

Beamlike photon pairs entangled by a 2 × 2 fiberHsin-Pin Lo,^{1,2} Atsushi Yabushita,² Chih-Wei Luo,² Pochung Chen,¹ and Takayoshi Kobayashi^{2,3,4,5}¹*Department of Physics, National Tsing Hua University, Hsinchu, 300, Taiwan, Republic of China*²*Department of Electrophysics, National Chiao-Tung University, Hsinchu, 300, Taiwan, Republic of China*³*Core Research for Evolutional Science and Technology, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi, Saitama, 332-0012, Japan*⁴*University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo, 182-8585, Japan*⁵*Institute of Laser Engineering, Osaka University, 2-6 Yamada oka, Suita, Osaka, 565-0971, Japan*

(Received 18 February 2011; published 1 August 2011)

Polarization-entangled photon pairs have been widely used as a light source of quantum communication. The polarization-entangled photon pairs are generally obtained at the crossing points of the light cones that are generated from a type-II nonlinear crystal. However, it is hard to pick up the photon pairs coming out from the crossing points because of their invisible wavelength and low intensity. In our previous work, we succeeded in generating polarization-entangled photon pairs by overlapping two light paths for the photon-pair generation. The photon pairs could be entangled in all of the generated photon pairs without clipping the crossing points, even with some difficulty in its alignment to overlap the two light paths. In this paper, we have developed an optical system which generates polarization-entangled photon pairs using a beamlike photon pair, without the difficulty in alignment. The measured results show that the photon pairs generated in the system are entangled in their polarizations.

DOI: [10.1103/PhysRevA.84.022301](https://doi.org/10.1103/PhysRevA.84.022301)

PACS number(s): 03.67.Bg, 03.65.Ud

I. INTRODUCTION

Polarization-entangled photon pairs have been widely used to demonstrate quantum information protocols, such as quantum teleportation and quantum key distribution [1]. As a relatively bright source, spontaneous parametric down-conversion (SPDC) in a nonlinear crystal is generally used to generate the polarization-entangled photon pairs. Photon pairs generated by SPDC can also be entangled in a wave vector to demonstrate quantum imaging [2,3], photonic de Broglie wavelength measurement [4–6], two-photon interference [7,8], and quantum lithography [9–11]. Moreover, nonlocal pulse shaping [12] and spectroscopy [13] have been performed by SPDC photon pairs entangled in frequency [14].

Photon pairs generated by using a type-II β -BaB₂O₄ (BBO) crystal consist of a horizontally polarized photon and a vertically polarized photon. Figure 1(a) shows a schematic graph of the photon-pair generation. A CCD image of the observed photon pairs is shown in Fig. 1(b). Photon pairs are polarization entangled only at the crossing points of the light cones; therefore polarization-entangled photon pairs could be obtained by using a spatial filter to block other photons, which do not pass through the crossing points. The spatial filtering results in low production efficiency of the polarization-entangled photon pairs. This is a general method used to generate polarization-entangled photon pairs; however, the photons out of the crossing points go to waste because they have no polarization entanglement.

By adjusting the angle of the BBO crystal, the beamlike photon pairs [15] can be generated as shown in Fig. 1(c). Figure 1(d) shows a CCD image of the generated photon pairs. In a previous paper by Ou and co-workers [16], the polarization-entangled beamlike photon pairs were generated by using two type-II BBO crystals.

Two rings of SPDC light cones were reported to be identical in their intensities [17] when a cw laser was used as the pump

source. In our present work, we generated SPDC light cones using a femtosecond pulse laser and found that the intensities are different for the ordinary photon and the extraordinary photon. The difference between the previous works and our present work can be explained as follows: When the narrow-band cw laser is used as the pump source of SPDC photons, the energy-conservation rule under the narrow-band excitation requires the bandwidth of the ordinary photon to be exactly equal to that of the extraordinary photon.

Meanwhile, when the broadband femtosecond laser generates SPDC photons, the broad bandwidth of the femtosecond laser allows the bandwidth of the SPDC photons to be affected by the phase-matching bandwidth of the BBO crystal. In the type-II phase-matching condition, the phase-matching bandwidth of the ordinary wave is much broader than that of the extraordinary wave. The difference of the phase-matching bandwidth in the type-II crystal is also applied for the pulse-characterization technique of spectral-phase interferometry for direct electric-field reconstruction (SPIDER) [18], which is one of the most popular pulse-characterization methods for ultrashort pulses. Therefore, SPDC photon pairs generated by the femtosecond pulse laser have different bandwidths for the ordinary photon and the extraordinary photon [19]. If the SPDC photon pairs pass through narrow-band interference filters, the bandwidth difference is observed as the intensity difference of the transmitted photons. In our present work, the CCD image was observed by putting the narrow-band interference filter in front of the CCD to suppress noise. This is the reason that the intensity of the CCD image was observed to be different for the ordinary photon and the extraordinary photon.

In our previous work [20], we developed a scheme to generate beamlike photon pairs which demonstrate two-photon interference and polarization entanglement. By rotating the angles of quarter-wave plates in the light paths of the photon

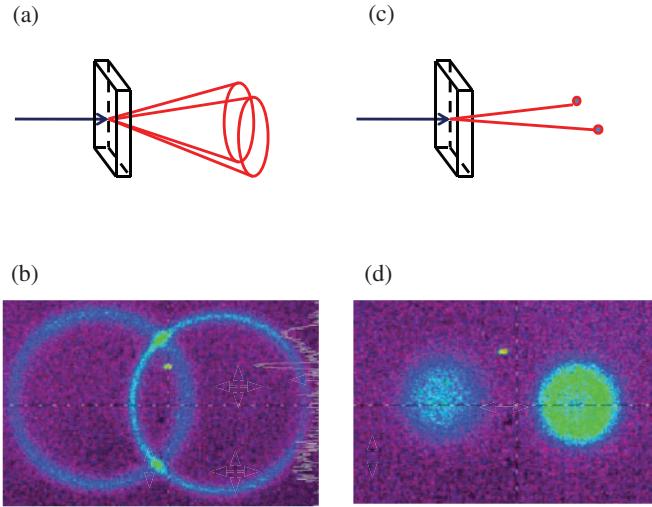


FIG. 1. (Color online) (a) and (c) The SPDC light cones when they are overlapped and beamlike, respectively. (b) and (d) The CCD images of the SPDC light cones of (a) and (c), respectively.

pairs, we could also generate polarization-entangled beamlike photon pairs. This enabled us to make the polarization entanglement for all of the photon pairs generated in the crystal, without performing any spatial filtering. However, the scheme involves a difficult alignment, which requires the light paths of the two beamlike photon pairs to overlap. In the present work, we have developed a scheme to generate the polarization-entangled beamlike photon pairs by using a 2×2 fiber which has no need for alignment.

II. EXPERIMENT

The schematic drawing of our experimental setup is shown in Fig. 2. A Ti:sapphire oscillator (Spectra-Physics, model Tsunami, 1.4 W, 100 fs, 80 MHz at 780 nm) was used to pump a frequency doubler unit (Spectra-Physics, model 3980-4) and generate a second-harmonic (SH) signal of 470 mW. The SH beam pumps a 2-mm-thick type-II BBO crystal to generate the photon pairs via the SPDC process. Each photon pair consists of two photons whose polarizations are orthogonal to each other. For the sake of convenience, the photon in each photon pair whose polarization is horizontal is labeled as *H*, and the one with vertical polarization is labeled as *V*. Generally, these photons (*H* and *V*) of the SPDC pairs are emitted conically from a point on the BBO crystal illuminated by the pump beam [see Fig. 1(a)]. In this work, the angle of the crystal was adjusted to generate the beamlike photon pairs as shown in Fig. 1(c).

To generate the polarization entanglement, the beamlike photon pairs are mixed by a 2×2 fiber (Thorlabs, FC830-50B-FC). The position of the fiber coupler (FC) coupling a horizontally polarized beamlike photon was adjusted to make the optical path equal for the *H* photon and the *V* photon, as shown in the next section. The polarizations of the photons coming out from two ports of the 2×2 fiber were analyzed by two linear polarizers, and their coincidence was detected by a pair of single-photon counting modules (PerkinElmer, SPCM-AQR-14), a time-to-amplitude converter

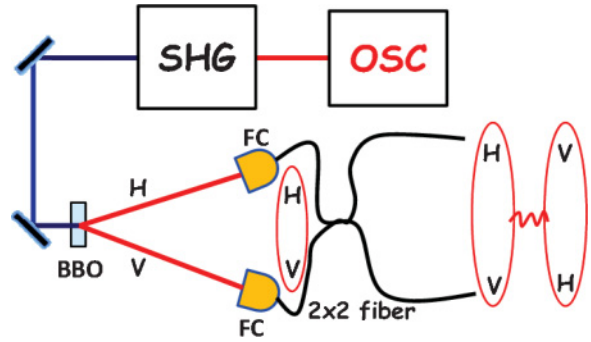


FIG. 2. (Color online) Schematic drawing depicting how to generate polarization-entangled photon pairs and mixed beamlike photon pairs in a 2×2 fiber. OSC, Ti:sapphire laser oscillator; SHG, second-harmonic generator (frequency doubler); BBO, β -BaB₂O₄ crystal; FC, fiber coupler.

(ORTEC, model 567), and a multichannel analyzer (ORTEC, TRUMP-PCI-2k).

III. RESULTS AND DISCUSSION

A. Hong-Ou-Mandel dip measurements for path-length adjustment

In Fig. 3(a), the position of the FC coupling a horizontally polarized beamlike photon was adjusted to make the optical

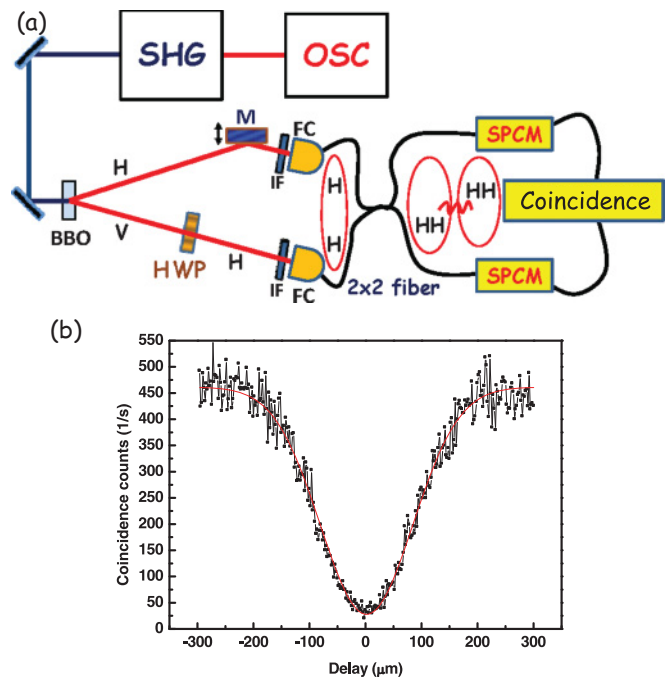


FIG. 3. (Color online) (a) Schematic drawing of the measurement of the HOM dip for path-length adjustment. OSC, Ti:sapphire laser oscillator; SHG, second-harmonic generator (frequency doubler); BBO, β -BaB₂O₄ crystal; M, mirror; FC, fiber coupler; HWP, half-wave plate; IF, interference filter; SPCM, single-photon counting module; Coincidence, instruments for coincidence measurement, which consist of a time-amplitude converter and a multichannel analyzer. (b) The HOM dip observed by scanning the position of mirror M. Solid curves are the fitting results.

path equal for the H photon and the V photon as follows: The polarization of the V photon was rotated 90° by a half-wave plate (HWP), which makes both photons in each photon pair have the same polarization. The coincidence counts of the parallel polarization photons are thought to exhibit a Hong-Ou-Mandel (HOM) dip [8] when the path lengths of the two photons are equal. The position of a mirror M was scanned to observe the coincidence of the photons, which come out from the 2×2 fiber. The coincidence counts clearly reveal the HOM dip as shown in Fig. 3(b). The width of the HOM dip shows the coherence length of the fields of the SPDC photons, which corresponds to the inverse of the bandwidth of interference filters (Semrock: LL01-780-25, 3 nm) put in front of each FC. Hereafter, the path length from the BBO crystal to each FC was set to be equal by fixing the position of M at the bottom of the HOM dip. The visibility of the observed HOM interference was estimated as $94.0 \pm 0.8\%$. It is comparable to the value obtained in other relevant works [8,21].

B. Generation and measurement of polarization-entangled photon pairs

We have fixed the positions of FC at the bottom of the HOM dip as described in the previous section. By removing the HWP from the setup shown in Fig. 3(a), the orthogonally polarized photons are mixed by the 2×2 fiber and the photons coming out from the two exits of the 2×2 fiber are entangled in their polarization. The polarization entanglement of the photons was estimated in the coincidence counts of the photon pairs by rotating the angles of the polarizers (POL1 and POL2) between the 2×2 fiber and the single-photon counting modules (SPCM). Figure 4(a) shows the setup for the generation and measurement of the polarization-entangled photon pairs. When the coincidence counts of the photon pairs are measured by putting a linear polarizer in an optical path of each photon of an Einstein, Podolsky, and Rosen (EPR) photon pair [22], $|EPR\rangle \equiv 1/\sqrt{2}(|HV\rangle - |VH\rangle)$, the probability of the coincidence counting can be given as

$$\langle \widehat{\theta}_1 \widehat{\theta}_2 \rangle = \frac{1}{2} \sin^2(\theta_1 - \theta_2), \quad (1)$$

where θ_1 and θ_2 correspond to the angles of the two polarizers put in the optical paths of the two photons. Similarly, the coincidence probabilities for other angles can be given as

$$\left\langle \widehat{\theta}_1 + \frac{\pi}{2} \widehat{\theta}_2 + \frac{\pi}{2} \right\rangle = \frac{1}{2} \sin^2(\theta_1 - \theta_2), \quad (2)$$

$$\left\langle \widehat{\theta}_1 + \frac{\pi}{4} \widehat{\theta}_2 \right\rangle = \frac{1}{2} \cos^2(\theta_1 - \theta_2), \quad (3)$$

$$\left\langle \widehat{\theta}_1 \widehat{\theta}_2 + \frac{\pi}{4} \right\rangle = \frac{1}{2} \cos^2(\theta_1 - \theta_2). \quad (4)$$

We define the value of $E(\theta_1, \theta_2)$ as

$$E(\theta_1, \theta_2) = \frac{\langle (\widehat{\theta}_1 - \theta_1 + \frac{\pi}{4})(\widehat{\theta}_2 - \theta_2 + \frac{\pi}{4}) \rangle}{\langle (\widehat{\theta}_1 + \theta_1 + \frac{\pi}{4})(\widehat{\theta}_2 + \theta_2 + \frac{\pi}{4}) \rangle}. \quad (5)$$

Equations (1)–(5) give $E(\theta_1, \theta_2) = -\cos 2(\theta_1 - \theta_2)$. Here, we define a parameter S as

$$S = E(\theta_1, \theta_2) - E(\theta_1, \theta'_2) + E(\theta'_1, \theta'_2) + E(\theta'_1, \theta_2). \quad (6)$$

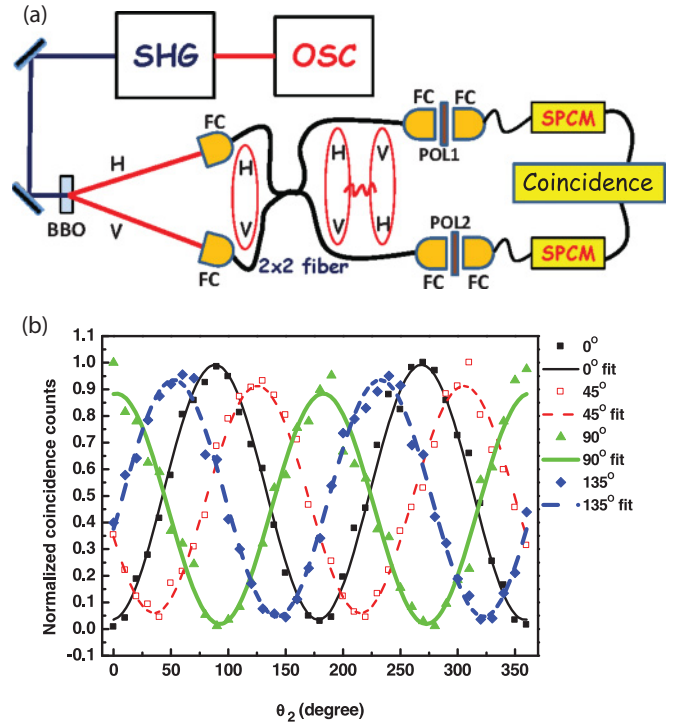


FIG. 4. (Color online) (a) Schematic drawing to generate polarization-entangled photon pairs mixing beamlike photon pairs in a 2×2 fiber. OSC, Ti:sapphire laser oscillator; SHG, second-harmonic generator (frequency doubler); BBO, β -BaB₂O₄ crystal; FC, fiber coupler; POL1 and POL2, linear polarizers; IF, interference filter; SPCM, single-photon counting module; Coincidence, instruments for coincidence measurement, which consist of a time-amplitude converter and a multichannel analyzer. (b) Normalized coincidence counts observed as a function of θ_2 while fixing θ_1 at 0° , 45° , 90° , and 135° , where θ_1 and θ_2 are the angles of POL1 and POL2, respectively. The solid and dashed lines are the fitting results.

By setting the angles as

$$\theta_1 - \theta_2 = -\theta'_1 + \theta_2 = \theta'_1 - \theta'_2 = \frac{1}{3}(\theta_1 - \theta'_2) = \frac{\theta}{2}, \quad (7)$$

the parameter S can be expressed as

$$S = -3 \cos \theta + \cos 3\theta = 4 \cos^3 \theta - 6 \cos \theta. \quad (8)$$

Therefore, the parameter S of the EPR photon pair has a minimum value of $-2\sqrt{2}$ and a maximum value of $2\sqrt{2}$, when θ is 135° and 45° , respectively. If the generated photon pairs are classical states, the parameter S satisfies $|S| \leq 2$, which is called the Clauser, Horne, Shimony, and Holt (CHSH) inequality [23]. Therefore, when S has a value larger than 2, the state is an entangled state, which can never be described by classical theory. In the following, we confirm that the photon pairs generated in the setup shown in Fig. 4(a) are entangled in their polarization, violating the CHSH inequality. Here, θ_1 and θ_2 correspond to the angles of the polarizers (POL1 and POL2, respectively). We express the coincidence counts observed as a function of θ_2 by fixing θ_1 at 0° , 45° , 90° , and 135° as

$$C_{0^\circ} = A_{0^\circ}(1 - V_{0^\circ} \cos 2\theta_2), \quad (9)$$

$$C_{45^\circ} = A_{45^\circ}[1 - V_{45^\circ} \cos 2(\theta_2 - 45^\circ)], \quad (10)$$

$$C_{90^\circ} = A_{90^\circ} [1 - V_{90^\circ} \cos 2(\theta_2 - 90^\circ)], \quad (11)$$

$$C_{135^\circ} = A_{135^\circ} [1 - V_{135^\circ} \cos 2(\theta_2 - 135^\circ)], \quad (12)$$

respectively. The parameters A_i and V_i ($i = 0^\circ, 45^\circ, 90^\circ, 135^\circ$) represent amplitudes and visibilities, respectively, of the curves of the coincidence counts. To confirm the violation of the CHSH inequality, we set $(\theta_1, \theta'_1, \theta_2, \theta'_2) = (22.5^\circ, -22.5^\circ, 0^\circ, -45^\circ)$ to satisfy Eq. (7) for $\theta = 45^\circ$. Using Eqs. (9)–(12), the parameter S defined in Eqs. (5) and (6) can be expressed as

$$S = -\sqrt{2} \left(\frac{A_{0^\circ} V_{0^\circ} + A_{90^\circ} V_{90^\circ}}{A_{0^\circ} + A_{90^\circ}} + \frac{A_{45^\circ} V_{45^\circ} + A_{135^\circ} V_{135^\circ}}{A_{45^\circ} + A_{135^\circ}} \right). \quad (13)$$

Figure 4(b) shows the coincidence counts of the photons observed by fixing an angle of POL1 (θ_1) at 0° (solid thin line), 45° (dashed thin line), 90° (solid thick line), and 135° (dashed thick line) and rotating the angle of POL2 (θ_2) from 0° to 360° in 10° increments. The measured result estimated the parameters as $(A_{0^\circ}, A_{45^\circ}, A_{90^\circ}, A_{135^\circ}) = (0.51 \pm 0.01, 0.49 \pm 0.01, 0.45 \pm 0.01, 0.49 \pm 0.01)$ and $(V_{0^\circ}, V_{45^\circ}, V_{90^\circ}, V_{135^\circ}) = (0.93 \pm 0.02, 0.88 \pm 0.03, 0.96 \pm 0.04, 0.9 \pm 0.02)$, which gives $S = 2.59 \pm 0.08$. This confirms that the generated state is highly entangled in polarization and violating the CHSH inequality by more than $7 (= |2.59 - 2|/0.08)$ standard deviations. The CHSH Bell inequality is reported to be violated by over 22 standard deviations in the relevant work [24]. In the present work, the low event rate of SPDC resulted in a large value of the standard deviation, which results in less violation of the CHSH Bell inequality. It would be improved by increasing the pump power and replacing the optics with better-performing ones in order to increase the event rate. The standard deviation can also be suppressed by improving the mechanical stability of the optical setup.

In the present work, we have demonstrated that our methodology can generate polarization-entangled photon pairs. However, the enhanced rate of emission was not noticeable. It is thought to be caused by the loss of four fiber couplers around two polarizers [see Fig. 4(a)]. This problem will be solved if the 2×2 fiber is replaced with a 2×2 fiber which has two built-in polarizers. Another possible way to enhance the rate is by replacing the pump source. If we use a high-power narrow-band cw laser as the pump source, the number of photon pairs increases, and the spectrum bandwidths are equalized between the ordinary photon and the extraordinary

photon. This will help to improve the coincidence count rate of the photon pairs transmitting through the narrow-band IF.

IV. CONCLUSION

In our previous work [15], we developed a scheme to generate polarization-entangled beamlike photon pairs which demonstrates two-photon interference and polarization entanglement. By rotating the angles of quarter-wave plates in the light paths of photon pairs, we could also generate the polarization-entangled beamlike photon pairs. However, the scheme involves a difficult alignment, which requires the light paths of the two beamlike photon pairs to overlap. In the present work, we have developed a scheme to generate the polarization-entangled beamlike photon pair by using a 2×2 fiber which has no necessity for alignment. A type-II BBO crystal was used to generate the beamlike photon pair, which consists of two orthogonally polarized photons.

To entangle the photon pair at the crossing point of the 2×2 fiber, the difference between the optical path lengths from the BBO crystal to the crossing point of the 2×2 fiber should be much smaller than the coherence length of the generated photons. Therefore, the mirror M was used to adjust the position corresponding to the valley of the HOM dip, after making all of the polarizations of the photons parallel by using the half-wave plate [see Fig. 3(a)].

After the path-length adjustment, the polarizations of the photons are set to be orthogonal again by rotating the HWP, and the polarization-entangled photon pairs are obtained. To confirm whether the generated state has entanglement, the coincidence counts are observed by rotating the angle of POL2 while fixing the angle of POL1 at 0° , 45° , 90° , and 135° [see Fig. 4]. The estimated value S of 2.59 ± 0.08 indicates that the generated state is highly entangled in the polarization, violating the CHSH inequality by more than 7 standard deviations.

ACKNOWLEDGMENTS

This work was supported by the National Science Council of the Republic of China, Taiwan (Grants No. NSC 98-2112-M-009-001-MY3 and No. NSC 99-2923-M-009-004-MY3), a grant from the Ministry of Education, Aiming for Top University (MOE ATU) Program at National Chiao-Tung University (NCTU), and the International Cooperative Research Project (ICORP) program of the Japan Science and Technology Agency (JST).

[1] W. Wittel and G. Weihs, *Quantum Inf. Comput.* **1**, 3 (2001).
 [2] Y. H. Shih, *J. Mod. Opt.* **49**, 2275 (2002).
 [3] T. B. Pittman, Y. H. Shih, D. V. Strekalov, and A. V. Sergienko, *Phys. Rev. A* **52**, R3429 (1995).
 [4] E. J. S. Fonseca, C. H. Monken, and S. Pádua, *Phys. Rev. Lett.* **82**, 2868 (1999).
 [5] J. Jacobson, G. Björk, I. Chuang, and Y. Yamamoto, *Phys. Rev. Lett.* **74**, 4835 (1995).
 [6] K. Edamatsu, R. Shimizu, and T. Itoh, *Phys. Rev. Lett.* **89**, 213601 (2002).

[7] D. V. Strekalov, A. V. Sergienko, D. N. Klyshko, and Y. H. Shih, *Phys. Rev. Lett.* **74**, 3600 (1995).
 [8] C. K. Hong, Z. Y. Ou, and L. Mandel, *Phys. Rev. Lett.* **59**, 2044 (1987).
 [9] M. D'Angelo, M. V. Chekhova, and Y. Shih, *Phys. Rev. Lett.* **87**, 013602 (2001).
 [10] R. Shimizu, K. Edamatsu, and T. Itoh, *Phys. Rev. A* **67**, 041805 (2003).
 [11] A. N. Boto, P. Kok, D. S. Abrams, S. L. Braunstein, C. P. Williams, and J. P. Dowling, *Phys. Rev. Lett.* **85**, 2733 (2000).

- [12] M. Bellini, F. Marin, S. Viciani, A. Zavatta, and F. T. Arecchi, *Phys. Rev. Lett.* **90**, 043602 (2003).
- [13] A. Yabushita and T. Kobayashi, *Phys. Rev. A* **69**, 013806 (2004).
- [14] A. Yabushita and T. Kobayashi, *J. Appl. Phys.* **99**, 063101 (2006).
- [15] S. Takeuchi, *Opt. Lett.* **26**, 843 (2001).
- [16] X.-L. Niu, Y.-F. Huang, G.-Y. Xiang, G.-C. Guo, and Z. Y. Ou, *Opt. Lett.* **33**, 968 (2008).
- [17] R. S. Bennink, Y. Liu, D. D. Earl, and W. P. Grice, *Phys. Rev. A* **74**, 023802 (2006).
- [18] C. Iaconis and I. A. Walmsley, *IEEE J. Quantum Electron.* **35**, 501 (1999).
- [19] W. P. Grice and I. A. Walmsley, *Phys. Rev. A* **56**, 1627 (1997).
- [20] H. P. Lo, A. Yabushita, C. W. Luo, P. Chen, and T. Kobayashi, *Phys. Rev. A* **83**, 022313 (2011).
- [21] O. Cosme, S. Pádua, F. A. Bovino, A. Mazzei, F. Sciarrino, and F. DeMartini, *Phys. Rev. A* **77**, 053822 (2008).
- [22] A. Einstein, B. Podolsky, and N. Rosen, *Phys. Rev.* **47**, 777 (1935).
- [23] J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, *Phys. Rev. Lett.* **23**, 880 (1969).
- [24] J. Fan, M. D. Eisaman, and A. Migdall, *Phys. Rev. A* **76**, 043836 (2007).