



Article

Three-Dimensional Liquid Crystal Optical Switch for Quantum Optical Communication

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Abstract

We propose a three-dimensional (3D) integrated optical switch that leverages liquid crystal (LC) birefringence to achieve reconfigurable light routing for particular suitability for quantum optical communication. In our design, the large refractive index contrast between an LC's ordinary (n_o) and extraordinary (n_e) indices is exploited by using n_o as an effective cladding and n_e as the core of voltage-controlled waveguides. This allows dynamic waveguide formation not only in-plane (horizontal routing on chip) but also vertically through stacked polymer layers, realizing a 3D switching architecture beyond traditional planar photonic circuits. A prototype multi-layer structure on a silicon substrate is described, incorporating alternating polymer cladding and core films with embedded LC cells that act as switchable waveguide segments. Simulations confirm that the LC switch can confine and direct light between different layers with low loss, enabling compact 3×3 and potentially up to 10×10 port-count switching matrices. The device is electrically driven (no moving parts) and can be operated at low voltages, ensuring compatibility with photonic integrated circuit fabrication. The simulated LC response time on ON/OFF is on the order of 1.1 ms/45 ms, which is slower than MEMS or electro-optic switches, but, however, sufficient for quantum key distribution and other quantum network applications where ultrafast switching is not required. Overall, this LC cell-based 3D optical switch offers a promising route toward scalable, low-loss photonic switching nodes for next-generation quantum communication networks.

Keywords: quantum communication; 3D switch; liquid crystal; photonic integrated circuit; quantum key distribution



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1. Introduction

The information age demands continual advancements in smaller, faster, and more efficient information-processing systems. While long-distance communications have already transitioned to optical fiber, similar optical interconnects are now being pursued at shorter distances and even on-chip. To enable optical information processing at the chip scale, researchers are developing integrated light sources, modulators, switches, and detectors for chip-to-chip and intra-chip applications. In other words, the trend is shifting from optical table setups toward photonic integrated circuits on silicon chips [1–4].

Optical switches can be broadly categorized into (1) free-space/mechanical switches and (2) waveguide-based switches. Mechanical switches (such as MEMS or Digital micro-

Mirror Devices) physically redirect light and can offer high port counts, but waveguide-based switches are more amenable to on-chip integration [5]. Waveguide switches are typically implemented in Planar Lightwave Circuits (PLCs), which consist of optical waveguides fabricated on a substrate using processes analogous to semiconductor fabrication (thin-film deposition, photolithography, dry etching, etc.) [4,6–8].

Most integrated optical switching devices operate on an interference principle: light is split into two or more paths or modes and recombined, and switching is achieved by inducing a phase difference of π (half a wavelength) between the paths. Common designs like Mach–Zehnder interferometers (MZI) [9], directional couplers, and multimode interferometers exploit this principle, often using thermo-optic or electro-optic effects (including controlled birefringence) to attain the necessary phase shift. However, interferometric switches typically require a certain interaction length (on the order of millimeters to centimeters) to accumulate a π phase change at telecommunication wavelengths. For example, silicon photonic Mach–Zehnder switches using the thermo-optic effect may need ~ 10 mm of waveguide length to produce a full switching phase shift [10–12]. This requirement limits how compact such devices can be. Various approaches for further miniaturization have been explored—including resonant structures and high-index contrast waveguides (e.g., plasmonic or photonic crystal waveguides)—but current on-chip optical switches remain essentially planar structures and have not yet achieved a truly three-dimensional configuration. Thus, there is a clear need for new switching device concepts that can break out of the planar paradigm to enable further miniaturization and integration density.

In this paper, we propose a new 3D optical switch using liquid crystal (LC) on top of a silicon substrate. In the display manufacturing process or LCOS (Liquid Crystal on Silicon) manufacturing process [13–16], the final stage of the semiconductor manufacturing process involves bonding between glasses, flexible substrates, and glass-semiconductor substrates, injecting LC, and sealing. In this proposal, we describe the advantages of using LC waveguides. This makes it possible to implement electrodes in three-dimension and presents new possibilities for the manufacture of optical integrated circuits. In this paper, we (1) propose the structure of a 3D LC optical switch, (2) simulate the optical input/output characteristics, and (3) describe the switching speed and its application to quantum communication.

2. Proposed Device Structure

We propose a novel 3D LC optical switch with a three-dimensional architecture implemented using LC block waveguide and conventional polymer waveguide technology on a silicon wafer. Figure 1 shows the appearance and switching properties of the LC block. Figure 1(1) shows a Si wafer. Figure 1(2) shows the 3D LC switch chip. Figure 1(3) shows a 3D front view with key structural dimensions ($D = 144 \mu\text{m}$ total width, $W = 28 \mu\text{m}$ waveguide width, $Dh = 72 \mu\text{m}$ horizontal LC block pitch, $Dv = 72 \mu\text{m}$ vertical LC block pitch, $L = 14 \mu\text{m}$ LC block length). Here, we explain our proposal using a 3×3 switch as an example. From the Si substrate side, channel waveguides 1, 4, and 7 are the first waveguide layer. Channel waveguides 2, 5, and 8 form the second waveguide layer. Channel waveguides 3, 6, and 9 form the third waveguide layer. The cladding and core materials are poly (methyl methacrylate) (PMMA) and polycarbonate (PC), with refractive indices of $n_{\text{PC}} = 1.583$ and $n_{\text{PMMA}} = 1.482$. The LC material is selected such that n_e matches the core (PC) refractive index and n_o matches the cladding (PMMA) refractive index. Area A (Figure 1(4)) has a structure (electrode structure) suitable for horizontal switching. Area B (Figure 1(5)) has a structure (electrode structure) suitable for vertical switching.

Then, the LC block (aggregation of LC cells) area is created. A $20 \mu\text{m} \times 30 \mu\text{m}$ flat area is etched as the first core layer on top of the PMMA layer of the first clad across the

three channels to secure the LC block assembly area. In area A, 5×5 pieces are arranged in each of the two LC blocks.

AREA A (the horizontal switching layer) contains LC block (LC cells and patterned electrode) designed to reroute light in-plane within a given waveguide layer. As shown in Figure 1(4), when a voltage is applied, the refractive index increases along the stepped electrode pattern, forming a waveguide. In Figure 1(4-1), switching occurs from waveguide 3 to waveguide 6. In Figure 1(4-2), switching occurs from waveguide 3 to waveguide 9. The refractive index of the LC with applied voltage is n_e , and it is considered to be a low-loss bending, although it is slightly wavy between the electrodes. The electrode shape in region A is a step-like structure, but its tilt angle is about 15 degrees on the waveguide. When no voltage is applied, the LC region remains at index n_0 and does not guide light. Therefore, each waveguide is in the default state, adjacent to the cladding, and the waveguides remain isolated from each other.

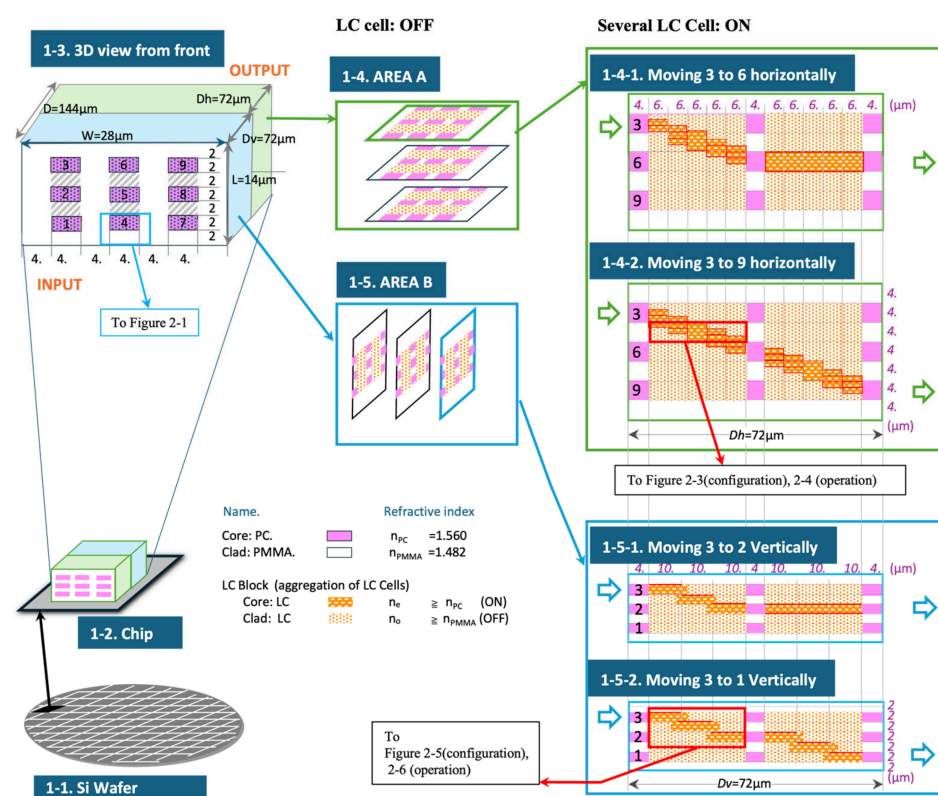


Figure 1. Proposed LC Switch. The inset legend distinguishes five material regions: Core: PC (solid pink, $n_{PC} = 1.583$), Clad: PMMA (white, $n_{PMMA} = 1.482$), LC Block: aggregation of LC cell (dot-hatched, detailed in Figure 2), Core: LC (orange-hatched, $n_e \cong n_{PC}$ when ON), and Clad: LC (orange light-hatched, $n_o \cong n_{PMMA}$ when OFF). Key device dimensions are indicated in panel 1-3: total width $D = 144 \mu\text{m}$, waveguide width $W = 28 \mu\text{m}$, horizontal LC block pitch $D_h = 72 \mu\text{m}$, vertical LC block pitch $D_v = 72 \mu\text{m}$, and LC block length $L = 14 \mu\text{m}$. 1-1: Si wafer. 1-2: The chip. 1-3: 3D view from the front showing the device cross-section and dimensions. 1-4: LC blocks B (horizontal switching). 1-4-1: Moving waveguide 3 to waveguide 6 horizontally. 1-4-2: Moving waveguide 3 to waveguide 9 horizontally. 1-5: LC blocks A (vertical switching). 1-5-1: Moving waveguide 3 to waveguide 2 vertically. 1-5-2: Moving waveguide 3 to waveguide 1 vertically. The red box in each switching diagram indicates the active LC block (see Figure 2). The orientation of LC is n_0 to n_e when the switch is ON.

AREA B (the vertical switching region) uses a different electrode configuration to route light between stacked layers. Here, electrodes above and below an LC cell (refer to Figure 1(5-1 and 2)) create an electric field through the thickness, aligning the LC molecules

vertically. In the upper illustration of Figure 1(5-1), an activated LC directs light from waveguide 3 up into waveguide 2. The tilt angle is 11 degrees, which is gentle. The lower illustration of Figure 1(5-2) shows waveguide 3 being linked down to waveguide 1. To facilitate a gentle vertical transition, the electrodes in Area B can be slightly offset or angled. As shown in Figure 2(6), when the field is applied at an angle, the LC orientation follows a slanted profile, creating a smoothly inclined waveguide rather than a 90°. This sloped LC waveguide helps to maintain mode confinement during vertical routing.

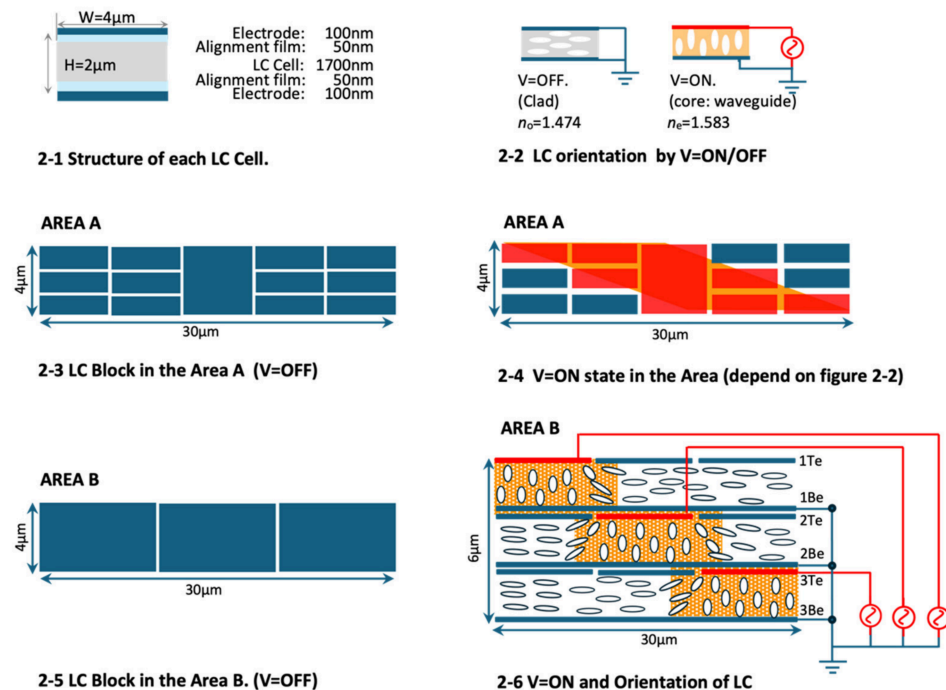


Figure 2. Liquid crystal (LC) block structure, operating principle, and electrode design. 2-1: LC block (cell) structure. 2-2: Operating principle. When voltage (V) is OFF, the LC molecules are aligned along the alignment film. When V is ON, the LC molecules are aligned according to the electric field. 2-3: Electrode structure of area A (V: OFF). 2-4: Electrode structure of area A (V: ON). 2-5: Electrode structure of area B (V OFF). 2-6: Electrode structure of area B (V: ON). In 2-4 and 2-6, when the voltage is ON, it is red, and the formed waveguide has an orange hatch pattern. Only (6) shows the alignment of the LC molecules. 1Te, 1Be, 2Te, 2Be, 3Te and 3Be mean first top electrode, first bottom electrode, second top electrode, second bottom electrode, third top electrode and third bottom electrode.

In both Area A and Area B, the key principle is that the LC has two refractive states: n_o (the voltage it remains index-matched to the surroundings (inactive)) and n_e (the voltage it provides a higher index contrast (active)) to guide light. By combining these in-plane and out-of-plane switching blocks, the device can dynamically reconfigure optical paths in three dimensions. This 3D LC switch architecture enables complex routing—for instance, forming a compact 3×3 optical cross-connect or even larger multi-port networks (potentially up to 10×10 ports as the design is scaled).

3. Leverage of Liquid Crystal Cell

Figure 2 shows the structure, operation principle, and electrode design of the LC block. Figure 2(1) shows the structure of the LC block (cell). The structure of each LC cell is as follows: (1) A 100 nm metal electrode on a substrate. (2) A 50 nm LC alignment film on top of that. (3) An LC cell is placed on top of that. (4) A 50 nm LC alignment film is placed on top of the LC. (6) A 100 nm metal electrode is placed on top of that. This structure allows the formation of a stacked structure. Figure 2(2) shows the operating principle. When the

voltage is off, the LC molecules are aligned along the alignment film. When V is on, the LC molecules are aligned according to the electric field.

Figure 2(3) shows the electrode structure of area A (V: off). Figure 2(4) shows the electrode structure of area A (V: on). By configuring the electrode structure as shown in Figure 2(3), light can be propagated from waveguide 3 to waveguide 6 (orange hatch pattern). Figure 2(5) shows the electrode structure of region B (V off). Figure 2(6) shows the electrode structure of region B (V: on). When a voltage is applied between the electrodes in the up–down or diagonal direction, the LC molecules tilt, as shown in the figure. This forms a waveguide, as shown in the orange hatch pattern, allowing light to propagate. Using this hierarchical structure of area A and area B, our design realizes two types of switching functions, as shown in Figure 1(4-1, 1-4-2, 1-5-1 and 1-5-2).

The refractive index specifications $n_e = 1.583$ and $n_o = 1.482$, as described in Section 2, represent ideal target values for high-performance photonic elements (optical waveguides, phase modulators, etc.). In practice, the LC material 5PCH used in this work has $n_e = 1.5918$ and $n_o = 1.4739$, which closely match these targets. LCs require injection and sealing processes. Other physical properties of 5PCH are shown in Table 1.

Table 1. Physical properties of 5PCH.

Property and Symbol	Value and Units
Rotation viscosity γ_1	0.1507 Pa s
Dielectric anisotropy $\Delta\epsilon$	12.7
Splay elastic constant K_{11}	9.6×10^{-12} N
Bend elastic constant K_{33}	19.4×10^{-12} N

Regarding incident light polarization: the waveguide mode is designed to be TM-polarized, consistent with coupling into the extraordinary index n_e when voltage is applied. The LC cell is filled with pure nematic LC (5PCH); no polymer–LC composite is used, and light scattering from polymer-dispersed LC (PDLC) effects is therefore not a concern. If the input light is unpolarized or carries mixed polarization states, a polarization splitter-rotator at each input port would be required to ensure that only TM-polarized light enters the LC switching region. This polarization sensitivity is a practical consideration that should be addressed in future device integration, particularly for quantum communication applications where maintaining polarization fidelity is critical.

Figure 3 shows the angular (θ) distribution of the LC molecule directors between electrodes inside the LC cell. The shortest length of the electrode is 2 μm , and considering the distance between the two electrodes, it can be considered to be about 1.7 μm . The maximum value of θ can be obtained around the center and it reaches 90 degrees under 5 V. After that, at 10 V, θ is 90° at a position of approximately 0.3–1.2.

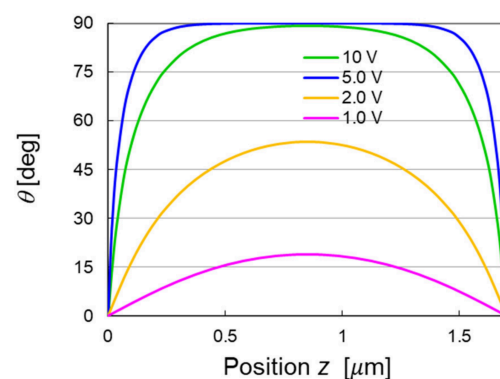


Figure 3. Orientation angle of liquid crystal (LC) molecule for the guided light.

We estimate the average refractive index of the LC cell given by the following formula (1).

$$\langle n_{LC} \rangle = \int_0^d \frac{n_o n_e}{\sqrt{\sin^2 \theta(z) n_o^2 + \cos^2 \theta(z) n_e^2}} dz, \quad (1)$$

where $\theta(z)$ is the obtained LC director distribution shown in Figure 3. As a result, we obtained the average refractive index of the LC cell as a function of the applied voltage shown in Figure 4. When voltages of 1.2 V and 2.6 V are applied to the LC cell, each average refractive index becomes equal to that of PMMA and PC, respectively.

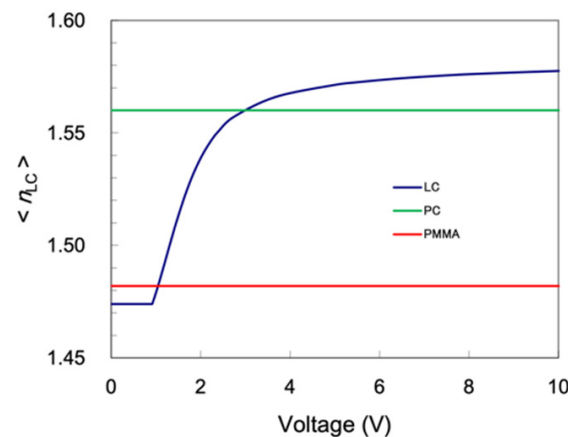


Figure 4. Applied voltage vs. average refractive index of the LC cell on the wavelength of 1550 nm.

4. Switching Speed

We first calculated τ_{OFF} and τ_{ON} using Equations (2) and (3).

$$\tau_{OFF} = \frac{\gamma d^2}{K_{11} \pi^2} \quad (2)$$

$$\tau_{ON} = \frac{\tau_{OFF}}{\left(\frac{V}{V_{th}}\right)^2 - 1} \quad (3)$$

Here, γ : Rotational viscosity coefficient, K_{11} : Elastic constant, d : Cell film thickness ($=1.7 \mu\text{m}$), V : Applied voltage, and V_{th} : Threshold voltage ($=1 \text{ V}$). At an applied voltage of 5 V, the rise time when the voltage was applied was about 1.1 ms. On the other hand, the fall time (relaxation time) when the voltage was removed was about 45 ms. The LC dynamic orientation response is modeled as follows.

$$\theta_{ON}(t) = \frac{\pi}{2} (1 - e^{-\frac{t}{\tau_{ON}}}) \quad (0 \text{ V to } 5 \text{ V}) \quad (4)$$

$$\theta_{OFF}(t) = \frac{\pi}{2} (e^{-\frac{t}{\tau_{OFF}}}) \quad (5 \text{ V to } 0 \text{ V}) \quad (5)$$

Based on the time constants derived from Equations (2) and (3) and the dynamic response model described by Equations (4) and (5), we performed a simulation of the switching state of the LC. The orientation angle as a function of time is determined by these equations, and the instantaneous refractive index is then calculated using Equation (1). Figure 5 shows the simulation results of the time when the refractive index (n_e) forms a waveguide and the time when the refractive index (n_e) returns to the original refractive index (n_o).

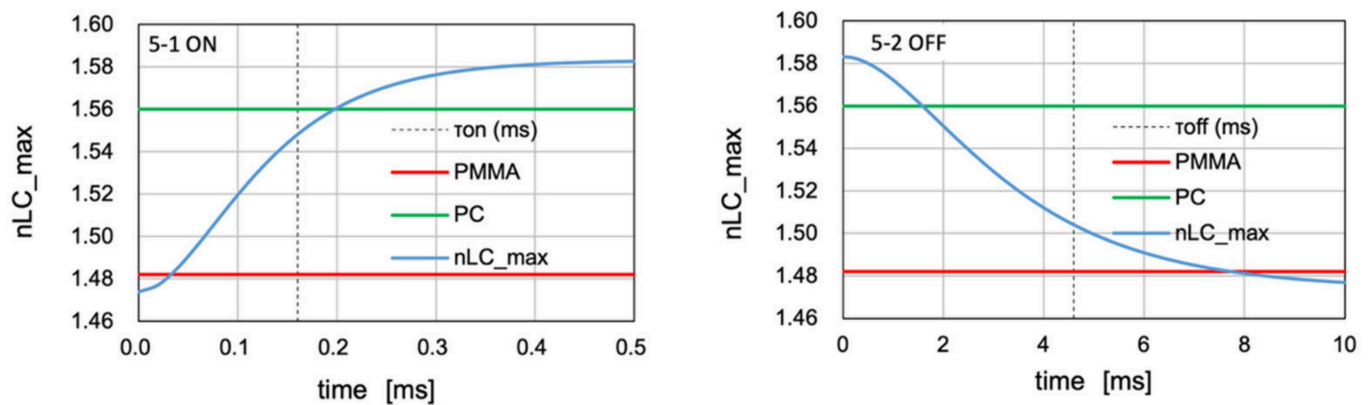


Figure 5. Switch ON and OFF. 5-1: ON. 5-2: OFF. Applied voltage is 5 V. n_{LC_max} means the maximum refractive index of LC. The figure shows how the effective refractive index of the LC rises (turn-on) and falls (turn-off) over time. τ_{ON} is 0.89 ms (rising: 1.1 ms) and τ_{OFF} is 25.45 ms (falling: 45 ms).

As can be seen from the time constant results, the rise and fall patterns are different, as shown in Figure 5. This large difference between the turn-on and turn-off times is characteristic of nematic LC devices, where the electric-field-driven alignment is relatively fast, but the relaxation back to the unaligned state is slower due to molecular inertia. For comparison, micro-electro-mechanical (MEMS) mirror switches (including digital micromirror devices) can switch in the kHz–MHz range, and electro-optic switches based on the Pockels effect or carrier injection can reach GHz speeds. The LC’s millisecond-scale response is a known trade-off for its advantages in low loss and analog tunability. Importantly, this slower speed does not preclude many potential applications. For instance, in display technology or optical network protection routing, switching times on the order of milliseconds are acceptable. In the context of quantum communications—such as quantum key distribution (QKD) networks—ultra-high switching speed is not essential, because the data rates are limited by photon detection and protocol overhead. What matters more in those systems are low optical loss, stability, and the ability to accommodate many channels/nodes.

Our proposed LC switch, with its compact 3D geometry and low-loss waveguide design, addresses these needs: it can be integrated to form multi-port switching nodes for quantum networks, reconfiguring paths as needed on a time scale of milliseconds, which is sufficient for routing quantum signals between multiple users or channels. In summary, although the LC switch is too slow for packet-level routing in classical telecom, it is well-aligned with the requirements of emerging quantum optical communication where switching events occur infrequently and prioritize fidelity over speed.

Table 2 compares the proposed LC 3D switch with other optical switching technologies, including Mach–Zehnder interferometers (MZIs), MEMS switches, and electro-optic (EO) switches. The comparison covers dimensionality, switching speed, power consumption, insertion loss, crosstalk suppression, device size, fabrication complexity, suitability for high-speed and quantum communications, and port expandability. It can be seen that the proposed 3D LC switch is superior to other methods in terms of power consumption, size reduction, ease of manufacturing, compatibility with quantum communication, and expandability to other ports.

Table 2. Comparison of representative optical switching technologies, including Mach–Zehnder interferometers (MZIs), MEMS-based switches, electro-optical (EO) devices, and the proposed liquid crystal (LC) 3D switch. Evaluation criteria include dimensionality, speed, integration, and suitability for quantum communication systems.

Comparison Item	MZI (Mach–Zehnder Interferometer)	MEMS Switch	EO Switch (LiNbO ₃ /InP)	LC 3D Switch (This Work)
Structure Type	planar waveguide	Mechanical Mirrors/Reflection	Pockels effect/ Index modulation	LC anisotropy + multilayer 3D structure
Dimensionality	2D (planar)	2D or free-space	2D (planar)	3D (Vertical + Horizontal)
Switching Speed	μs–ms (thermal) ns (EO)	ms–μs (mechanical)	ns–ps (GHz)	1.1 ms (rise), 45.0 ms (fall)
Power Consumption	High (thermal)/Medium (EO)	Medium–High (drive circuits)	Low–Medium (depends on speed)	Low (5 V drive, energy-efficient)
Insertion Loss	1–3 dB	<1 dB (very low)	1–2 dB	Low (design-dependent)
Crosstalk Suppression	High (design dependent)	High (physical separation)	High (fast control)	Moderate (depends on layout/electrodes)
Scalability (Size)	Compact (limited by phase length)	Medium–Large (requires actuators)	Medium (requires drivers)	High (stacked layer integration)
Ease of Fabrication	High (CMOS compatible)	Moderate (MEMS process)	Difficult (special material processing)	High (LC filling and stacking)
High-Speed Communication	Excellent	Fair (mainly for protection switching)	Excellent (main application)	Poor (too slow for classical data rates)
Quantum Communication	Good (with careful design)	Limited (size/speed tradeoff)	Good	Excellent (low speed, low loss, compact)
Multi-Port Expandability	Moderate (matrix configuration)	Excellent (up to 100 × 100 ports)	Limited (complex design)	Excellent (e.g., 3 × 3 to 10 × 10 possible)

5. Simulation of Beam Profile of INPUT/OUTPUT in the Waveguide

Figure 6 illustrates the calculated beam profiles at the entrance and exit of the LC waveguide. The analysis comprises three key components: (1) Design Structure: The waveguide’s structural layout is presented. (2) Light Confinement: Using the Equivalent Refractive Index method [17–21], we calculated the confinement of light into the channel-type waveguide. The results demonstrate successful confinement of the incident light into the channel shape. (3) Propagation and Output: We analyzed light propagation through various cross-sections of the waveguide. The final output beam profile is depicted, confirming maintained confinement throughout the structure.

The waveguide’s layer structure is as follows: Planar direction: A repeating pattern of clad (4 μm)/core (4 μm), totaling seven layers. Vertical direction: A similar layered structure with 2 μm thicknesses. Our calculations confirm that this configuration effectively confines light within the designated core regions, preventing unwanted coupling or leakage to adjacent channels. This design ensures precise control over light propagation, which is crucial for efficient optical switching and routing in advanced photonic devices.

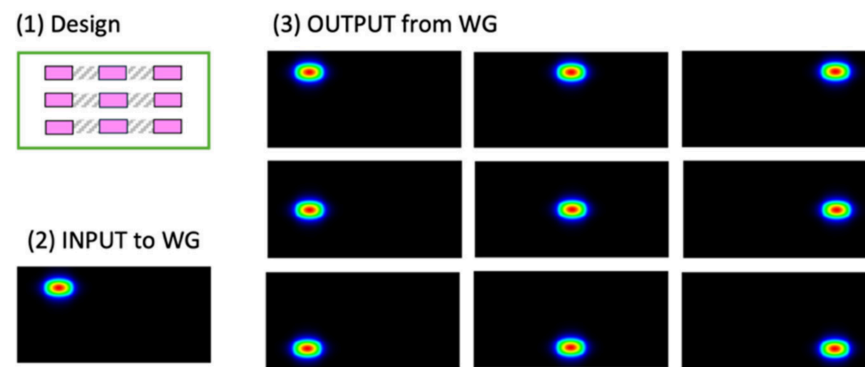


Figure 6. Illustrates the design shape, light confinement upon entering the channel waveguide, and light confinement within the channel waveguide after passing through each liquid crystal (LC) waveguide. Scattering effects from the LCs and losses due to the waveguide shape are not considered. ‘WG’ denotes waveguide.

6. Discussion

First, we must consider the separation of liquid crystal cells. Adjacent liquid crystal cells—specifically the closely spaced electrode pairs 1B–2T and 2B–3T—are separated by a 0.1 μm PMMA layer rather than an air gap, so the governing mechanism is solid-state dielectric breakdown rather than gaseous discharge. With a 5 V drive across this 0.1 μm layer, the applied field is 50 kV/mm (0.5 MV/cm). Reported dielectric strengths for thin polymer dielectric films of this class are on the order of 2–5 MV/cm (200–500 kV/mm); the operating field therefore lies roughly a factor of 4–10 below the intrinsic breakdown field [22,23].

At the ~ 100 nm scale, the behavior departs from the bulk: the dielectric strength per unit thickness increases as the thickness decreases and approaches a nearly constant “intrinsic” regime. For a given 100 nm film, however, the breakdown voltage can vary by a factor of two to three—from the low-20 V range to above 50 V—depending on film quality, chiefly residual solvent, solvent type and deposition conditions, pinholes and other defects, and the presence or absence of cross-linking.

Adopting the common reliability guideline of operating at about one-third of the breakdown voltage, a non-cross-linked 100 nm film supports a routine operating range of roughly 5–7 V, consistent with organic thin-film transistors that operate below 10 V using PMMA gate dielectrics. The 5 V drive used here, therefore, lies within a safe margin, and electrical discharge breakdown between the closely spaced electrodes is not expected.

Next, to evaluate the practical significance and applicability of the proposed LC-based 3D optical switch, we compare it with three representative optical switching technologies: Mach–Zehnder interferometer (MZI), MEMS-based optical switch, and electro-optical (EO) switch. Table 2 summarizes the performance characteristics and trade-offs of these technologies in terms of key criteria, including dimensional scalability, switching speed, loss, and compatibility with quantum communication.

Table 2 highlights that while MZI [24] and EO switches [3,25–29] offer high-speed operation suitable for conventional communication systems, they are inherently limited to planar configurations and often require large device footprints and complex high-speed driving circuitry. On the other hand, MEMS switches [5,30–33] offer excellent scalability and very low insertion loss but suffer from mechanical complexity and relatively slow switching speed. In contrast, the proposed LC 3D switch offers the unique advantage of dynamically reconfiguring the waveguide in three dimensions by using birefringent LC materials and multilayer polymer stacking. The low power consumption, low voltage operation, and the ability to integrate multiple vertical and horizontal switching paths

make them very promising for applications such as quantum key distribution (QKD) where fast switching is not a primary requirement.

The proposed LC-based 3D optical switch presents a promising paradigm shift from conventional planar photonic architectures. Exploiting the anisotropic refractive index behavior of LC molecules allows the formation of dynamically reconfigurable waveguides in both the in-plane and vertical directions, leading to significant advantages in compactness and switch density. This is particularly important in emerging quantum photonic systems, where node integration, minimal optical losses, and flexible routing topologies are essential, while ultrafast switching speeds are less critical.

One of the key strengths of the LC 3D switch is its simplicity of actuation and fabrication. The device leverages a simple electrode configuration and low voltage operation (~ 5 V), allowing it to operate with minimal power consumption. Furthermore, its structural compatibility with multilayer polymer waveguide platforms opens new possibilities for volumetric photonic integration, leading to reduced device footprints and improved channel scalability.

Alternative LC electro-optical modes with faster response times are worth comparing. Ferroelectric LC (FLC) can achieve switching times of 10–100 μs , three orders of magnitude faster than nematic LC, but requires thinner cells (below 2 μm) and is considerably more sensitive to temperature fluctuations and mechanical shock. Polymer-stabilized LC (PSLC) reduces the relaxation time τ_{OFF} by approximately one order of magnitude at the cost of increased light scattering. Dual-frequency LC allows active driving of both ON and OFF transitions, improving the overall reconfiguration speed. For quantum communication applications, where switching events occur on timescales much longer than the data rates, the millisecond response of nematic 5PCH remains fully adequate. FLC or dual-frequency LC would be preferable if sub-millisecond reconfiguration is required in future implementations. For a comprehensive review of LC electro-optical modes, alignment techniques, and device physics, see Ref. [34].

The spatial resolution and pixel crosstalk of the proposed switch are also important parameters. In the current design, the center-to-center pitch between adjacent LC electrode pixels is approximately 8 μm (4 μm core plus 4 μm cladding gap). Evanescent field coupling between adjacent waveguide channels is negligible at this pitch for the wavelengths of interest. The minimum achievable pixel pitch, constrained by lithographic resolution and LC alignment stability, is estimated at approximately 4–5 μm . This would support switching matrices of up to 10×10 ports within a device footprint of approximately 1 mm $\times$ 1 mm, offering a favorable trade-off between integration density and crosstalk isolation. I corrected the numbers and the order.

However, there are several constraints to consider. Most notably, the time response of LC materials (switching and relaxation times in the order of milliseconds) makes current designs unsuitable for conventional high-speed optical communications. This constraint limits the use of LC materials to applications such as quantum key distribution (QKD) and circuit-level reconfiguration in optical networks, where speed is not as critical. Another constraint is the polarization sensitivity of the LC switch: because the device relies on the birefringent contrast between n_e and n_o , it operates on a single linear polarization state (TM). Unpolarized or mixed-polarization inputs would require polarization management elements such as polarization splitter-rotators at each port, adding to the overall device complexity. Another constraint is the complexity of fabrication. Achieving uniform alignment of LCs throughout the multilayer structure, especially in the vertical direction, is a challenge in terms of both process control and repeatability. Misalignment or non-uniform alignment can lead to increased insertion loss and poor switching performance. In addition, optical

losses at the waveguide transitions (especially between the LC and polymer boundaries) require careful optimization of electrode geometry and alignment layer materials.

Finally, the long-term reliability and thermal stability of LC-based optical components in integrated platforms have yet to be fully explored. Environmental sensitivities such as temperature changes and mechanical stresses can affect device stability over time and need to be addressed by encapsulation and packaging strategies. Despite these challenges, the fundamental concept of voltage-controlled 3D waveguide switching using LCs opens up new design space in photonic integration. We hope that continued efforts in materials engineering, simulation-based optimization, and prototyping will alleviate current limitations and pave the way towards scalable quantum-enabled optical switching solutions.

7. Conclusions and Future Work

In this study, we propose a novel 3D optical switch architecture based on the birefringence of LCs for integration into quantum optical communication systems. By utilizing the large refractive index difference between the normal and abnormal states of LC molecules, the proposed device enables voltage-controlled waveguide formation in both the in-plane and vertical directions (stack direction). This structural innovation paves the way for compact, reconfigurable, and low-power optical switching components that exceed the limits of conventional planar photonic devices.

Simulation results confirm that the device achieves optical confinement in both horizontal and vertical channels, enabling optical routing across different layers. The switching mechanism operates with a simple electrode configuration and requires low driving voltages (~ 5 V). Although the response and relaxation times are on the order of milliseconds, this speed level is sufficient for many quantum communication applications such as quantum key distribution (QKD), where switching speed is not a major limiting factor. Rather, properties such as low insertion loss, node scalability, and compatibility with photonic integration are of higher priority, and the proposed LC 3D switch effectively realizes these properties.

Future work includes optimizing the electrode layout to reduce scattering and propagation losses, improving the LC alignment technique to stabilize device performance, and fabricating and testing physical prototypes. Future work includes extending the switch matrix to larger port counts (e.g., 10×10), evaluating crosstalk and isolation, and integrating the switches with quantum photonic circuits. Ultimately, the LC-based 3D switching platform has the potential to be a key foundation for realizing scalable quantum photonic networks and reconfigurable optical signal processing at the chip scale.

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