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Cavity-enhanced generation of polarization-entangled photon pairs

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Abstract

Spontaneous parametric down-conversion (SPDC) is the most common source in quantum optics for generating correlated photon pairs. Yet, the low efficiency reduces its applicability. By placing the crystal in a linear cavity for the pump mode we achieved a factor of 7 enhancement of the pair production rate, thus enabling improved experiments and bringing an all-solid state source of NIR © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Photon pairs, as created by spontaneous parametric down-conversion (SPDC) [1] have become an important tool in experiments on the foundations of quantum mechanics [2]. The inherent entanglement between the photons created by this process makes them indispensable for quantum communication [3] and, lacking applicable single photon sources, also for quantum cryptography [4]. In SPDC photons of an intense pump laser beam convert into photon pairs when interacting with a nonlinear medium according to the phase matching conditions [5]. Although SPDC outperforms other sources of photon pairs, e.g. atomic cascade emissions, by far, the quality of many experiments suffers from the low conversion efficiency. Even when using large frame ion lasers as the pump source, one still has to find an unpleasant compromise between high interference visibility on the one side and reasonable count rates on the other side, which, however, often can be achieved only when accepting large spectral bandwidth or poor mode quality.

In this letter we show that the efficiency of the down-conversion source can be significantly increased by resonant enhancement of the pump field with an optical cavity. Increasing the yield of down-conversion photons is mandatory for a series of new experiments and possible applications in quantum communication and should finally allow us to replace the expensive pump laser, usually an Argon-ion laser, by a compact and inexpensive diode laser source.

Two further ideas of enhancing the yield of SPDC-sources have been presented recently. The

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first idea deals with a two-crystal geometry realized with type-I BBO-crystals, whose optical axes are mutually perpendicular. This enables one to use the higher conversion efficiency of type-I crystals also for generating polarization entangled photon pairs [6]. The second idea enhances the degenerate parametric down-conversion modes with an optical cavity to enforce the conversion of the pump photons [7]. In that special experiment the photon pairs are degenerated in momentum and wavelength, however, variation of this technique might also yield entangled pairs [8]. Our experiment complements these other developments.

2. Setup of the experiment

The experimental realization is schematically shown in Fig. 1. The pump light with a wavelength of 351 nm was provided by a single-line, single-frequency Argon-ion laser of 60 MHz bandwidth, followed by a dispersion prism to remove unwanted laser fluorescence. The pump beam was focused into the linear cavity by a telescope, consisting of three lenses (L_1, L_2, L_3), to control waist size w_0 and waist position d_0 independently by adjusting either the first or the third lens.

The flat cavity output mirror M_2 was coated to have a reflectivity of 99.99% for the fundamental wave and to be highly transparent ($T = 85\%$) for the down-conversion beams at 702 nm wavelength. The BBO-crystal was anti-reflection coated for 351 nm giving a transmission through the crystal of 99.2%. For impedance matching, the input mirror M_1 was thus coated for 4% transmission at 351 nm. This mirror had a radius of curvature of 20 m resulting, for a cavity length of 2 cm, in a beam waist of $w_0 = 265\ \mu$m. This waist ensures stable operation of the cavity and is still big enough not to broaden the

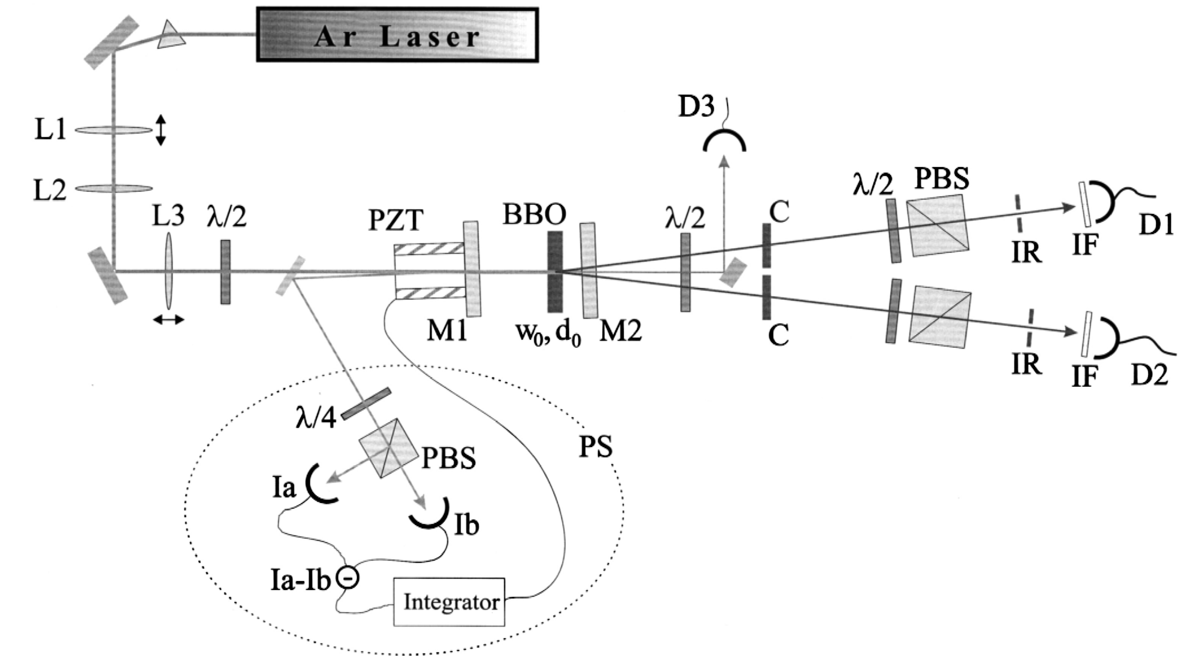

Fig. 1. Experimental setup: Lenses L1, L2, L3 allowed mode matching of the Ar^+-laser light to the cavity formed by mirrors M1 and M2. Entanglement between photon pairs produced by the BBO crystal was improved by half-wave plate ($\lambda/2$) and compensator crystals (C) and analyzed by adjustable half-wave plates and polarizing beam splitters (PBS). The entangled photons were selected by irises (IR, 2 mm) and interference filters (IF) and registered by Silicon avalanche single photon detectors (D1, D2). The UV-cavity was stabilized by polarization spectroscopy (PS) and analyzed by the transmission to photodiode D3.

momentum phase matching condition. With these optical and geometrical parameters and assuming perfect mode matching an enhancement $A = 45$ of the pump mode intensity was considered achievable [9]. In this case the enhancement factor $A = I/I_0$ was given by the ratio of the intensity I in the cavity to the incident laser intensity I_0.

The input mirror M_1 was mounted on a piezo tube (PZT), which allowed us to tune the cavity or to lock on resonance. The stabilization of the cavity resonance frequency to the laser frequency was achieved by polarization spectroscopy [10] of the laser beam partly reflected at the cavity. In order to avoid loss we omitted the linear polarizer inside the cavity. The cavity was therefore resonant not only to one polarization component but to both polarization components (vertical and horizontal), yet, due to the birefringence of the crystal, at different resonator lengths. Fig. 2a shows the (theoretical) enhancement for zero tilt of the cavity when changing the cavity length or phase, respectively. The stabilization unit itself consisted of a half-wave plate ($\lambda/2$) in the pump beam, which rotated the vertical polarization by a small amount, and polarization analysis for circular polarization. As in the original scheme, the polarization of the light reflected from the cavity remained linear at resonance and thus gave a zero in the error signal obtained by electronic subtraction of the photodiode signals I_a and I_b. The calculated error signal is illustrated in Fig. 2b). Since the zero crossings of the two resonances exhibited different gradients, they could be distinguished and the relevant resonance could be selected.

In order to avoid disturbing optical feedback by reflections from the cavity back to the pump laser either an optical isolator had to be used or the axis of the pump cavity had to be slightly tilted relative to the pump beam. Both possibilities reduce the maximal achievable pump power: either by absorption in the isolator or by reduction of the pump field enhancement. For this first demonstration, we decided to tilt the cavity by about 0.5 mrad, which reduced the theoretically achievable enhancement to $A = 11$.

The BBO-crystal, with a thickness of 2 mm, was cut for type-II phase matching at $\theta_{pm} = 51.1°$ so that the horizontally and the vertically polarized light cones of 702 nm wavelength overlapped along two spatially separated directions [11], enclosing an angle of 6°. To obtain high degree of entanglement, the emitted photons passed a half-wave plate and compensator crystals to compensate the transverse and longitudinal walk-off effects caused by the birefringence of the down-conversion crystal [12]. By slightly tilting the compensator crystals the quantum state of the photon pairs could be adjusted, e.g. to the Bell-state $|\Psi\rangle^+ = 1/\sqrt{2}(|H\rangle|V\rangle + |V\rangle|H\rangle)$. Interference filters (IF) centered at 702 nm in front of both detectors limited the bandwidth to 5 nm (FWHM) and reduced background radiation. Two irises with apertures of 2 mm and 85 cm away from the crystal defined the down-conversion modes to achieve high polarization-correlation. Silicon avalanche photodiodes (Si-APD's) were used to detect single photons, coincidences were selected within a 2 ns time window.

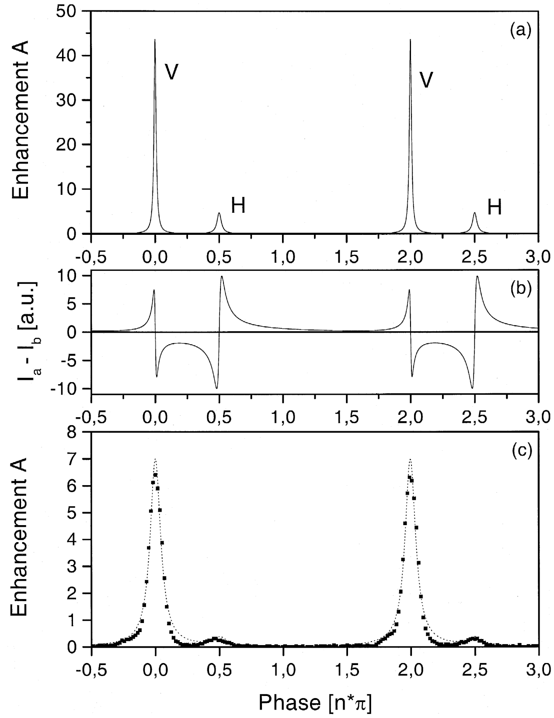

Fig. 2. (a) Calculated enhancement $A = I/I_0$ of the pump intensity inside the cavity and (b) resulting error signal ($I_a - I_b$) from polarization spectroscopy. Enhancement and error signal are shown dependent on the resonator phase. (c) Measured enhancement of the pump intensity for the tilted cavity when varying the resonator length (thus the resonator phase).

3. Results

In this first test we achieved an enhancement of $A = 7.00 \pm .06$, as compared to the theoretical enhancement of 11, for the pump intensity inside the tilted cavity. The intensity enhancement decreased very fast when tilting the cavity because the almost flat mirrors caused a fast dispersion of the field. Yet, after tilting the cavity axis and thus avoiding any disturbance of Argon-ion laser, the whole system was running stable over hours. The resulting pump field intensity (Fig. 2c) was analyzed with photodiode D_3 measuring the transmitted pump beam behind mirror M2 while the cavity length was varied with a piezo (PZT). Sharp airy intensity peaks occurred, when the cavity was on resonance with one of the two polarization components. The enhancement factor A was obtained by comparing the transmitted laser power with and without mirror M1 inserted in the cavity.

In Fig. 3 the coincidence count rates with and without mirror M1 are compared. As a consequence of the phase matching condition, parametric down-conversion only occurred for the vertical polarization component of the pump laser. For cavity on resonance with this polarization mode, the coincidence count rate was enhanced and an absolute coincidence count rate of 10 500 s^{-1} for 100mW laser pump power and iris apertures of 2 mm was reached. This rate is 7 times higher than the coincidence count rates without a cavity, where we obtained 1 500 s^{-1} with mirror M1 removed.

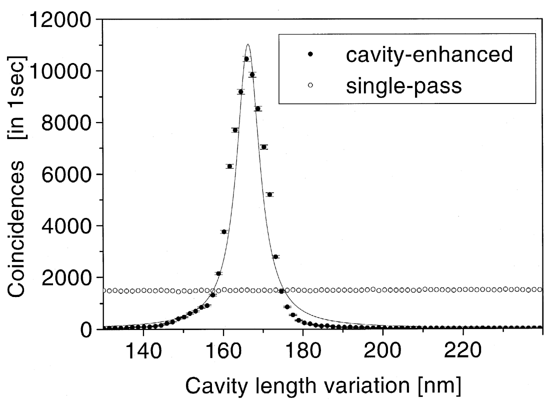

Fig. 3. Cavity-enhanced (circles) and single-pass coincidence count rates (squares) in dependence of the cavity tuning. For the measurement of the non-enhanced coincidence count rate input mirror M1 was removed.

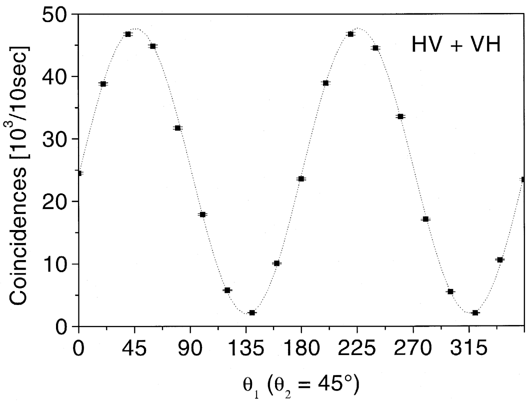

Fig. 4. Measurement of the polarization entanglement for photon pairs in the $|\Psi^+\rangle$-state when polarization analyzer 1 was varied while analyzer 2 was set to $+45°$. A visibility of $V = 92.2 \pm .3\%$ was observed for iris diameter of 2 mm.

Furthermore, the polarization-entanglement of the photon pairs was measured to completely characterize the source. Entanglement was analyzed with adjustable polarizers, consisting of a rotatable half-wave-plate and a polarizing beam splitter, in each arm. The degree of correlation was determined by measuring the polarization correlation along horizontal and vertical polarization (HV-basis) and under $\pm 45°$. Fig. 4 clearly exhibits the expected sinusoidal polarization-correlation for the $|\Psi^+\rangle$-state measured in the $\pm 45°$-basis, i.e. by rotating one polarizer and keeping the other fixed at 45°. In this measurement the iris-apertures were again set to 2 mm resulting in a visibility of $V = 92.2 \pm .3\%$ compared with a visibility of $V = 96.1 \pm .1\%$ without cavity. For iris-apertures of 1 mm a fringe visibility of $V = 94.8 \pm .3\%$ was achieved. We attribute the reduced visibility to the fact that, due to the tilt of the cavity, SPDC was not pumped by the well defined Gaussian mode but rather by the resulting cavity field with a full width of about 1.6 mm. The use of an optical isolator avoids such a reduction of the visibility.

4. Conclusion and outlook

In this first proof-of-principle demonstration the use of a cavity for the pump-laser has enabled an increase of the yield of polarization entangled photon pairs by a factor of 7. Employing an optical isolator instead of tilting the cavity, and taking absorption losses and non-perfect mode-matching into account, a further enhancement by a factor of 3 should be possible. As the down-conversion rate is proportional to power and crystal length the possibility of using a more intense laser or a longer crystal instead of the pump-cavity scheme comes into mind. A more intense laser, however, would immensely increase the expenses, whereas a longer crystal would inevitably enlarge the transverse walk-off effect such that it cannot be corrected anymore.

The method presented here allows better quality experiments with photon pairs created by parametric down-conversion. The increase achieved allows narrower filtering or finer mode selection of the entangled photons. Resonant enhancement of the pump field should also enable the use of frequency-doubled laser diodes or of the new blue laser diode [13] for down-conversion experiments in the near infrared, where efficient low-noise detectors exist. Thus applications like quantum communication or demonstration set-ups for experiments on the foundations of quantum mechanics become possible in experimentally simple environments.

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References

[1] D.C. Burnham, D.L. Weinberg, Phys. Rev. Lett. 25 (1970) 84.

[2] R.Y. Chiao, P.G. Kwiat, A.M. Steinberg, in: B. Bederson, H. Walther (Eds.), Advances in Atomic, Molecular and Optical Physics, Academic Press, New York (1994), Vol. 34; J.G. Rarity, P.R. Tapster, Phil. Trans. R. Soc. Lond. A 355 (1997) 2267; A. Zeilinger, Rev. Mod. Phys. 71 (1999) 288.

[3] K. Mattle, H. Weinfurter, P.G. Kwiat, A. Zeilinger, Phys. Rev. Lett. 76 (1996) 4656; D. Bouwmeester, J.W. Pan, K. Mattle, M. Eibl, H. Weinfurter, A. Zeilinger, Nature 390 (1997) 575.

[4] C.H. Bennett, G. Brassard, N.D. Mermin, Phys. Rev. Lett. 68 (1992) 557; A.K. Ekert, Phys. Rev. Lett. 69 (1992) 1293; T. Jennewein, Chr. Simon, G. Weihs, H. Weinfurter, A. Zeilinger, Phys. Rev. Lett. 84 (2000) 4719; D.S. Naik, C.G. Peterson, A.G. White, A.J. Berglund, P.G. Kwiat, Phys. Rev. Lett. 84 (2000) 4733; W. Tittel, J. Brendel, H. Zbinden, N. Gisin, Phys. Rev. Lett. 84 (2000) 4737.

[5] R.W. Boyd, Nonlinear Optics, Academic Press, San Diego CA (1992).

[6] P.G. Kwiat, E. Waks, A.G. White, I. Applebaum, P.H. Eberhard, Phys. Rev. A 60 (1999) 773.

[7] Z.Y. Ou, Y.J. Lu, Phys. Rev. Lett. 83 (1999) 2556.

[8] J.H. Shapiro, N.C. Wong, J. Opt. B: Quantum Semiclass. Opt. 2 (2000) L1.

[9] M. Brieger, H. Büsener, A. Hese, F. v. Moers, A. Renn, Opt. Commun. 38 (1981) 423; C.C. Davis, Lasers and Electro-Optics, Cambridge University Press, Cambridge, 1996.

[10] T.W. Haensch, B. Couillaud, Opt. Commun. 35 (1980) 441.

[11] P.G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, A.V. Sergienko, Y. Shih, Phys. Rev. Lett. 75 (1995) 4337.

[12] M.H. Rubin, QD.N. Klyshko, Y.H. Shih, A.V. Sergienko, Phys. Rev. A 50 (1994) 5122.

[13] Laser diode model NLHV500A, Nichia Corporation, www.nichia.co.jp.