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Photon doughnut-shaped pair for easy production of entangled photon pairs

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Parametric down-conversion in a nonlinear crystal-generated photon pair in which photons have orthogonal polarization. The pair was emitted in a cone shape for each polarization and collimated by a lens to be doughnut shaped. The doughnutlike photon pair runs collinear to the pump laser. The group delay and walk-off between the orthogonal polarization photons in the pair were compensated passing through a half-wave plate and a nonlinear crystal. Then, the photon doughnut pair was coupled into a 1 × 2 fiber together with a pump laser, i.e., the intense pump laser was used as a guide for alignment. After the alignment was finished, a cut filter was inserted in the optical path to cut the pump laser transmitting the photon doughnut pair. The coincidence measurement of the output of the 1 × 2 fiber showed that the photon pairs are entangled in polarization.

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I. INTRODUCTION

Spontaneous parametric down-conversion (SPDC) generates a photon pair whose parameters are entangled. One of the most widely used entanglements is polarization entanglement applied for quantum teleportation and quantum key distribution [1]. The polarization entangled photon pairs are also used to study steering effect [2] and violation of high-dimensional Bell inequality [3]. Wave-vector entanglement has been utilized for quantum imaging [4,5], photonic de Broglie wavelength measurement [6–8], quantum interference [9,10], and quantum lithography [11–13]. Frequency entanglement was used for nonlocal pulse shaping [14] and spectroscopy [15].

Irradiating a type-II β-BaB$_2$O$_4$ (BBO) crystal by pump laser, SPDC in the crystal generates a photon pair in which polarization is orthogonal to each other between the two photons. Each photon is generated in a cone shape, and the direction of the center axis of the light cone is different between the two photons of the pair. When the light cone pair has a cross section, photon pairs running on the crossing lines of the cones are entangled in polarization [see Fig. 1(a)]. Spatially selecting the photon pair coming from the crossing lines, the polarization entangled photon pair can be obtained, although most of the SPDC photon pairs cannot be used being generated out of the crossing lines. In our previous work, we have generated the photon pair in beam shape [see Fig. 1(b)] to entangle its polarization [16,17] for all of the generated SPDC photon pairs. However, in the proposed scheme, it was difficult to align the photon pair to couple into detectors because the light intensity of the photon pair is extremely low as the photon counting level.

In the experiment of the entangled photon pair generation, the most difficult part is to couple the generated photon pairs into photon counters via an optical fiber. If some parts of the photon pairs are coupled into the fibers, alignment of the optical components can be easily optimized observing the coincidence counts. Meanwhile, when no photon pairs are coupled into the fibers, there is no way to know whether the optical components are being adjusted in the correct direction or not, which results in inefficient blind alignment.

In the present paper, we propose and demonstrate a scheme to generate a polarization entangled photon pair much easier than previous methods. Using the pump light as a guide for the alignment, part of the generated photon pair was coupled into the input of a 2 × 2 fiber simultaneously. The photon pair coming out from the 2 × 2 fiber is entangled in its polarization. Observing the coincidence of the photon pair, the coupling between the generated photon pair and the input of the 2 × 2 fiber could be easily optimized to get the coincidence rate of 100 Hz. The experimental result shows that the generated photon pair is entangled in polarization.

II. EXPERIMENTAL

Figure 2 shows the schematic of the experimental setup. The cw pump laser (MDL-III-405-50 mW-1%, Ultralasers, Inc.) with an average power of 50 mW, center wavelength of 402 nm, and spectral width of <2 nm was focused into a 2-mm-thick type-II BBO crystal to generate photon pairs via the SPDC process. Each photon pair consists of a horizontally polarized photon and a vertically polarized photon. These photons of the SPDC pair are emitted conically from a point at which the pump laser was focused in the BBO crystal.

Both of the two light cones are collimated by a lens to transfer the photon pairs keeping the same diameter in the doughnut shape. The two doughnut-shaped photons, each of which corresponds to each polarization, are called the photon doughnut pair.

The two light cones are emitted in different directions. Numerical simulation shows that the angle between the signal field and the idler field is 5.3°, i.e., they are separated from each other by 12 mm at a distance of 100 mm from the focusing point. Thus, both of the fields can be collimated by a single lens which has a 1-in. (25.4-mm) diameter.

After being generated in the BBO crystal, the horizontally polarized photon is delayed compared with the vertically polarized photon. It is because BBO is a negative uniaxial

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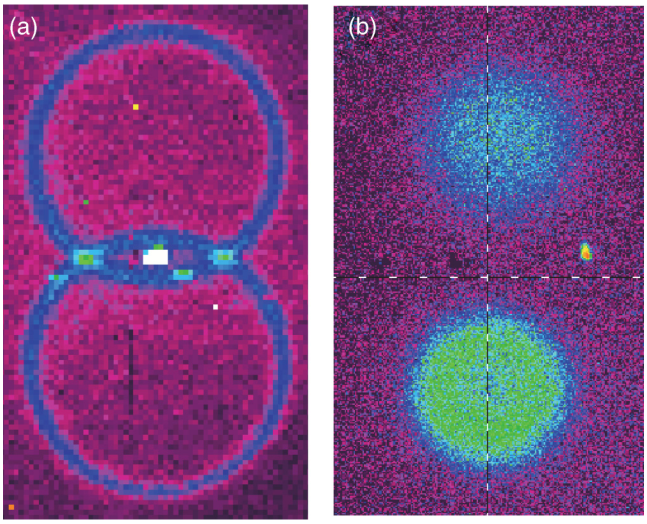

FIG. 1. (Color online) CCD image of the SPDC photon pair generated from a type-II BBO nonlinear crystal. (a) Doughnutlike photon pair. (b) Beamlike photon pair.

crystal in which the refractive index is smaller for horizontally (extraordinary) polarized light than for vertically (ordinary) polarized light. To compensate the group delay between the orthogonally polarized photons in each photon pair, a half-wave plate [(HWP); WPH10M-808, Thorlabs, Inc.] and a 1-mm-thick BBO crystal were inserted in the optical path of the photon doughnut pair. The HWP rotates the polarization of the photons by 90° changing the horizontally polarized photon to be vertically polarized and vice versa. Then, passing through the 1-mm-thick BBO crystal, the group delay between the two photons was compensated.

The pump pulse runs collinearly to the photon pair doughnuts. The pump pulse and the photon pair doughnuts were focused by a lens into one of the inputs of a 2 × 2 fiber. The 2 × 2 fiber (FC830-50B-FC, Thorlabs, Inc.) was used in place of a 1 × 2 fiber using only one of the two input fibers. The crossing point of the 2 × 2 fiber works as a half beam splitter. When one photon comes out from each output of the 2 × 2 fiber, the output photons are entangled in their polarization.

After coupling the photon pair doughnuts into the fiber by the easy alignment, a long-pass filter (DIF-50S-RED, Sigma-koki, Inc.) and a bandpass filter (FB800-10, Thorlabs, Inc.) were inserted in front of the fiber input, which is to cut the pump pulse and pass the SPDC photon.

Each output fiber of the 2 × 2 fiber was connected to the input of a fiber-to-fiber coupler, FFC1 or FFC2, (FBP-B-FC, Thorlabs, Inc.) in which a polarizer, POL1 or POL2, (PCB-2.5-NIR, Thorlabs, Inc.) was installed to analyze the polarization correlation between the two photons of the SPDC photon pair. Each output of the fiber-to-fiber couplers was connected to a single photon counting module, SPCM1 or SPCM2 (SPCM-AQR-14, PerkinElmer, Inc.) via a multimode fiber-optic patch cable. The counting signal from SPCM1 and that from SPCM2 were connected to a time-to-amplitude converter (ORTEC, Model 567) and a multichannel analyzer (ORTEC, TRUMP-PCI-2k) for the coincidence measurement.

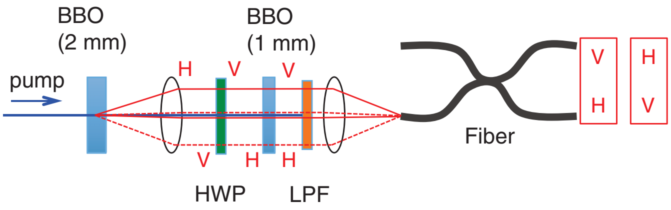

FIG. 2. (Color online) Schematic of the experimental setup. BBO: β-BaB$_2$O$_4$ crystal; HWP: half-wave plate; LPF: low-pass filter.

All of these alignments were performed using the pump light whose wavelength is 402 nm, half the wavelength of the SPDC photon pair (804 nm). The optical setup includes several refractive optics having chromatic aberration. Thus, the coupling between the photon pair and the input of the 2 × 2 fiber was not optimized in the beginning. Even with the incomplete alignment, we could detect a coincidence signal of 40 Hz. Maximizing the coincidence counts with fine adjustment of the optical components, we obtained the coincidence counting rate was as high as ∼100 Hz, which is still useful for quantum information experiments.

For the convenience of alignment in the demonstration, we have used a fiber launch with a FC-connectorized fiber holder (Thorlabs, Inc., MBT613D) and an objective lens (Thorlabs, Inc., RMS10×) to couple the photon pair into the input of the 2 × 2 fiber. Thus, the fine adjustment of the optical path was easily performed, but the coupling efficiency was suppressed because of the short focus length (10.6 mm) of the objective lens. The coincidence rate obtainable by the present scheme could be improved replacing the objective lens with a standard lens with a longer focus length (∼100 mm).

III. RESULTS AND DISCUSSION

At first, the angles of POL1 θ_1 and that of POL2 θ_2 were set to transmit vertically polarized photons, and this is used as the origin (0°) of their angles. The θ_1 was fixed at 0°, and θ_2 was scanned from −180° to +180° at 15° steps measuring the coincidence counts between SPCM1 and SPCM2. The result is plotted by red curves (circles) in Fig. 3. We have performed the coincidence measurements scanning θ_2 when θ_1 was fixed

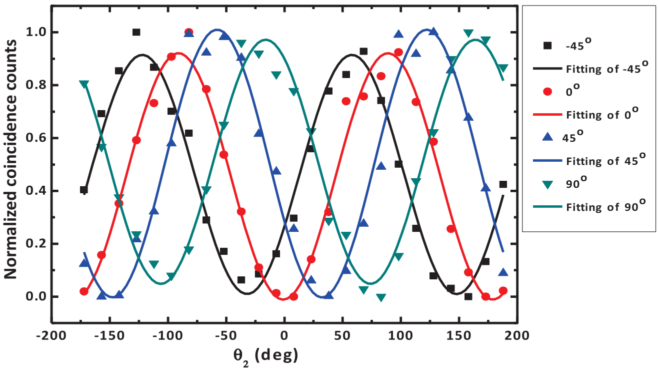

FIG. 3. (Color online) Normalized coincidence counts observed as a function of θ_2 while fixing θ_1 at −45°, 0°, 45°, and 90°, where θ_1 and θ_2 are the angles of POL1 and POL2, respectively. The solid lines are the fitting results.

at 45°, 90°, and −45°, and the results are plotted as blue, green, and black curves, respectively, in Fig. 3.

If the photon pair is a mixed state having no polarization entanglement, the coincidence signal should show no θ_2 dependence when θ_1 is set at 45° or −45°. If the photon pair is entangled in polarization, the coincidence signal should show a maximum count when $(\theta_1, \theta_2) = (45°, -45°)$ and $(-45°, 45°)$ and a minimum count when $(\theta_1, \theta_2) = (45°, 45°)$ and $(-45°, -45°)$. The experimental result of Fig. 3 indicates that the photon pairs detected by SPCM1 and SPCM2 are entangled in polarization. The difference from the theoretically expected visibility of unity is thought to be caused by a misalignment in the hand adjustment of the inserted optics, such as the BBO crystals, the half-wave plate, and the polarizers.

The visibility of the θ_2 dependence of the coincidence counts can be calculated as follows. The quantum state of the photon pair of $|\psi\rangle = |H\rangle_1|V\rangle_2 + e^{i\phi}|V\rangle_1|H\rangle_2$ can be described as

$$\begin{aligned}|\Psi\rangle = {}& \tfrac{1}{2}(1+e^{i\phi})(|+\rangle_1|+\rangle_2 - |-\rangle_1|-\rangle_2)\\ &+ \tfrac{1}{2}(1-e^{i\phi})(|+\rangle_1|-\rangle_2 - |-\rangle_1|+\rangle_2),\end{aligned}$$

utilizing diagonal linearly polarized bases of $|+\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$ and $|-\rangle = \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle)$. Thus, the coincidence count rate of $|+\rangle_1|H\rangle_2, |+\rangle_1|+\rangle_2, |+\rangle_1|V\rangle_2, |+\rangle_1|-\rangle_2$ is calculated as

$$\begin{aligned}|\langle\Psi|+\rangle_1|H\rangle_2|^2 &= \left|\langle\Psi|+\rangle_1\frac{1}{\sqrt{2}}(|+\rangle_2 + |-\rangle_2)\right|^2\\ &= \left|\frac{1}{2\sqrt{2}}(1+e^{i\phi}) + \frac{1}{2\sqrt{2}}(1-e^{i\phi})\right|^2 = \frac{1}{2},\\ |\langle\Psi|+\rangle_1|+\rangle_2|^2 &= \left|\frac{1}{2}(1+e^{i\phi})\right|^2 = 1+\cos\phi,\\ |\langle\Psi|+\rangle_1|V\rangle_2|^2 &= \left|\langle\Psi|+\rangle_1\frac{1}{\sqrt{2}}(|+\rangle_2 - |-\rangle_2)\right|^2\\ &= \left|\frac{1}{2\sqrt{2}}(1+e^{i\phi}) - \frac{1}{2\sqrt{2}}(1-e^{i\phi})\right|^2 = \frac{1}{2},\\ |\langle\Psi|+\rangle_1|-\rangle_2| &= \left|\frac{1}{2}(1-e^{i\phi})\right|^2 = 1-\cos\phi,\end{aligned}$$

respectively. Therefore, when θ_1 is set at 45° to pass the photon of $|+\rangle_1$, the θ_2 dependence of the coincidence counts gives $|\cos\phi|$ from its visibility. Similarly, the value of $|\cos\phi|$ can also be estimated from the visibility when θ_1 is set at −45° to pass the photon of $|-\rangle_1$. If $\phi = 0°$ or 180°, the photon pair is maximally entangled being one of the Bell states and shows visibility of unity. The experimental result of the visibility gives $|\cos\phi| = 0.906 \pm 0.04$ showing that the photon pair is highly entangled in polarization. The difference from unity of the visibility is thought to be caused by fine misalignment of the optics resulting in $\phi \neq 0°$.

The entanglement $E(\Psi)$ can be calculated as follows [18–21]:

$$\begin{aligned}E(\Psi) &= h\left(\frac{1+\sqrt{1-\mathcal{C}^2}}{2}\right),\\ h(x) &= x\log_2 x - (1-x)\log_2(1-x),\\ \mathcal{C}(\Psi) &= |\langle\Psi|(\sigma_y \otimes \sigma_y)|\Psi^*\rangle|.\end{aligned}$$

Here, σ_y is the Pauli matrix,

$$\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}.$$

Minimally and maximally entangled states have zero and unity, respectively, of $E(\Psi)$. As the concurrence $\mathcal{C}(\Psi)$ increases from 0 to 1, $E(\Psi)$ also increases from 0 to 1 monotonously corresponding to the stage changing from minimally to maximally entangled, respectively. Therefore, the concurrence can be one of the measures of the entanglement. The concurrence of the state is calculated as $\mathcal{C} = |\cos\phi|$. Thus, as we have calculated $|\cos\phi|$ from the observed visibility, the concurrence of the generated polarization entangled photon pair was estimated as $C = 0.906 \pm 0.04$ showing that the photon pair is highly entangled in polarization. The difference from unity of the visibility is thought to be caused by fine misalignment of the optics resulting in $\phi \neq 0°$.

IV. CONCLUSION

Preparation of the entangled photon pair has been thought to be hard because of the difficulty to couple the generated photon pairs into detectors from zero lacking any guide of alignment. Meanwhile, the scheme proposed in the present paper solves the difficulty to couple the generated photon pairs into the fibers with an alignment guide by the pump laser. The alignment easiness of the present scheme is available here.

In previous methods, the polarization entangled photon pair was produced in a direction different from that of the pump pulse. Thus no alignment guide is available, even though the intensity of the photon pair is as low as the photon counting level. The alignment to couple the photon pair into the fiber could be performed only by grabbling the photon counts on single photon counting modules, which results in difficulty of alignment.

Meanwhile, the present scheme solves the alignment difficulty, which has been unavoidable in the previous schemes. In the present scheme, the photon doughnut pair running collinearly to the pump pulse can be coupled into the fiber guiding the intense pump pulse into the same fiber input. The coupling between the photon pair and the fiber can be easily optimized observing the coincidence counts, which is already partially detected after the above initial coupling process guided by the pump light.

After finishing the alignment to couple the light into the fiber input, the long-pass fiber was inserted to cut the pump pulse still passing the photon pair. From the fiber output of the 2 × 2 fiber, the polarization entangled photon pair was obtained. The entanglement of the photon pair was measured by concurrence estimated to be 0.906 ± 0.04, showing that the photon pair is highly entangled in polarization.

The scheme proposed in the present paper solves the long-standing alignment difficulty in previous methods in the generation of entangled photon pairs, and we believe that the proposed scheme could be widely used for real applications, such as quantum key distribution.

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