

Experimental realization of universal quantum gates and a six-qubit entangled state using a photonic quantum walk

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For quantum computation using photons, performing deterministic quantum gate operations is a challenge due to the probabilistic nature of the photon-photon interaction. Encoding qubits in multiple degrees of freedom of photons and controlling operations between them is one of the promising ways to navigate the probabilistic behavior. Using the single-photon discrete-time quantum walk in combination with polarization and path degrees of freedom, we experimentally demonstrate the realization of a universal set of quantum gates with high fidelity at room temperature. The deterministic realization of quantum gates through the photonic quantum walk are characterized via quantum state tomography. For a three-qubit system using a single photon, the first qubit is encoded using polarization information, and the other two qubits are encoded using path information, closely resembling a Galton-board setup. To generate a six-qubit Greenberger-Horne-Zeilinger state, entangled photon pairs are used to entangle the two three-qubit modules on which gate operations are performed. We also provide insights into the mapping of photonic quantum walk operations to quantum circuit representation and propose method to resourcefully scale. This demonstration marks significant progress towards using quantum walks for quantum computing and provides a framework for using fewer photons in combination with different degrees of freedom of photons to scale the number of qubits.

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I. INTRODUCTION

Quantum computers promise to address problems that are beyond the reach of classical computation. By leveraging the principles of quantum mechanics—including superposition, entanglement, interference, and uncertainty—they offer a powerful framework to model and explore complex quantum systems in nature, which are otherwise inaccessible to classical computing methods. Although numerous quantum algorithms have been developed and demonstrated on a small scale on various quantum computing platforms [1–11], the construction of a practical quantum computer with sufficient scale and capabilities remains an ongoing challenge. Multiple schemes for realizing qubits and performing quantum operations have been developed across different quantum computing platforms. Among them, the photonic platform employs diverse approaches, such as discrete-variable, continuous-variable, measurement-based, and fusion-based methods [12–15]. Since photons are naturally resistant to interactions with background electromagnetic fields, they can

function efficiently at room temperature while maintaining stability and coherence during quantum operations. This makes them an ideal candidate for qubits compared to other systems, despite the inherent probabilistic nature of the photon-photon interaction that has to be invoked to probabilistically implement quantum gate operations, reducing the success probability of the computational task [16–18]. However, the probabilistic nature of the photon-photon interaction has also been an advantage and resulted in performing large-scale complex computational tasks, such as boson sampling [19–23]. In addition, one can access various degrees of freedom of single photons to simultaneously encode multiple qubits and experimentally control them to generate complex quantum states; the demonstration of 18-qubit Greenberger-Horne-Zeilinger (GHZ) state generation using six entangled photons is one such example [24]. Any scheme demonstrating efficient realization of deterministic universal quantum gate operations among different degrees of freedom of photons significantly enhances the prospects of the discrete-variable approach for photonic quantum computation. In this work, we present a scheme to realize a universal set of quantum gates by combining polarization and path degrees

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of freedom of single photons using the photonic quantum walk and report its experimental realization with high fidelity.

Quantum walks, known in both continuous-time and discrete-time forms, have played a fundamental role in the development of quantum algorithms [25–28] and quantum simulation schemes [29–39]. In particular, discrete-time one-dimensional quantum walks have been employed to engineer various high-dimensional quantum states, highlighting their versatility and potential [40,41]. These quantum walks have also been experimentally implemented using linear optical systems that control the polarization, path, and other degrees of freedom of single-photon states [42–48]. Additionally, theoretical proposals report that quantum walks are also primitive for implementing quantum gates, thereby enabling universal quantum computation using both continuous-time [49–51] and discrete-time [52,53] quantum walk variants. Among them, our mathematical model reported previously, based on a discrete-time quantum walk [52–54], offers a more tangible and logical foundation for the photonic quantum computing architecture in a discrete-variable setting. Therefore, in this work, we present a mapping of the quantum walk model to the photonic system involving polarization and path degrees of freedom, presenting the architecture for implementing universal gate sets and experimentally demonstrating its validation.

This polarization-path dual encoding facilitates the implementation of polarization-controlled operations and path-controlled operations, enabling quantum computations to be performed by emulating gates through unitary evolution. This approach offers a structured and physical framework for photonic quantum computation, making it a critical component for building quantum processors. One of the main criteria for a system to be considered suitable for universal quantum computation is its ability to implement a universal set of quantum gates. The universal gate set typically includes single-qubit gates like phase (P) and Hadamard (H) gates, along with the two-qubit controlled NOT (CNOT) gate. The focus of this work is to harness the power of the single-photon discrete-time quantum walk to develop a three-qubit module and demonstrate implementation of the universal set of quantum gate operations on it and configure a six-qubit system using entangled photon pairs. For the experimental demonstration of gate operations on a three-qubit system, we use heralded single photons from the spontaneous parametric down-conversion (SPDC) process and control their propagation across four path degrees of freedom. To demonstrate a six-qubit system, two three-qubit modules are combined using an entangled photon pair. A single photon's polarization and its interference along different paths achieve all multi-qubit gate operations in a three-qubit system. These are definite and not probabilistic in nature, making this a robust scheme. We report high fidelity for all universal quantum

gate operations by performing quantum state tomography (QST). At the six-qubit level, by controlling the entanglement between the two-photon polarization degrees of freedom and the path degrees in each three-qubit module, any six-qubit entangled state can be generated and we demonstrate the generation of the six-qubit GHZ state, which is characterized by the entanglement visibility. This work provides a scalable framework for photonic quantum computing using fewer photons in combination with polarization and path degrees of freedom to increase the success rate of the multiqubit gate operations.

II. RESULTS

A. Photonic quantum walk and universal quantum gates

The dynamics of a one-dimensional discrete-time quantum walk is defined by a configuration of Hilbert space composed of the coin space, which is the internal degree of freedom of the particle and position space, $\mathcal{H}_w = \mathcal{H}_C \otimes \mathcal{H}_S$ [55,56]. For a discrete-variable photonic quantum walk, the coin space is spanned by the horizontal and vertical polarization states of the photon, $\mathcal{H}_C = \text{span}\{|H\rangle, |V\rangle\}$. A one-dimensional position space is spanned by $\mathcal{H}_S = \text{span}\{|-x\rangle, \dots, |-1\rangle, |0\rangle, |1\rangle, \dots, |x\rangle\}$, representing the range of possible paths that a photon can take.

The standard form of evolution operator for each step of the quantum walk is defined using two sequential operations, $\hat{W} = [\hat{S}(\hat{C}(\theta) \otimes \mathbb{I})]$; the first is the unitary quantum coin operation only acting on the particle's Hilbert space. A general form of the quantum coin operation would be a $U(2)$ matrix consisting of four parameters:

$$\hat{C}(\tau, \eta, \zeta, \theta) = e^{i\tau} \begin{bmatrix} e^{i\eta} \cos(\theta) & e^{i\zeta} \sin(\theta) \\ -e^{-i\zeta} \sin(\theta) & e^{-i\eta} \cos(\theta) \end{bmatrix}. \quad (1)$$

It is followed by the conditional shift operation that acts on the entire Hilbert space:

$$\hat{S} = \sum_x [|H\rangle\langle H| \otimes |x-1\rangle\langle x| + |V\rangle\langle V| \otimes |x+1\rangle\langle x|].$$

If we consider the initial coin state to be $|\psi\rangle_C = \alpha|H\rangle + \beta|V\rangle$, then the initial state for the complete system will be $|\Psi(t=0)\rangle = |\psi\rangle_C |x=0\rangle$. The state after t steps will be $|\Psi(t)\rangle = \hat{W}^t |\Psi(t=0)\rangle$. We experimentally achieve complete control of the polarization state of a single photon using a combination of quarter-half-quarter (Q-H-Q) wave plates, by neglecting the global phase of $C(\tau, \eta, \zeta, \theta)$, i.e., (τ) [57]. Encoding of the path and polarization-dependent path is accomplished by applying a beam splitter (BS) and a polarizing beam splitter (PBS), respectively. In different settings, various realizations of photonic quantum walks have already been experimentally demonstrated and what remains here would be to map the quantum

walk operations to universal quantum gate operations in polarization-path-encoded qubits and demonstrate quantum computation using the photonic quantum walk.

The universal set of quantum gates for quantum computation consists of two single-qubit gates—the P gate and the H gate—along with one two-qubit gate, the CNOT gate. In mathematical form, it can be represented as follows:

$$U = \left(\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \right).$$

Combining these three gates, we can achieve optimal accuracy for all single- and two-qubit operations.

For the quantum computation model using the discrete-time quantum walk, a general form of shift operators and quantum coin operator is defined in Refs. [52,53]. The shift operations are configured to enable control of the shift of the particle to either the left or to the right, along with possibility of being on the same path, depending on the coin state of the particle. In a consolidated manner, we can write the equation as

$$\hat{S}_{\pm}^k = \sum_{l \in \mathbb{Z}} \left[|k\rangle \langle k| \otimes |l \pm 1 \bmod m\rangle \langle l| + \sum_{i \neq j}^{\mu} |i\rangle \langle i| \otimes |l\rangle \langle l| \right]. \quad (2)$$

In Eq. (2), μ is the total number of internal degrees of freedom and $\hat{S}_{+}^0$ or $\hat{S}_{-}^0$ dictates the shift of the particle to the right or left if the coin state is $|0\rangle$, representing the polarization state of the photon, $|H\rangle$. Similarly, $\hat{S}_{+}^1$ and $\hat{S}_{-}^1$ acting on $|1\rangle$ represent the polarization state of the photon, $|V\rangle$; this type of shift operation can be achieved using a combination of half-wave plates (HWPs) and PBS. The mod m comes from the closed-graph dynamics of the quantum walk. The collection of operators $\{\hat{S}_{\pm}^0, \hat{S}_{\pm}^1, \hat{C}(\tau, \eta, \zeta, \theta), \mathbb{I}\}$ constitutes a versatile set of operators representing the quantum walk. Moreover, this set of operators can be effectively employed to realize the universal set of quantum gates within the discrete-time quantum walk framework.

B. Qubit encoding and universal gate implementation

Encoding qubits on the basis of the polarization degree and the path degrees of freedom of photons forms the foundation of the photonic quantum computing approach presented here. For example, using the polarization state of a photon and a four-path basis for it, we can define a three-qubit system. While it is possible to extend the number of available paths for photons to increase the number of realizable qubits, this approach does not scale efficiently. Hence, we first present the encoding of two qubits and three qubits on the polarization and path bases and then address the challenges of scalability.

TABLE I. Q-H-Q angles for Pauli gates.

Gates	Q-H-Q angles	Operator
σ_X	$(0, \frac{\pi}{4}, 0)$	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$
σ_Y	$(\frac{\pi}{2}, -\frac{\pi}{4}, 0)$	$\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$
σ_Z	$(0, \pi, \frac{\pi}{2})$	$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$
$S(\frac{\pi}{2})$	$(\frac{\pi}{4}, \frac{7\pi}{8}, \frac{5\pi}{4})$	$e^{i\pi/4} \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/2} \end{pmatrix}$
$P(\frac{\pi}{4})$	$(\frac{3\pi}{4}, \frac{3\pi}{16}, \frac{3\pi}{4})$	$-e^{-i\pi/8} \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$

1. Polarization information as qubits

A qubit for the polarization degree of freedom can be written as

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right) |H\rangle + e^{i\phi} \sin\left(\frac{\theta}{2}\right) |V\rangle. \quad (3)$$

Here, varying the parameters $\theta \in [0, \pi]$ and $\phi \in [0, 2\pi)$, we can span all the points on the Bloch sphere. This can be realized using a combination of two quarter-wave plates (QWPs) and one HWP. The matrix structures of HWP and QWP derived from Jones calculus are

$$H(x) = \begin{pmatrix} \cos 2x & \sin 2x \\ \sin 2x & -\cos 2x \end{pmatrix},$$

$$Q(x) = e^{-i\pi/4} \begin{pmatrix} \cos^2 x + i \sin^2 x & (1-i) \sin x \cos x \\ (1-i) \sin x \cos x & i \cos^2 x + \sin^2 x \end{pmatrix}. \quad (4)$$

Since the determinant values of the HWP and QWP are -1 and $+1$, respectively, the determinant value of the two QWPs and one HWP will always be -1 . The Pauli matrices, $\{\sigma_x, \sigma_y, \sigma_z\}$, which form the basis for single-qubit gate operations also have a determinant value of -1 . In Table I, the Q-H-Q angles to realize the Pauli matrices and phases, $\pi/4$ and $\pi/8$, are given. Using three wave plates in different orders, Q-H-Q, Q-Q-H, or H-Q-Q, with the appropriate choice of angle, any arbitrary rotation on the Bloch sphere can be realized.

The set of Pauli matrices along with identity ($\mathbb{I}_2$), $\{\mathbb{I}_2, \sigma_x, \sigma_y, \sigma_z\}$, form a basis for unitary matrices in the (2×2) space. By choosing appropriate angles for Q-H-Q, we can get all the Pauli matrices, enabling all the single-qubit operations on polarization qubits. In Fig. 1(a), we demonstrate that any arbitrary polarization state $|\psi\rangle$, which is an arbitrary linear combination of the states $|H\rangle$ and $|V\rangle$, can be generated from the horizontal polarization state, $|H\rangle$, using a combination of Q-H-Q plates. Additionally, the experimental results for specific polarization states

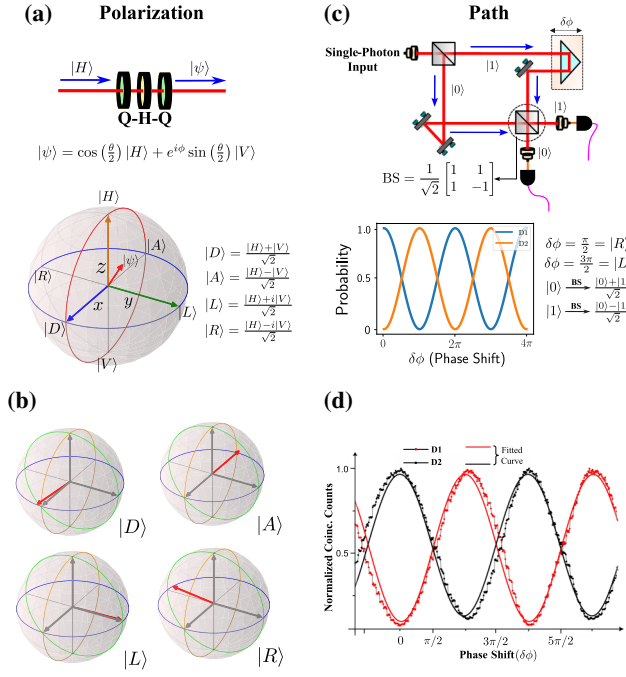


FIG. 1. Qubit in polarization and path encoding. (a),(c) Illustration of encoding polarization and path information of a single photon as qubits. For polarization encoding, Q-H-Q plates are used to traverse the entire Bloch sphere. Similarly, for path encoding, phase adjustments in open and closed Mach-Zehnder interferometers enable access to all required orthogonal basis states. (b),(d) Experimentally obtained data for single-photon polarization purity of $|D\rangle$, $|A\rangle$, $|L\rangle$, and $|R\rangle$ and single-photon interference visibility in path encoding indicate the purity of the path qubit, respectively. D1 and D2 in the plots show the coincidence counts with the heralding photon, and solid red and black plots represent the numerical fit that is in agreement with experimental data.

$|L\rangle$, $|R\rangle$, $|A\rangle$, and $|D\rangle$ are shown in Bloch sphere notation in Fig. 1(b).

2. Path information as a qubit

Path encoding becomes most comprehensible through the lens of a Mach-Zehnder interferometer (MZI) designed for a single photon. The output quantum state of the MZI takes the form $|\psi\rangle = (1 + e^{i\delta\phi})/2 |0\rangle + (1 - e^{i\delta\phi})/2 |1\rangle$, where $|0\rangle$ and $|1\rangle$ represent the path encoding of the photon achieved after the first beam splitter. Here, $\delta\phi$ is the relative phase difference between $|0\rangle$ and $|1\rangle$; in our experimental setup, we use a nanometric precision piezostage in one of the arms to control $\delta\phi$. The output count of the interferometer varies as a function of $\delta\phi$; counts in the $|1\rangle$ and $|0\rangle$ path follow $\cos^2(\delta\phi/2)$ and $\sin^2(\delta\phi/2)$, respectively. In Fig. 1(c), we show the setup of MZI for single-photon interference and the probability of detecting a photon at the two output ports. In Fig. 1(d), the measured visibility for the single-photon MZI of $V \approx 93.4\%$ is shown.

In general, the beam-splitter matrix takes the form

$$U_{BS} = \begin{bmatrix} \sqrt{T} & -e^{-i\phi}\sqrt{R} \\ e^{i\phi}\sqrt{R} & \sqrt{T} \end{bmatrix}. \quad (5)$$

If we consider transmitted (T) = reflected (R) = $1/2$ and $\phi = 0$, then we get back the general 50:50 beam-splitter matrix; U_{BS} will take the form $U_{BS}(\phi = 0) = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}$. Since BS has a Hadamard operation for our purpose, we always consider an extra phase of π for the $|1\rangle$ arm, so that the final unitary transformation matrix exactly resembles the Hadamard transformation [58,59].

From the perspective of quantum information encoding, manipulating $\delta\phi$ enables the preparation of all fundamental states: $|+\rangle$, $|-\rangle$, $|L\rangle$, and $|R\rangle$. This highlights the versatility of path encoding and its potential for information manipulation in the quantum domain. In our context, path encoding initially disregards polarization information.

To achieve a comprehensive description of polarization-path encoding, we must account for the polarization of each path. This results in a Hilbert space denoted as $\mathcal{H}_{P-P} = \mathcal{H}_{pol} \otimes \mathcal{H}_{path}$, encompassing a total of four modes for a single photon, two polarization states and two path states, effectively representing the polarization-path quantum state. The general two-qubit state can be expressed as

$$|\Psi\rangle_{gen} = \alpha |H\rangle |0\rangle + \beta |H\rangle |1\rangle + \gamma |V\rangle |0\rangle + \delta |V\rangle |1\rangle, \quad (6)$$

where $\{\alpha, \beta, \gamma, \delta\} \in \mathbb{C}$ and $|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1$. A general two-qubit-state preparation is discussed in Supplementary Material [60]. The computational basis takes the form $|H\rangle |0\rangle = |00\rangle$, $|H\rangle |1\rangle = |01\rangle$, $|V\rangle |0\rangle = |10\rangle$ and $|V\rangle |1\rangle = |11\rangle$.

To prepare a two-qubit entangled state in polarization-path encoding, we use a PBS to split the polarization information of the photon into different paths. If the input state in the polarization and path combination is $|\psi\rangle_{in} = (\alpha |H\rangle + \beta |V\rangle) |0\rangle_{in}$, where $|0\rangle_{in}$ represents the input path of a PBS, then the output state becomes $|\psi\rangle_{out} = \alpha |H\rangle |0\rangle_{out} + \beta |V\rangle |1\rangle_{out}$; a polarization-path entangled state, $|1\rangle$, represents the other arm of the PBS.

a. One- and two-qubit gate implementation: For the realization of a two-qubit state in the polarization-path combination, heralded single photons of 810 nm, obtained via the SPDC process using a periodically poled potassium titanyl phosphate (PPKTP) crystal, were used. To perform QST and reconstruct the density matrix, additional path interference is involved. To experimentally obtain the gate fidelity for all universal gates, we prepared different initial states on which the specific gate action was prominent and involved the coherence between polarization-path encoding. For $\{H \otimes \mathbb{I}_2, \text{CNOT}(1, 2), P \otimes \mathbb{I}_2, \text{CNOT}(2, 1)\}$, the initial state was prepared as $|\Psi\rangle_{in} = (|H\rangle |0\rangle + |V\rangle |1\rangle)/\sqrt{2}$, and the gate operations were implemented, followed by fidelity

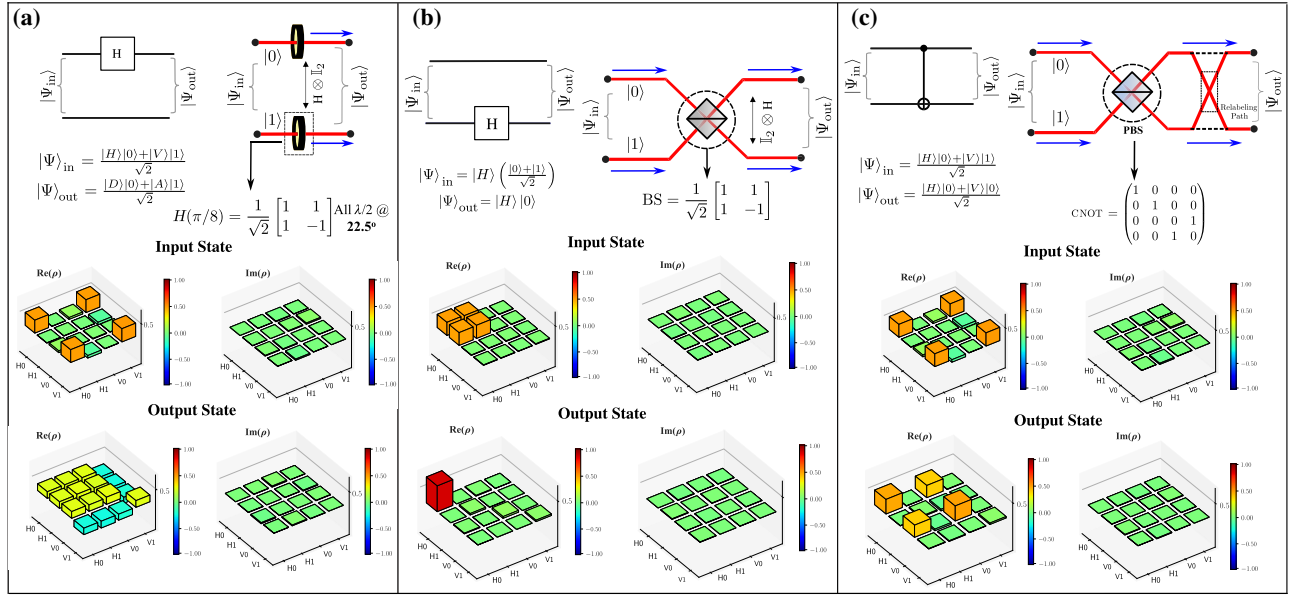


FIG. 2. Hadamard operation on the polarization and path qubit along with polarization controlled CNOT operation on the two-qubit state. Illustration of implementation of the Hadamard gate on polarization and path qubits separately, as well as the two-qubit CNOT gate, where polarization serves as the control, in (a)–(c), respectively. Each subfigure presents the optical schematics of the gates, along with the experimentally obtained input and output states using quantum state tomography. For all the quantum states, both the real and imaginary parts of the tomography are shown. In (a), $H(\pi/8)$ represents a HWP set at an angle of 22.5° .

calculations. For the remaining two gates $\{\mathbb{I}_2 \otimes H, \mathbb{I}_2 \otimes P\}$, we considered the initial state to be $|H\rangle \left((|0\rangle + |1\rangle)/\sqrt{2} \right)$. Starting from state preparation to QST, an average of ten gate operations in the form of the standard circuit model are executed. Figures 2(a)–2(c) illustrate the circuit model and optical schematic, along with the input and experimentally obtained output states using quantum state tomography for the Hadamard gate on polarization and path qubits, and the CNOT gate with polarization as the control; this is applicable to the general quantum state in Eq. (6). Similarly, Figs. 3(a)–3(c) illustrate the circuit model and optical schematic, along with the experimentally obtained states using QST for the phase ($\pi/8$) gate on polarization and path qubits, and the CNOT gate with the path as the control; this is applicable to the general quantum state in Eq. (6).

For all quantum states, both the real and imaginary parts of the tomography are shown. In Table II, the fidelity is reported for all one- and two-qubit quantum gate operations on the two-qubit state composed of polarization and path degrees of freedom obtained after performing QST. The role of visibility of each interferometer in the multipath interference configuration on the final fidelity and measures to improve the reported fidelity are discussed in Sec. IV. In this quantum walk framework, it is also possible to implement the universal gate set using path-path-encoded qubits. For example, the two-step quantum walk evolution will give access to four spatial modes, $|00\rangle$, $|01\rangle$, $|10\rangle$, and $|11\rangle$, which naturally encode two

qubits in the path degrees of freedom. The implementation of single-qubit gates, such as the Hadamard and Phase gates, in this encoding is identical to the one described by the path degree of freedom in the polarization-path encoding scheme. Moreover, the CNOT gate between the path-encoded qubits can be realized more easily by appropriately rerouting or relabeling the paths, making the implementation of the two-qubit gate straightforward and efficient.

3. Three- and six-qubit systems

For a three-qubit system, the polarization degree of freedom of a photon represents the first qubit, while the four path degrees of freedom represent the second and third qubits, respectively. The Hilbert space is given by $\mathcal{H}_{\text{pol}} \otimes \mathcal{H}_{\text{path}_1} \otimes \mathcal{H}_{\text{path}_2}$. The implementation of Toffoli and Fredkin gate operations on this three-qubit system in a standard circuit model, along with their equivalent optical schemes in the polarization-path-path-encoded three-qubit system, is illustrated in Fig. 4. Additionally, it is worth noting that realizing the Hadamard operation on a path-encoded qubit involves interferometry, and implementing the CNOT gate, which is typically challenging in other setups, is simplified in this scheme by swapping the paths, as shown in Fig. 7 and Appendix.

To calculate the fidelities of the gate operations, starting from the three-qubit general state preparation to performing quantum state tomography, a maximum of 28 gate

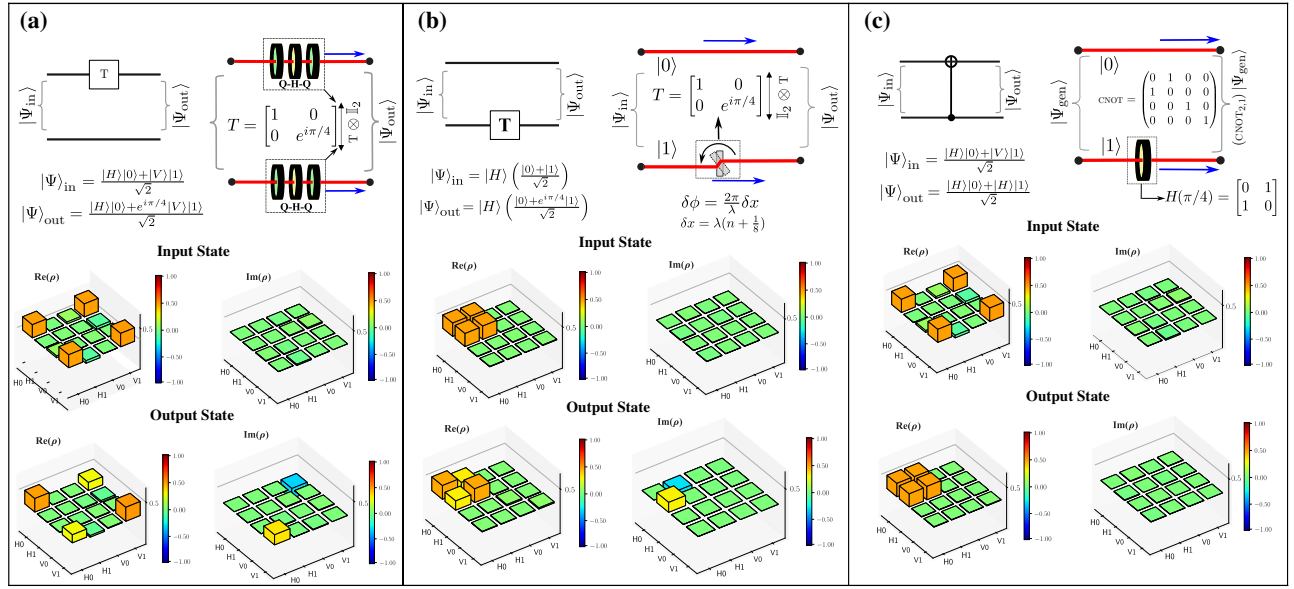


FIG. 3. Phase gate for polarization and path qubit along with path controlled CNOT operation of two-qubit state. Illustration of implementation of phase gate on polarization and path qubits separately, as well as the two-qubit CNOT gate, where the path serves as the control, in (a)–(c), respectively. In (a), Q-H-Q denotes a combination of wave plates, aligned at specific angles to introduce a $\pi/8$ phase difference between $|H\rangle$ and $|V\rangle$, with the global phase defined as previously described. For the phase gate in the path degree of freedom, an additional phase delay is introduced using a glass beam splitter controlled by a piezoelectric stage. Finally, in (c) $H(\pi/4)$ represents a half-wave plate set at an angle of 45° , which will convert $|H/V\rangle$ and $|V/H\rangle$, for path $|1\rangle$, which serves as CNOT operation. Each subfigure presents the optical schematics of the gates, along with the experimentally obtained input and output states using quantum state tomography. For all the quantum states, both the real and imaginary parts of the tomography are shown.

operations are executed. Since the fidelities of Hadamard operations are same as those given in Table II, only CNOT operations for different combination of qubits are given. We note that the fidelity of the CNOT gate between two path qubits is very high when compared to the CNOT gate between the polarization and path qubits. This is because it uses only swapping of the paths between path qubits to implement the CNOT gate. This allows for efficient handling of multiqubit operations using the path basis.

One method to realize a six-qubit system is illustrated in Fig. 5. A six-qubit system is sourced by the entangled photon pair given by $|\Psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_s |V\rangle_i + |V\rangle_s |H\rangle_i)$ generated from the SPDC process using a type-II PPKTP crystal. Each photon from the entangled pair is used as an input to two separate three-qubit systems. Various operations on the six-qubit system can be configured, first by controlling entanglement between the two photons, and these two photons are sourced to the two three-qubit systems where gate operations are performed as discussed previously for the three-qubit system. For example, we can easily convert an

entangled state into the $|\Psi'\rangle = \frac{1}{\sqrt{2}}(|H\rangle_s |H\rangle_i + |V\rangle_s |V\rangle_i)$ state using a HWP in one of the arms (signal arm). By placing a PBS in the two separate three-qubit units, we can generate the six-qubit GHZ state:

$$|\Psi\rangle_{\text{GHZ}} = \frac{1}{\sqrt{2}}(|0\rangle^{\otimes 6} + |1\rangle^{\otimes 6}).$$

Though all six qubits in the system are not directly connected to one another, through entangled photon pairs they

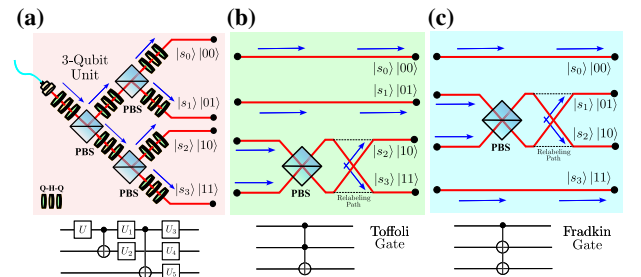


FIG. 4. Three-qubit system in polarization-path-path encoding. (a) Schematic of the circuit and optical scheme for preparing a polarization-path-path-encoded three-qubit system. (b),(c) Circuit and optical scheme to implement the Toffoli and Fredkin gates on the three-qubit state.

TABLE II. Fidelity of two-qubit gate operation.

Gate	$H \otimes \mathbb{I}_2$	$T \otimes \mathbb{I}_2$	$\text{CNOT}_{1,2}$	$\mathbb{I}_2 \otimes H$	$\mathbb{I}_2 \otimes T$	$\text{CNOT}_{2,1}$
F	0.97(8)	0.96(7)	0.91(2)	0.92(9)	0.94(7)	0.97(4)

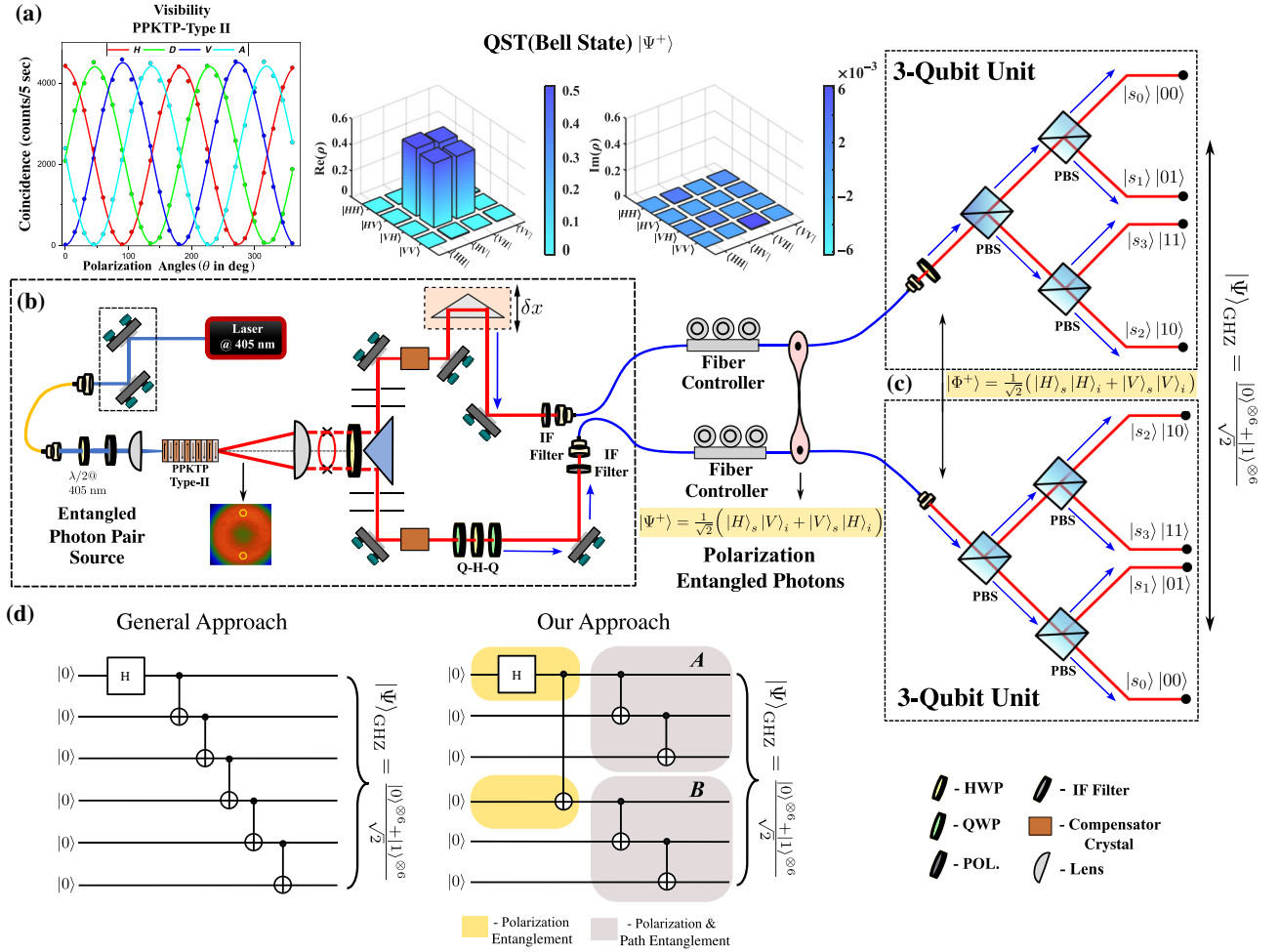


FIG. 5. Six-qubit system using two photons in polarization-path-path degrees of freedom. (a) Visibility observed in the four different basis sets and QST for the polarization entangled state $|\Psi^+\rangle$ from the type-II SPDC process illustrated in (b). (c) Entangled photons are coupled to two fiber paddle controllers, which have independent wave plates that will alter the polarization of transmitted light in a single-mode fiber before being directed to two separate three-qubit modules, as shown in the right. By utilizing the entanglement between two photons, we connect the distinct three-qubit units and use the necessary gates on each unit as required. For the preparation of the six-qubit GHZ state, we apply two consecutive CNOT gates, with polarization serving as the control in each three-qubit unit. (d) Schematic of the circuit for our approach to prepare the six-qubit GHZ state and the preparation of the general GHZ state. $|s_i\rangle$ represents the polarization information of each path.

can be connected and engineered to control a six-qubit system, as shown in Fig. 5(d). To assess the quality of the prepared GHZ state, we used an entanglement witness measurement in the path states associated with specific polarizations. Due to the CNOT gate operations, we performed visibility checks between the $|00\rangle$ and $|10\rangle$ paths of the two three-qubit units. Similarly, visibility checks were conducted between the $|01\rangle$ and $|11\rangle$ paths of the two three-qubit units. The visibility in the H and D bases for these paths was measured to be 98.3% and 95.1%, respectively as shown in Fig. 6. From the structure of the six-qubit GHZ state and the preparation method illustrated in Fig. 5, it is evident that coincidences occur between the $|00\rangle$ and $|11\rangle$ paths of the three-qubit units for $|H\rangle_s |00\rangle |H\rangle_i |00\rangle$ and $|V\rangle_s |11\rangle |V\rangle_i |11\rangle$, respectively.

The number of accidental coincidences between the other paths of two three-qubit units are low, as predicted by our method of preparation. By performing these coincidence measurements and visibility checks, which serve as entanglement witnesses, we confirm the successful preparation of the GHZ state.

4. Scaling

The number of qubits can be scaled by using multiple four-path basis sets in a tensor network configuration of two qubits and entangling them with a single photon, as given in the mathematical model of the scheme [52,53]. However, a single photon in the multiple network of two-qubit position basis sets will result in a

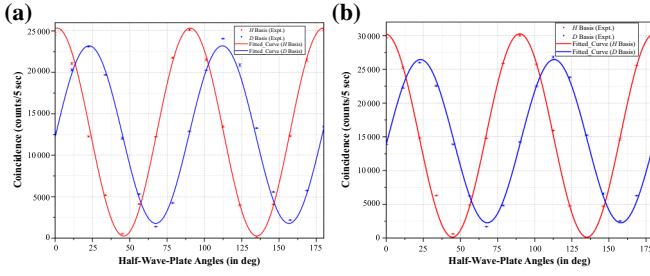


FIG. 6. Entanglement witness of the GHZ state. (a),(b) Coincidence between arms $|00\rangle, |00\rangle$ and $|11\rangle, |11\rangle$ for H and D basis sets, respectively, as shown in Fig. 5. Red and blue dots are data points measured experimentally, and solid blue and red lines are numerical fits. Obtained coincidence visibility for H and D basis sets is 98.3% and 95.1%, respectively. This entanglement witness measurement in the path states that carry a specific polarization can be inferred to assess the quality of the prepared GHZ state.

loss of fidelity. As demonstrated for six qubits here, further scaling with a combination of six-qubit systems can be explored by entangling other degrees of freedom of photons and involving more photons. However, involving more photons makes the connection between each module of smaller qubits probabilistic but overall efficiency becomes better than the standard approach of using a single photon in dual-rail encoding to represent each qubit.

The discrete-time quantum walk framework reported here can be readily implemented on photonic integrated circuits (PICs), provided polarization control within the circuit is achievable, and promising results are being reported in this direction [11]. The reported fidelities for various quantum gates using our scheme in bulk optics can be improved in PICs, which offer advantages over bulk optics, including better scalability by mitigating issues like alignment and sustained stability. At the same time, bulk optics provides flexibility and ease of reconfiguration, which are valuable for experimental prototyping and validation.

III. CONCLUSION

In this work, we reported the experimental demonstration of realizing a universal set of quantum gates using the photonic quantum walk. In the scheme, multiple qubits were encoded using polarization and path degrees of freedom of single photons, and universal quantum gates were implemented with 100% success probability and high fidelity. The fidelity of each gate operation was characterized by performing quantum state tomography at room temperature. For a two-qubit and three-qubit system, the first qubit is encoded with the polarization state of the photon, and path information is used for encoding other qubits. For the six-qubit system, an entangled photon pair from the SPDC process was used to source two three-qubit modules

and realize the full six-qubit GHZ state. In the scheme, only one photon was involved to realize two-qubit and three-qubit systems. Not invoking direct photon-photon interactions resulted in very high fidelity quantum gate operations. This also makes the realization of all gate operations possible. Fidelities directly account for experimental inaccuracies involved in the process. We demonstrated that some of the two-qubit gates, CNOT between path qubits, were easily realizable in the scheme compared to other approaches. This quantum walk based quantum computing scheme can be extended to other photonic degrees of freedom, such as frequency, time bin, and orbital angular momentum, using hybrid encoding strategies. This flexibility enables scalable and high-dimensional quantum photonic architectures. This experimental demonstration of the long-standing theoretical proposal of realizing quantum gates using quantum walks indicates promising progress towards using photonic quantum walks for quantum computing. It also provides a general framework for photonic quantum computing at room temperature using fewer photons in combination with paths and other degrees of freedom of photons.

IV. METHODS

To generate heralded single photons and entangled photon pairs, the type-II SPDC process using a PPKTP crystal was used. A 10-mm-long PPKTP crystal was pumped using a continuous-wave diode laser at 405 nm (Toptica TopMode laser @ 405 nm). The astigmatism of the pump beam was corrected by coupling it through a single-mode fiber, and the collimated output was horizontally polarized using a wire-grid polarizer [Fig. 5(b)]. A planoconvex lens (L1) with a focal length of 17.5 cm focused the beam at the center of the crystal, which was maintained at a temperature of 32.3 °C to achieve degenerate SPDC at 810 nm. An SPDC cone angle of 0.83° was chosen to optimize photon collection. The down-converted photons were collimated using another planoconvex lens (L2) with a focal length of 10 cm. By applying a PBS in the path of down-converted photons, one of photons (signal) in the photon pair of specific polarization was chosen and the other photon (idler) was used for heralding purposes. At a pump power of 15 mW, the photon generation rate was 6.93×10^5 counts/s, with a heralding efficiency of 22.3% after coupling to a single-mode fiber. We used the single-photon-counting module (SPCM) SPCM-800-44-FC, Excelitas, with a detection efficiency at 810 nm of approximately 63%.

For entangled photon-pair generation, a prism mirror was used to separate the down-converted rings into two halves. Two diametrically opposite points were then carefully collected from each half of the ring. A HWP set at 45° and 5-mm KTP crystals for temporal compensation were introduced in each path, as shown in Fig. 5(b).

Residual pump photons were removed using bandpass filters ($810\text{ nm} \pm 10\text{ nm}$), and polarization integrity was maintained using fiber polarization controllers [61–63]. This configuration produced polarization entangled photon pairs at a rate of approximately 16 400 pairs/(s mW). QST indicated a fidelity of 98.12% with the ideal Bell state. At a pump power of 0.15 mW, accidental counts were reduced to 16 counts/s. The measured visibilities in the H/V and A/D basis sets were 98.6% and 98.1%, respectively, with a Bell-Clauser-Horne-Shimony-Holt (CHSH) inequality violation of $S = 2.77(\pm 0.001)$.

Using the heralded single-photon source, a polarization-path entangled state was prepared, and all universal gates were implemented. The input and output states were characterized via tomography, as detailed in the Supplemental Material [60]. Building on the polarization-path-encoded state, the two paths are further split to realize the polarization-path-path-encoded state, enabling a three-qubit system. Finally, to prepare the six-qubit GHZ state, we utilize the entangled photon pairs and two separate three-qubit units, each consisting of polarization-path-path-encoded states.

For two-qubit state tomography requiring external (additional) path interference from the output state, the beam splitter used for interference is not exactly 50:50 (BS005) for both S and P polarizations. This discrepancy significantly impacts the fidelity of all the universal quantum gates we consider.

Path-encoded qubits are sensitive to phase instability. Although we did not employ active stabilization methods, we minimized the phase fluctuations between the two arms of the interferometer by using passive stabilization techniques. The interferometer was fully enclosed using a custom-built isolation cover and mounted within cage assemblies to suppress air currents and enhance environmental isolation. To minimize path-length variations caused by temperature changes, precision mirror mounts with low thermal expansion coefficients were employed, effectively reducing phase fluctuations. Additionally, motorized wave plates were incorporated to avoid repeatedly opening and closing the enclosure, thereby maintaining consistent environmental conditions. Optical fibers used in the setup were jacketed and thermally insulated to further suppress phase noise arising from temperature fluctuations. For specific cases, the performance of the Hadamard gate on the polarization qubit can be improved by using a motorized half-wave plate with high angular precision. Similarly, the Hadamard gate on the path qubit inherently relies on path interference, which slightly lowers its fidelity during QST. For the polarization-controlled CNOT gate, we used a PBS with an extinction ratio of 1000:1. Enhancing this extinction ratio would lead to better results. Although the phase gate for polarization involves three wave plates in each arm, reducing the number of wave plates in one path and using high-precision rotation mounts can improve its performance. The phase gate in

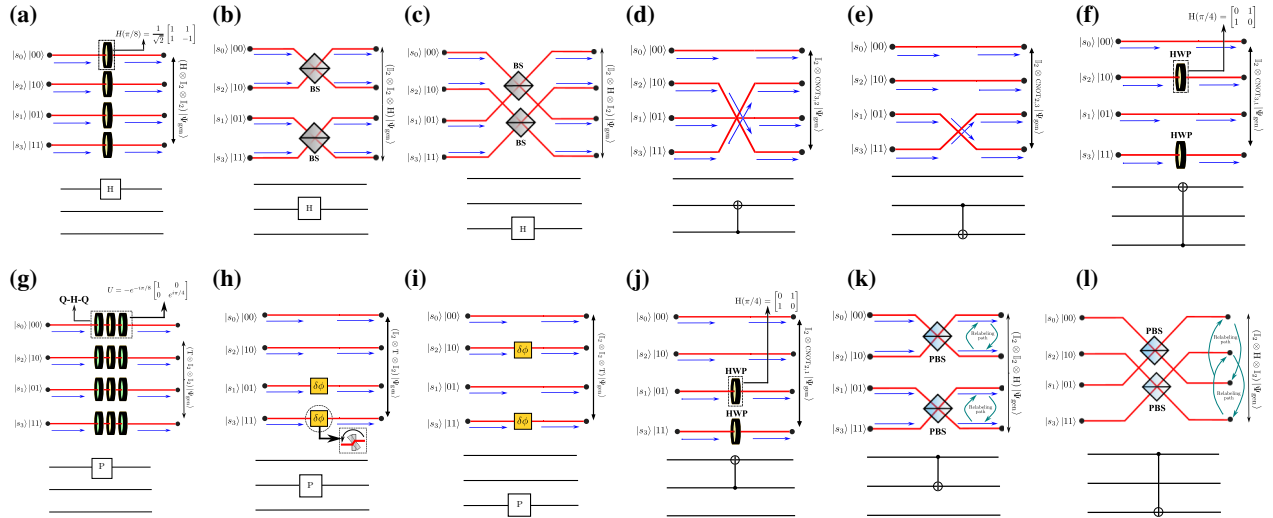


FIG. 7. Gate operations in the three-qubit system in polarization-path-path configuration. Schematic illustration of all three-qubit gate operations for polarization-path-path-encoded quantum states. As mentioned earlier, the four paths are labeled as $|00\rangle$, $|01\rangle$, $|10\rangle$, and $|11\rangle$, arranged from top to bottom in the optical diagrams. (a)–(c) Hadamard gate applied to polarization, the first path qubit, and the second path qubit, respectively. (d), CNOT gate, where the first path qubit serves as the control for the second, which is implemented by relabeling the $|10\rangle$ and $|11\rangle$ paths. (e) Second path qubit controls the first qubit, which is achieved by swapping the $|01\rangle$ and $|11\rangle$ paths. (f) Polarization-controlled CNOT gate is implemented for the second path qubit. (g)–(i) Phase-gate ($\pi/8$) operation for polarization, the first path qubit, and the second path qubit, respectively. (j) Polarization-controlled CNOT gate for the first path qubit; (k) the implementation of such a gate for the first path qubit. (l) Polarization-controlled CNOT operation for the second path qubit.

the path qubit requires nanometric piezocontrollers and high stability, which, if utilized, can enhance its accuracy. A similar explanation applies to the CNOT gate, where the path acts as the control, and precise wave-plate adjustments are essential for optimal operation.

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C.M.C. conceived the idea. All authors contributed towards developing the experimental setup, performing experiments, and collecting data. C.M.C. and K.S. accomplished theoretical calculations and data analysis. The manuscript was written through contributions from all authors.

The authors declare no competing interests.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX

All three-qubit universal gate optical schematics are listed in Fig. 7. It is worth noting that the CNOT gates in path-path qubits are achieved just by swapping the path or relabeling; this provides a great advantage with respect to other quantum computing architectures.

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