Journal of Chemical Engineering & Process Technology

OPEN ACCESS Freely available online

Review Article

Liquid Crystals: Unlocking the Quantum Revolution in Computing

Katarzyna Matczyszyn[1], **Edward Otieno**[2*], **Shakil Kashem**[2], **Nelson Mokaya**[2]

[1]*Department of Chemistry, Wroclaw University of Science and Technology, Wroclaw, Poland;* [2]*Department of Chemistry and Engineering of Materials, Wroclaw University of Science and Technology, Wroclaw, Poland*

ABSTRACT

Quantum computing holds the potential to revolutionize information processing with exponential improvements, driving the need for suitable materials to support quantum qubits and gates. Generally recognized for their electro-optical properties and widespread use in displays, liquid crystals have recently emerged as promising candidates for quantum computing applications.

This review delves into the role of liquid crystals in quantum information processing, starting with an overview of their characteristics, classification, and phase transition mechanisms. It then directs focus to their quantum attributes, their ability to display quantum coherence and entanglement. Finally, it will showcase the validations of quantum phenomena in liquid crystals, highlighting their suitability for use in quantum systems.

Recent advances are discussed, including the development of liquid crystal qubits, quantum gates, and circuits. The review also explores the integration of liquid crystals with quantum photonic devices, emphasizing their role in enhancing quantum communication and information processing. Potential room temperature operation applications such as quantum sensing and quantum cryptocurrency are illustrated through case studies.

Challenges such as material synthesis, decoherence, stability, and compatibility with existing technologies are addressed, with proposed solutions including hybrid systems and novel fabrication techniques. Future research directions focus on innovative liquid crystal materials, interdisciplinary collaboration, and their use in emerging quantum technologies.

Keywords: Quantum computing; Liquid crystals; Quantum coherence; Quantum photonic device

INTRODUCTION

Quantum computing is poised to revolutionize technology by addressing complex problems that are beyond the capabilities of classical computers. Unlike traditional computers, which use bits to represent information, quantum computers use qubits. Qubits can exist in multiple states simultaneously through the principles of superposition and entanglement, enabling quantum computers to perform certain calculations exponentially faster than classical systems. This represents a fundamentally new aspect of computing, with significant potential to transform fields such as cryptography, optimization, machine learning, and simulations by tackling challenges that were previously considered intractable [1].

Liquid crystals, traditionally known for their role in display technologies, have recently gained attention for their potential applications in quantum computing [2]. Their unique electro-optical properties make them ideal for manipulating photons—a critical component in quantum systems [3,4].

Specifically, liquid crystals are effective in managing the polarization states of photons, which is essential for the operation of optical quantum gates. These gates perform operations on qubits, a fundamental process in quantum computing [5]. Moreover, liquid crystals can adjust phases at very low photon levels, helping to preserve the fragile quantum states of qubits while minimizing interference and decoherence-challenges that current quantum computing technologies often face [6,7].

Another advantage of liquid crystals in quantum computing is their ability to integrate seamlessly with existing computing materials and substrates. This integration not only reduces costs but also opens the door to developing powerful quantum computing devices, as demonstrated in various experimental setups. The potential

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Correspondence to: Edward Otieno, Department of Chemistry and Engineering of Materials, Wroclaw University of Science and Technology, Wroclaw, Poland, E-mail: otienoedwardotieno82@gmail.com

Received: 16-Sep-2024, Manuscript No. JCEPT-24-34081; **Editor assigned:** 19-Sep-2024, PreQC No. JCEPT-24-34081 (PQ); **Reviewed:** 04-Oct-2024, QC No. JCEPT-24-34081; **Revised:** 11-Oct-2024, Manuscript No. JCEPT-24-34081 (R); **Published:** 18-Oct-2024, DOI: 10.35248/2157-7048.24.15.517

Citation: Matczyszyn K, Otieno E, Kashem S, Mokaya N (2024). Liquid Crystals: Unlocking the Quantum Revolution in Computing. J Chem Eng Process Technol. 15:517.

to combine different types of liquid crystal molecules with other materials offers promising avenues for future commercialization and expansion of quantum computing technology [5-7].

Fundamental properties of liquid crystals for quantum computing

Liquid crystals are a unique state of matter that exhibit properties of both solids and liquids. This dual nature allows them to have an ordered molecular arrangement like a crystal while maintaining the fluidity of a liquid. This combination makes them highly responsive to external stimuli, such as electric and magnetic fields, enabling changes in their molecular orientation [8]. These responsive characteristics are important in quantum computing, where precise control over quantum states is essential.

Phases of liquid crystals

Liquid crystals can be classified into different phases based on their molecular organization and properties, each offering distinct advantages for quantum computing applications:

Nematic phase: Molecules are oriented in parallel but lack positional order. This phase is highly responsive to electrical and magnetic fields, making it ideal for precise control in quantum devices as shown in Figure 1a [9-11].

Smectic phase: Molecules are arranged in parallel layers. The layered structure enhances stability and is important for maintaining quantum coherence, a key requirement in quantum computing as shown in Figure 1b.

Chiral (cholesteric) phase: Molecules exhibit a helical structure without positional order. This phase is characterized by its ability to reflect circularly polarized light, which is useful for specific quantum applications where control over light polarization is required as shown in Figure 1c [9].

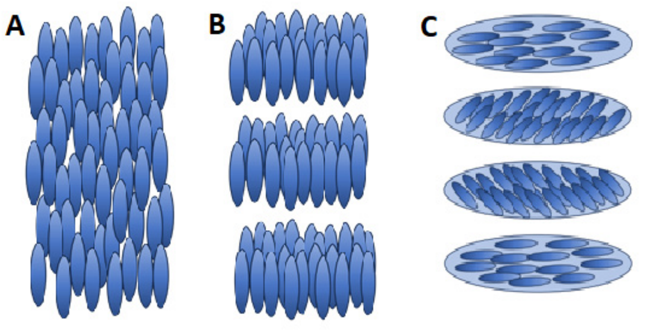

Figure 1: Phases of liquid crystal. **Note:** A): Nematic phase; B): Smectic phase; C): Cholesteric phase.

Blue phase: Exhibits a three-dimensional cubic structure with helical orientation. It responds rapidly to applied electric fields and can form Photonic Bandgaps (PBGs), making it highly suitable for fast and efficient quantum information processing [8,9,11].

Physical and chemical properties

Liquid crystals are characterized by their anisotropy, meaning their physical properties vary depending on the direction in which they are measured [10,12,13]. This anisotropy stems from the unique molecular structures of liquid crystals, typically rod-like or discotic shapes, and the regular packing of these molecules in space [9,10]. The most notable forms of anisotropy in liquid crystals that are particularly relevant to quantum computing include:

Electrical anisotropy: Liquid crystals exhibit different electrical properties depending on the direction in which an electric field is applied. This anisotropy enables liquid crystals to modulate light propagation, a feature critical for display technologies and increasingly important in quantum computing applications. Precise control over light is necessary for operations such as quantum gating and qubit manipulation. The ability to modulate light through electrical anisotropy in liquid crystals has been explored extensively, highlighting its importance in both photonic devices and emerging quantum technologies [9,10,14]

Optical anisotropy: This property affects how light interacts with liquid crystals, often resulting in phenomena such as birefringence. Birefringence, where a single light wave splits into two separate rays, is important in optical switches and modulators, which are essential components for controlling the flow of quantum information in photonic quantum computers. The ability of liquid crystals to exhibit strong optical anisotropy has been leveraged in various photonic devices, making them indispensable in developing advanced quantum computing technologies [9,10].

Magnetic anisotropy: Influences how liquid crystals react to magnetic fields, a feature that can be utilized in quantum computing applications. Liquid crystals' capability to display magnetic anisotropy enables accurate management of quantum states *via* magnetic field adjustments—an asset in quantum information processing and storage scenarios. Researchers have explored this property to improve the reliability and consistency of qubits in sensitive quantum systems [14-16].

Other significant properties of liquid crystals include viscosity and elasticity, which are also direction-dependent, as well as thermal properties that influence phase transitions. These properties are critical in determining the stability and responsiveness of liquid crystals in various applications, including quantum computing [14,17].

Liquid crystals are valued for their feature in quantum computing. They can alter their optical properties when exposed to electric fields. This fascinating electro-optical trait enables the manipulation of light polarization and phase states critical for running quantum gates and various optical parts within quantum computers [1,9,11].

LITERATURE REVIEW

Quantum attributes of liquid crystals

Quantum computing explores the unique quantum properties found in liquid crystals, which plays an important role in manipulating the quantum states of photons, often acting as qubits. Liquid crystals are particularly notable for their anisotropic qualities and their responsiveness to external influences such as electric and magnetic fields. These attributes enable precise quantum functions, including the preparation, manipulation, and measurement of quantum states, with exceptional accuracy and minimal energy consumption. These properties make liquid crystals an exciting material for advancing quantum technologies [9,11].

Twisted Nematic Liquid Crystals (TNLCs) have demonstrated significant potential in quantum applications, particularly in their ability to control the phase and polarization of light within quantum systems. TN-LCs have proven their effectiveness in setups like the Mach-Zehnder interferometer, where they can modulate light with minimal energy input. This efficiency and precision make them strong contenders for furthering the capabilities of quantum computing technologies [9,11].

Additionally, other intriguing phases of liquid crystals, such as ferroelectric liquid crystals, particularly the Smectic C phase* are also of great interest. The Smectic C* phase offers key characteristics like bistability and rapid switching times, which are essential for ensuring qubit stability and coherence. These properties make ferroelectric liquid crystals highly suitable for the development of quantum gates [11].

Moreover, the emerging class of Ferroelectric Nematic Liquid Crystals (FNLCs) holds exciting potential for improving fault tolerance in quantum systems, enhancing coherence times, and enabling the efficient generation of entangled photon pairs. These advancements position liquid crystals as pivotal materials in the ongoing development of quantum computing, offering the potential for enhanced performance and scalability [15].

Superposition in liquid crystals: Superposition refers to a fundamental principle of quantum mechanics, where a quantum system, such as a qubit, can exist in multiple states simultaneously rather than being limited to just one state at a time. In the context of quantum computing, this means that a qubit can represent both 0 and 1 at the same time, allowing quantum computers to process vast amounts of information more efficiently than classical systems, which rely on bits being in either state 0 or 1 [11,15].

Liquid crystals, particularly TN-LCs, support this superposition of quantum states by enabling the precise manipulation of photons. TN-LCs can adjust the polarization of photons-used as qubits-by modifying the orientation of their molecules in response to external electric or magnetic fields. This capability ensures that qubits remain in superposition, allowing for complex quantum operations to be performed with high accuracy and minimal disruption throughout the quantum computing process. By maintaining qubits in a superposition, liquid crystals help unlock the computational power that distinguishes quantum computers from classical ones [11].

Quantum coherence and entanglement in liquid crystals: Quantum coherence refers to the phenomenon in a quantum system where particles exhibit wave-like correlations, maintaining a consistent phase relationship over time and distance. In the context of liquid crystals, quantum coherence can be observed as the ability of molecules to maintain phase connections over extended distances. This type of coherence is imporatant in systems like quantum computers and sensors, where preserving quantum states without decoherence is essential for accurate and reliable operation [16].

Liquid crystals like TN-LC can control the polarization, phase, and rotation of light effectively, which makes them ideal for applications in optical quantum computing. One notable use case is employing TN-LC in a Mach-Zehnder interferometer, a tool that divides a beam into two paths, manipulates them separately, and then merges them to generate interference patterns [18]. In quantum optics, the Mach-Zehnder interferometer is employed to control and measure the interference of quantum light, an important aspect of quantum information processing. Terazawa et al., investigated the use of TN-LCs within a Mach-Zehnder interferometer to perform optical logic operations. They demonstrated that by altering the orientation of the liquid crystals, they could manipulate the polarization and phase of light, thereby controlling the quantum interference patterns and photon counts. These changes were achieved with high precision, highlighting the effectiveness of TN-LCs in modulating light for quantum computing applications [16].

These LC devices are particularly valuable in quantum computing as they facilitate the encoding of quantum bits (qubits) by modifying the polarization state of light. This enables the superposition of 0 and 1 states, which is essential for executing quantum logic operations [16].

Studies have showcased how we can control the polarization of light in pathways using TN-LCs in setups like Mach-Zehnder interferometers [16]. Studies by Terazawa et al., demonstrated alterations in optical interference patterns and photon counts at different levels, highlighting the potential for incorporating LC devices into logic operation elements.

In their experiment, a change in interference pattern was observed when voltage was applied to the TN-LC cell, resulting in fluctuations in photon numbers under weak lighting conditions. At 1 V, there was no interference due to a 90° shift in laser beam polarizations. However, at voltages of 2 V or higher, interference patterns started emerging as the laser beam polarization gradually changed.

The study revealed a ring pattern in the interference image, indicating the interference between two laser beams, with fringe patterns shifting as the voltage increased. Photon counting experiments showed a decrease in photon counts and saturation at 0.77 counts at 5 V, underscoring alterations in interference scenarios with changes in voltage [16].

These findings underscore the effectiveness of TN-LCs in achieving quantum coherence and controlling optical interference states, setting the stage for advancements in quantum information processing.

Controlling the potential to manipulate quantum coherence and entanglement within crystals shows prospects for advancing innovative quantum technologies.

Quantum entanglement refers to the phenomenon where particles, such as photons, become so deeply interconnected that the state of one particle instantaneously influences the state of another, no matter how far apart they are.

This non-local correlation is a fundamental aspect of quantum mechanics, with profound implications for quantum computing, communication, and cryptography in terms of securing information and enhanced processing. In an entangled state, the properties of one particle (like its polarization) are directly linked to the properties of another, meaning that a change in one immediately affects the other, even across vast distances [15,16].

Recent research has explored how liquid crystals, particularly Q-plates, can be used to manipulate and control these entangled states. Q-plates are specialized liquid crystal devices with patterned, non-uniform structures designed to alter the quantum properties of photons. By carefully controlling the patterns within the liquid crystal, Q-plates can manipulate the polarization and Orbital Angular Momentum (OAM) of photons—two key characteristics used in quantum information processing [15].

Q-plates play a role in creating interconnected states in which the polarization and Orbital Angular Momentum (OAM) of photons are closely linked together. The passage of a photon through a plate can lead to entanglement between its polarization and OAM. Any alteration in polarization will cause a corresponding change in OAM and vice *versa*. This connection enables the transfer of quantum information between photon attributes, such as polarization and OAM. This facilitates advanced and resilient methods of quantum communication.

Moreover, Q-plates are also instrumental in quantum cloning, where they are used to duplicate the quantum information encoded in the OAM of qubits. This process is vital for tasks such as quantum key distribution, where securely transmitting information without loss or alteration is important [15].

The ability to create and manipulate such entangled states is demonstrated in several key experiments, showcasing the potential of Q-plates in advancing quantum technologies. These experiments highlight how Q-plates can be used to establish strong entanglement between photons, thereby enabling more sophisticated quantum computing and communication protocols [15,16].

Generation of entangled states: Q-plates are specialized liquid crystal devices designed to manipulate both the polarization and Orbital Angular Momentum (OAM) of photons. These plates are engineered with a patterned structure that imposes a specific phase shift on passing photons, depending on their polarization state. When a photon passes through a Q-plate, the interaction between its polarization and the unique configuration of the Q-plate causes the photon's polarization state to become entangled with its OAM state as shown in Figure 2 [18,19].

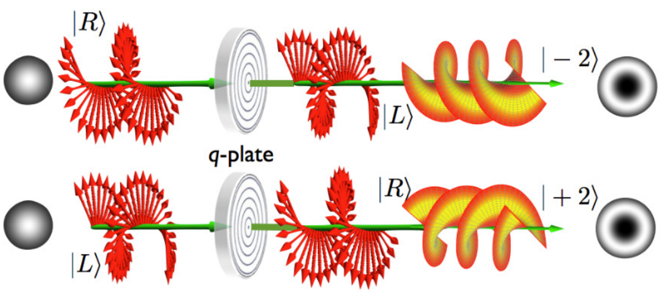

Figure 2: Photon polarization control using a q-plate: The q-plate converts circular polarization states (|R⟩|L⟩) into orbital angular momentum states (± 2), demonstrating liquid crystals' role in manipulating quantum states for quantum computing applications.

For instance, consider a photon that starts in a polarized condition. When this photon passes through the Q-plate, it undergoes a change that links its polarization with its Angular Momentum (OAM). This transformation can lead to the creation of a quantum state where the polarization and OAM become interconnected. In particular, a linearly polarized photon can give rise to the entangled state as described below;

$$|H\rangle \rightarrow 1\sqrt{2}\left(|R,+2\rangle+|L,-2\rangle\right) \ldots. (1)$$

Here, $|H\rangle$ is the horizontal polarization state, $|R\rangle$and $|L\rangle$ are the right and left circular polarization states, and

$|\pm 2\rangle$ denotes the OAM states [18,19].

In a different configuration, when a photon with right ($|R\rangle$) or left ($|L\rangle$) circular polarization passes through the Q-plate, the resulting state can similarly become entangled, such as:

$$|H\rangle|+2\rangle+|V\rangle|-2 \ldots. (2)$$

This means that the photon's polarization state (whether it is right or left circularly polarized) is now directly linked to its OAM state. $\left(|+2\rangle or |-2\rangle\right)$.

Such entangled states are important for a variety of quantum information applications. In quantum computing, for example, these entangled states can serve as qubits where the polarization and OAM jointly encode information. This enables more complex quantum operations and facilitates the encoding, transmission, and processing of quantum information with a high degree of precision. Moreover, these entangled states are foundational for quantum communication protocols, such as quantum teleportation and quantum key distribution, where the integrity and security of the transmitted quantum information rely on the entanglement between different degrees of freedom, such as polarization and OAM [18,19].

Quantum information transfer: Q-plates facilitate the transfer of quantum information between a photon's polarization and its Orbital Angular Momentum (OAM). This capability is important for advancing quantum communication and computation, as it allows the encoding of information across multiple degrees of freedom within a single photon. Such an approach enhances the capacity and flexibility of quantum information systems [19].

When a photon travels through a Q-plate in real-world scenarios, its polarization state gets intertwined with its OAM state, forming an interconnected system where alterations in one aspect (like polarization) immediately impact the other (such as OAM). This interconnection allows for the leveraging of both aspects of encoding information, resulting in the enhancement of the capacity for data transmission and the expansion of the range of tasks achievable in quantum computing setups [19].

Recent experiments have demonstrated that this transfer mechanism can be achieved with high efficiency and fidelity, ensuring that the quantum information remains intact during transmission. This is vital for maintaining the integrity of quantum states over long distances, which is a significant challenge in quantum communication networks. The high fidelity observed in these experiments underscores the reliability of Q-plates in preserving delicate quantum information during processing and transmission, making them indispensable tools for the next generation of quantum technologies as shown in Figure 3 [19].

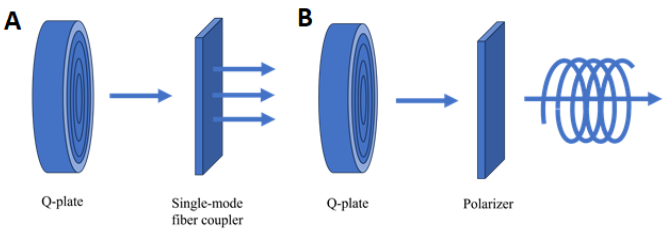

Figure 3: Q-plate configurations for photon state conversion. **Note:** A): OAM to SAM conversion using a single-mode fiber coupler; b): SAM to OAM conversion with a polarizer, demonstrating control over photon spin and orbital angular momentum.

Hong-ou-mandel coalescence: The Hong-Ou-Mandel (HOM) effect is a quintessential demonstration of quantum interference, where two identical photons, when passed through a beam splitter, interfere in such a way that they always exit together through the same output port, effectively "merging" into the same mode. This phenomenon occurs because of the indistinguishable nature of the photons and is a clear manifestation of their quantum properties interference [19].

In recent studies, the HOM effect has been extended to include photons that carry non-zero Orbital Angular Momentum (OAM), revealing even more complex quantum behaviors. By employing photons with non-zero OAM in HOM experiments, researchers have been able to observe how these additional degrees of freedom (like OAM) interact in quantum interference processes. The results from these experiments not only verify the HOM effect with OAM-carrying photons but also emphasize the utility of Q-plates in manipulating and studying these quantum states [19].

Q-plates play a role in quantum optical research by connecting a photon's polarization state with its Orbital Angular Momentum (OAM) as shown in Figure 4. By adjusting the OAM of photons using plates, researchers can delve into the complex dynamics of quantum interference in systems with higher-dimensional Hilbert spaces. This enhances our grasp of quantum mechanics and opens up new possibilities for applications in quantum information processing and communication [19].

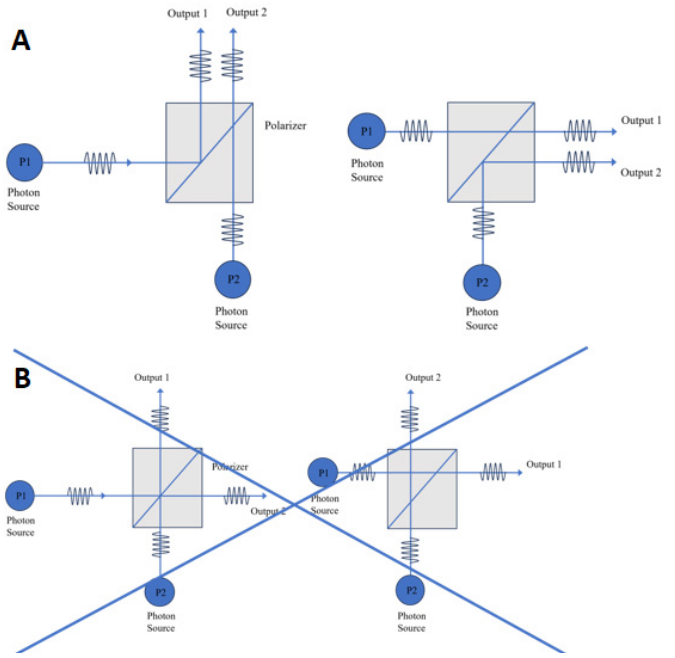

Figure 4: Illustrate the Hong-Ou-Mandel (HOM) effect, a quantum interference phenomenon. When two identical photons from sources P1 and P2 enter a beam splitter simultaneously, they coalesce, emerging together in the same output mode (either Output 1 or Output 2). This results in photon bunching, as shown in (b), where no photons are detected at one of the outputs. The HOM effect is critical for quantum information processing, quantum computing, and entanglement-based experiments.

Moreover, the study illustrated the alterations in the polarization state of two photons when influenced by an electric field. Using polarization tomography, the scientists reconstructed the density matrix of the two-photon states. The study revealed that by adjusting the molecular orientation of FNLC with an applied field, it was possible to change the two-photon polarization state from horizontal to vertical or any point in between [20].

Quantum cloning: Q-plates are employed to enhance the quantum replication of qubits encoded in Orbital Angular Momentum (OAM) states, a process known as quantum cloning. Quantum cloning is important in quantum error correction and communication protocols as it involves copying the information contained in a quantum state into multiple states while preserving the essential quantum properties, such as coherence and entanglement [19].

In the experiments, photons passing through the Q-plates experienced a transformation where their polarization states were converted into OAM states and vice *versa*. This transformation process is vital for quantum operations that require the manipulation of multiple degrees of freedom of photons.

The ability of Q-plates to maintain quantum coherence and entanglement during these transformations ensures that the quantum information encoded in the photons is preserved without degradation [19].

Experimental demonstrations of quantum behaviors in liquid crystals

Recent research has offered compelling evidence for liquid crystals' quantum characteristics, particularly when combined with quantum dots and other nanomaterials. These findings are vital for advancing quantum information technologies like quantum communication and quantum computing. This review delves into some of these experimental demonstrations, which give insights into how liquid crystals exhibit quantum behaviors.

Quantum dot doping in liquid crystal: Recent studies have demonstrated that the incorporation of quantum dots into liquid crystals can lead to significant enhancements in their dielectric properties. Kocakulah et al., conducted a comprehensive study on the effects of doping liquid crystals with quantum dots, specifically examining parameters such as bandgap, transmittance, and dielectric constants [21]. Their research showed that the introduction of Indium Phosphide/Zinc Sulfide (InP/ZnS) quantum dots into liquid crystals results in notable alterations in their dielectric characteristics. These modifications suggest potential for the development of advanced optical systems, where improved dielectric properties are critical for enhancing performance and efficiency [22].

Similarly, Rani et al., investigated the impact of doping liquid crystals with Cadmium Selenide/Zinc Sulfide (CdSe/ZnS) quantum dots, with a focus on ion dynamics within the liquid crystal matrix [23]. This study revealed that the method of doping could significantly influence ion movement, which is a key factor in the behavior of liquid crystals in quantum devices. This alteration in ion movement, induced by the presence of quantum dots, plays an important role in optimizing the performance of quantum devices, making it an important consideration in the design and development of next-generation quantum technologies [22].

Topological solitons and knots: Topological solitons and knots have been experimentally seen in soft condensed matter systems like liquid crystals and colloids. These structures, which include skyrmions, hopfions, and torons, are stable within the liquid crystal matrix, allowing for precise experimental characterization and manipulation with tools such as laser tweezers and structured light fields [14,24].

Skyrmions are vortex-like structures characterized by a swirling configuration of the liquid crystal molecules, while hopfions and torons are more complex, with the former featuring knotted field lines and the latter involving twisted configurations within a toroidal topology. The stability of these topological solitons within liquid crystal matrices is particularly noteworthy, as it allows for their precise characterization and manipulation in experimental settings. Tools such as laser tweezers and structured light fields have been effectively employed to manipulate these structures, enabling researchers to probe their properties with high precision [24].

The behavior of these topological features often mirrors quantum phenomena despite being observed in classical systems. For instance, their stability and interactions are reminiscent of the behavior of quantum particles, making these structures valuable for exploring and testing concepts from quantum field theories within a controlled laboratory environment. This analogy is particularly useful for experimental investigations that connects classical and quantum systems, providing insights into the underlying principles of quantum mechanics through the lens of classical topological structures [24].

Furthermore, the ability to experimentally manipulate and control topological solitons and knots opens up new avenues for research in soft condensed matter physics. The robustness of these structures against perturbations, combined with their complex and stable configurations, makes them potential prospects for applications in advanced material science and quantum information technologies. As such, their study not only contributes to a deeper understanding of topological phenomena in physical systems but also holds potential for practical applications in emerging quantum technologies [24,25].

Quantum fluctuations, nematic phases: Experiments on the nematic phases of liquid crystals have uncovered quantum fluctuations that significantly influence the order parameters of these systems. These fluctuations plays an important role in understanding the phase transitions and critical phenomena in liquid crystals, which exhibit characteristics similar to those observed in quantum critical systems. By investigating these quantum effects, researchers have been able to draw parallels between the behavior of liquid crystals and that of quantum materials near critical points [24,25].

Neutron scattering and advanced spectroscopic techniques have been instrumental in probing these quantum fluctuations. Neutron scattering, in particular, has provided detailed information about the atomic-scale interactions within the liquid crystal matrix, revealing how quantum fluctuations disrupt and modify the long-range order of the nematic phase. Similarly, sophisticated spectroscopy has allowed for the examination of how these quantum effects interplay with thermal fluctuations, influencing the macroscopic properties of liquid crystals [24,25].

These experimental approaches have offered valuable insights into the complex interaction between thermal and quantum fluctuations, deepening our understanding of the fundamental processes that govern phase behavior in liquid crystals. By drawing connections to quantum critical systems, these experiments not only enhance our knowledge of liquid crystal physics but also contribute to broader discussions on critical phenomena in condensed matter systems. The findings underscore the importance of quantum effects in determining the stability and dynamics of ordered phases in liquid crystals, opening new avenues for exploring quantum phenomena in soft matter [25].

Light-matter interaction and quantum optics: The interaction of light, with liquid crystals has made opportunities for exploring quantum optics effects. The unique properties of liquid crystals, such as birefringence, allow for the creation of light patterns that can be used to explore concepts like quantum entanglement and coherence. Recent studies have successfully demonstrated the generation and control of photons using devices based on liquid crystals. This evidence underscores the role of liquid crystals in applications related to quantum communication and information processing [16,18,24,26,27].

Quantum interference and liquid crystal device: Quantum interference effects have been observed in devices like Polarization Beam Splitters (PBS) and Photonic Crystal Fibers (PCF) using liquid crystals. The unique properties of LCs enhance birefringence, which is essential for splitting or combining quantum light states. Developing core crystal fibers (PS DC PCF PBS) filled with nematic liquid crystals has led to the creation of extremely short splitting lengths and wide bandwidths, making them beneficial for quantum communication systems [25].

Other experimental demonstrations include the preservation of quantum coherence in a liquid crystal medium and manipulating quantum entanglement. Researchers can manipulate and analyze entangled states by embedding quantum dots or other quantum systems within a liquid crystal matrix, making use of the anisotropic features of LCs. This technique uses liquid crystals' tunability to dynamically modify entanglement properties, resulting in a versatile platform for quantum information processing. Furthermore, the structured structure of liquid crystals determines the coherence of quantum states, allowing for greater control over light propagation and polarization. This management is critical for preserving quantum coherence across more considerable distances than traditional mediums [18,28].

Advances in liquid crystal-based quantum devices

Liquid crystal qubits present benefits in quantum computing systems compared to other types of qubits. By utilizing the adaptability and adjustability of liquid crystals, it becomes possible to accurately control quantum states and perform intricate quantum computations. Additionally, liquid crystal qubits have the potential to offer a cost-efficient solution for quantum computing since these materials can be easily incorporated into semiconductor fabrication methods [7,29].

Recent research has highlighted the viability of liquid crystal qubits. Researchers have explored using liquid crystal materials to encode and manipulate quantum information, utilizing their unique properties to achieve coherent control and efficient readout of quantum states [30]. Furthermore, researchers have explored incorporating liquid crystal qubits into superconducting networks, showcasing the possibilities for integrating quantum technology on a scale [31].

Liquid crystal devices have shown promise for quantum computing applications, such as linear optical quantum computing. These devices are specifically designed to effectively regulate the polarization of laser light, which is essential for quantum information processing. LC devices feature four distinct operating points to control photon polarization, making them suitable for quantum computing [7].

The LC material LIXON5049XX, along with the chiral agent C 15, offers stability, allowing for the control of tuning properties in

LC devices. Building LC devices with accurate and consistent cell thickness is important in maintaining performance in quantum computing applications [7].

To ensure optimal conditions for quantum operations, voltage-transmittance characteristics are measured to evaluate the qualities of LC cells. LC devices boast simpler structures and lower operating voltages than other optical devices, making them appealing for quantum computing applications. The successful implementation of LC devices in several optical quantum studies highlights their adaptability and potential for quantum information processing [7,32].

Quantum gates and circuits using liquid crystals: Recent developments in Liquid crystal technology have opened up possibilities for quantum computing, especially in the realm of building quantum gates and circuits. Nematic Liquid Crystals (NLCs), known for their rod-like molecular structure and capacity to create topological defects, have shown potential in quantum computing. These defects can be accurately altered using external electric fields, allowing for developing and controlling nematic bits (nbits) that work similarly to classical and quantum bits. Kos et al., established the notion of nbits by mapping LC defects onto the Poincare-Bloch sphere, illustrating how single nbit operations similar to Pauli and Hadamard gates can be accomplished using electric fields [33].

The capacity to manipulate Liquid crystals defects with electric fields enables the creation of fundamental quantum gates. Manipulating the direction of the nematic director field allows for single-qubit gates such as the Pauli-X, Pauli-Y, and Hadamard gates. Furthermore, multi-nbit designs have been demonstrated to implement universal classical logic gates such as NOR and NAND, as well as more complicated continuous logic functions [33].

Kos et al., research demonstrated that nbit states can be manipulated along paths on the poincare bloch sphere using electric field techniques. This capability is important for developing quantum circuits that demand the management of qubit states and their interactions [33].

Various forms of quantum gates have been created with crystals by leveraging their birefringence. These gates consist of the Pauli X, Y, and Z gates for quantum computing. To achieve the targeted phase adjustment or polarization modification, LC molecules are typically aligned in a manner [33].

One prominent example is the tristate Pauli gate, which employs liquid crystals to encode information in three states rather than the typical two. This boosted encoding is accomplished *via* wavelength encoding techniques, in which the states of the signals are determined by their wavelength. This method overcomes the constraints of phase encoding, which is susceptible to disturbances that might alter the phase and, hence, the information [34].

Finite Difference Time Domain (FDTD) methods are commonly employed to replicate circuit performance. Through simulations, it is demonstrated that these circuits can handle signals concurrently with loss and rapid response times. As an illustration, the integrated tristate Pauli Y gate circuit is designed to execute four operations representing the gate matrices Y1, Y2, Y3, and Y4. Each output exhibits phase shifts as necessitated by quantum algorithms [32].

Incorporating quantum gates into circuits is important in building quantum computing systems. Scientists have managed to design and model circuits that utilize state Pauli X, Y, and Z gates made from liquid crystal. These circuits are built using two crystals, offering a streamlined and effective medium for transmitting signals [34,35].

Finite Difference Time Domain (FDTD) methods are frequently employed to replicate circuit functioning. The simulations indicate that these circuits can handle signals simultaneously with loss and quick response times. For instance, the integrated tristate Pauli Y gate circuit is structured to execute four operations linked to the gate matrices Y1, Y2, Y3, and Y4. Each output showcases a unique phase shift in line with the needs of quantum algorithms [32,34,35].

Tunable optical properties of liquid crystals in quantum photonic devices

Recently, there has been growing interest in using Liquid crystals in quantum photonic devices, especially as Single-Photon Sources (SPS) for quantum communication and computing applications. Though liquid crystals are not classical quantum systems, they possess unique tunable optical properties, making them valuable in quantum technologies [19,29].

Liquid crystals can modulate optical characteristics through molecule orientation or the application of external fields such as electric fields. This enables dynamic control over the polarization state of photon pairs, a critical feature for quantum devices.

The alignment of LC molecules allows for precise tunability of two-photon quantum states, making them useful for creating quantum systems with pixel-wise adjustable optical characteristics. This reconfigurability is vital for photon-pair production with desired polarization and spectral properties, facilitating the fine-tuning of quantum devices for specific tasks [10,12].

One of the significant breakthroughs in the field was demonstrated by Sultanov et al., who identified Spontaneous Parametric Down-Conversion (SPDC) in FNLCs, specifically in DIO-BF2 (4-(1-(4-dodecyloxybenzoyloxy)benzoyloxy)-2-(3,5-difluorobenzoyloxy)-1,3,5,6,7,8-hexahydro-2H-benzo[f]chromen-2-yl), marking the first observation of this phenomenon in such materials [11]. This discovery showcases the potential of FNLCs for generating entangled photon pairs with tunability that rivals traditional nonlinear crystals. By adjusting the electric field, researchers can instantly modify the optical properties and polarization of photon pairs, enhancing the flexibility of quantum systems [20].

The ability to tune optical properties in real time, combined with the ability to generate broadband photon pairs with uniform distribution, suggests that FNLCs have great potential as quantum light sources. This adaptability offers significant advantages in quantum communication, quantum sensors, and information processing, where precise control of photon characteristics is critical for device performance and security [20].

Integration of quantum dots with liquid crystals for enhanced quantum systems

Integrating Liquid crystals with quantum dots opens up new possibilities in quantum photonic devices, enhancing optical properties and enabling unique quantum phenomena such as coherence and spin-dependent effects. Quantum dots, which are semiconductor nanocrystals, exhibit discrete energy levels and tunable optical characteristics depending on their size. When combined with liquid crystals, these systems gain the adjustability of LCs and the quantum traits of QDs, making them ideal for generating single photons and Circularly Polarized Luminescence (CPL) [15,36].

One notable application is the creation of color-changing circularly polarized light effects by doping Blue-Phase Liquid Crystal Elastomers (BPLCEs) with quantum dots. This setup enhances luminescence dissymmetry and creates CPL signals independent of PBGs, making it suitable for high-sensitivity tasks like anti-counterfeiting [36,37].

In addition, liquid crystal polymers, which respond to stimuli such as temperature, pH, and electric fields, provide further opportunities for developing quantum materials with adaptive behaviors. This responsiveness could be useful for creating tunable quantum systems capable of handling complex tasks in quantum communication, optical storage, and quantum key distribution. Continued exploration of quantum dotes-doped liquid crystal films and their optical characteristics is expected to lead to significant advancements in hybrid quantum systems, particularly in the areas of quantum encryption and secure communication [15,36,37].

Liquid crystals in PBG materials for quantum devices

PBG materials, which control the propagation of light within specific wavelength ranges, have gained prominence in quantum photonics due to their ability to guide and manipulate photons. Liquid crystals are increasingly being integrated into PBG materials for use in quantum communication systems, photonic circuits, and quantum information processing [26,27].

Liquid crystals' anisotropy and reconfigurable optical properties make them ideal for developing PBG structures capable of dynamic light control. By adjusting the LC's molecular orientation using electric fields, the PBG can be fine-tuned in real time, which is critical for creating adaptable quantum devices. This feature allows for the precise control of photon flow, which is essential for quantum circuits and signal processing as shown in Figure 5 [26].

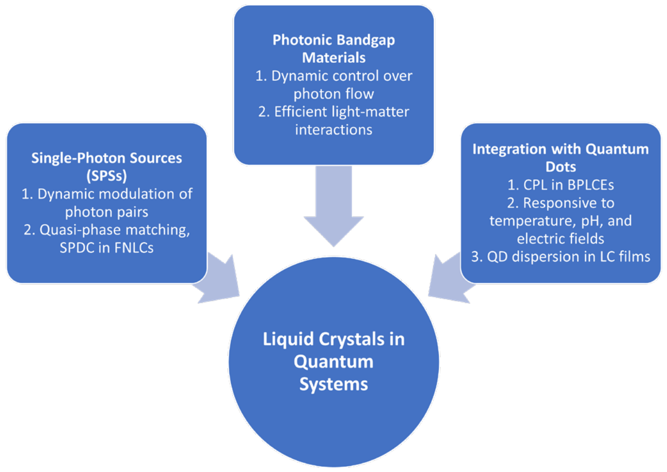

Figure 5: Pictorial illustration of liquid crystals in quantum systems with detailed features.

One major application of liquid crystals in PBG materials is their integration into photonic circuits for quantum communication. In these circuits, LCs help manipulate the polarization and phase of light, enabling the creation of dynamic electromodulators that adjust photon states for secure communication and efficient data transmission. Such functionality is important for the success of quantum key distribution systems, where secure and flexible photon transmission is paramount [27,38].

Moreover, the ability to precisely control photon routing and entanglement distribution using LCs within PBG structures enhances the potential for scalable quantum information processing systems. Despite the challenges associated with manufacturing LC-based quantum systems, advancements in integrating LCs with photonic materials are expected to reduce costs and improve the sustainability of quantum devices [26,27].

DISCUSSION

Technical challenges in material synthesis and device fabrication for liquid crystal-based quantum computing

The development of liquid crystal-based quantum computing systems faces several technological obstacles in material synthesis and fabrication. First, the physical aspect involved in these systems proves to be a tough technological nut to crack and would require a deep insight into quantum mechanics and materials science to completely explain. Significant progress has been made in several physical implementations of quantum computing, but a true breakthrough has yet to be realized in any one approach.

Designing a system that can effectively shield itself from influences while remaining manageable for executing logical quantum operations and facilitating measurements poses a major obstacle [39,40]. Quantum computing requires storing quantum information in a set of two-level systems, processing this information using quantum gates, and a means of final readout. Technologies based on quantum optical and solid-state systems are among the most advanced candidates. However, accurate quantum control of the coherent evolution is necessary to implement gate operations while avoiding decoherence [41].

The strict standards require the development of materials and tools used in crystal-based quantum computing. Advancements in superconducting materials, van der Wals materials, and moire quantum matter provide faith for various quantum technologies, including quantum computing [42]. Combining crystals with materials employed in quantum computing systems poses challenges [43]. This involves ensuring compatibility to avoid disruptions in the characteristics of liquid crystals. Establishing an interface between liquid crystals and substrates, like silicon or graphene, requires innovative manufacturing techniques and thorough material analysis [44,43].

Another challenge is preserving the uniformity of liquid crystal phases under changing external circumstances, such as temperature and pressure. The purity of the starting ingredients and the presence of contaminants can significantly affect the performance and dependability of the liquid crystals, complicating the synthesis process [44].

On the other side, fabricating devices that use liquid crystals for quantum computing involves numerous technical challenges. One major challenge is the perfect alignment of liquid crystal molecules, which is critical for peak device performance. Traditional approaches, such as rubbing or photo alignment, have limitations in scalability and homogeneity, often resulting in flaws that might reduce device efficiency [28,41,45,46].

Furthermore, integrating liquid crystal materials into current quantum computing architecture, such as superconducting qubits or photonic circuits, necessitates sophisticated fabrication procedures. It is challenging to ensure the stability of liquid crystals within these devices, mainly when operating under low temperatures and electromagnetic fields [40].

The fabrication process must, additionally, include liquid crystal encapsulation to prevent contamination and degradation over time. This encapsulation entails creating strong encapsulation materials and processes that do not interfere with the liquid crystal's optical and electrical capabilities [45].

Scaling up the fabrication process for mass production while maintaining device quality and performance remains a significant challenge. Each stage of the fabrication process, from material deposition to patterning and assembly, must be precisely optimized to achieve reproducibility and high yields [42,45].

To tackle these challenges, researchers need to collaborate across fields such as materials science, chemistry, physics, and engineering. Progress in nanofabrication techniques, comprehension of liquid crystal behaviors at a quantum scale, and creative synthesis approaches will play key roles in surmounting these obstacles. The continuous effort for innovation and teamwork across disciplines is anticipated to speed up the advancement of quantum computing technology based on liquid crystals.

Potential for room-temperature quantum operations using liquid crystal-based quantum computing

Quantum computing has been the focus of much research, and several systems are being investigated as potential platforms for scalable and fault-tolerant quantum information processing. One interesting approach is the use of trapped ions, which have shown outstanding control and coherence, as well as the ability to grow into more extensive systems [47].

Nevertheless, achieving low temperatures has been a significant obstacle in the advancement of practical quantum computing. The demand for cooling systems adds layers of intricacy and expense, limiting the reach and expansion potential of these technologies. In response, scientists have explored approaches like leveraging liquid crystals capable of executing quantum functions at ambient room temperatures [20,47,48].

Liquid crystals are a unique class of materials with characteristics that fall somewhere between solids and liquids [10]. Their unique qualities, such as their capacity to maintain long-range order and coherence at ambient temperature, make them an appealing choice for quantum computing. Recent research has shown that liquid crystals can store and control quantum information, bringing up new possibilities for the creation of practical quantum computers [47].

Using crystals for quantum computing offers a benefit in attaining high performance at room temperature. In contrast to trapped ion setups that need cooling, quantum computers based on crystals can operate at regular room temperatures, reducing system complexity and cost [47].

This review also searches into liquid crystals that can act as robust single-photon sources. Specifically, cholesteric liquid crystals doped with dye molecules like terylene have shown promise for room-temperature quantum processes. These systems take advantage of the PBG features of cholesteric liquid crystals, which can improve the emission properties of the dye molecules, resulting in more efficient single-photon generation [16,25].

These sources that emit photons are currently being worked on to make them efficient, lasting, and pure in polarization. The improvements focus on selecting dye molecules and liquid crystal materials as well as refining PBG structures to match the fluorescence bands of the dyes [49]. For instance, positioning dye molecules to boost excitation efficiency and adjusting the band gap microcavities have been identified as methods for enhancing performance.

Moreover, attention has shifted to quantum crystals, which represent a state of matter where electrons act like molecules in liquid crystals-they flow freely but maintain a preferred direction. This property is beneficial for quantum computing as it helps maintain quantum coherence and enables the flow of quantum information at room temperature. The discovery of quantum crystals holds promise for ultrafast quantum computers [28,30,50].

Liquid crystals can also be utilized in cavity systems that operate within the realm of quantum mechanics at room temperature. These systems manipulate quantum states by interacting oscillators with cavities. Combining quality oscillators made from materials like silicon nitride with liquid crystals can achieve low thermal noise and high thermal conductance–both important for controlling quantum effects and minimizing photothermal impacts [15,44,51].

The successful advancement of room-temperature quantum processes using liquid crystal-based systems could open doors to widespread and workable quantum computing technology. Ongoing studies in this field aim to enhance our understanding of processes at elevated temperatures and investigate quantum phenomena, potentially leading to significant progress in quantum science and technology.

Researchers are moving towards creating effective room-temperature quantum systems by leveraging the characteristics of liquid crystals and innovative optomechanical designs. This development holds potential for the future of quantum computing, making it more accessible and adaptable across technologies.

Case studies and applications of liquid crystals in room-temperature quantum computing

The search for practical and scalable quantum computing has prompted extensive study on materials and systems that can work at ambient temperature. Liquid crystals, with their unique electro-optical capabilities, have emerged as attractive prospects in this field [30,52].

PBG materials with liquid crystals: Cholesteric liquid crystals, when combined with quantum dots, create PBG materials that exhibit enhanced emission efficiency. The helical structure of CLCs interacts with quantum dots, which are semiconductor nanoparticles that can emit photons. This combination allows the system to operate at room temperature, which is essential for practical quantum communication and cryptography applications [53].

At the University of Central Florida, scientists developed these materials by embedding quantum dots into cholesteric liquid crystal hosts. The CLCs' natural ability to selectively reflect light enhances the performance of the quantum dots, enabling them to emit single photons more efficiently and in a controlled manner. This emission of single photons is important for quantum cryptography, where photons are used as carriers of quantum information [53].

By tuning the helical pitch of the CLCs, the system can be optimized for different wavelengths of light, making it versatile for various quantum applications. The synergy between the cholesteric liquid crystals and quantum dots represents a significant advancement in developing room-temperature photon emitters for quantum technologies.

Nematic Quantum Hall Liquid (NQHL): NQHL is a phase of matter where quantum fluids display properties in different directions. These states hold potential in the field of quantum computing due to their ability to maintain coherence at room temperature and showcase novel electrical characteristics. This section delves into case studies and applications of NQHLs within quantum computing [54].

Scientists discovered nematic quantum hall states on the surface of Bismuth (Bi(111)). This research revealed that electronic states on bismuth's surface exhibit order under magnetic fields, leading to the breaking of rotational symmetry. Utilizing scanning tunneling microscopy, this study demonstrated the capacity of NQHLs to preserve quantum states, which is important for advancements in quantum computing [54].

Another notable work looked into the production of nematic quantum hall fluids, which lack the usual stripe patterns found in some quantum hall systems. This study revealed that nematic order might be created by electrical interactions in specific quantum hall regimes, thereby providing a new method for manipulating quantum states without the requirement for elaborately patterned substrates [53-55].

Applications

Development of robust qubits: Qubits, also known as quantum bits, are the fundamental units of quantum information. Similar to bits in classical computing, qubits can exist in superpositions of states. Qubits' resilience refers to their capacity to retain coherence and prevent decoherence for lengthy durations [33]. Because of their quantum coherence, these quantum liquid crystals become excellent candidates for generating resilient qubits. These qubits are important for creating scalable quantum computers operating efficiently without cryogenic cooling [33,47].

The development of qubits is important for the advancement of quantum computing. As discussed earlier in this review, advancements in crystal-based technologies and other materials are opening doors to achieving quantum coherence at room temperature and enabling quantum applications [47,56]. Ongoing studies in this area offer hope for overcoming limitations and making quantum computing more accessible for use [56-58].

Quantum information processing: Liquid crystals can be used in cavity optomechanical systems, where they interact with- mechanical oscillators and optical cavities to regulate quantum states. These interactions are possible at average temperatures, reducing the complexity and cost of typical quantum computing systems that require cryogenic conditions [44,56,59]. This application is especially useful for constructing scalable quantum information processing systems.

Quantum sensing: Quantum sensing involves applying the principles of quantum mechanics to leverage quantum states and entanglement for sensitive measurements. Liquid crystals, renowned for their electro characteristics, show great promise in quantum sensing applications, particularly under normal room conditions. Their distinctive features make them ideal for quantum sensors that find utility in fields like healthcare diagnostics, environmental surveillance, and industrial control systems demanding pinpoint accuracy [43,59].

Quantum communications and cryptocurrency: Liquid crystals could contain dye molecules and quantum dots that serve as single photon emitters. These emitters play a role in ensuring secure quantum communication channels and cryptography by enabling information transfer through quantum mechanics principles. By incorporating these emitters into structures made of crystals, their performance and reliability are enhanced even at room temperature [27,41].

Integrating liquid crystals into quantum computing systems operating at room temperature offers advantages, including effective photon control, strong quantum coherence, and simplified experimental processes. The practical examples and uses outlined in this context demonstrate the impact that liquid crystals can have on advancing quantum computing and related fields as shown in Figure 6. Ongoing exploration and advancements in this area are expected to enhance the accessibility and scalability of quantum technology [15,30,37].

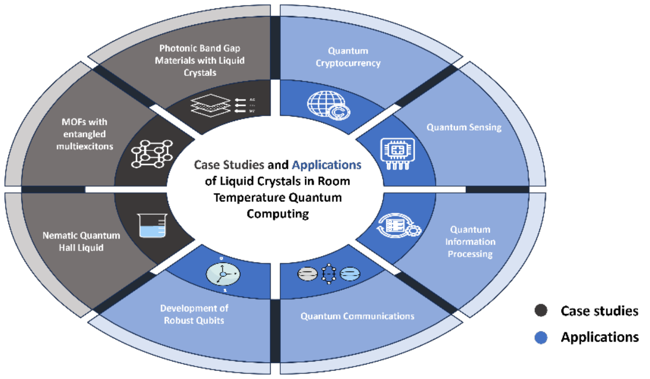

Figure 6: Case studies and applications of liquid crystals in room-temperature quantum computing.

The future outlook of liquid crystal-based quantum computing: Addressing gaps and exploring new horizons

Quantum computing has emerged as a transformational technology with the potential to alter industries ranging from data encryption to drug development. Exploring liquid crystal-based systems, which can potentially improve the scalability and performance of quantum devices, is a potential field of quantum computing research [28,52,60].

Realizing practical, scalable quantum devices requires overcoming challenges related to qubit stability, error rates, and integration with classical computing systems. In this context, Liquid crystals have emerged as a potential material platform for addressing some of these challenges. Liquid crystals, with their tunable optical, electrical, and mechanical properties, offer significant potential in enhancing the performance and scalability of quantum devices. Despite the progress, several gaps remain in the research, presenting opportunities for future exploration, particularly through interdisciplinary collaboration [28,60,61].

Enhanced quantum coherence and entanglement: One of the most significant challenges in quantum computing is maintaining quantum coherence and facilitating entanglement over long periods and distances. Liquid crystals, with their ability to modulate the polarization of light, have shown promise in supporting quantum coherence. However, research so far has largely focused on the optical properties of LCs in isolation, and there is a need for more studies on how these materials can stabilize qubit coherence in practical quantum computing systems [62-66]. Additionally, while LCs can support entanglement, integrating this capability into more complex quantum gate operations or error-correcting qubit structures remains underexplored [16,67,68].

Integration with quantum dots and PBG materials: Recent advances have shown that combining liquid crystals with quantum dots and PBG materials could enable the creation of programmable quantum systems with tunable optical properties. However, existing studies tend to focus on proof-of-concept demonstrations, often in simplified or controlled laboratory environments. Real-world quantum computing applications will require systems that are more scalable, efficient, and capable of operating under diverse conditions [15,36,56,69].

Applications in quantum communication and photonic circuits: Liquid crystals have demonstrated their potential to significantly enhance quantum communication and photonic circuits by modulating photon flow and enabling dynamic control of optical properties. However, while several studies highlight LCs' role in these areas, there is a gap in translating these properties into fully integrated quantum systems that can be mass-produced and deployed in practical quantum communication networks or photonic chips [40,70].

Future research directions

Interdisciplinary collaboration between materials science, quantum optics, and computational modeling is important for advancing liquid crystal-based quantum computing. By investigating the interactions between LCs and qubits across different scales, especially at cryogenic temperatures where quantum coherence is more stable, researchers can unlock new possibilities in quantum coherence and error correction [71,72]. Exploring new LC materials, such as topological liquid crystals and metamaterials, offers the potential for enhancing qubit interactions and improving quantum gate fidelity. Additionally, developing fault-tolerant architectures using LC-based systems could lead to more robust quantum computing platforms, incorporating effective quantum error correction methods to mitigate errors and increase system reliability [40,45,73].

Future research in quantum networking should focus on developing liquid crystal-based quantum communication systems that are scalable and can be integrated seamlessly with quantum key distribution technologies. LC-based tunable photonic circuits offer the potential to dynamically control photon properties, enhancing the efficiency and security of quantum communication systems and making them more resistant to external threats. Additionally, the development of integrated quantum photonic chips that leverage the reconfigurability of LCs represents an important research direction [74]. This effort would benefit from interdisciplinary collaboration with nanotechnology and photonics experts to optimize LC materials for waveguides, modulators, and photon routers at a chip-scale level. However, a significant challenge remains in the manufacturing scalability of LC-based quantum devices. Addressing this gap requires a focused effort on creating low-cost manufacturing processes and chip designs that can be easily fabricated and deployed in extensive quantum networks [75].

Optimizing hybrid Liquid Crystal-Quantum Dot (LC-QD) systems is important for future advancements, particularly in addressing issues related to scalability and energy efficiency. Research should focus on improving the distribution and alignment of QDs within LC matrices, as well as exploring how external stimuli such as electric fields can dynamically adjust system properties to optimize performance. Additionally, the development of multi-functional hybrid materials that combine LCs, QDs, and other elements like nanophotonic structures offers potential for advanced quantum technologies. These materials could enable programmable features like real-time photon emission modulation and the generation of entanglement. Further exploration of LC-based PBG materials, which allow precise photon flow control, could lead to the creation of new architectures that dynamically manage light-matter interactions. This would be essential for building adaptive and responsive photonic circuits and quantum communication systems capable of operating in various environments [16,40,61,76].

CONCLUSION

Liquid crystals offer significant promise for advancing quantum computing due to their tunability, scalability, and ability to operate at room temperature. Experimental demonstrations have shown quantum behaviors in LCs, with advancements in material synthesis and device manufacturing playing a critical role in the development of LC-based quantum devices. Challenges such as maintaining quantum coherence, achieving precise molecular alignment, and integrating LCs with existing quantum systems remain, but ongoing research is steadily addressing these issues. Notably, LCs have shown potential in developing qubits, quantum gates, and circuits, as well as in quantum communication and cryptography, showcasing their versatility.

The integration of LCs with other quantum materials, such as quantum dots, is expected to drive progress, enhancing the performance and scalability of quantum computing systems. As this interdisciplinary field evolves, LCs are poised to contribute significantly to next-generation quantum technologies. The future of LC-based quantum computing is bright, and continued research and innovation in this area are essential to unlocking the full potential of these materials for quantum information science and technology.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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