We experimentally demonstrate a polarization-entangled photon source at 810 nm using a type-II phase-matched PPKTP crystal pumped by a low-cost, broadband laser diode with a central wavelength of 405 nm and a typical bandwidth of 0.53 nm. The PPKTP crystal is placed in a Sagnac-loop to realize the compact size and high stability. The downconverted biphotons, the signal and the idler, have typical bandwidths of 5.57 nm and 7.32 nm. We prepare two Bell states $|\Psi^+\rangle$ and $|\Psi^-\rangle$ with the fidelities of $0.948\pm0.004$ and $0.963\pm0.002$. In polarization correlation measurement, the visibilities are all higher than 96.2%, and in the Bell inequality test, the S value can achieve $2.78\pm0.01$. This high-quality and low-cost entangled photon source may have many practical applications in quantum information processing.

I. INTRODUCTION

Quantum entanglement, which represents a non-classical correlation among several quantum subsystems, is a critical feature of quantum information science. High-quality entangled photon pairs play an important role in many quantum information technologies, such as quantum communication [1, 2], quantum computation [3, 4], and quantum measurement [5]. A photon has many degrees of freedom, e.g., time, frequency, polarization, position, momentum, and each degree of freedom can be entangled [3, 5]. Polarization-entangled photons, which are relatively easy to generate and characterize, have been widely investigated. As early as 1988, Shih et al. [10] and Ou et al. [11] demonstrated the polarization-entangled photons using Type-I phase-matched spontaneous parametric down-conversion (SPDC) scheme by pumping potassium dihydrogen phosphate (KDP) crystals with monochromatic continuous-wave (CW) lasers. In 1995, Kwiat et al. showed a new entangled photon source by pumping a $\beta$-barium borate (BBO) crystal under type-II phase-matching condition using argon ion laser [12]. From then on, many schemes of entangled photon sources have been demonstrated with different pump lasers (monochromatic CW laser [13, 14] or ultra-fast pulsed laser [13, 16]), different nonlinear crystals (Periodically poled potassium titania phosphate (PPKTP) [17], BBO [18], or periodically poled lithium niobate (PPLN) [19]), different phase-matching types (Type-0 [20, 21], Type-I [22, 23], or Type II [22–26]), or different wavelengths (e.g., 810 nm or 1550 nm). See a recent review article on entangled photon sources in [27].

It can be noticed from the above works that the pump lasers used in the previous entangled sources are almost monochromatic CW lasers or ultrafast pulsed lasers. However, the low-cost broadband multi-mode (longitudinal mode) laser is not widely used. Recently, quantum optical technologies are spreading out from laboratory to industrialization. In practical use, the low-cost and high stability entangled photon sources are indispensable. With the rapid development of blue laser technologies, the inexpensive high-power blue laser diode (LD) can easily provide high power of over 100 mW at 405 nm. Therefore, it is necessary to investigate the multi-mode laser, especially to apply it to the field of quantum optics, e.g., for the preparation of an entangled photon source. Recently, Jeong et al. adopted the method of “universal Bell-state synthesizer” [28] to prepare an entangled photon source by pumping a type-II phase-matched PPKTP with a broadband multi-mode LD [29]. Lohrmann et al. prepared an entangled photon-pair source using the configuration of “linear beam displacement interferometer” using broadband LD and type-0 phase-matched PPKTP [30].

Compared with the above two schemes, there are other optical path configurations, such as the Sagnac-loop structure, which has the merits of compact design and high stability. The first polarization-entangled photon pair using a Sagnac interferometer was demonstrated by Shi et al. [31] with a BBO crystal in 2004. Later, Kim et al. optimized the scheme by using a type-II phase-matched PPKTP crystal for higher brightness and stability [32]. Subsequently, the Sagnac-PPKTP scheme has been widely used in the research of quantum entangled sources at around 800 nm wavelength. For example, a bright entangled photon source was realized by using a mode-locked pulse pumping [33]; a wavelength-tunable and narrow-band entangled photon source was demonstrated by using a CW pumping [34]; a non-collinear PPKTP-Sagnac scheme was demonstrated
using a type-0 phase-matched PPKTP \[35\]. Especially, a high-quality satellite-based entangled source adopted the configuration of the PPKTP-Sagnac scheme and pumped by single-longitudinal-mode LD \[36, 37\]. The PPKTP-Sagnac entangled photon source was also demonstrated at telecom wavelengths and pumped by pico-second laser \[38\], femto-second laser \[17\], or CW lasers \[14\]. The PPKTP-Sagnac scheme at the telecom wavelengths has extra merit of high spectral purity \[39\]. In this work, we further develop the PPKTP-Sagnac scheme to be pumped by a broadband multi-mode LD. This new polarization-entangled photon source has the merits of low-cost, high brightness, and high stability.

II. EXPERIMENT

The experimental setup is shown in Fig. 1. A broadband multi-mode LD was utilized as the pump laser. A typical spectrum of the LD is shown in Fig. 2(a), with a central wavelength of 405.1 nm and a FWHM (\(\Delta\lambda\)) of 0.53 nm, which was measured by a spectrometer of Princeton Instruments SP2300. The pump laser was coupled into a single-mode fiber (SMF) to filter the spatial mode, and the SMF with an FC/APC-type connector also functioned as an isolator to block the back-reflected pump laser from the Sagnac loop. After passing through a QWP (quarter-wave plate), an HWP (half-wave plate), an SPF (short-wave pass filter), and a lens (L\(_2\)), the pump photons were sent into a triangle-shape Sagnac loop, which had a compact size of about 9 cm + 12.7 cm + 9 cm. In the Sagnac loop, the DPBS (dual-wavelength polarization beam splitter) and the DHWP (dual-wavelength HWP) worked for both 405 and 810 nm wavelengths. The PPKTP crystal was type-II phase-matched (y→y+z) with a poling period of 9.825 \(\mu\)m. The downconverted biphotons, i.e., the signal (y-polarized) and the idler (z-polarized), had a degenerate wavelength of around 810 nm at the temperature of 92.5 °C, and their FWHMs were measured to be 5.57 nm and 7.32 nm, respectively, as shown in Fig. 2(b-c). We also theoretically simulated their joint spectral intensity (JSI), as shown in Fig. 2(d) (Also see Fig. A1 in the Appendix). The simulated JSI explained the experimental phenomenon that the signal has a narrower bandwidth than the idler. For simplicity, in this simulation, we assumed the PPKTP crystal was 10 mm long, and the spectrum of the pump laser had a Gaussian distribution with a center wavelength of 405 nm and a bandwidth of 0.45 nm. Under this condition, the simulated FWHMs of the signal and idler are 5.25 nm and 7.78 nm, which are in good agreement with the experimental results. The biphotons generated from the clock-wise pump and the counter-clock-wise pump were separated by a DPBS, collimated by two lenses (L\(_2\) and L\(_3\)), filtered by two LPF (long pass filters), adjusted by two polarizers, and finally coupled into two SMFs, which was connected to single-photon detectors (SPCM-AQRH-10-FC, Excelitas) and a coincidence counter (Picolharp 300, PiccoQuant). For quantum correlation measurement, each polarizer was composed of an HWP and a PBS.

As theoretically analyzed in Ref. \[32\], the output state from the PPKTP-Sagnac scheme is

\[
|\Psi\rangle \propto |H\rangle|V\rangle + e^{i\phi} |\beta|V\rangle|H\rangle),
\]

where \(\phi\) and \(\beta\) are the relative phase and pump ratio between the clock-wise path and counter-clock-wise path.
By rotating HWP, QWP and by finely adjusting the position of PPKTP, we can prepare the Bell states $|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|HV\rangle + |VH\rangle)$ and $|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$. Figure 3 shows the polarization correlation measurement result for $|\Psi^\pm\rangle$ states. For $|\Psi^+\rangle$ state, the maximal coincidence was around 7 kcps with a pump power a 7 mW at each projection base. The corresponding overall brightness was 2 kcps/mW. Without any background subtraction, the visibilities of $0^\circ$, $45^\circ$, $90^\circ$, and $135^\circ$ were 99.5%, 96.4%, 96.6%, and 96.2%, respectively. For $|\Psi^-\rangle$ state, the corresponding visibilities were 99.4%, 96.2%, 99.0% and 96.6%, respectively. All the fringe visibilities in Fig. 3 were higher than 71%, the bound required to violate the Bell’s inequality. We also measured the Bell parameter $S$, which directly indicated the violation of Bell’s inequality. The $S$ values measured were 2.78±0.01 and 2.74±0.01 for $|\Psi^+\rangle$ and $|\Psi^-\rangle$, respectively, which were higher than the classical bound of 2.

We also performed the quantum state tomography of the polarization-entangled state. Polarizers 1 and 2 in Fig. 1 were replaced by combinations of HWP, QWP, and PBS. The density matrix was reconstructed with a maximum likelihood estimation method, as shown in Fig. 3. For states $|\Psi^+\rangle$ and $|\Psi^-\rangle$, the fidelities of the reconstructed density matrix were $0.948\pm0.004$ and $0.963\pm0.002$, respectively. These values indicated that the states were highly entangled.

### III. DISCUSSION

We compare this work with the previous single-mode LD pumped Sagnac-PPKTP scheme used for satellite application [33], the multi-mode laser pumped “universal Bell-state synthesizer” scheme [28], and the multi-mode laser pumped “linear beam displacement interferometer” scheme [30] in Tab. I. It is noteworthy that the type-0 phase-matched crystal has the highest brightness because the nonlinear coefficient of $d_{33}$ is much higher than the value of $d_{24}$ in type-II phase-matched condition. However, the spectral widths of the biphotons in type-0 phase-matched case are much broader. The Sagnac-PPKTP scheme can achieve comparable performance as the “universal Bell-state synthesizer” [28] scheme in stability and brightness, but the configuration is more compact. The single-mode LD laser pumped Sagnac-PPKTP scheme can also achieve high performance, but the pump laser has a higher cost.

The models and characteristics of the components used in this work are listed in Tab. A1 in the Appendix. It can be noticed that the entangled source used in this experiment can still be optimized by improving the collection efficiency of the whole system, especially the coupling efficiency to the SMF, the transmission efficiency of the LPFs. For example, we can optimize the beam waist of the pump laser by using a proper focusing lens and choose LPF with higher transmission efficiency. Nevertheless, we have shown that it is possible to prepare a highly entangled photon source using multi-mode LD pumped PPKTP-Sagnac configuration.
TABLE I. Comparison of this work with the previous results. L is the length of the PPKTP crystal, and \( \Lambda \) is the poling period. \( \lambda_c \) is the center wavelength, and \( \Delta \lambda \) is the FWHM.

| Parameter            | Yin2017 36 | Jeong2016 29 | Lohrmann2020 30 | This work         |
|----------------------|------------|--------------|-----------------|-------------------|
| **Configuration**    | Sagnac loop| universal Bell-state synthesizer | linear beam displacement interferometer | Sagnac loop       |
| **Pump laser**       | Single-mode LD, \( \lambda = 405 \) nm, 160 MHz | Multi-mode LD, \( \lambda = 406.2 \) nm, 0.5 nm | Multi-mode LD, \( \lambda = 405.5 \) nm, \( \approx 0.5 \) nm | Multi-mode LD, \( \lambda = 405.1 \) nm, 0.53 nm |
| **PPKTP**            | L=15 mm, – Type-II, collinear | L=10 mm, \( \Lambda=10 \) \( \mu \)m | L=10 mm, \( \Lambda=3.425 \) \( \mu \)m | L=10 mm, \( \Lambda=9.825 \) \( \mu \)m |
| **Biphotons**        | 811 nm, – | 812.4 nm, – | 780/842 nm, – | 810 nm, – |
| **brightness** (Kcps/mW) | over 91% | over 96% | 560 | over 96.2% |

For future applications this highly entangled photon source is applicable not only for foundational tests of quantum physics but also for quantum networks, e.g., entanglement-based quantum key distribution networks [40]. As shown in Fig. 2(d), the signal and idler photon are also entangled in frequency, so this source has the potential to be a hyper-entangled photon source [11, 42]. Further, the feature of low-cost makes it applicable for educational use. But this source is not useful for Hong-Ou-Mandel (HOM)-interference-based applications, e.g., teleportation or entanglement swapping, because the HOM interference visibility is very low due to the low spectral exchanging symmetry.

IV. CONCLUSION

In summary, we have demonstrated the combination of a broadband LD, a PPKTP, and a Sagnac loop to generate polarization-entangled photons. In polarization correlation measurement, the visibilities are all over 96%, and the S value of the Bell’s inequality reached 2.78±0.01. In a quantum state tomography measurement, the fidelity achieved 0.963±0.002. This entangled source has the merits of being cost-effective, compact, high-brightness, and high stability and may provide a good option for practical applications in quantum information processing.

ACKNOWLEDGEMENT

This work is supported by the National Natural Science Foundations of China (Grant Nos.12074299, 91836102, 11704290) and by the Guangdong Provincial Key Laboratory (Grant No. GKLQSE202102).

[1] Alipasha Vaziri, Gregor Weihs, and Anton Zeilinger, “Experimental two-photon, three-dimensional entanglement for quantum communication,” Phys. Rev. Lett. 89, 240401 (2002).
[2] J.-C. Boileau, R. Laflamme, M. Laforest, and C. R. Myers, “Robust quantum communication using a polarization-entangled photon pair,” Phys. Rev. Lett. 93, 220501 (2004).
[3] Daniel E. Browne and Terry Rudolph, “Resource-efficient linear optical quantum computation,” Phys. Rev. Lett. 95, 010501 (2005).
[4] P. Walther, K. J. Resch, T. Rudolph, E. Schenck, H. Weinfurter, V. Vedral, M. Aspelmeyer, and A. Zeilinger, “Experimental one-way quantum computing,” Nature 434, 169–176 (2005).
[5] Lorenzo Maccone and Changliang Ren, “Quantum radar,” Phys. Rev. Lett. 124, 200503 (2020).
[6] Onur Kuzucu, Marco Fiorentino, Marius A. Albota, Franco N. C. Wong, and Franz X. Kärtner, “Two-photon coincident-frequency entanglement via extended phase matching,” Phys. Rev. Lett. 94, 083601 (2005).
[7] Goro Oohata, Ryosuke Shimizu, and Keiichi Edamatsu, “Photon polarization entanglement induced by biexciton: Experimental evidence for violation of bell’s inequality,” Phys. Rev. Lett. 98, 140503 (2007).
[8] John C. Howell, Ryan S. Bennink, Sean J. Bentley, and R. W. Boyd, “Realization of the Einstein-Podolsky-Rosen paradox using momentum- and position-entangled photons from spontaneous parametric down conversion,” Phys. Rev. Lett. 92, 210403 (2004).
[9] J. Romero, D. Giovannini, S. Franke-Arnold, S. M. Barnett, and M. J. Padgett, “Increasing the dimension in high-dimensional two-photon orbital angular momentum entanglement,” Phys. Rev. A 86, 012334 (2012).

[10] Y. H. Shih and C. O. Alley, “New type of Einstein-Podolsky-Rosen-Bohm experiment using pairs of light quanta produced by optical parametric down conversion,” Phys. Rev. Lett. 61, 2921–2924 (1988).

[11] Z. Y. Ou and L. Mandel, “Violation of Bell’s inequality and classical probability in a two-photon correlation experiment,” Phys. Rev. Lett. 61, 50–53 (1988).

[12] Paul G. Kwiat, Klaus Matile, Harald Weinfurter, Anton Zeilinger, Alexander V. Sergienko, and Yanhua Shih, “New high-intensity source of polarization-entangled photon pairs,” Phys. Rev. Lett. 75, 4337–4341 (1995).

[13] W. P. Grice and I. A. Walsme, “Spectral information and distinguishability in type-II down-conversion with a broadband pump,” Phys. Rev. A 56, 1627–1634 (1997).

[14] Yan Li, Zhi-Yuan Zhou, Dong-Sheng Ding, and Bao-Heonoh Kim, Osung Kwon, and Han Seb Moon, “Pulsed Sagnac source of polarization-entangled photon pairs in telecommunication band,” Sci. Rep. 9 (2019).

[15] Morgan M. Weston, Helen M. Chrzanowski, Sabine Wellmann, Allen Boston, Joseph Ho, Lynden K. Shalm, Varun B. Verma, Michael S. Allman, Sae Woo Nam, Raj B. Patel, Sergei Slussarenko, and Geoff J. Pryde, “Efficient and pure femtosecond-pulse-length source of polarization-entangled photons,” Opt. Express 24, 10869–10879 (2016).

[16] Paul G. Kwiat, Edo Waks, Andrew G. White, Ian Appelbaum, and Philippe H. Eberhard, “Ultra-bright source of polarization-entangled photons,” Phys. Rev. A 60, R773–R776 (1999).

[17] Friedrich König, Elliott J. Mason, Franco N. C. Wong, and Marius A. Albota, “Efficient and spectrally bright source of polarization-entangled photons,” Phys. Rev. A 71, 033805 (2005).

[18] Yuanyuan Chen, Sebastian Ecker, Sören Wengerowsky, Lukas Bulla, Siddharth Koduru Joshi, Fabian Steinlechner, and Rupert Ursin, “Polarization entanglement by time-reversed Hong-Ou-Mandel interference,” Phys. Rev. Lett. 121, 200502 (2018).

[19] Haruka Terashima, Satoshi Kobayashi, Takahito Tsukiyama, and Kaoru Sanaka, “Quantum interferometric generation of polarization entangled photons,” Sci. Rep. 8, 15733 (2018).

[20] Radhika Rangarajan, Michael Goggin, and Paul Kwiat, “Optimizing type-I polarization-entangled photons,” Opt. Express 17, 18920–18933 (2009).

[21] Aitor Villar, Alexander Lohmann, and Alexander Ling, “Experimental entangled photon pair generation using crystals with parallel optical axes,” Opt. Express 26, 12396–12402 (2018).

[22] A. Martin, A. Issautier, H. Herrmann, W. Sohler, D. B. Ostrowsky, O. Allibart, and S. Tannizzi, “A polarization entangled photon-pair source based on a type-II PPLN waveguide emitting at a telecom wavelength,” New J. Phys. 12, 103005 (2010).

[23] Rolf Horn and Thomas Jennewein, “Auto-balancing and robust interferometer designs for polarization entangled photon sources,” Opt. Express 27, 17369–17376 (2019).

[24] Yoon-Chang Jeong, Kang-Hee Hong, and Yoon-Ho Kim, “Bright source of polarization-entangled photons using a PPKTP pumped by a broadband multi-mode diode laser,” Opt. Express 24, 1165 (2016).

[25] Alexander Lohmann, Chithrabhanu Perumangatt, Aitor Villar, and Alexander Ling, “Broadband pumped polarization-entangled photon-pair source in a linear beam displacement interferometer,” Appl. Phys. Lett. 116, 021101 (2020).

[26] Yao-Ho Kim, Sergei P. Kulik, Maria V. Chekhova, Warren P. Grice, and Yanhua Shih, “Experimental entanglement concentration and universal Bell-state synthesizer,” Phys. Rev. A 67, 010301(R) (2003).

[27] Yoon-Chang Jeong, Kang-Hee Hong, and Yoon-Ho Kim, “Bright source of polarization-entangled photons using a PPKTP pumped by a broadband multi-mode diode laser,” Opt. Express 24, 1165 (2016).

[28] Youn-Chang Jeong, Kang-Hee Hong, and Yoon-Ho Kim, “Polarization-entangled photon-pair source obtained via type-II non-collinear SPDC process with PPKTP crystal,” Opt. Express 24, 2941–2953 (2016).

[29] Ali Anwar, Chithrabhanu Perumangatt, Fabian Steinlechner, Thomas Jennewein, and Alexander Ling, “Entangled photon-pair sources based on three-wave mixing in bulk crystals,” Rev. Sci. Instrum. 92, 041101 (2021).

[30] Youn-Ho Kim, Sergei P. Kulik, Maria V. Chekhova, Warren P. Grice, and Yanhua Shih, “Experimental entanglement concentration and universal Bell-state synthesizer,” Phys. Rev. A 67, 010301(R) (2003).

[31] Ali Anwar, Chithrabhanu Perumangatt, Fabian Steinlechner, Thomas Jennewein, and Alexander Ling, “Entangled photon-pair sources based on three-wave mixing in bulk crystals,” Rev. Sci. Instrum. 92, 041101 (2021).

[32] Yoon-Ho Kim, Sergei P. Kulik, Maria V. Chekhova, Warren P. Grice, and Yanhua Shih, “Experimental entanglement concentration and universal Bell-state synthesizer,” Phys. Rev. A 67, 010301(R) (2003).

[33] Ali Anwar, Chithrabhanu Perumangatt, Fabian Steinlechner, Thomas Jennewein, and Alexander Ling, “Entangled photon-pair sources based on three-wave mixing in bulk crystals,” Rev. Sci. Instrum. 92, 041101 (2021).
APPENDIX

Figure A1 shows how the JSI in Fig. 2(d) was simulated.

The models and performance of the experimental components in this work are shown in Tab. A1.

A photograph of the setup is shown in Fig. A2.
FIG. A1. The joint spectral amplitude (JSA) is the product of pump-envelope function (PEF) and phase-matching function (PMF) [39], and the absolute square of JSA is JSI, which is shown in Fig. 2(d).

| Name                  | Type                        | Characteristics                                      |
|-----------------------|-----------------------------|------------------------------------------------------|
| Laser                 | LR-BSP-405nm/100mw (LR laser Co.) | $\lambda_c=405.1$ nm, FWHM=0.53 nm                   |
| Fiber coupler         | GCX-L005-FC (Daheng Co.)     | $\eta_c=52.6\%$                                     |
| SMF (405 nm)          | PM-S405-XP (Thorlabs)        | with FC/APC connector                                |
| Mirror (405 nm)       | LLM0025-45-397-405 (Union Optics Co.) | $\eta_r=99.2\%$                                    |
| QWP (405 nm)          | WPZ4420-405 (Union Optics Co.) | $\eta_t=100\%$                                     |
| HWP (405 nm)          | WPZ2420-405 (Union Optics Co.) | $\eta_t=100\%$                                     |
| PBS (405 nm)          | PBS0120-397-405 (Union Optics Co.) | extinction ratio=1000:1                             |
| Lens 1 (405 nm)       | PCX1809-300-500 (Union Optics Co.) | $f=200$ mm, $\eta_t=100\%;$ fused silica          |
| Lens 2/3 (810nm)      | PCX0810-780-810 (Union Optics Co.) | $f=200$ mm, $\eta_t=100\%;$ K9 glass             |
| Mirror (810 nm)       | GCC-102202 (Daheng Co.)      | protected silver with $\eta_r=98.2\%$             |
| QWP (810 nm)          | GCL-060704 (Daheng Co.)      | zero order QWP                                      |
| HWP (810 nm)          | GCL-060714 (Daheng Co.)      | zero order HWP                                      |
| SPF                   | GCC-211002 (Daheng Co.)      | $\eta_t=96.7\%$ for 400-630 nm                     |
| LPF1(DM)              | DIM-K9-25.4-3 (Union Optics Co.) | $\eta_t=96\%(810$ nm), $\eta_r=94\%(405$ nm)      |
| LPF2                  | RG-715 (Edmund Co.)          | $\eta_t=89.7\%(810$ nm)                            |
| DHWP                  | DHWP (Union Optics Co.)      | HWP for 405 nm and 810 nm                           |
| DPBS                  | DPBS (Union Optics Co.)      |                                                      |
| SMF (810 nm)          | GCX-XSM-4/125-FC/PC (Daheng Co.) | SMF at 810 nm                                      |
| PPKTP                 | PPKTP (Raicol Co.)           | size=$1\times2\times10$ mm, $\Lambda=9.825$ $\mu$m |
| Oven                  | TC038-PC (HC Photonics Co.)   | resolution=$0.1^\circ$ C, range=0-200$^\circ$     |
| Rotator               | OSMS-60YAW (Sigma Koki Co.)  | controlled by LabVIEW software                      |
| Si-APD                | SPCM-AQRH-10-FC (Excelitas Co.) | $\eta_d \approx 60\%$ at 810 nm                   |

TABLE A1. The models and characteristics of the main components for the LD-pumped PPKTP-Sagnac entangled photon source. $\eta_c$ is the coupling efficiency, $\eta_d$ is the detection efficiency, $\eta_t$ is the transmission ratio, and $\eta_r$ is the reflection ratio.
FIG. A2. A photograph of the setup.