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Experimental Engineering of Photonic Quantum Entanglement

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1. Introduction

Entangled photons are a crucial resource for linear optical quantum communication and quantum computation. Besides the remarkable progress of photon state engineering using atomic memories (Kimble (2008); Yuan et al. (2008)) the majority of current experiments is based on the production of photon pairs in the process of spontaneous parametric down-conversion (SPDC), where the entangled photon pair is concluded from post-selection of randomly occurring coincidences. Here we present new insights into the heralded generation of photon states (Barz et al. (2010); Wagenknecht et al. (2010)) that are maximally entangled in polarization (Schrödinger (1935)) with linear optics and standard photon detection from SPDC (Kwiat et al. (1995)). We utilize the down-conversion state corresponding to the generation of three pairs of photons, where the coincident detection of four auxiliary photons unambiguously heralds the successful preparation of the entangled state (Śliwa & Banaszek (2003)). This controlled generation of entangled photon states is a significant step towards the applicability of a linear optics quantum network (Nielsen & Chuang (2000)), in particular for entanglement distribution (Bennett et al. (1996)), entanglement swapping (Kaltenbaek et al. (2009); Pan et al. (1998)), quantum teleportation (Bouwmeester et al. (1997)), quantum cryptography (Bennett & Brassard (1984); Ekert (1991); Jennewein et al. (2000)) and scalable approaches towards photonics-based quantum computing schemes (Browne & Rudolph (2004); Gottesman & Chuang (1999); Knill et al. (2001)).

2. Background

Photons are generally accepted as the best candidate for quantum communication due to their lack of decoherence and their possibility of photon broadcasting (Bouwmeester et al. (2000)). However, it has also been discovered that a scalable quantum computer can in principle be realized by using only single-photon sources, linear-optics elements and single-photon detectors (Knill et al. (2001)). Several proof-of-principle demonstrations for linear optical quantum computing have been given, including controlled-NOT gates (Gasparoni et al. (2004); O'Brien et al. (2003); Pittman et al. (2003; 2001); Sanaka et al. (2004)), Grover's search algorithm (Grover (1997); Kwiat et al. (2000); Prevedel et al. (2007)), Deutsch-Josza

algorithm (Deutsch (1985); Tame et al. (2007)), Shor's factorization algorithm (Lanyon et al. (2007); Lu et al. (2007); Politi et al. (2009)) and the promising and new model of the one-way quantum computation (Chen et al. (2007); Kiesel et al. (2005); Prevedel et al. (2007); Vallone et al. (2008); Walther et al. (2005)). A main issue on the path of photonic quantum information processing is that the best current photon source, SPDC, is a process where the photons are created at random times (Zukowski et al. (1993)). All photons involved in a protocol need to be measured including a detection of the desired output state. This impedes the applicability of many of the beautiful proof-of-principle experiments, especially when multiple photon-pairs are involved (Bouwmeester et al. (2000)).

Other leading technologies in this effort are based on other physical systems including single trapped atoms and atomic ensembles (Kimble (2008); Yuan et al. (2008)), quantum dots (Michler et al. (2000)), or Nitrogen-Vacancy centers in diamond (Kurtsiefer et al. (2000)). Although these systems are very promising candidates, each of these quantum state emitters faces significant challenges for realizing heralded entangled states; typically due to low outcoupling efficiencies or the distinguishability in frequency.

Within linear optics several approaches exist to overcome the probabilistic nature originating from SPDC and to prepare two-photon entangled states conditioned on the detection of auxiliary photons (Eisenberg et al. (2004); Hnilo (2005); Śliwa & Banaszek (2003); Kok & Braunstein (2000b); Pittman et al. (2003); Walther et al. (2007)). It was shown that the production of one heralded polarization-entangled photon pair using only conventional down-conversion sources, linear-optics elements, and projective measurements is not possible with less than three initial pairs (Kok & Braunstein (2000a)). Here we describe an experimental realization for producing heralded two-photon entanglement along these lines, suggested by Śliwa and Banaszek that relies on triple-pair emission from a single down-conversion source (Śliwa & Banaszek (2003)). This scheme shows significant advantages compared to other schemes where either several SPDC sources (Pittman et al. (2003)) or more ancilla photons (Walther et al. (2007)) are required.

Current down-conversion experiments allow for the simultaneous generation of up to six photons (Lu et al. (2009; 2007); Prevedel et al. (2009); Radmark et al. (2009); Wieczorek et al. (2009); Zhang et al. (2006)) with typical detection count rates, dependent on the experimental configuration, of about 10^{-3} to 10^{-1} s^{-1} . In the demonstrated case the coincident detection of four photons is used to predict the presence of two polarization entangled photons in the output modes. The auxiliary photons thus herald the presence of a Bell state without performing a measurement on that state.

3. Theory and experimental design

Figure 1 gives a schematic diagram of the used setup to generate the heralded state

$$|\phi^+\rangle = \frac{1}{\sqrt{2}} \left(t_{1H}^\dagger t_{2H}^\dagger + t_{1V}^\dagger t_{2V}^\dagger \right) |vac\rangle, \quad (1)$$

where H and V denote horizontal and vertical polarization, respectively, whereas t_1 and t_2 correspond to the transmitted modes after the beam splitters. For generating the heralded state, $|\phi^+\rangle$, three photon pairs have to be emitted simultaneously into spatial modes a_1 and a_2 , which can be expressed in terms of creation operators:

$$|\Psi_3\rangle = \frac{1}{12} \left(a_{1H}^\dagger a_{2V}^\dagger - a_{1V}^\dagger a_{2H}^\dagger \right)^3 |vac\rangle. \quad (2)$$

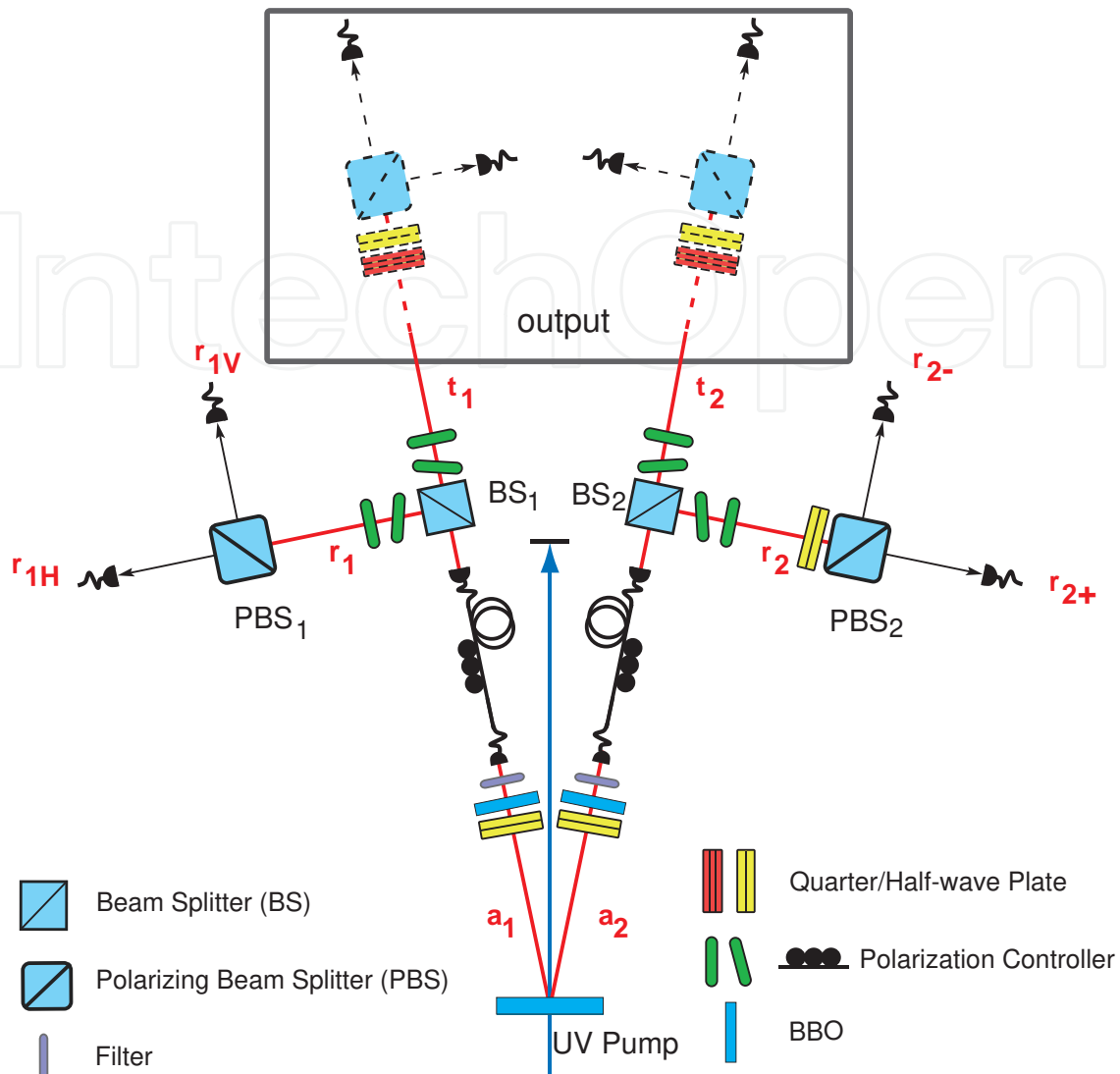


Fig. 1. Setup for the heralded generation of entangled photon pairs. Six photons are created simultaneously by exploiting higher-order emissions in a spontaneous parametric down-conversion process. The photons are brought to beam splitters and the reflected modes are analyzed in $|H/V\rangle$ basis and in $|\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle \pm |V\rangle)$ basis, respectively, using polarizing beam splitters and half-wave plates. State characterization of the heralded photon pair in the transmitted modes is performed via polarization analysis and the help of quarter-wave plates, half-wave plates and polarizing beam splitters.

These photons are guided to non-polarizing beam splitters (BS1 and BS2) with various splitting ratios. The scheme only succeeds when four photons, two photons at BS1 and BS2, respectively, are reflected, and detected in each of the output modes as four-fold coincidence. The two reflected photons of BS1 are projected onto the $|H/V\rangle$ basis for mode r_1 , while the two reflected photons of BS2 are measured in the $|\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle \pm |V\rangle)$ basis for mode r_2 .

Only the case where one photon is present in each of the modes $r_{1H,1V}$ and $r_{2+,2-}$ is of interest for a successful heralding of the output state. Considering only these terms, the output state

results in

$$|\Psi_3\rangle = C(\theta_1, \theta_2) \cdot \frac{1}{\sqrt{2}} \left(t_{1H}^\dagger t_{2H}^\dagger + t_{1V}^\dagger t_{2V}^\dagger \right) \cdot r_{1H}^\dagger r_{1V}^\dagger r_{2+}^\dagger r_{2-}^\dagger |vac\rangle \quad (3)$$

where $C(\theta_1, \theta_2)$ is a constant depending on transmission coefficients of beam splitters. The coincident detection of one and only one photon in the modes r_{1H} , r_{1V} , r_{2+} and r_{2-} heralds the presence of an entangled photon pair in $|\phi^+\rangle$ state in the output modes t_1, t_2 .

In the present scheme such a case can only be achieved by three (or more)-pair emission from SPDC. The contribution from two-pair emission is suppressed by destructive quantum interference in the half-wave plate (HWP) rotation used for $r_{2+,2-}$. At this specific angle any possible four-photon state, emitted into the four modes, $r_{1H,1V}$ and $r_{2+,2-}$, will result only in a three-fold coincidence when projected on the $|H/V\rangle$ basis. Thus, these two photons will never contribute to a fourfold coincidence. This results from the quantum interference (see Figure 2) of

$$r_{2+}^\dagger r_{2-}^\dagger = r_{2H}^\dagger r_{2H}^\dagger - r_{2V}^\dagger r_{2V}^\dagger. \quad (4)$$

This quantum interference together with the use of number-resolving detectors ensures that the remaining two photons are found in the transmitted modes. If a high transmittance of the beam splitters is chosen, it still can be assumed that the two photons are transmitted even without the use of number-resolving detectors. The quantum interference can be seen when rotating the HWP in mode r_2 . Figure 2 shows this dependency of the four-fold coincidences with a visibility of $(86.7 \pm 1.2)\%$

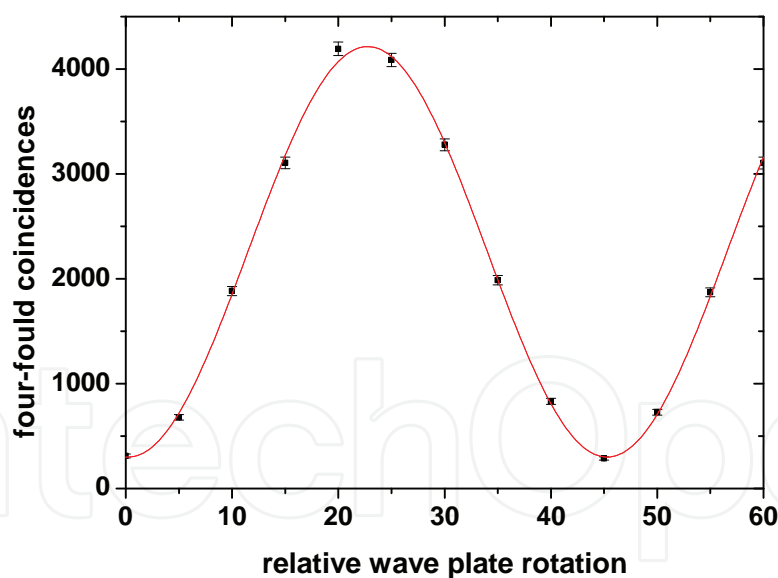


Fig. 2. Visibility of the four-fold coincidences at the reflected modes r_{1H}, r_{1V} and r_{2+}, r_{2-} . The quantum interference for the detected two-pair emission can be seen with respect to the half-wave plate (HWP) used for r_{2+}, r_{2-} . At the specific HWP rotation of 0° relative to the $|\pm\rangle$ basis, the curve shows a suppression of the corresponding four-photon detection. An angle of 22.5° relative to the $|\pm\rangle$ basis results in a measurement in the $|H/V\rangle$ and thus leads to a maximum of the four-fold rates. This quantum interference is a key feature of the experiment as it enables the triggering on the desired six-photon emission by measuring only four detection events.

4. Experimental setup

Six photons in the $|\Psi_3\rangle$ -state are produced simultaneously by using higher-order emissions of a non-collinear type-II SPDC process. A mode-locked Mira HP Ti:Sa oscillator is pumped by a Coherent Inc. Verdi V-18 laser to reach output powers high enough to be able to exploit third-order SPDC emissions. The pulsed-laser output ($\tau = 200$ fs, $\lambda = 808$ nm, 76 MHz) is frequency-doubled using a 2 mm thick Lithium triborate (LBO) crystal, resulting in UV pulses of 1.2 W cw-average. A stable source of UV-pulses is achieved by translating the LBO with a stepper-motor to avoid optical damage to the anti-reflection coating of the crystal (count-rate fluctuations less than 3 % over 24 h). Afterwards, dichroic mirrors are used to separate the up-converted light from the infrared laser light.

The UV beam is focused on a 2 mm-thick β -barium borate (BBO) crystal cut for non-collinear type-II parametric down-conversion. Half-wave plates and additional BBO-crystals compensate walk-off effects and allow the production of any Bell-state. Narrowband interference filters ($\Delta\lambda = 3$ nm) are used to spatially and spectrally select the down-converted photons which are then coupled into single mode fibers that guide them to the analyzer setup. At this detection unit, the photon pairs are directed to non-polarizing beam splitters with different splitting ratios for different experiment runs. The reflected modes are analyzed in $|H/V\rangle$ basis and in $|\pm\rangle$ basis, respectively, as described above. This is implemented by using a half-wave plate (HWP) oriented at 45° followed by PBS2.

5. Methods

In the demonstrated case of using standard detectors (photo-avalanche diodes by PerkinElmer) the transmission of the non-polarizing beam splitters should ideally be as high as possible; i.e. that a measured four-photon coincidence corresponds to precisely four photons and thus heralds the desired state in the output modes t_1 and t_2 . Obviously the trade-off for increasing this probability of heralding $|\phi^+\rangle$ - which in principle can be approximately unity - is a reduction in the four-fold coincidence rate for triggering this state. Therefore for demonstrating this dependency beam splitters with different transmission rates T , of 17%, 50% and 70% are chosen. For each of this beam splitter ratios the density matrix ρ of the heralded entangled pair, triggered by the successful registration of a four-fold coincidence in modes $r_{1H}, r_{1V}, r_{2+}, r_{2-}$ is reconstructed. This density matrix is obtained by an over-complete tomographic set of measurements, where 36 combinations of the single photon projections $|H/V\rangle, |\pm\rangle$, and $|R/L\rangle = \frac{1}{\sqrt{2}}(|H\rangle \pm i|V\rangle)$, on each of the two photons in modes t_1 and t_2 were used. Successful projections are signaled by 6-photon coincidence measurements and the most likely physical density matrix for the 2-qubit output states is extracted using maximum-likelihood reconstruction (Banaszek et al. (1999); Hradil (1997); James et al. (2001)).

6. Results

The rate R of the four-fold and the six-fold coincidences are shown in Table 1. Figure 3 shows the probability of obtaining the heralded state, i.e. to find a photon pair in the output modes triggered by the four-fold coincidence, with respect to the beam splitter transmission.

The probabilities were $P_{17/83} = 2.5 \pm 0.2\%$, $P_{50/50} = 29.4 \pm 1.0\%$ and $P_{70/30} = 77.2 \pm 6.6\%$ for the different transmission rates (see Figure 3). Obviously, these obtained values for heralding

	four-fold rate /minute	six-fold rate /day
17/83	83	30
30/70 ^{LP}	22	5
50/50	14	60
70/30	0.4	5

Table 1. Overview over the experimental four-fold coincidence rates showing high- and low-power (LP) measurements.

$|\phi^+\rangle$ reflect the limitations of photon losses, mostly due to using standard detectors without the capability of resolving the photon number.

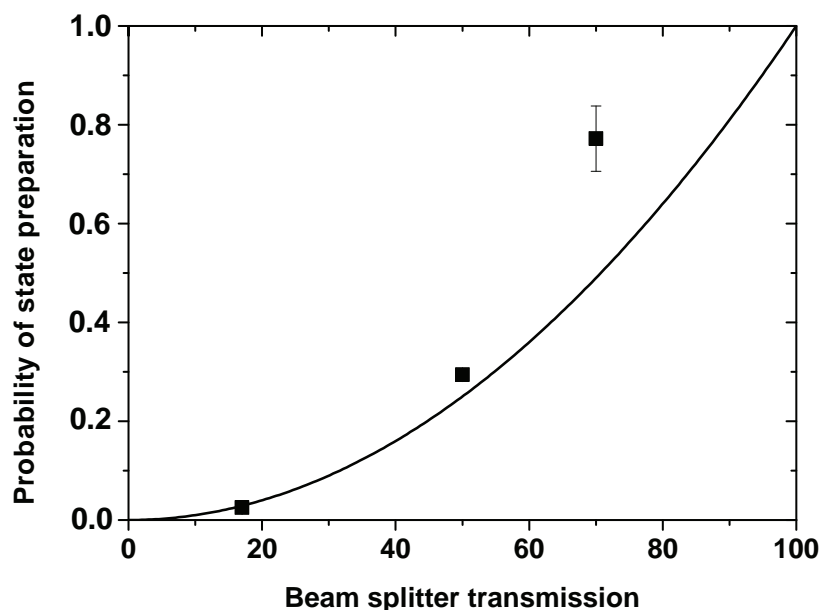


Fig. 3. Heralding efficiency. Probability of the heralded entangled photon-pair generation with respect to various beam splitter transmission rates in %. The deviation from the expected quadratic behavior (black line) originated from spurious high-order emissions, which increase the probability of preparing the entangled state $|\phi^+\rangle$ for higher beam splitter transmissions.

The corresponding fidelity, $F = \langle \phi^+ | \rho | \phi^+ \rangle$ of the heralded photon pair with the pure quantum state $|\phi^+\rangle$, was $F_{17/83} = 63.7 \pm 4.9\%$, $F_{50/50} = 57.5 \pm 3.4\%$, and $F_{70/30} = 61.9 \pm 7.7\%$ for the different beam splitters via local unitary transformations (see Figure 4).

The corresponding density matrices are shown in Figure 5. Uncertainties in quantities extracted from these density matrices were calculated using a Monte Carlo routine and assumed Poissonian errors. As expected, these fidelities are basically independent of the beam splitter ratio. The small deviation can be explained by the typical variations of the quality for these custom-made beam splitters. The reduced fidelities to the real state $|\phi^+\rangle$, however, is a result of the eight-photon emission. At the given laser power the probability of obtaining a higher-order emission for a given six-fold coincidence is about 10%.

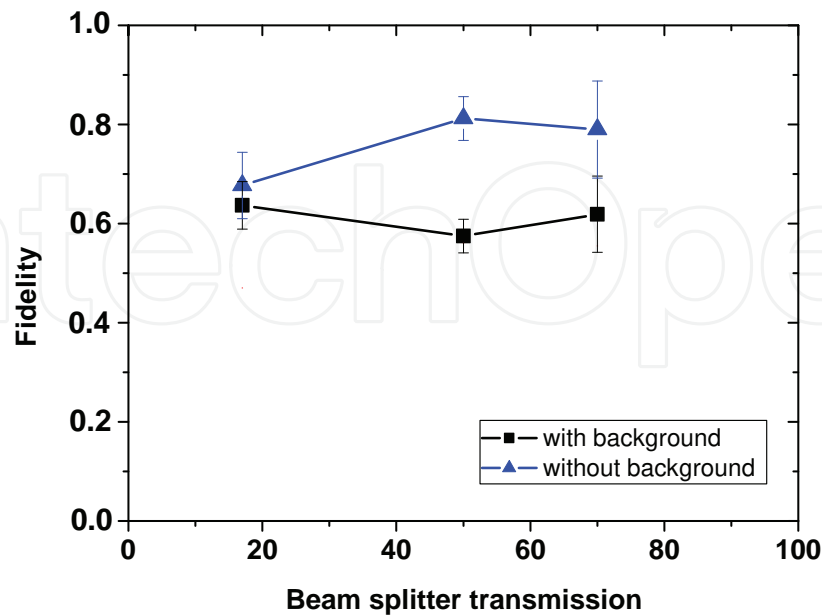


Fig. 4. Fidelities. The experimentally obtained quantum state fidelities with respect to the ideal state $|\phi^+\rangle$ is shown with (squares) and without (triangles) background for various beam splitter transmission rates in %. The background was assumed to be mostly state $|\psi^-\rangle$ originating from from eight-photon emissions.

This unwanted contribution adds a significant $|\psi^-\rangle$ component to the density matrices and thus reduces the overlap with the ideal state $|\phi^+\rangle$. A theoretical calculation based on the used experimental parameters allowed to estimate this unwanted background which is qualitatively different than the desired output state. When subtracting this $|\psi^-\rangle$ contribution from the measured density matrices the corrected fidelities became $F'_{17/83} = 67.7 \pm 6.7\%$, $F'_{50/50} = 81.2 \pm 4.4\%$, and $F'_{70/30} = 79.0 \pm 9.8\%$, which demonstrates the that laser systems with less peak power per pulse but much higher repetition rate could achieve such state fidelities. From this data, the tangle (Coffman et al. (2000)) is extracted as a measure of entanglement that ranges from 0 for separable states to 1 for maximally entangled states. The values are $t_{17/83} = 0.43 \pm 0.08$, $t_{50/50} = 0.37 \pm 0.03$ and $t_{70/30} = 0.45 \pm 0.11$ for the different beam splitter ratios. It is important to note that the noise is not intrinsic in the setup and is only due to practical drawbacks. For demonstrating that this limitation will be overcome in the near future, an additional experimental run with a reduced laser power of 620 mW and beam splitter transmissions of 30% was performed. The post-selected density matrix of this state is shown in Figure 2b. The extracted state of $F_{30/70} = (84.2 \pm 8.5)\%$ and a tangle of $\tau_{30/70} = 0.55 \pm 0.19$ evidently demonstrate the generated entanglement for this measured state.

This state's density matrix as shown in Figure 6, if commonly used in the coincidence basis, would allow a violation of local realistic theories by almost 2 standard deviations as the it implies a maximum Clauser-Horne-Shimony-Holt (Clauser et al. (1969); Horodecki et al. (1995)) Bell parameter of $S = 2.36 \pm 0.22$.

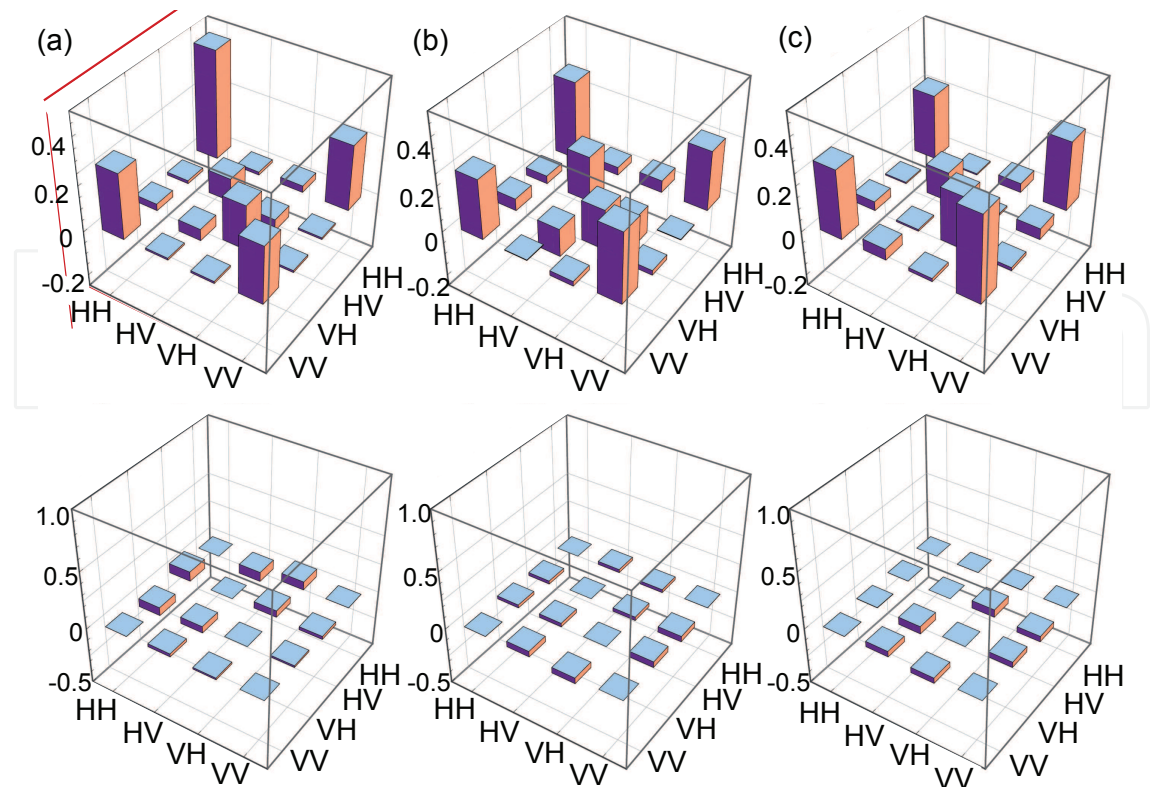


Fig. 5. The two-qubit density matrix for different beam splitter transmissions. Shown are the real (top) and imaginary (bottom) parts of the reconstructed density matrix for beam splitter transmissions of 17% (a), 50% (b), and 83% (c). Large diagonal elements in the $|HH\rangle$ and $|VV\rangle$ positions along with large positive coherences indicate that this state has the qualities of the desired heralded entangled state $|\phi^+\rangle$. The real density matrix was reconstructed by way of a maximum likelihood method using six-photon coincidence rates obtained in 36 polarization projections. The experimentally measured density matrix has a fidelity of $(63.7 \pm 4.9)\%$ (a), $(57.5 \pm 3.4)\%$ (b), and $(61.9 \pm 7.7)\%$ (c) with the ideal state $|\phi^+\rangle$ via local unitary transformations.

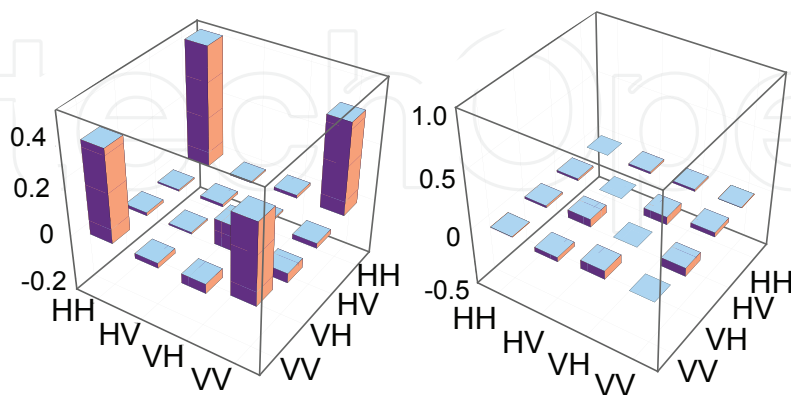


Fig. 6. Low-power density matrix. The reduction of the background is demonstrated when reducing the laser-power. The experimentally reconstructed real part (left) and imaginary part (right) of the two-qubit polarization density matrix is shown. The measurements were performed with a reduced laser-power of 0.62 Watt and a beam splitter transmission of 30%.

7. Conclusion

In conclusion, an efficient method for the generation of heralded polarization-entangled photon states, which are a crucial resource for photonic quantum computing, quantum communication and quantum metrology is demonstrated. This experiment uses currently available technologies - it relies only on linear optics, parametric down-conversion and standard photon detection - and is therefore of direct practical relevance. The performance of the photon-pair source was characterized by measuring the quantum state fidelity of the output states and by demonstrating the relation of the preparation efficiency with respect to the beam splitter transmission rate. A fidelity of better than 84% and a state preparation efficiency of 77% have been achieved. The feasibility of this experiment and the promising application for linear optics quantum information processing and quantum metrology makes it important and interesting for future quantum information experiments.

8. References

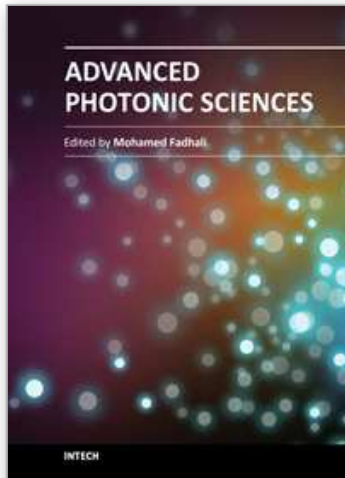
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