From an integration time of only 5 s per data point, we achieved a value of $S=2.629\pm0.0074$ for the combined correlation coefficient that exceeds the maximal value of 2 allowed by local realistic theories by 85 standard deviations.

To summarize, polarization-entangled photon pairs in the NIR can be efficiently created with an all-solid-state source. The photon pair rates are comparable to those observed with ion-laser systems, but at much lower costs and experimental effort. The advent of reliable blue single-mode laser diodes will allow a further simplification of the setup. Polarization entanglement of the created photon pairs was demonstrated with the measurement of the polarization correlation in H/V and $+45°/-45°$ basis and by violating the CHSH–Bell inequality. This system, therefore, provides a compact, cheap, and easy to handle alternative for many applications in quantum information, photon-pair-enhanced microscopy, quantum metrology, or other experiments, where the continuous availability of polarization entangled photon pairs in the NIR region is needed.

One of the authors (H.W.) acknowledges initial discussions with R. Egger. This work was supported by the Deutsche Forschungsgemeinschaft and the ESPRIT Project QUCOMM (IST-1999-10033).

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