Review Article

ADVANCED PHOTONICS

# Quantum entanglement on photonic chips: a review

Xiaojiong Chen,[a,†] Zhaorong Fu,[a,†] Qihuang Gong,[a,b,c,d] and Jianwei Wang[a,b,c,d,*]
[a]Peking University, School of Physics, State Key Laboratory for Mesoscopic Physics, Beijing, China
[b]Peking University, Frontiers Science Center for Nano-Optoelectronics, Collaborative Innovation Center of Quantum Matter, Beijing, China
[c]Shanxi University, Collaborative Innovation Center of Extreme Optics, Taiyuan, China
[d]Peking University Yangtze Delta Institute of Optoelectronics, Nantong, China

**Abstract.** Entanglement is one of the most vital properties of quantum mechanical systems, and it forms the backbone of quantum information technologies. Taking advantage of nano/microfabrication and particularly complementary metal-oxide-semiconductor manufacturing technologies, photonic integrated circuits (PICs) have emerged as a versatile platform for the generation, manipulation, and measurement of entangled photonic states. We summarize the recent progress of quantum entanglement on PICs, starting from the generation of nonentangled and entangled biphoton states, to the generation of entangled states of multiple photons, multiple dimensions, and multiple degrees of freedom, as well as their applications for quantum information processing.

Keywords: quantum entanglement; integrated optics; photonic chip.

Received Aug. 21, 2021; revised manuscript received Nov. 8, 2021; accepted for publication Nov. 15, 2021; published online Dec. 7, 2021.



[DOI: 10.1117/1.AP.3.6.064002]

## 1 Introduction

The famous Einstein–Podolsky–Rosen (EPR) state was originally proposed[1] and later named "entangled state"[2] for the debate of the completeness of the quantum mechanical description of reality. Pioneering experiments of EPR entanglement have allowed the exclusion of the presence of local hidden variables by violating the Bell inequality[3] and allowed significant Bell tests with a closure of detection and distance loopholes.[4–6] Moreover, entanglement has also become the enabling resource for quantum information applications in the fields of quantum communication and networks,[7] quantum metrology and imaging,[8,9] and quantum computation and simulations.[10,11] In all of the above fundamental investigations and technological developments, the photon has been in the core position, owing to its low-noise nature, ease of control, room-temperature operation, and high-speed transmission.[12] For example, the loophole-free Bell tests were implemented in entangled photonic systems.[4–6] The photon is recognized as the inevitable carrier for global-scale quantum key distribution[13] and quantum internet.[14] Recently, Boson sampling with photons was used to demonstrate quantum computational advantages.[15] Universal quantum computing with photons is possible with largely entangled cluster states.[16–18] Integrated quantum photonics provides a compact, reliable, reprogrammable, and scalable platform for the study of fundamental quantum physics and for the implementation of profound quantum applications.[19] Leveraging mature complementary metal-oxide-semiconductor (CMOS) fabrication, integrated photonic quantum technology progressed significantly since its first demonstration in the controlled-NOT logic gate on silica waveguide circuits in 2008.[20] This includes the development of advanced material systems,[20–32] implementations of major quantum communication protocols,[28,32,33] and proof-of-principle demonstrations of quantum computation and quantum simulation algorithms.[34–36] We recommend other reviews of those topics in Refs. 19 and 37.

In this review, we summarize the experimental progress of on-chip generation, manipulation, and measurement of entangled photonic states on integrated silicon-photonic quantum chips. In Sec. 2, we introduce the representation of on-chip quantum states in various degrees of freedom (DoFs) of single photons. In Sec. 3, we introduce integrated parametric photon-pair sources (nonentangled photon-pairs). In Sec. 4, we then focus on various types of photonic entangled states, including entangled biphoton states and entangled states of multiple

*Address all correspondence to Jianwei Wang, jianwei.wang@pku.edu.cn
†These authors contributed equally to this work.

photons, multiple dimensions, and multiple DoFs. Finally, we briefly review possible chip-scale applications with entangled states and discuss future challenges and opportunities.

## 2 On-Chip Encoding Single-Photon Quantum States

A photon features a broad spectrum of different DoFs that can represent the basic units of quantum information, i.e., qubit $\alpha|0\rangle + \beta|1\rangle$, where $\alpha, \beta$ are the complex amplitudes. The available DoFs include position (path), polarization, frequency (wavelength), and spatial and temporal modes. Notably, the basic quantum information unit usually is defined in the binary format as a qubit, but it can be generally defined in the $d$-nary format as a qudit $\frac{1}{\sqrt{d}}\sum_{i=0}^{d-1} c_i|i\rangle$, where $|i\rangle$ is the logical state in the $i$'th mode.

In bulk-optics quantum experiments, the DoF of polarization has been extensively explored, e.g., in early seminal demonstrations.[38–40] Similar to the bulk-optics realization of polarized qubits by a birefringent waveplate and polarization beamsplitter (PBS) on integrated photonic chips, the polarization of photons can be manipulated by an integrated polarization rotator and PBS (i.e., birefringent waveguide or structure), which have been well developed in the silicon-photonics field.[41,42] Another commonly implemented DoF is the location or position information of photons. On integrated photonic chips, the $|0\rangle$ and $|1\rangle$ logic states can be well-defined in two modes in two separate optical waveguides that are physically phase-stabilized when manipulating the qubit states. This approach usually refers to path-encoding or dual-rail encoding in integrated quantum photonics. Path-encoded qubits can be manipulated by integrated beamsplitters and optical interferometers with high levels of fidelity, universality, dense integration, and reprogrammability, and therefore have been widely adopted in many integrated photonic quantum experiments.[24,43,44] The temporal mode of photons is also one of the available DoFs. Using fast light modulation or long optical delays, qubit states in two temporal modes or time bins can be generated. With the recent development of fast modulator and low-loss waveguides, time-bin encoded photons may provide an efficient solution for the implementation of chip-scale quantum key distributions. Moreover, optical waveguides support high-order eigenmodes, which allows the encoding of qubit or qudit states in the spatial mode DoF. The recent development of multimode silicon photonics enables mode-entanglement and its applications.[45,46] Such a mode-encoding state in optical waveguides can be reliably operated and transmitted, which is fundamentally similar to the case of optical orbital angular momentum in bulk-optics, where it is reliable.[47–50] Discrete frequency bins, usually existing in optical microresonators, can be in a coherent superposition state, thus allowing the preparation of qubits or qudits in the frequency DoF.[51] This approach recently has allowed interesting demonstrations of frequency entanglement.[52,53]

## 3 Integrated Waveguide Photon-Pair Sources

High-quality single-photon sources are indispensable in photonic quantum technologies. An ideal single-photon source has to produce pure photons with high efficiency, and the photons have to be identical to those from other independent sources. Parametric nonlinear-optical sources emit photons nondeterministically, and they can be integrated into large arrays, in which each owns high purity, heralding efficiency and indistinguishability. Such parametric photon sources produce a pair of photons, and the success of detecting one of them indicates the presence of the other, referring to heralding single-photon sources. The integration of parametric nonlinear-optical sources not only provides the possibility for future multiplexing high-efficiency single-photon sources[54] but also for the generation of different entangled states.

The generation of entangled photons relies on the spontaneous parametric down conversion (SPDC) process in $\chi^{(2)}$ materials or the spontaneous four-wave mixing (SFWM) process in $\chi^{(3)}$ materials. Integrated SPDC photon-pair sources and entangled sources have been demonstrated in periodically poled lithium niobate,[26,27] gallium arsenide,[30,31] and aluminum nitride[55] waveguides and structures. Here, we focus more on the discussion of third-order silicon-based material systems, such as silicon-on-insulator and silicon nitride.

The physical laws governing photon-pair generation are the conservations of momentum and energy. The former usually refers to the phase matching condition for nonlinear-optical processes. The simplest photon-pair source is the one using straight waveguides, e.g., silicon waveguides. By optimizing the waveguide geometry such as waveguide width, thickness, or etching depth to engineer group velocity dispersion, photon pairs can be generated in a wide spectrum through SFWM. This type of straight waveguide source can be easily and reliably implemented on chip, for example, an array of 16 waveguide sources.[43] However, it only reaches high spectral purity at the expense of losing brightness and heralding efficiency. To achieve both high purity and heralding efficiency, dual-pump SFWM[56,57] and intermodal SFWM[58] have been proposed. Recently, a multimode waveguides source based on a dual-mode pump-delayed excitation scheme was demonstrated in silicon, with a spectral purity of 0.9904(6), a mutual indistinguishability of 0.987(2), and >90% heralding efficiency.[59] Another type of integrated photon-pair source is based on optical microresonators, e.g., microring and microdisk. For a simple point-coupled ring resonator, the maximum photon pair generation rate can be achieved at a critical coupling point, but the heralding efficiency of photon pairs is bounded by 0.50, implying a trade-off balance.[60] At the same time, the spectral purity relies on the quantity factor, and it shows a theoretical upper limit of the purity of 0.93.[61] An experimental demonstration of an array of microresonator-based photon-pair sources was reported with purity of 0.90, heralding efficiency of 0.50, and indistinguishability of 0.90.[62] Two approaches are proposed to improve the performance. One is to adopt two delayed pulsed lights for pumping, in which the pump spectral width can be increased, and thus the upper limit of purity can be improved up to 0.999.[63] The second is to use a dual-MZI-coupled microring resonator to independently control the linewidths of the pump and signal (idler) photons working at different coupling points,[61] and a purity of 0.95 was experimentally obtained.[64] A similar scheme has also been experimentally investigated.[65]

## 4 Generation, Manipulation, and Measurement of Entanglement on Photonic Chips

The generation, manipulation, and measurement of large entanglement structure is at the heart of on-chip quantum information processing. For instance, one-way quantum computing requires large-scale cluster states to transmit coherent logical operators along the entanglement structure.[16,66] Quantum internet relies on the distribution of entanglement between quantum processors at different locations.[14] In this section, we introduce how to entangle photons such as Bell states on quantum photonic chips, and, in particular, how to generate multi-DoF, multiphoton, and multidimensional entanglement states.

Integrated photonics is able to engineer multiple DoFs to encode and process quantum information. The coherent conversion between different DoFs of photons can make use of their own advantages for implementing different tasks. For example, path-to-polarization conversion allows the reliable distribution of entangled states between two separate chips, maintaining coherence and robustness both on chip and in optical fibers[62,67] [see Fig. 1(a)]. Coherent conversion of entangled states between path, polarization, and transverse mode was also reported in a silicon chip[68] [see Fig. 1(b)]. Moreover, simultaneously entangling multiple DoFs of photons, named hyperentanglement, provides an efficient way to expand the Hilbert space and enrich applications.[69,70] In bulk-optics, three different DoFs (path, polarization, and orbital angular momentum mode) of six photons have been simultaneously entangled to deliver an 18-qubit

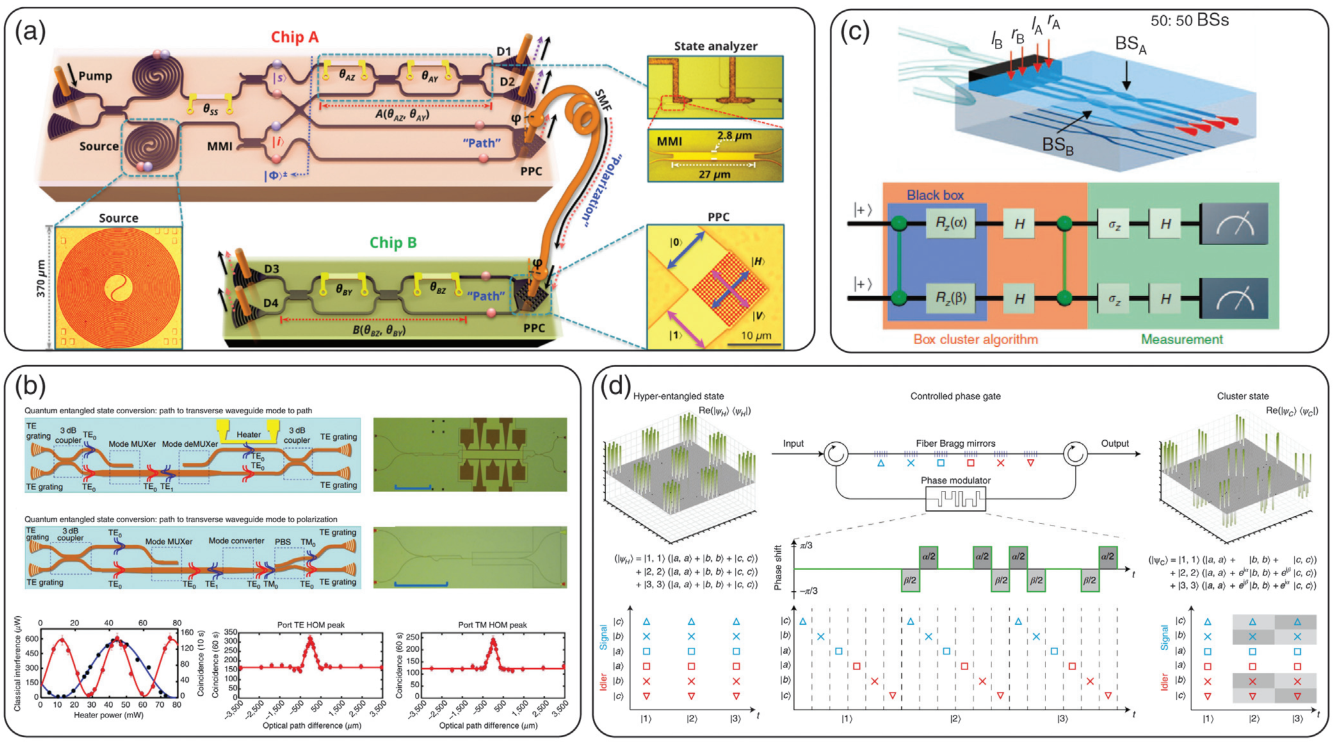


**Fig. 1** On-chip conversion of multiple DoFs and multi-DoF entanglement. (a) Chip-to-chip quantum entanglement distribution by path-polarization interconversion. A pair of entangled photons, coded in path, were generated on chip A, then one photon was distributed to chip B via two-dimensional grating couplers, while the other photon remained on chip A. As a result, a two-photon entangled state $|\phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$ was distributed coherently between two separate chips. Bell-type violation of $S = 2.638 \pm 0.039$ showed the strong entanglement between two separate photons. (b) Quantum entangled state conversion between different DoFs of path, transverse mode, and polarization. Two photons were coupled into the silicon chip, and then NOON entangled state, $\frac{1}{\sqrt{2}}(|2\rangle_0|0\rangle_1 + |0\rangle_0|2\rangle_1)$ coded in path, was generated by an interference. With a mode multiplexer, the entangled state coded in path was first converted into a transverse waveguide mode $TE_0/TE_1$. Then, the quantum information was converted back to the path by a mode demultiplexer or to polarization by a PBS. Two-photon interference and Hong–Ou–Mandel effect measurements show the preservation of quantum coherence during the conversion between different DoFs. (c) Four-qubit hyperentanglement cluster state by entangling the path and polarization simultaneously. Quantum state tomography and genuine multipartite entanglement witness were analyzed to ensure high fidelity of the prepared four-qubit cluster state. Based on the model of one-way quantum computing, Grover's search algorithm was performed, where the average success rate of the algorithm was $0.960 \pm 0.007$. (d) Two photon 4-qutrit hyperentangled cluster state. Three-level time-bin entangled state with three frequency modes $|\psi_H\rangle$ was created on a micro-ring resonator. Then, hyperentanglement of time-frequency $|\psi_C\rangle$ was realized by a controlled phase gate (composed of fiber Bragg mirrors and an electro-optical phase modulator). Basic high-dimensional one way quantum computing operators were tested. Panels reproduced from: (a) Ref. 67, Optica; (b) Ref. 68, Springer Nature; (c) Ref. 34, Springer Nature; and (d) Ref. 72, Springer Nature.

entangled state.[71] The first on-chip demonstration of hyperentanglement was implemented on silica waveguide circuits fabricated by laser writing techniques[34] [see Fig. 1(c)]. Path and polarization DoFs were adopted to prepare a four-qubit cluster state, which then was used to process the Grover's search algorithm in the one-way model. A four-qutrit cluster state with hyperentanglement of frequency and time bins was created in a micoring resonator together with fiber optics[72] [see Fig. 1(d)].

A multiphoton (three-photon) Greenberger–Horne–Zeilinger (GHZ) entangled state was proposed and experimentally demonstrated in 1997 with strong incompatibility to local realism,[73] and it then became a key resource for quantum computing[74] and communication.[75] In a bulk-optics system, to date, an up to 12-photon GHZ entangled state has been reported.[76] In photonic chips, the number of GHZ entangled photons has been limited to 4 to date,[62,77] due to a far less-optimized photon source and relatively high loss of the chip. Multiphoton quantum interference or multiphoton nonentangled states have been prepared on chip.[78–81] The first on-chip demonstrations of four-photon GHZ entanglement were reported on two silicon chips, one enabled to be reconfigured to generate both the GHZ state and graph state[77] [see Fig. 2(b)], and the other chip with micro-ring resonant sources to create and verify genuine GHZ entanglement and teleportation[62] [see Fig. 2(a)]. Recently, four-photon eight-qubit graph entangled states were generated on a silicon photonic chip by remapping the qudit state into qubits.[82] It was reconfigured to implement the one-way quantum computing model and to implement error-corrected qubits [see Fig. 2(c)].

Going beyond the two-level qubit systems, multilevel quantum dit (qudit) systems offer unique properties and new capacities.[83] It not only leads to the expansion of Hilbert space, but brings in new physics and applications, such as stronger Bell violation,[84] noise-robustness in quantum communication,[85] and

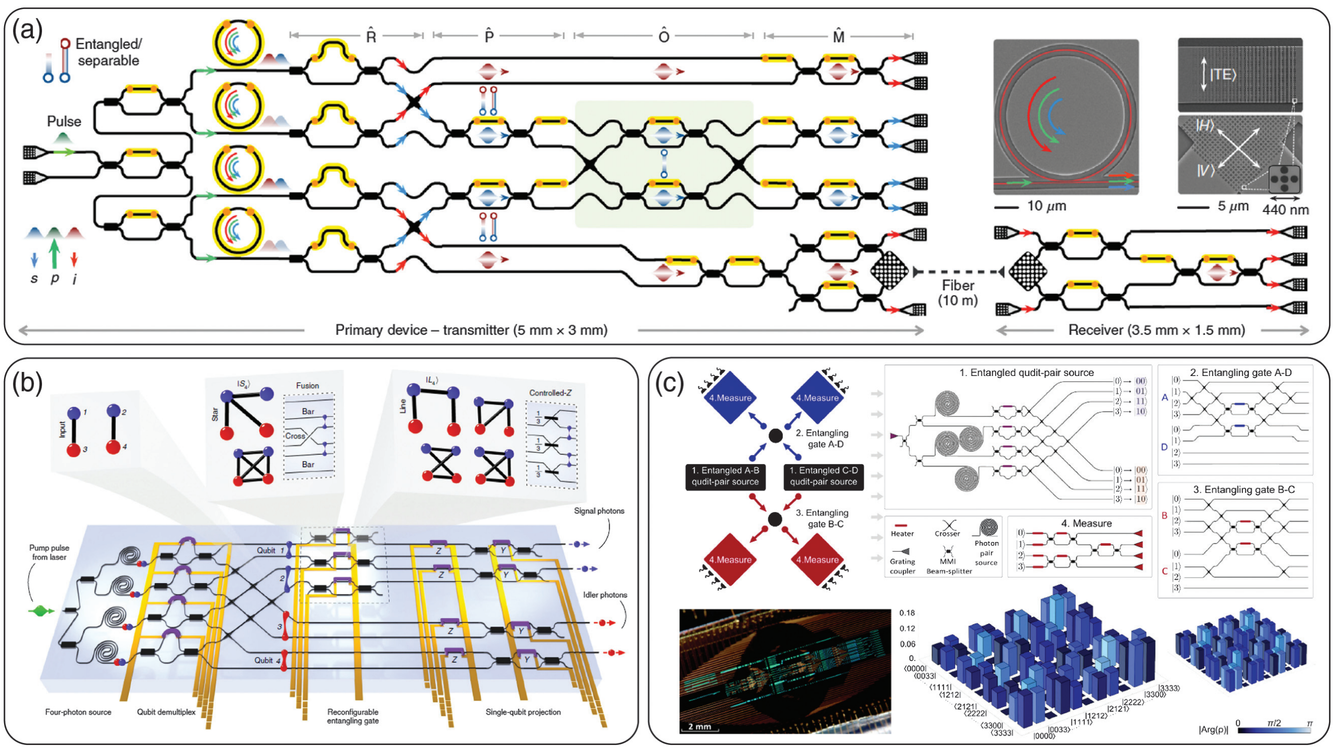


**Fig. 2** On-chip generation of multiphoton entanglement. (a) Generation of four-photon four-qubit genuine GHZ entangled states on a silicon photonic chip. Two photon-pairs with high purity and indistinguishability were produced by an array of microring resonators. Then, a reconfigurable fusion entangling operator was performed on two indistinguishable photons, generating the genuine four-photon GHZ entangled state. Entanglement witness confirmed the genuine multiphoton entanglement. (b) Generation of four-photon four-qubit cluster states on a silicon photonic chip. An entangling gate could be tuned to perform either a fusion operator or controlled-$Z$ operator, by which the linear- and star-cluster states were created. Thanks to the highly reconfigurable photonics chip, all types of four-photon graph states were prepared. Nonlocality of the multiphoton state was verified by the Mermin test. (c) Generation of four-photon eight-qubit graph states on a silicon photonic chip, in which each of the four-dimensional qudits was remapped into two qubits. High-dimensional entangling gates were ultilized to generate four-photon four-dimensional entanglement from two pairs of two-photon four-dimensional entangled states. Error-corrected qubits were used to implement quantum computational algorithms. When running the phase-estimation algorithm with error protection, the success rate would raise from 62.5% to 95.8%. Panels reproduced from: (a) Ref. 62, Springer Nature; (b) Ref. 77, Springer Nature; and (c) Ref. 82, Springer Nature.

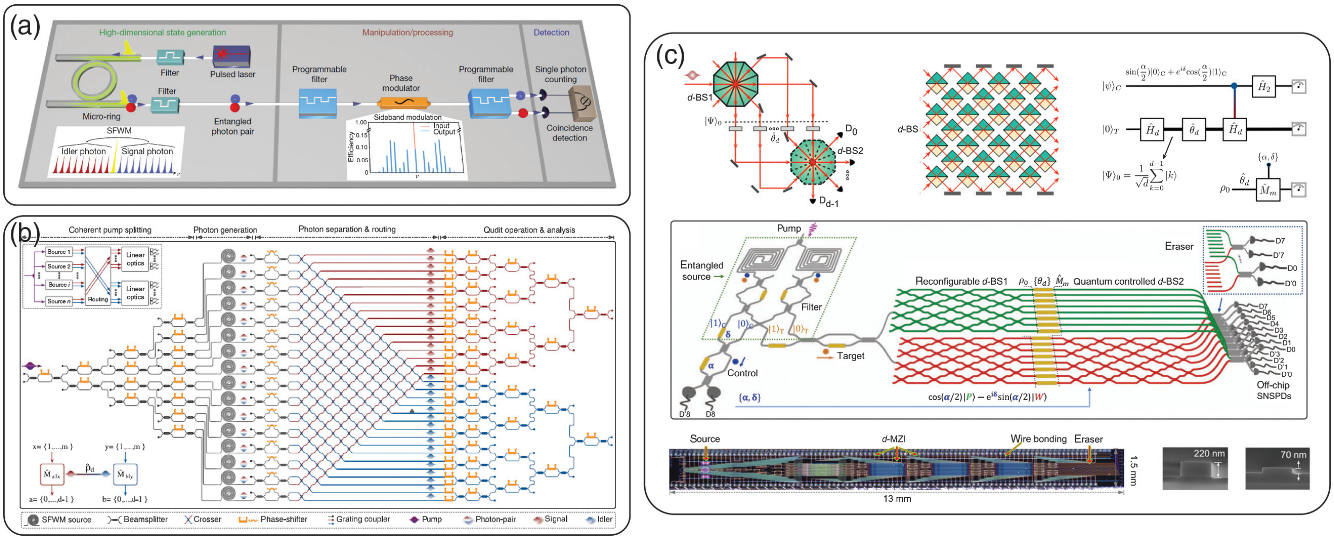

**Fig. 3** On-chip generation of multidimensional entanglement. (a) Generation of frequency-bin encoded multidimensional entangled state. An integrated microring resonator was used to produce a pair of frequency-entangled photons with up to 10-dimensions. High-dimensional gate operations in the frequency domain were executed on qudits, demonstrating qudit two-photon interference and qudit tomography. (b) Generation of path-encoded multidimensional entanglement on a large-scale programmable silicon-photonic chip, where 16 identical SFWM single-photon sources and qudit operation/analyzing networks were all integrated monolithically. Each single-photon source would generate a pair of highly indistinguishable photons. By this means, this chip can create, control, and measure $15 \times 15$ entangled states. Genuine multidimensional entanglement was verified by quantum state tomography, and experimental violation of generalized Bell inequality and steering inequality. (c) Multipath wave-particle duality experiment on a large-scale silicon chip. The state-process entanglement technique was adopted to implement the quantum-controlled generalized Hadamard operations. The process (wave/particle) of the target photon going through would be coherently controlled by the state of the control photon. The generalized multipath wave-particle duality was demonstrated qualitatively and quantitatively. Panels reproduced from: (a) Ref. 51, Springer Nature; (b) Ref. 43, AAAS; and (c) Ref. 90, Springer Nature.

high efficiency in quantum computing.[86] Photonics naturally allows the preparation of multidimensional entanglement in various DoFs. Utilizing an integrated microring, multidimensional entangled states with a 10 frequency-bin have been demonstrated [see Fig. 3(a)],[51] in which arbitrary operation is performed by telecommunication fiber optical components. Qudit states encoded in multiple paths can be arbitrarily and reconfigurably manipulated by integrated quantum photonic circuits.[87,88] A 15-dimensional entangled state has been demonstrated on a large-scale silicon chip,[43] allowing the generation, manipulation, and measurement of entanglement [see Fig. 3(b)]. Genuine multidimensional entanglement was verified by quantum state tomography and experimental violation of generalized Bell inequality and steering inequality. A three-dimensional entangled state was obtained by a similar method.[89] In addition, generalized multipath wave-particle duality, multipath coherence, and multimode quantizations were confirmed on a large-scale integrated quantum chip, providing the basics for multidimensional quantum technologies [see Fig. 3(c)].[90]

## 5 Outlook and Conclusion

Generation and control of entanglement with integrated quantum photonics could enable profound applications in quantum communication, computing, and simulations. The first chip-to-chip entanglement distribution[67] and quantum teleportation[62] were demonstrated between two programmable photonic chips. The path-polarization conversion technique was invented to ensure the stability and coherence of the chip-to-chip system. Integrated optics may lead to low-cost, compact, fast, and portable chip-scale quantum communication chips. Integrated quantum photonics could provide a reliable, programmable, and scalable system to generate largely entangled cluster states, which is the key for the implementation of measurement-based quantum computing.[34,77] Four-photon four-qubit GHZ states[62] and cluster states[77] have been generated on silicon photonic chips. Two-photon four-qubit cluster states[34] and four-photon eight-qubit graph states[82] have been demonstrated on photonic chips. Such controllable quantum devices may find near-term applications in the simulations of complex physical and chemical systems. For example, phase estimation,[91] variational eigenvalue solver,[92] and their combined algorithm[35] were demonstrated to calculate the ground state energy of molecules. Together with machine learning techniques, integrated photonic chips could be adopted to validate the Hamiltonian model and verify the simulating device.[36]

The functionality and capability of integrated quantum photonics rely on the ability to generate, control, and analyze complex entanglement. It thus requires further and continuous development of on-chip multi-DoF entanglement with many different DoFs, multiphoton entanglement with a large number of single photons, and multidimensional entanglement with a large number of spatial modes.

Thanks to a mature silicon-on-insulator CMOS fabrication process,[93] a large quantity of quantum photonic components can be integrated monolithically on a single silicon chip.[43,44,90,94] Meanwhile, CMOS-compatible platforms based on other material systems, like silicon nitride and high-index doped silica,[95] are also explored widely to make use of their intrinsic optical properties. The negligible two-photon absorption gives silicon nitride a huge advantage over silicon, while the intrinsic ultra-low loss makes silica a strong candidate for next generation of integrated quantum photonics platform. Lithium niobate[96] is the first choice for ultra-fast on-chip modulators. The key technical challenge is how to integrate various materials monolithically on a single chip by means of hybrid integration. An integrated chip with multiple superior performances may become the next development direction of integrated photonics quantum technology.

## Acknowledgments

We would like to acknowledge the support from the National Key Research and Development (R&D) Program of China (Nos. 2019YFA0308702, 2018YFB1107205, and 2016YFA0301302), the National Natural Science Foundation of China (Nos. 61975001, 61590933, 61904196, 61675007, 11975026, and 12075159), Beijing Natural Science Foundation (No. Z190005), and the Key R&D Program of Guangdong Province (No. 2018B030329001).

## References

1. A. Einstein, B. Podolsky, and N. Rosen, "Can quantum-mechanical description of physical reality be considered complete?" *Phys. Rev.* **47**(10), 777–780 (1935).
2. E. Schrödinger, "Probability relations between separated systems," *Math. Proc. Cambridge Philos. Soc.* **32**(3), 446–452 (1936).
3. J. S. Bell, "On the Einstein–Podolsky–Rosen paradox," *Phys.* **1**(3), 195–200 (1964).
4. B. Hensen et al., "Loophole-free bell inequality violation using electron spins separated by 1.3 kilometres," *Nature* **526**(7575), 682–686 (2015).
5. L. K. Shalm et al., "Strong loophole-free test of local realism," *Phys. Rev. Lett.* **115**(25), 250402 (2015).
6. M. Giustina et al., "Significant-loophole-free test of Bell's theorem with entangled photons," *Phys. Rev. Lett.* **115**(25), 250401 (2015).
7. N. Gisin et al., "Quantum cryptography," *Rev. Mod. Phys.* **74**(1), 145–195 (2002).
8. V. Giovannetti, S. Lloyd, and L. Maccone, "Quantum-enhanced measurements: beating the standard quantum limit," *Science* **306**(5700), 1330–1336 (2004).
9. G. B. Lemos et al., "Quantum imaging with undetected photons," *Nature* **512**(7515), 409–412 (2014).
10. T. D. Ladd et al., "Quantum computers," *Nature* **464**(7285), 45–53 (2010).
11. I. M. Georgescu, S. Ashhab, and F. Nori, "Quantum simulation," *Rev. Mod. Phys.* **86**(1), 153–185 (2014).
12. J.-W. Pan et al., "Multiphoton entanglement and interferometry," *Rev. Mod. Phys.* **84**(2), 777–838 (2012).
13. N. Gisin and R. Thew, "Quantum communication," *Nat. Photonics* **1**(3), 165–171 (2007).
14. H. J. Kimble, "Quantum internet," *Nature* **453**(7198), 1023–1030 (2008).
15. H.-S. Zhong et al., "Quantum computational advantage using photons," *Science* **370**(6523), 1460–1463 (2020).
16. R. Raussendorf and H. J. Briegel, "A one-way quantum computer," *Phys. Rev. Lett.* **86**(22), 5188–5191 (2001).
17. P. Kok et al., "Linear optical quantum computing with photonic qubits," *Rev. Mod. Phys.* **79**(1), 135–174 (2007).
18. J. L. O'Brien, "Optical quantum computing," *Science* **318**(5856), 1567–1570 (2007).
19. J. Wang et al., "Integrated photonic quantum technologies," *Nat. Photonics* **14**(5), 273–284 (2020).
20. A. Politi et al., "Silica-on-silicon waveguide quantum circuits," *Science* **320**(5876), 646–649 (2008).
21. J. C. F. Matthews et al., "Manipulation of multiphoton entanglement in waveguide quantum circuits," *Nat. Photonics* **3**(6), 346–350 (2009).
22. P. J. Shadbolt et al., "Generating, manipulating and measuring entanglement and mixture with a reconfigurable photonic circuit," *Nat. Photonics* **6**(1), 45–49 (2012).
23. H. Takesue et al., "Entanglement generation using silicon wire waveguide," *Appl. Phys. Lett.* **91**(20), 201108 (2007).
24. J. W. Silverstone et al., "On-chip quantum interference between silicon photon-pair sources," *Nat. Photonics* **8**(2), 104–108 (2014).
25. B. J. Smith et al., "Phase-controlled integrated photonic quantum circuits," *Opt. Express* **17**(16), 13516–13525 (2009).
26. S. Tanzilli et al., "PPLN waveguide for quantum communication," *Eur. Phys. J. D* **18**(2), 155–160 (2002).
27. H. Jin et al., "On-chip generation and manipulation of entangled photons based on reconfigurable lithium-niobate waveguide circuits," *Phys. Rev. Lett.* **113**(10), 103601 (2014).
28. X. Lu et al., "Chip-integrated visible-telecom entangled photon pair source for quantum communication," *Nat. Phys.* **15**(4), 373–381 (2019).
29. X. Zhang et al., "Integrated silicon nitride time-bin entanglement circuits," *Opt. Lett.* **43**(15), 3469–3472 (2018).
30. R. Horn et al., "Monolithic source of photon pairs," *Phys. Rev. Lett.* **108**(15), 153605 (2012).
31. J. Wang et al., "Gallium arsenide (GaAS) quantum photonic waveguide circuits," *Opt. Commun.* **327**, 49–55 (2014).
32. P. Sibson et al., "Chip-based quantum key distribution," *Nat. Commun.* **8**, 13984 (2017).
33. H. Semenenko et al., "Chip-based measurement-device-independent quantum key distribution," *Optica* **7**(3), 238–242 (2020).
34. M. A. Ciampini et al., "Path-polarization hyperentangled and cluster states of photons on a chip," *Light Sci. Appl.* **5**(4), e16064 (2016).
35. R. Santagati et al., "Witnessing eigenstates for quantum simulation of Hamiltonian spectra," *Sci. Adv.* **4**(1), eaap9646 (2018).
36. J. Wang et al., "Experimental quantum Hamiltonian learning," *Nat. Phys.* **13**(6), 551–555 (2017).
37. J. C. Adcock et al., "Advances in silicon quantum photonics," *IEEE J. Sel. Top. Quantum Electron.* **27**(2), 6700224 (2021).
38. A. Aspect, P. Grangier, and G. Roger, "Experimental realization of Einstein–Podolsky–Rosen–Bohm *Gedankenexperiment*: a new violation of Bell's inequalities," *Phys. Rev. Lett.* **49**(2), 91–94 (1982).
39. D. Bouwmeester et al., "Observation of three-photon Greenberger–Horne–Zeilinger entanglement," *Phys. Rev. Lett.* **82**(7), 1345–1349 (1999).
40. D. Bouwmeester et al., "Experimental quantum teleportation," *Nature* **390**(6660), 575–579 (1997).
41. D. Dai et al., "Polarization management for silicon photonic integrated circuits," *Laser Photonics Rev.* **7**(3), 303–328 (2013).
42. N. Matsuda et al., "A monolithically integrated polarization entangled photon pair source on a silicon chip," *Sci. Rep.* **2**(1), 817 (2012).
43. J. Wang et al., "Multidimensional quantum entanglement with large-scale integrated optics," *Science* **360**(6386), 285–291 (2018).

44. X. Qiang et al., "Large-scale silicon quantum photonics implementing arbitrary two-qubit processing," *Nat. Photonics* **12**(9), 534–539 (2018).
45. L.-T. Feng et al., "On-chip transverse-mode entangled photon pair source," *NPJ Quantum Inf.* **5**, 2 (2019).
46. A. Mohanty et al., "Quantum interference between transverse spatial waveguide modes," *Nat. Commun.* **8**, 14010 (2017).
47. A. Mair et al., "Entanglement of the orbital angular momentum states of photons," *Nature* **412**(6844), 313–316 (2001).
48. R. Fickler et al., "Quantum entanglement of high angular momenta," *Science* **338**(6107), 640–643 (2012).
49. M. Malik et al., "Multi-photon entanglement in high dimensions," *Nat. Photonics* **10**(4), 248–252 (2016).
50. A. Babazadeh et al., "High-dimensional single-photon quantum gates: concepts and experiments," *Phys. Rev. Lett.* **119**(18), 180510 (2017).
51. M. Kues et al., "On-chip generation of high-dimensional entangled quantum states and their coherent control," *Nature* **546**(7660), 622–626 (2017).
52. L. Olislager et al., "Frequency-bin entangled photons," *Phys. Rev. A* **82**(1), 013804 (2010).
53. L. Olislager et al., "Creating and manipulating entangled optical qubits in the frequency domain," *Phys. Rev. A* **89**(5), 052323 (2014).
54. F. Kaneda and P. G. Kwiat, "High-efficiency single-photon generation via large-scale active time multiplexing," *Sci. Adv.* **5**(10), eaaw8586 (2019).
55. X. Guo et al., "Parametric down-conversion photon-pair source on a nanophotonic chip," *Light Sci. Appl.* **6**(5), e16249–e16249 (2017).
56. Y. Zhang et al., "Dual-pump approach to photon-pair generation: demonstration of enhanced characterization and engineering capabilities," *Opt. Express* **27**(13), 19050–19061 (2019).
57. B. Fang et al., "State engineering of photon pairs produced through dual-pump spontaneous four-wave mixing," *Opt. Express* **21**(3), 2707–2717 (2013).
58. S. Signorini et al., "Intermodal four-wave mixing in silicon waveguides," *Photonics Res.* **6**(8), 805–814 (2018).
59. S. Paesani et al., "Near-ideal spontaneous photon sources in silicon quantum photonics," *Nat. Commun.* **11**, 2505 (2020).
60. Z. Vernon, M. Liscidini, and J. E. Sipe, "No free lunch: the trade-off between heralding rate and efficiency in microresonator-based heralded single photon sources," *Opt. Lett.* **41**(4), 788–791 (2016).
61. Z. Vernon et al., "Truly unentangled photon pairs without spectral filtering," *Opt. Lett.* **42**(18), 3638–3641 (2017).
62. D. Llewellyn et al., "Chip-to-chip quantum teleportation and multi-photon entanglement in silicon," *Nat. Phys.* **16**(2), 148–153 (2020).
63. J. B. Christensen et al., "Engineering spectrally unentangled photon pairs from nonlinear microring resonators by pump manipulation," *Opt. Lett.* **43**(4), 859–862 (2018).
64. Y. Liu et al., "High-spectral-purity photon generation from a dual-interferometer-coupled silicon microring," *Opt. Lett.* **45**(1), 73–76 (2020).
65. B. M. Burridge et al., "High spectro-temporal purity single-photons from silicon micro-racetrack resonators using a dual-pulse configuration," *Opt. Lett.* **45**(14), 4048–4051 (2020).
66. P. Walther et al., "Experimental one-way quantum computing," *Nature* **434**(7030), 169–176 (2005).
67. J. Wang et al., "Chip-to-chip quantum photonic interconnect by path-polarization interconversion," *Optica* **3**(4), 407–413 (2016).
68. L.-T. Feng et al., "On-chip coherent conversion of photonic quantum entanglement between different degrees of freedom," *Nat. Commun.* **7**, 11985 (2016).
69. J. T. Barreiro, T.-C. Wei, and P. G. Kwiat, "Beating the channel capacity limit for linear photonic superdense coding," *Nat. Phys.* **4**(4), 282–286 (2008).
70. M. Fiorentino and F. N. C. Wong, "Deterministic controlled-not gate for single-photon two-qubit quantum logic," *Phys. Rev. Lett.* **93**(7), 070502 (2004).
71. X.-L. Wang et al., "18-qubit entanglement with six photons' three degrees of freedom," *Phys. Rev. Lett.* **120**(26), 260502 (2018).
72. C. Reimer et al., "High-dimensional one-way quantum processing implemented on *d*-level cluster states," *Nat. Phys.* **15**(2), 148–153 (2019).
73. N. D. Mermin, "What's wrong with these elements of reality?" *Phys. Today* **43**(6), 9–11 (1990).
74. M. Gimeno-Segovia et al., "From three-photon Greenberger–Horne–Zeilinger states to ballistic universal quantum computation," *Phys. Rev. Lett.* **115**(2), 020502 (2015).
75. Z.-D. Li et al., "Experimental quantum repeater without quantum memory," *Nat. Photonics* **13**(9), 644–648 (2019).
76. H.-S. Zhong et al., "12-photon entanglement and scalable scattershot boson sampling with optimal entangled-photon pairs from parametric down-conversion," *Phys. Rev. Lett.* **121**(25), 250505 (2018).
77. J. C. Adcock et al., "Programmable four-photon graph states on a silicon chip," *Nat. Commun.* **10**, 3528 (2019).
78. S. Paesani et al., "Generation and sampling of quantum states of light in a silicon chip," *Nat. Phys.* **15**(9), 925–929 (2019).
79. M. Zhang et al., "Generation of multiphoton quantum states on silicon," *Light Sci. Appl.* **8**(1), 41 (2019).
80. L.-T. Feng et al., "Observation of nonlocal quantum interference between the origins of a four-photon state in a silicon chip," arXiv: 2103.14277 (2021).
81. C. Reimer et al., "Generation of multiphoton entangled quantum states by means of integrated frequency combs," *Science* **351**(6278), 1176–1180 (2016).
82. C. Vigliar et al., "Error protected qubits in a silicon photonic chip," *Nat. Phys.* **17**, 1137–1143 (2021).
83. M. Erhard, M. Krenn, and A. Zeilinger, "Advances in high-dimensional quantum entanglement," *Nat. Rev. Phys.* **2**(7), 365–381 (2020).
84. D. Collins et al., "Bell inequalities for arbitrarily high-dimensional systems," *Phys. Rev. Lett.* **88**(4), 040404 (2002).
85. N. J. Cerf et al., "Security of quantum key distribution using *d*-level systems," *Phys. Rev. Lett.* **88**(12), 127902 (2002).
86. B. P. Lanyon et al., "Simplifying quantum logic using higher-dimensional Hilbert spaces," *Nat. Phys.* **5**(2), 134–140 (2009).
87. C. Schaeff et al., "Experimental access to higher-dimensional entangled quantum systems using integrated optics," *Optica* **2**(6), 523–529 (2015).
88. W. R. Clements et al., "Optimal design for universal multiport interferometers," *Optica* **3**(12), 1460–1465 (2016).
89. L. Lu et al., "Three-dimensional entanglement on a silicon chip," *NPJ Quantum Inf.* **6**(1), 30 (2020).
90. X. Chen et al., "A generalized multipath delayed-choice experiment on a large-scale quantum nanophotonic chip," *Nat. Commun.* **12**, 2712 (2021).
91. S. Paesani et al., "Experimental Bayesian quantum phase estimation on a silicon photonic chip," *Phys. Rev. Lett.* **118**(10), 100503 (2017).
92. A. Peruzzo et al., "A variational eigenvalue solver on a photonic quantum processor," *Nat. Commun.* **5**, 4213 (2014).
93. A. H. Atabaki et al., "Integrating photonics with silicon nanoelectronics for the next generation of systems on a chip," *Nature* **556**(7701), 349–354 (2018).
94. N. C. Harris et al., "Quantum transport simulations in a programmable nanophotonic processor," *Nat. Photonics* **11**(7), 447–452 (2017).
95. D. J. Moss et al., "New CMOS-compatible platforms based on silicon nitride and hydex for nonlinear optics," *Nat. Photonics* **7**(8), 597–607 (2013).
96. C. Wang et al., "Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages," *Nature* **562**(7725), 101–104 (2018).


**Xiaojiong Chen** received his bachelor's degree in physics from Zhejiang University, Hangzhou, China, in 2018. He is currently a PhD student at

the School of Physics of Peking University. His current research focuses on the integrated silicon photonic platform for quantum information, especially in multidimensional quantum technology for fundamental sciences and applications.

**Zhaorong Fu** is a senior undergraduate student majoring in physics at Peking University. He joined the PKU Q-chip Lab in 2019. His research focuses on integrated photonics and quantum information.

**Qihuang Gong** is currently the Boya Chair Professor and Cheung Kong Professor of Physics at Peking University, Beijing, China. His current research interests include ultrafast optics and spectroscopy, nonlinear and quantum photonics, and mesoscopic optical devices for applications in optical information processing and communication. He is an academician of the Chinese Academy of Sciences, a member of the World Academy of Sciences, president of the Chinese Optical Society, and vice president of the Chinese Physical Society. He is a standing committee member of China Association for Science and Technology, vice president for International Commission for Optics, and vice chair for IUPAP C17.

**Jianwei Wang** received his bachelor's and master's degrees from Zhejiang University, Hangzhou, China, in 2008 and 2011, respectively, and his PhD in physics from the University of Bristol, Bristol, UK, in 2016. He is currently an assistant professor at the School of Physics, Peking University, Beijing, China. He was a postdoc at the University of Bristol. His current research focuses on quantum information science and technologies with photons, in both fundamental physics and advanced applications.