

Dynamic Quantum Gate Based on Controllable Chiral Liquid Crystal Nanostructure

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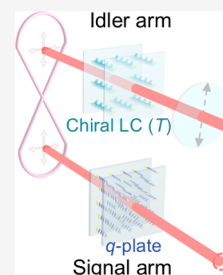
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ABSTRACT: The photonic quantum system, as a prominent candidate for quantum information processing, possesses inherent advantages of room-temperature operation, a long coherence time, and a large encoding capacity. However, a conventional photonic quantum gate is usually limited by its bulky volume, complicated protocols, and fixed functions. Here, we find that chiral liquid crystal (CLC) nanostructure can offer a feasible platform for a dynamic photonic quantum gate. Tuning a uniformly self-assembled nanostructure enables a full rotation of the Bloch sphere within the short wavelength circular regime of the CLC, facilitating efficient implementation of the identity gate, S gate, and Pauli-Z gate. Furthermore, such a CLC gate enables dynamic control over the transformation between polarization-entangled states. It is utilized to control hybrid entanglement between the polarization and orbital angular momentum, linking the Poincaré sphere to the higher-order Poincaré sphere. This work demonstrates the potential of soft-matter CLC nanostructure to serve as a versatile platform in the photonic quantum system.

KEYWORDS: chiral liquid crystal nanostructure, quantum gate, dynamic control, hybrid entanglement



Quantum information processing (QIP) has witnessed remarkable development in recent years,¹ ranging from quantum communication,^{2,3} quantum metrology,^{4,5} and quantum computing^{6,7} to quantum imaging.^{8–12} Among the candidate systems of QIP, the photonic quantum system is one of the most prominent platforms,¹³ where the photon serves as an excellent flying qubit.^{14,15} The photon, as the boson, can be operated at room temperature and is robust against decoherence resulting from interactions with the environment, contributing to a long coherence time.¹⁶ Moreover, the photon possesses multiple degrees of freedom (DoFs),^{17–19} such as spin angular momentum, orbital angular momentum (OAM),^{20–22} and path.²³ These diverse DoFs result in superior encoding capacity and operational parallelism.

The implementation of QIP requires various quantum gates²⁴ and measurements^{25–28} to act as fundamental operations on quantum bits (i.e., qubits). In photonic systems, they are usually constructed from fundamental optical elements,²⁹ e.g., beam splitters and phase shifters. However, those gates are always limited by bulky volumes, complicated protocols, and fixed functions, highlighting the strong demand for compact and efficient linear elements with tunable functionalities. Liquid crystals (LCs)^{30–33} have become one of the most attractive materials for tunable optical devices due to their high efficiency, large birefringence, and sensitive external stimulus response. Recent years have witnessed remarkable advances in handling classical light, such as optical edge detection,^{34,35} multiplexed holography,^{36,37} and structured light manipulation.^{38,39} However, those applications of LCs have been restricted to harnessing classical light. It

remains to be explored in constructing the controllable quantum gate, which is of great significance for the QIP.

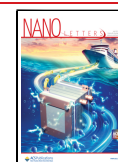
In this work, we propose a thermo-controllable scheme for constructing a dynamic quantum gate based on chiral LC (CLC) nanostructure.^{40–42} By leveraging its short wavelength circular regime, a uniformly self-assembled CLC superstructure provides a tunable and highly efficient optical rotation for any input linear polarization. This serves as the core of a dynamic single-qubit gate, where a narrow temperature variation of 7 °C enables a full rotation around the Bloch sphere, facilitating the identity gate, S gate, and Pauli-Z gate. Moreover, this gate enables dynamic control over the polarization-entangled states and transforms them into desired biphoton states. This capability is further explored to control hybrid entanglement^{43,44} between the polarization DoF and the OAM DoF (Figure 1a), effectively linking the Poincaré sphere to the higher-order Poincaré sphere (HOPS), as validated by the temperature-dependent change in superposition modes under coincidence measurement (Figure 1b). This work verifies the great potential of CLC nanostructure in controllable transformation of quantum states, facilitating the fundamental operations in QIP.

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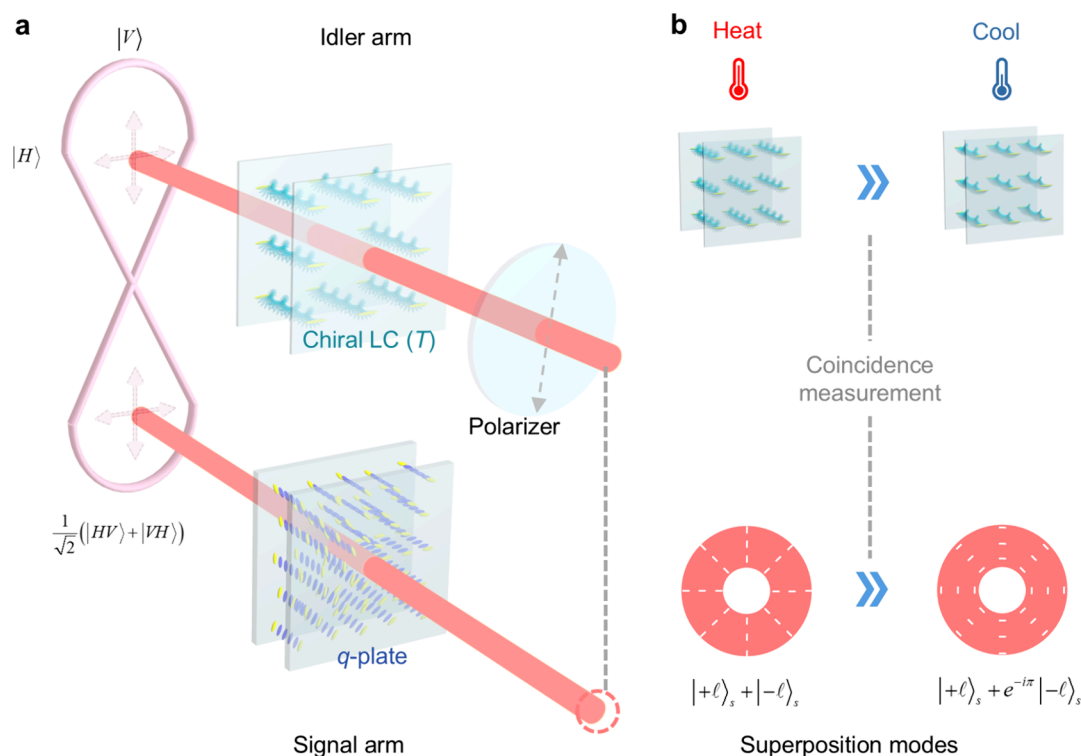


Figure 1. Dynamic control of hybrid entanglement via the CLC quantum gate. (a) Schematic of the dynamic control of the hybrid entanglement via the CLC gate. The polarization of the idler photon and the OAM of the signal photon are entangled, with the CLC enabling dynamic control of their entanglement. The idler photon is projected onto a vertical polarization state (gray arrow), and the signal photon nonlocally collapses into distinct superposition modes at different temperatures, as detected through coincidence measurement (indicated by the dashed gray line between idler and signal arms). (b) Temperature-dependent superposition modes observed under coincidence measurement. Cooling lengthens the helical pitch of the CLC (red and blue thermometers represent higher and lower temperatures, respectively), modifying the optical rotation and thus the polarization of the idler photon. As a result, coincidence measurements at different temperature nonlocally select distinct superposition modes for the signal photon (white short lines indicate local linear polarization of the superposition modes).

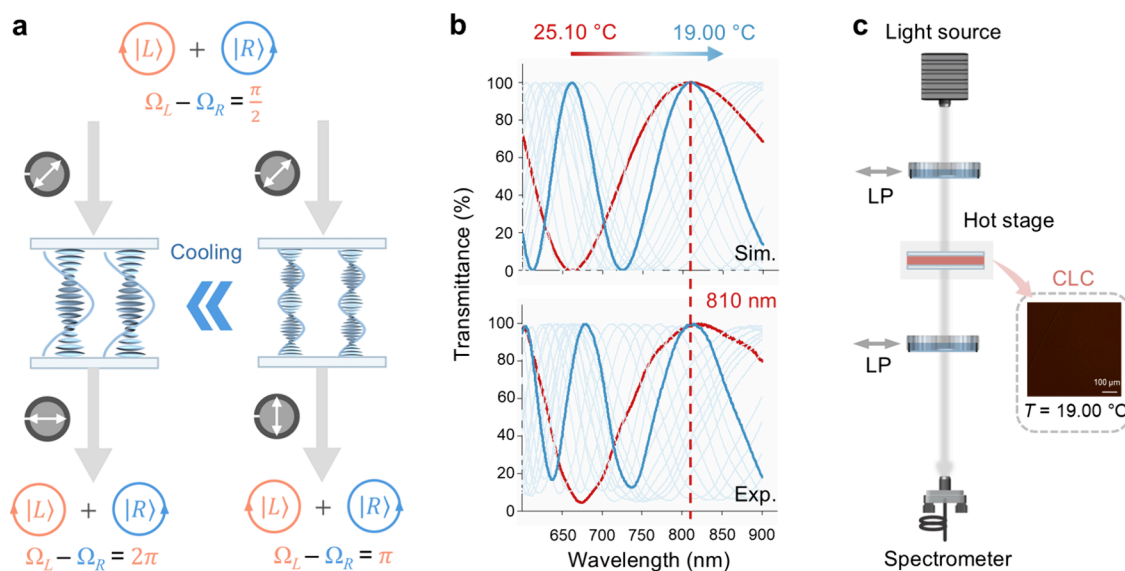


Figure 2. Dynamic response characterization of the CLC device. (a) Dynamic control of polarization rotation. Cooling the CLC (blue arrow) increases the rotation angle of the output linear polarization state (white arrows). (b) Dynamic control of the transmission spectrum. The gradient color arrow (red to blue) positioned at the top denotes a decrease in temperature (25.10 to 19.00 °C). The spectral curves from top to bottom are the simulated and experimental spectra, respectively. The direction of the gradient arrow corresponds to the spectral red-shift of the short wavelength circular regime induced by cooling. (c) Experimental setup for dynamic response characterization of the CLC device. Schematic of the transmission measurement under parallel polarizers, including a light source, a high-precision hot stage, polarizers, and a spectrometer. The inset shows a micrograph of the CLC device at 19.00 °C. Scale bar, 100 μm .

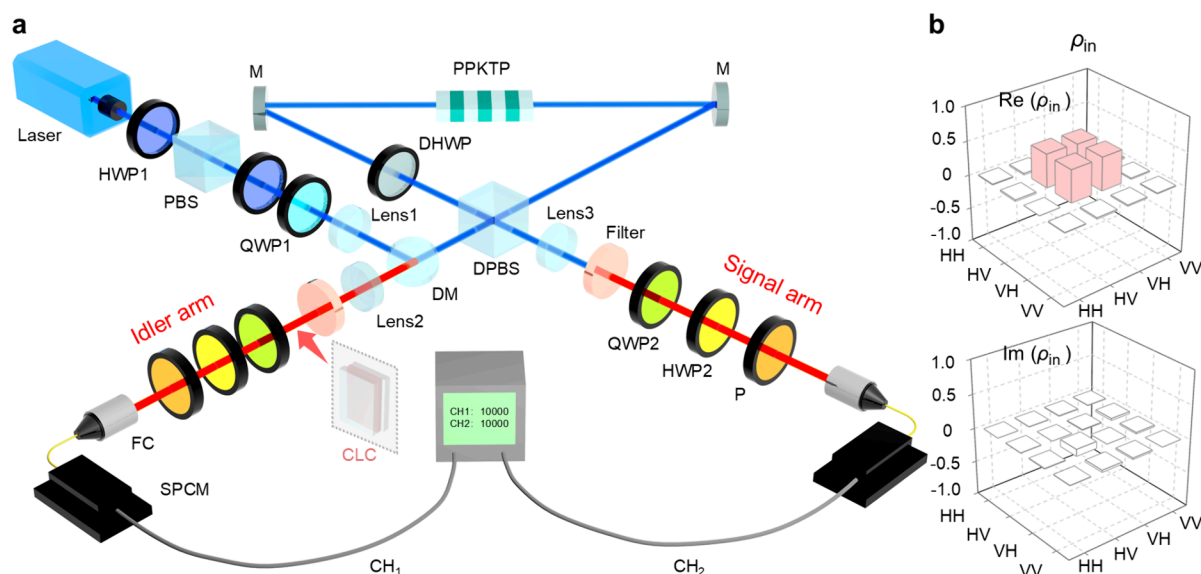


Figure 3. Optical setup of the entangled quantum source and its characterization. (a) Whole experimental setup, including a quantum entangled source. The fabricated CLC device can be inserted between the filter and the quarter-wave plate in the idler arm for quantum state modulation. Abbreviations: HWP, half-wave plate; PBS, polarization beam splitter; QWP, quarter-wave plate; DM, dichromatic mirror; DPBS, dual wavelength PBS; DHWP, dual wavelength HWP; PPKTP, periodically poled KTiOPO_4 ; M, mirror; FC, fiber coupler; P, polarizer; SPCM, single-photon counting module; CH_1 , channel 1; CH_2 , channel 2. (b) Real and imaginary parts of density matrix ρ_{in} of the two photon states.

The self-assembled helical organization of the CLC nanostructure results in a spin-selective photonic band gap (PBG), which selectively reflects circularly polarized light, matching the handedness of the helix. Outside this PBG, in the spectral region known as the circular regime, the CLC medium exhibits optical activity, where the propagating normal modes are almost two circularly polarized waves with opposite handednesses. This circular regime is divided into two regimes: the long wavelength circular regime and the short wavelength circular regime.

For a right-handed CLC operating in the short wavelength circular regime, the left-handed circular polarization (LCP) propagation mode exhibits a larger wavenumber than the right-handed circular polarization (RCP), and thus LCP accumulates more dynamic phase. Therefore, the CLC medium exhibits an outstanding circular birefringence, whereas a left-handed CLC leads to the opposite phase accumulation between LCP and RCP. The polarization state of any incident linearly polarized light (i.e., the superposition of RCP and LCP) is modulated as

$$|R\rangle + e^{i\Delta\Omega}|L\rangle \xrightarrow{\text{CLC}} e^{i\Omega_C}[e^{-i\alpha d}|R\rangle + e^{i(\Delta\Omega+\alpha d)}|L\rangle] \quad (1)$$

where $\Delta\Omega$ represents the initial phase difference between RCP and LCP and Ω_C represents the extra phase accumulation for both RCP and LCP. The optical activity of the CLC results in a relative phase difference of $2\alpha d$ between the LCP and RCP modes, where α is its optical rotatory power and d is the CLC thickness, indicating a linear dependence on d . α is inherently determined by birefringence Δn of the host LC, helical pitch p of the CLC medium, and incident wavelength λ . Notably, the CLC medium is sensitive to external stimuli,^{32,33} such as heat, electric/magnetic field, and light irradiation. In particular, pitch p could be thermally controlled, varying with temperature through winding or unwinding of the helix structure. Neglecting the birefringence Δn change in the host LC over a reasonable temperature range, the rotatory power in the short wavelength circular regime takes the following form:

$$\alpha(T) = \frac{\pi(\Delta n)^2 p(T)}{4\lambda^2} = \frac{1}{2}(k_L - k_R) \quad (2)$$

CLC pitch $p(T)$, which is a function of temperature T , serves as the key tuning parameter. k_L and k_R are the wavenumbers for the normal LCP and RCP modes, respectively. Within the common smectic–nematic pretransition regime, $p(T)$ lengthens upon cooling and shortens upon heating.³³ As illustrated in Figure 2a, this dynamic control of $p(T)$ directly modulates optical rotatory power $\alpha(T)$, enabling dynamic control over the linear polarization state. Accordingly, the polarization modulation is determined by only the operating temperature and the thickness of CLC device, independent of the incident polarization state.

When the input photon is vertically polarized $|V\rangle$, cooling the CLC device drives the output polarization mode to undergo a full rotation around the z -axis of the Poincaré sphere, sequencing through antidiagonal ($|A\rangle$), horizontal ($|H\rangle$), and diagonal ($|D\rangle$) modes before returning to vertical ($|V\rangle$) mode. Since the accumulated phase difference is proportional to d , a smaller d leads to a smaller phase difference and hence a weaker polarization rotation over the same temperature range (Figure S1). Notably, this manipulation can be represented by operator $\mathbf{M}(T)$, which acts on a single qubit physically induced by the photon's circular polarization:

$$\mathbf{M}(T) = R_z(2\alpha(T)d) = e^{-i\alpha(T)dZ} = \begin{pmatrix} e^{-i\alpha(T)d} & 0 \\ 0 & e^{i\alpha(T)d} \end{pmatrix} \quad (3)$$

where Z stands for the Pauli matrix. By controlling the cooling process, $\mathbf{M}(T)$ introduces a controllable relative phase difference $2\alpha d$ between the RCP and LCP state. When $2\alpha d$ equals 0, $\pi/2$, and π , it theoretically corresponds to the identity gate, S gate, and Pauli-Z gate, respectively.

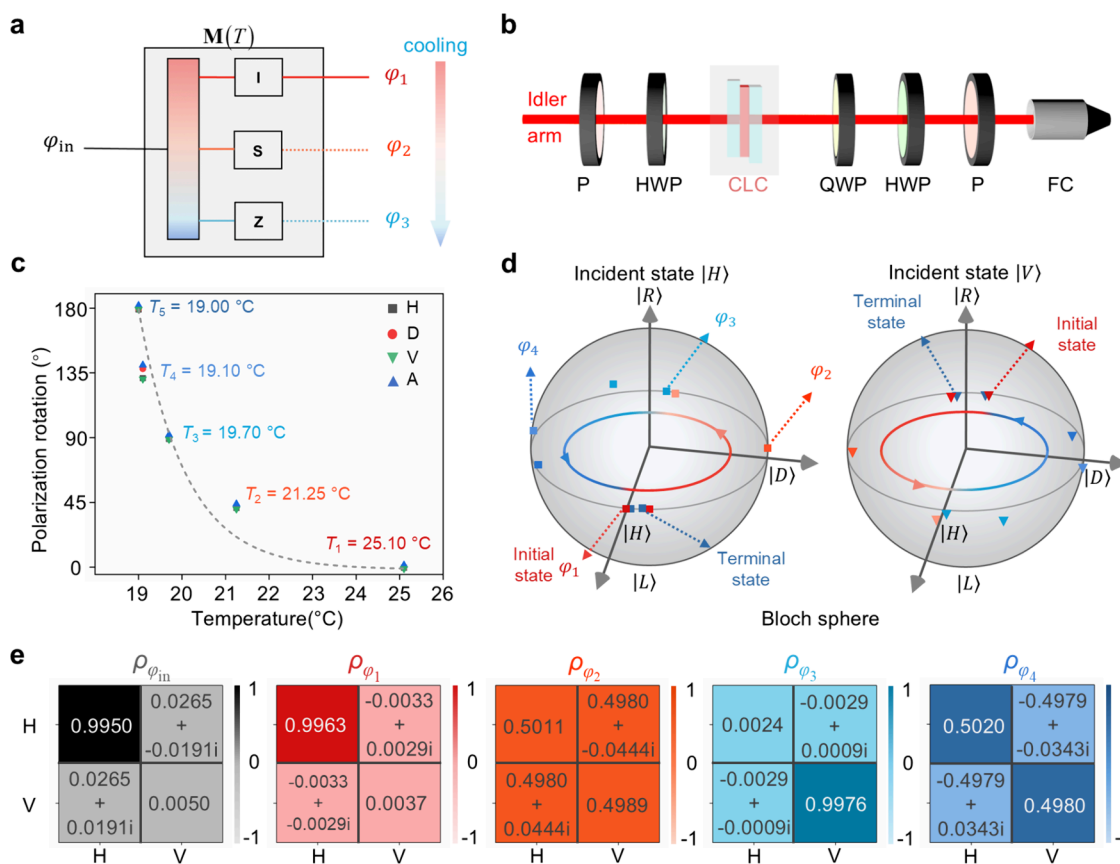


Figure 4. Dynamic CLC quantum gate for single-photon manipulation. (a) Schematic of the CLC quantum gate for a single photon. (b) Experimental setup for the characterization of the CLC gate. (c) Measured polarization rotation angles as a function of temperature for different input states. (d) Evolution of the output states on the Bloch sphere for horizontal and vertical state incidence during cooling from 25.10 to 19.00 °C. The rainbow-colored trajectory illustrates a complete 360° revolution around the z-axis, with arrows indicating the cooling direction. (e) Reconstructed density matrices for the input and output states in the experiment.

■ DYNAMICALLY CONTROLLABLE CLC QUANTUM GATE

To achieve thermal control, the CLC material is prepared by mixing nematic LC E7, right-handed chiral dopant R811, and left-handed chiral dopant S5011 at a weight ratio of 75.9:22.7:1.4. In particular, by carefully designing the concentration of S5011, the short wavelength circular regime is adjusted to include the intended wavelength of 810 nm. Cell gap d is chosen to be as thick as 30 μm to produce a sufficient dynamic phase difference. Based on photosensitive SD1, the surface alignment is set perpendicular to the unsealed boundaries of the LC cell. After being filled with the prepared CLC material at 60 °C, the cell is cooled to room temperature and kept in the dark for 2 days. Driven by the system's tendency to minimize the free energy, CLC standing helices self-assemble and ultimately evolve into the designed uniform chiral superstructure.

The thermal response of the CLC device is characterized by measuring its transmittance spectrum under parallel polarizers (Figure 2c), with the device mounted on a high-precision hot stage. As shown in Figure 2b, decreasing the temperature from 25.10 to 19.00 °C induces a red-shift of the short wavelength circular regime. This spectral shift corresponds to a change in the polarization state of the transmitted light, as confirmed by the close match between the simulated and experimental spectra. Consequently, the transmittance at 810 nm undergoes a full modulation cycle, falling from a maximum to a minimum

before returning to the maximum. This corresponds to a 360° polarization rotation around the z-axis of the Poincaré sphere, enabling a dynamic single-qubit gate. Furthermore, the observed spectral variation exhibits quasi-continuous behavior, which resulted from the parallel anchoring condition. This anchoring scheme stabilizes the pitch at discrete values and can offer inherent tolerance against thermal fluctuation.

To verify quantum state control, a Sagnac interferometer⁴⁵ is built as shown in Figure 3a. The frequency-degenerate type II quasi-phase matched collinear spontaneous parametric down-conversion (SPDC) process is used to generate a quantum source. The pump source is a 405 nm continuous-wave diode laser. A 10 mm long PPKTP crystal with a 10 μm poling period is implemented into the polarization Sagnac interferometer, and a stable thermoelectric controller is used for temperature stabilization at 27.8 ± 0.1 °C. The SPDC-generated photon pairs are collimated by achromatic doublet lenses with a focal length of 200 mm. Two 3 nm bandpass filters for frequency filtering are implemented before the fiber coupler. Accordingly, we prepare photon pairs as $|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|H\rangle_i|V\rangle_s + |V\rangle_i|H\rangle_s) = \frac{i}{\sqrt{2}}(|R\rangle_i|R\rangle_s - |L\rangle_i|L\rangle_s)$.

The output state is measured and reconstructed based on the quantum state tomography⁴⁶ (Figure 3b). The fidelity of the reconstructed density matrix for the input source with respect to the pure Bell state,⁴⁷ defined as $F_{\rho_{in}} = \langle \Psi^+ | \rho_{in} | \Psi^+ \rangle$, is 96.30%.

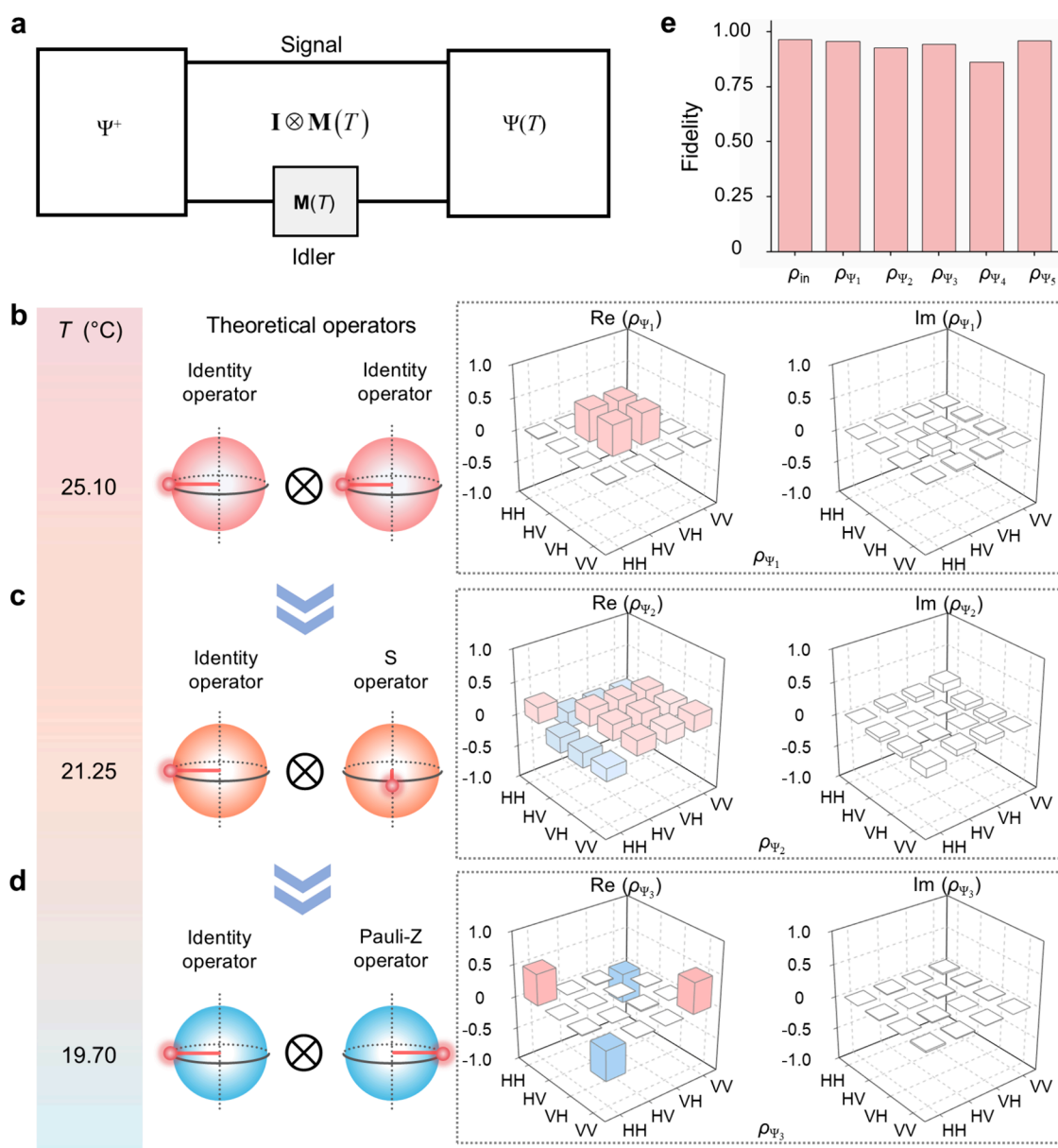


Figure 5. Dynamic CLC quantum gate for polarization-entangled state transformation. (a) Schematic of the CLC quantum gate for the polarization-entangled state. (b–d) Theoretical operators and reconstructed output density matrices at 25.10, 21.25, and 19.70 °C, respectively. In each, columns (from left to right) show the temperature, theoretical operator, and reconstructed density matrix. (e) Fidelities of the reconstructed input and output density matrices with respect to the pure entangled states.

A single-photon source is prepared in the idler arm of the Sagnac interferometer by using a polarizer and a half-wave plate to set its polarization state (Figure 4b). It is then used to verify the quantum state manipulation capability of the proposed CLC device. For input state $|H\rangle$, the output state evolves to $|H\rangle$, $|D\rangle$, $|V\rangle$, and $|A\rangle$ when the CLC device is set to temperatures of 25.10, 21.25, 19.70, and 19.10 °C, respectively. In the experiment, the device exhibits a high modulation efficiency up to 96.60%, defined as $\eta = \frac{C_{\text{out}}}{C_{\text{in}}}$, where C_{in} and C_{out} denote the average photon counts measured in 1 s before and after transmission, respectively, through the CLC device. The output states at different temperatures are characterized via quantum state tomography, which uses a series of polarization elements to reconstruct their density matrices (Figure 4e). The agreement between the reconstructed density matrices

($\rho_{\varphi_1} - \rho_{\varphi_4}$) and respective theoretical target density matrices ($\rho_H = |H\rangle\langle H|$, $\rho_D = |D\rangle\langle D|$, $\rho_V = |V\rangle\langle V|$, and $\rho_A = |A\rangle\langle A|$) is quantified by the fidelities. The fidelity is defined as $F(\rho_{\text{exp}}, \rho_{\text{tar}}) = [\text{Tr}(\sqrt{\sqrt{\rho_{\text{exp}}} \rho_{\text{tar}} \sqrt{\rho_{\text{exp}}}})]^2$, where ρ_{exp} and ρ_{tar} denote the reconstructed and the theoretical target density matrices, respectively. Since the target states in our experiment are pure states, i.e., $\rho_{\text{tar}} = |\zeta\rangle\langle\zeta|$, the fidelities could be simplified to $F(\rho_{\text{exp}}, |\zeta\rangle\langle\zeta|) = \langle\zeta|\rho_{\text{exp}}|\zeta\rangle$. Accordingly, the fidelities are calculated as $F_{\varphi_1} = \langle H|\rho_{\varphi_1}|H\rangle$, $F_{\varphi_2} = \langle D|\rho_{\varphi_2}|D\rangle$, $F_{\varphi_3} = \langle V|\rho_{\varphi_3}|V\rangle$, and $F_{\varphi_4} = \langle A|\rho_{\varphi_4}|A\rangle$, which are 99.63%, 99.80%, 99.76%, and 99.79%, respectively, demonstrating the high fidelities. For a left-handed CLC device, the opposite polarization rotation can be observed, as shown in Figure S2.

Crucially, this manipulation is determined by only the temperature and is independent of the incident polarization.

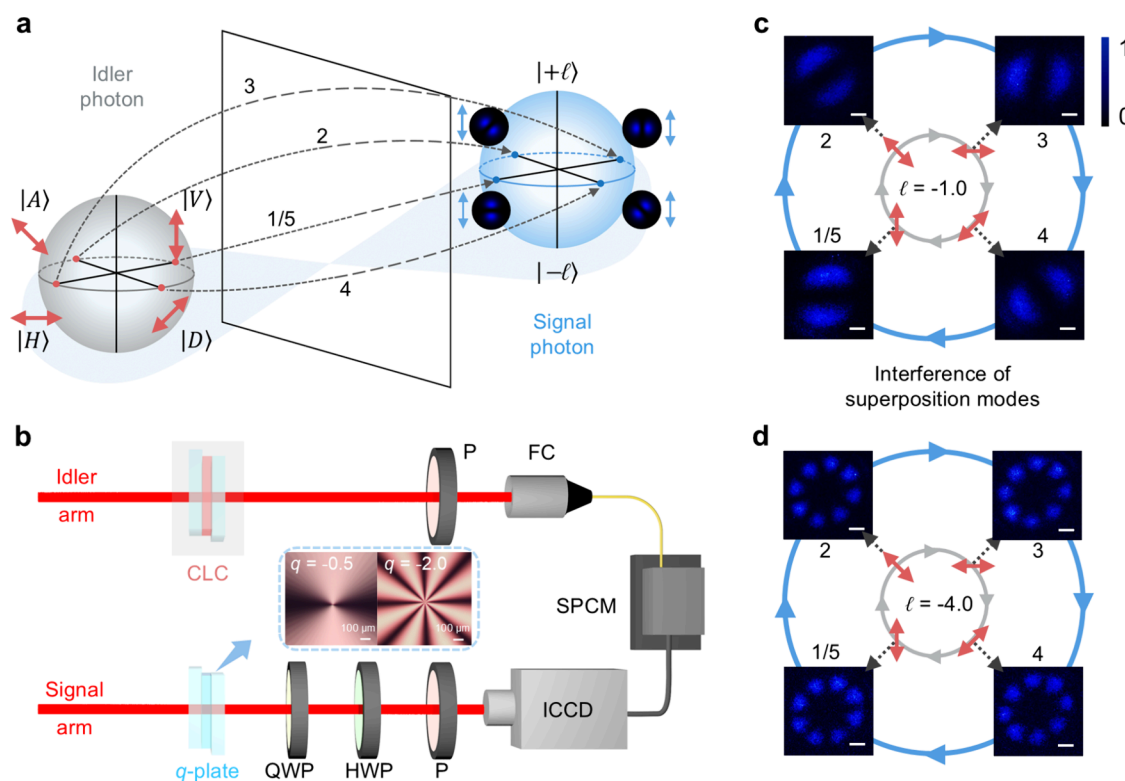


Figure 6. Dynamic CLC quantum gate for hybrid entanglement. (a) Dynamic control of hybrid entanglement. Conceptual diagram illustrating how cooling the CLC gate rotates the polarization state of the idler photon counterclockwise on the Poincaré sphere (gray), which in turn drives a clockwise rotation of the OAM state of the signal photon to the HOPS (blue). The sequence of five gray dashed arrows (labeled 1–5) corresponds to decreasing temperatures of 25.10, 21.25, 19.70, 19.10, and 19.00 °C, respectively. They trace the synchronous evolution of both states: the counterclockwise progression on the Poincaré sphere and the clockwise progression on the HOPS. The red arrows indicate the temperature-dependent measurement direction synthesized by the CLC gate in combination with a polarizer oriented vertically. The blue arrows indicate the projection of the signal photon. (b) Experimental setup for generating and measuring hybrid entanglement. Insets show micrographs of the q -plates ($q = -0.5$, and $q = -2.0$). Scale bars, 100 μm . (c and d) Interferograms of the superposition modes at different temperatures. All of the scale bars are 200 μm .

Through precise thermal control, polarization rotations approaching 0°, 45°, 90°, 135°, and 180° are achieved at a T_1 of 25.10 °C, a T_2 of 21.25 °C, a T_3 of 19.70 °C, a T_4 of 19.10 °C, and a T_5 of 19.00 °C, respectively (Figure 4c). Here, the rotation angles are defined as the azimuthal shift of the output states on the Bloch sphere relative to the input states. The rotation angle remains constant for different input polarization states at a fixed temperature and closely matches the prediction of eq 3. Therefore, the same CLC device functions as the identity gate, S gate, and Pauli-Z gate when cooled to T_1 – T_3 , respectively (Figure 4a). Furthermore, the T gate can also be realized at an intermediate temperature between T_1 and T_2 (Figure S3). The complete state evolution from the initial state to terminal state is visualized in their entirety on the Bloch sphere (Figure 4d and Figure S4). Notably, full rotations are accomplished within a narrow temperature variation of 7 °C, underscoring the high sensitivity of this dynamic CLC gate.

■ DYNAMIC TRANSFORMATION OF THE POLARIZATION-ENTANGLED STATE

Beyond single-qubit manipulation, this CLC gate also enables the transformation of the polarization-entangled state. This gate acts as a dynamic operator $\mathbf{I} \otimes \mathbf{M}(T)$ on the polarization-entangled state (Figure 5a) and transforms it into a desirable entangled state $|\Psi(T)\rangle$, expressed as

$$|\Psi(T)\rangle = [\mathbf{I}_i \otimes \mathbf{M}_s(T)]|\Psi^+\rangle = \frac{i}{\sqrt{2}}(e^{-i\alpha(T)}|L\rangle_i|R\rangle_s - e^{i\alpha(T)}|L\rangle_i|L\rangle_s) \quad (4)$$

The CLC gate functions as a different operator at different temperatures. It performs $\mathbf{I} \otimes \mathbf{I}$, $\mathbf{I} \otimes \mathbf{S}$, $\mathbf{I} \otimes \mathbf{Z}$, $\mathbf{I} \otimes (-\mathbf{S})$, and $\mathbf{I} \otimes \mathbf{I}$ at T_1 – T_5 , respectively, where $\mathbf{I}$, $\mathbf{S}$, and $\mathbf{Z}$ are the mathematical forms of the identity, S, and Pauli-Z gates, respectively. When operating on input state $|\Psi^+\rangle$, distinct entangled states $|\Psi(T_{1-5})\rangle$ are theoretically generated. Specifically, Bell states $|\Psi(T_{1/5})\rangle = |\Psi^+\rangle$ and $|\Psi(T_3)\rangle = |\Phi^-\rangle$ (Figure S5) are achieved at T_1 (T_5) and T_3 . Similarly, entangled states $|\Psi(T_2)\rangle = |\Gamma^+\rangle$ and $|\Psi(T_4)\rangle = |\Gamma^-\rangle$ (Figure S5) are realized at T_2 and T_4 .

The input state, characterized by density matrix ρ_{in} (Figure 3b), is transformed into different polarization-entangled states as illustrated in Figure 5b–d and Figure S6. These states are obtained via quantum state tomography, and their reconstructed density matrices are presented as $\rho_{\Psi_1} - \rho_{\Psi_5}$. Their fidelities with respect to the pure entangled states are defined as $F_{\Psi_{1-5}} = \langle \Psi(T_{1-5}) | \rho_{\Psi_{1-5}} | \Psi(T_{1-5}) \rangle$, and the corresponding values are 95.65%, 92.60%, 94.31%, 86.28%, and 95.87%, respectively (Figure 5e). Such high fidelities verify that the CLC quantum gate is indeed an efficient and reliable platform for entangled state manipulation.

■ DYNAMIC CONTROL OF HYBRID ENTANGLEMENT

Beyond transforming polarization-entangled states, the CLC quantum gate further enables dynamic control over hybrid entanglement between different DoFs. Here, hybrid entanglement refers to a nonclassical link between the polarization mode of one photon and the OAM mode of another. Geometrically, the polarization mode is represented on a Poincaré sphere, while the OAM is represented on a HOPS. Their hybrid entanglement establishes a geometric correspondence between these two spheres in the quantum region. Any unitary transformation applied to the polarization mode, such as a rotation by the CLC quantum gate, coherently modifies the overall hybrid entangled state. As the polarization mode is driven along a trajectory on its Poincaré sphere by the proposed CLC gate, the spatial mode consequently traces a corresponding trajectory on its HOPS (Figure 6a).

Hybrid entanglement is prepared by using a nematic LC q -plate in the signal arm as shown in Figure 6b (details in LC Superstructure Fabrication and Supporting Information Note 1). Consequently, the hybrid entanglement is established between the signal photon's OAM and the idler photon's polarization. The CLC gate implements the unitary transformation on the idler photon's polarization mode, leading to direct control of the hybrid entanglement between the Poincaré sphere of the idler photon and the HOPS of the signal photon. The resulting state is expressed as

$$|\psi\rangle_{\text{hy-2}} = \frac{i}{\sqrt{2}}(e^{-i\alpha(T)d}|R\rangle_i|-l\rangle_s - e^{i\alpha(T)d}|L\rangle_i|l\rangle_s) \quad (5)$$

where $|l\rangle_s$ and $|-l\rangle_s$ represent the OAM mode of the signal photon, as described in Supporting Information Note 1. The representation transformation reveals that the hybrid entanglement possesses an intrinsic geometric structure (details in Supporting Information Note 2). Temperature-dependent $\alpha(T)$ varies with the CLC gate cooling from 25.10 to 19.00 °C, which in turn modulates the hybrid entangled state. This geometrically manifests as opposite rotations of two spheres (Figure 6a). A projective measurement on the idler photon is performed, which projects the signal photon into a spatially variant polarization profile, expressed as

$$|\psi\rangle_s = i\langle V|\psi\rangle_{\text{hy-2}} = \frac{1}{2}(e^{-i\alpha(T)d}|-l\rangle_s + e^{i\alpha(T)d}|l\rangle_s) \quad (6)$$

When projected onto the vertical state, this profile yields a lobed intensity pattern and is captured by an intensified charge-coupled device (ICCD) using the idler photon as a trigger (Figure 6b). The lobed pattern arises from the superposition between the transverse spatial modes carrying opposite topological charges $\pm l$, with the number of lobes determined by $|2l|$. Upon cooling, the lobed pattern rotates counterclockwise (Figure 6c,d), which is in agreement with theoretical simulation (Figure S7). The full polarization response is further probed with the polarizer set to different orientations or just removed (Figures S8 and S9). Such temperature-dependent rotation of the pattern directly demonstrates the CLC gate's capability to dynamically manipulate the hybrid entanglement between different DoFs.

■ CONCLUSION

In summary, we have demonstrated a controllable quantum gate based on a uniformly self-assembled CLC nanostructure. The device exhibits precise and tunable optical activity,

enabling a full 180° rotation of linear polarization within a narrow 7 °C temperature range. It serves as a controllable and reliable operator on a qubit, implementing the identity, S, and Pauli-Z gates at different temperature. Furthermore, a variety of entangled states are efficiently harnessed by this CLC gate. It could transform a given polarization-entangled state into a range of distinct target states and further control hybrid entanglement. This work highlights the unprecedented capability of CLC nanostructure in quantum state manipulation and may promote fruitful applications in quantum communication, quantum computing, and quantum imaging.

■ MATERIALS AND METHODS

LC Superstructure Fabrication

A 0.35 wt % solution of photoalignment agent SD1 in dimethylformamide was prepared. SD1 reoriented perpendicular to the polarization direction of linearly polarized UV illumination and guided LC molecule alignment parallel to this direction. Indium–tin–oxide (ITO) glass substrates were sequentially cleaned by ultrasonic bathing, treated with UV and ozone, spin-coated with the SD1 solution, and cured at 100 °C for 10 min. Cells with different thicknesses were constructed by assembling two substrates using 30 μm mylar and an epoxy resin containing 6.9 μm spacers. The obtained cell thickness was verified through the Fabry–Perot interference measurement.

For fabrication of the CLC device, the uniformly aligned 30 μm cell was prepared via linearly polarized UV exposure and filled with the CLC mixture. Then this cell was stored in a dark environment to facilitate stable helical superstructure. The CLC consisted of E7 (HCCH, China), right-handed chiral dopant R811 (HCCH, China), and left-handed chiral dopant S5011 (HCCH, China), with a 75.9:22.7:1.4 E7:R811:S5011 weight ratio. Although the helical twisting power of S5011 is 10 times that of R811, the concentration of R811 was set more than 10 times higher, resulting in a right-handed chirality.

For fabrication of the q -plate, the 6.9 μm cell was imprinted with the designed alignment pattern via multistep partial overlapping exposure using a digital micromirror device (DMD)-based dynamic photopatterning system. Then the patterned cell was then filled with nematic LC E7 at 70 °C and gradually cooled to room temperature, to obtain stable structure.

Information for ICCD

The used ICCD camera (Andor iStar DH334T-18U-73) has a pixel size of 13 $\mu\text{m} \times 13 \mu\text{m}$ with an effective pixel count of 1024 $\times$ 1024. The camera is air-cooled to -30 °C to achieve 20% quantum efficiency. An external trigger mode and a Digital Delay Generator (DDG) gate mode are chosen for the ICCD camera to capture information about the signal photon. To capture heralded modes, the ICCD camera operates an external trigger mode and a DDG gate mode. The corresponding measurement conditions are a 1 s discrete exposure of each frame, 25 cumulative times, a 3600 gain, and a 6 ns gate width with a delay time of 7 ns. All images captured by ICCD have been normalized. Additionally, most optical and mechanical components were provided by JCOPTIX.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.nanolett.6c02279>.

Hybrid entanglement generation, a representative transformation of the hybrid entangled state, evolution of the output states for diagonal and antidiagonal state incidence, transformation of the polarization-entangled state, theoretical operators and reconstructed output

density matrices, simulated superposition modes, and full polarization analysis of superposition modes (PDF)

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Author Contributions

[§]S.-H.D. and D.Z. contributed equally to this work. P.C. conceived the original idea and designed the experiment. S.-H.D. and D.Z. conducted the designs, fabricated the samples, performed the experiments, and analyzed the data with the assistance of Y.-H.Z., S.-J.L., R.S., W.C., F.-T.C., J.-C.J., Y.-Q.L., and P.C. S.-H.D., D.Z., and P.C. prepared the initial manuscript. All authors participated in the discussion and contributed to refining the manuscript. P.C. supervised and directed the research.

Notes

The authors declare no competing financial interest.

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