Harnessing Liquid Crystals-based Techniques for Unleashing 6G Network Security Paradigms

Jinfeng Li, *Member, IAENG* and Haorong Li

***Abstract*—In the realm of wired and wireless telecommunications, the manipulation of electromagnetic wave encompasses the spatial modulation of phase, amplitude, polarization, spectral properties, and more recently, tailoring wavefronts to generate vortex orbital angular momentum (OAM) modes. This work leverages liquid crystals (LCs) based continuously-variable phase shifters and band-stop filters to penetrate the conventional territory of network security in the communication and sensing sectors. From the cryptography parlance, the continuous tuning resolution of LCs enables a surge in the key space (as compared with traditionally digital switching technology, e.g., p-i-n didoes), which is more resistant to cryptanalytic attack (e.g., brute-force attacks). In addition to creating highly directional, secure communication channels, the potential integration with decentralized technologies is first proposed and discussed, representing intersections of material science, microwave engineering, and information security, the insights informing future inventions, targeting broader audiences, including policymakers and industry professionals.**

***Index Terms*—adaptive encryption, communication and sensing, liquid crystal, IoT, mmW, OAM, RF, THz, 5G, 6G**

I. Introduction

In the ever-evolving landscape of telecommunications, the high-level vision of Six Generation (6G) technology [1][2] rolling out at high-frequency millimeter-wave (mmWave) [3] towards terahertz (THz) [4–6] promises groundbreaking advancements in connectivity, capacity, data transfer speeds, and power efficiency. The tsunami of late-breaking research milestones is evidenced [7], benefiting a host of potential application use cases, in particular, non-traditional scenarios, e.g., E-health [8], environment sensing [9], AR (augmented reality)/VR (virtual reality) for surgery, and the education sector [10][11]. However, with these great leaps forward come equally formidable challenges, particularly in the realm of network security [12] and the prevention of eavesdropping [13], data breaches, and cyberattacks [14–16]. As we stand on the precipice of this technological revolution, it is imperative to explore innovative (secure) solutions that can safeguard the beyond-5G networks.

Amidst the euphoria surrounding 6G's potential, eavesdropping [17] remains a significant and persistent threat. In an age where sensitive data flows like a river, the interception of information can have far-reaching consequences in terrestrial, non-terrestrial, maritime, and space scenarios. From personal privacy breaches to critical national security concerns, eavesdropping strikes at the heart of our digital existence. As such, anti-eavesdropping [18] and anti-jamming techniques [19] have increasingly been researched, with the core challenge for 6G networks being the precise phase modulation of mmWave or THz fields spatially and temporally [20]. This is where liquid crystals (LCs) [21], with their unique properties of reconfigurability, offer a glimmer of hope. In this paper, we delve into the exciting potential of LC technology in addressing these pressing concerns. LCs are materials that exhibit both liquid-like fluidity and crystalline order. They respond to external stimuli—such as electric [22], magnetic [23], or optical [24–26] fields—by continuously varying their dielectric constants (permittivity) at radio frequencies or their refractive indices at optical wavelengths. This behavior arises physically and chemically from their anisotropic molecular structure, typically rod-shaped [27], which results in stimuli-dependent dipole moments (variable polarizability) [28]. As illustrated in Fig. 1, the varying arrow lengths graphically represent this dielectric-tunable mechanism subject to varying bias voltages (0 to 10 V), explaining how LCs reconfigure permittivity across microscopic to macroscopic scales.

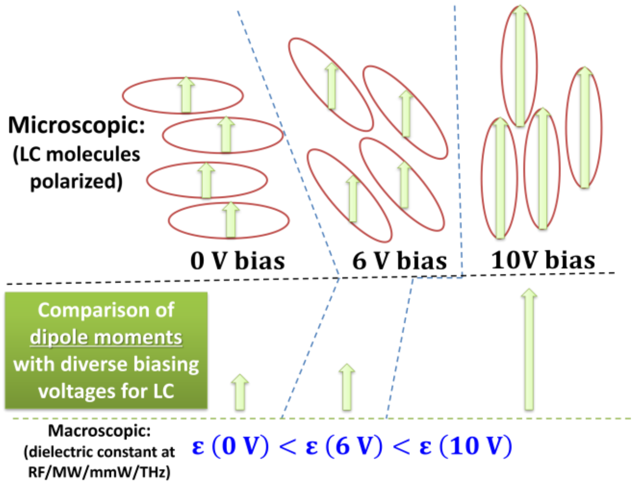

Fig. 1. A general schematic representation of the variable dielectric constant in nematic (rod-like) liquid crystals (positive dielectric anisotropy assumed), modulated by external stimuli such as a low-frequency low-power biasing voltage field up to 10 V.

Manuscript received February 10, 2025; revised April 12, 2025.

This work was supported in part by the National Natural Science Foundation of China (under Grant 62301043), and in part by the Fundamental Research Funds for the Central Universities (Beijing Institute of Technology Research Fund Program for Young Scholars) under grant number 220502052024011.

Jinfeng Li is an assistant professor of the Advanced Research Institute of Multidisciplinary Science, Beijing Key Laboratory of Millimeter Wave and Terahertz Technology, Beijing Institute of Technology, Beijing, 100081, China (corresponding author, e-mail: jinfengcambridge@bit.edu.cn).

Haorong Li is a postgraduate research student of the Beijing Key Laboratory of Millimeter Wave and Terahertz Technology, School of Integrated Circuits and Electronics, Beijing Institute of Technology, Beijing, 100081, China (email: haorong.li@bit.edu.cn).

Note that the electric biasing power (the voltage amplitude response) illustrated in Fig. 1 corresponds to a specific material type (nematic) and grade (GT3) of LCs utilized in our past prototypes, specifically, the enclosed coplanar waveguide (ECPW)-structured phase shifter at 60 GHz [29].

Combining LCs into real-world electronic components in the recent two decades, LCs have demonstrated remarkable functionality in reconfiguring phase at MW and mm-Wave regimes, as evidenced by a host of notable publications [29–31] regularly reported on LC-enabled phase shifters of reasonable tuning range [32] and insertion loss [33]. From conceptualization to realization, device performance and utility of LC-based mmWave phase shifting solutions were experimentally demonstrated in our prior works [29][34], exhibiting unprecedented features of phase-shifting resolutions [35] and insertion-loss balancing [24] without extra amplitude-compensating networks [36]. Accordingly, the costs and complexity have been reduced dramatically.

With the shape anisotropy representing this tunable dielectric material (sketched in Fig. 2), the dielectrically produced phase shift in a delay line is controlled continuously by analogue bias voltages (one of the most popular modulations means [37]). As a result, the steered beam features with a spatial continuity, as in (1), wherein the bias 1 ($\Phi_{21bias1}$) and the bias 2 ($\Phi_{21bias2}$) denote the two voltage biasing states (continuous voltage manipulation between V_{bias1} and V_{bias2}) for computing the targeting differential phase shifts of $\Delta\Phi_{21}$.

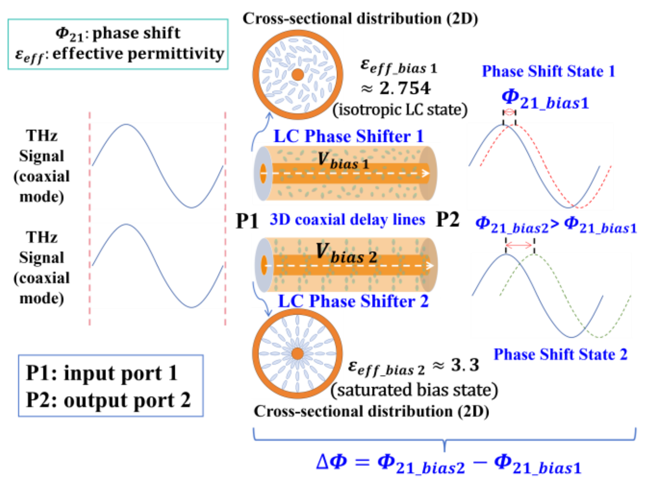

Fig. 2. Mechanism of nematic LC-enabled phase-reconfigurable devices (from dielectric material's tunability to device's tunability) for mmW and THz applications. Coaxial delay line and its two extreme tuning states with GT3-24002 LCs are exemplified.

$$\left|\Phi_{21_{bias1}}(V1) - \Phi_{21_{bias2}}(V2)\right| = \Delta\Phi_{21} \qquad (1)$$

While LCs have been used and credibly evidenced in various applications (e.g., displays [38] for many decades, optics [39], and microwave tunable components [24][40] recently), their potential in the realm of network security is only beginning to be explored. As first raised in this paper, LCs may potentially be used to address mmWave and THz eavesdropping in a few different ways, primarily by creating reconfigurable devices that can manipulate the polarization or phase of electromagnetic waves precisely and continuously in these wavelength ranges.

First, LC-based holographic encryption systems [41] can adapt and change encryption keys rapidly in response to potential threats, making it exceedingly challenging for eavesdroppers to intercept and decode sensitive information. Second, LC-based phase shifters can create dynamic, reconfigurable surfaces (e.g., reconfigurable intelligent surfaces [42]) that scatter or diffract signals in a controlled manner, thus creating secure communication zones, rendering eavesdropping practically impossible. Furthermore, LC-enabled orbital angular momentum (OAM) encoders and vortex beam steering [43–46] have the potential to resist quantum computing attacks that could break current encryption methods. This positions it as a robust hardware-based solution for the future of secure communication. The dynamic beam control techniques discussed empower a diverse range of application scenarios in beamforming, interference suppression, and channel optimization. It is worth noting that most contemporary publications and documentation on LC-based technologies are highly technical, often lacking broader discussions that inform a general audience about the diverse range of applications, deployment strategies, and associated challenges. To address this gap, the present tutorial work aims to bridge the divide by analyzing and mapping the technological advancements of LCs in relation to their industrial applications, as elaborated by section II.

II. Identification of Current Opportunities

As a means of reconfigurability, the unique ability of LCs to reorient their structure (shape anisotropy [29]) when subjected to external stimuli (e.g., low-power electric fields) can be a game-changer in the following regimes identified by this work.

A. *Dynamically Adaptive Encryption by Phase and/or Amplitude Tuning with LCs*

LC-based phase-modulation approach can be used in conjunction with other encryption techniques (cryptographic algorithms [47]) to secure mmWave and THz communication by encoding and decoding information at both ends of the communication link. First and foremost, LC-based phased shifters [29] or delay lines [30][48] can be harnessed to create dynamic encryption keys. By altering the phase of the transmitted signal, engineers can create interference patterns or encode information in the phase domain. This can make it more difficult for eavesdroppers to decode the transmitted data accurately.

By integrating LC-based step-less phase-shifting configurations (with infinite tuning resolution as depicted in Fig. 3), encryption systems can undergo truly dynamic changes, rendering intercepted data useless as it constantly evolves beyond the eavesdropper's understanding. By spatially modulating the dielectric constant (permittivity) of each LC-filled phase shifter that feeds the radiating element (i.e., antenna), the synthesized beam steering of the phased antenna array enables continuous phase adjustment, allowing for fine-grained control of the beam's direction and characteristics.

This avoids the coarse resolution of discretized phase states in traditional switches (as illustrated in the dashed lines in staircases shown at Fig. 3), enabling higher precision in beam alignment (particularly useful for high-frequency applications that demand tight tolerances).

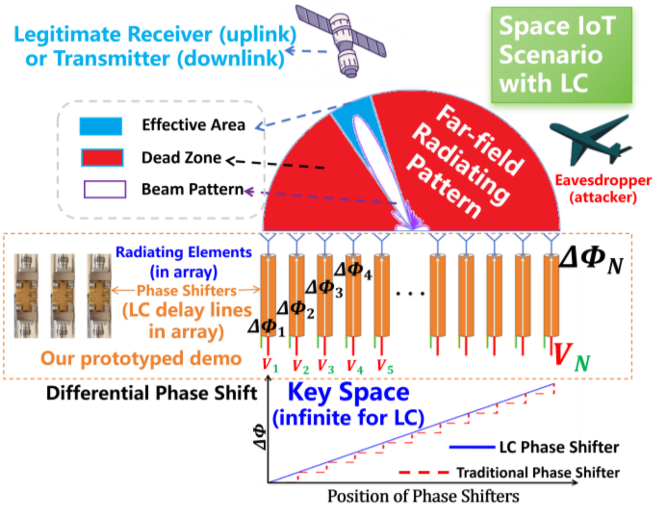

Fig. 3. Schematic depiction of the step-less tuning capability of the LC-based phase-shifting solution (our experimental demo shown on the left), emphasizing its advantage in achieving high-spatial-resolution beam steering and enhanced security through the generation of sensitive dead zones for 6G space IoT. The smooth phase shift transition (a surge in key space) makes it harder for adversaries to track or jam.

LC materials can be controlled electronically in a compact form factor with minimal power (e.g., voltage up to 10 V [29] as depicted in Fig. 3 for the feeding source of the control circuits), compared to traditional electronically controlled switches (e.g., beyond 100 V [11]). This low-power requirement is important in 6G IoT and AIoT networks, where energy efficiency is a critical design goal. The energy savings contribute to greener network operation, aligning with sustainability objectives [49].

Moreover, the encryption system with LC manipulation can be upgraded by creating dynamic, reconfigurable intelligent surfaces (RIS) [2][18][42]. These surfaces could scatter or diffract signals in a controlled manner, effectively establishing secure communication zones where eavesdropping is an exercise in futility.

By way of illustration, a 5G/6G urban IoT/AIoT usage scenario consisting of multi-vehicle mobile communications with obstructions (e.g., buildings of various heights) presented is exemplified in Fig. 4. An all-optically addressable phase-shifting networks (0 to 180° reconfigurable phase delays) realized by azo dyes mixed with liquid crystal (azo-LCs) as a key enabler are featured in the RIS deployment, circumventing the conventionally electronic (or bulky magnetic) biasing circuits traditionally attached to the back of the antenna panel, i.e., furthering compactness.

In another word, the biasing circuit here (implemented by current-controlled laser illumination) has been transformed to be entirely external with respect to the RIS sub-system itself with this LC-driven method. This has two-fold benefits. First, the beamforming system becomes more modular and flexible. Second, the system can switch between active or passive operations with ease, i.e., another dimension of flexibility is obtained, adaptably covering more application scenarios for opening up new services possibilities to drive the revenue growth of 5G and 6G.

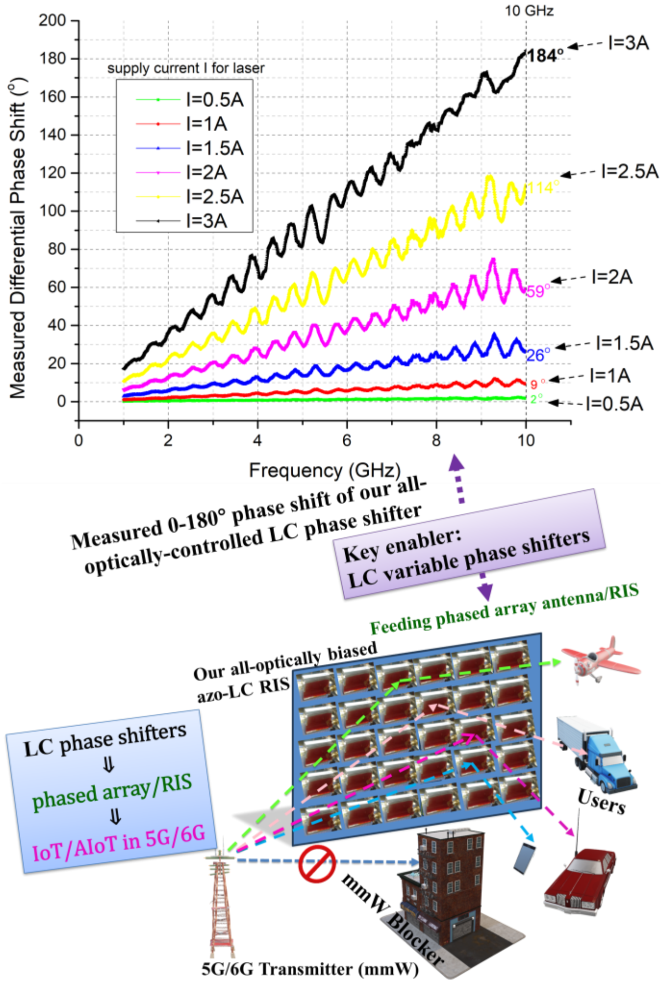

Fig. 4. A depiction of our LC-enabled phase-shifting solution envisioned for paving the way for RIS in the urban 5G/6G landscape (from concept to implementation) for beam steering, forming, tracking.

In addition, by harnessing the LC-RIS technology, we can enhance our ability to understand and respond to extreme weather events, ultimately improving disaster preparedness and response efforts. Secondly, amplitude encryption can be implemented using LC-based tunable attenuators or impedance tuners (developing underway in our group), offering enhanced specificity and stereoselectivity.

Last but not least, the looming quantum computing capabilities threaten to dismantle existing encryption paradigms. However, the dynamic tunability of LCs presents a promising avenue for quantum-resistant encryption solutions. LCs' ability to perform high-fidelity phase adjustments could support quantum key distribution or quantum entanglement distribution over long distances, which is another research focus currently being explored within our group.

B. New Dimension of Reconfigurability by OAM with LCs

A new dimension of the LCs' phase shifting capability and polarization reconfigurability can be exploited to enhance the generation of OAM (orbital angular momentum) beam [44] and spatial multiplexing [50]. This versatility is particularly beneficial in scenarios requiring dynamic switching between different OAM modes, e.g., mode-division multiplexing or quantum communication protocols. In addition to the phase and amplitude modulation, however, LCs for the aspect of OAM technology remains obscure in the past literature.

Due to the unique optical and electromagnetic properties of continuous reconfigurability in dielectric constant driven by low-power control methods (electrical, magnetic, optical, thermal, and a mix), exploiting LC-based blue-sky studies has potential to identify solutions for problems and unproven technologies that are intractable by conventional OAM production and modulation approaches.

Conventional OAM production by phased array antenna (e.g., uniform circular array [51]) is primarily susceptible to phased errors (and hence the side lobe compromise) as well as the complexity in the feeding networks (bulky, power-consuming). The reconfigurability is conventionally based on semi-conductor switches that are super-fast in response. However, pockets of phase shift continuity were maintained due to the binary nature of the on-off switching, for which the introduction of LCs [52] will tip the balance. By spatially modulating the dielectric constant (refractive index) of the LC layer, these devices can precisely create helical phase fronts necessary for OAM beam synthesis, enhancing the versatility of optical systems and unlocking new avenues of resolution-intensive applications.

In addition to dynamically shaping OAM beams (wavefront engineering), LC-based phase shifters can facilitate the generation and separation of multiple OAM modes, serving as reconfigurable OAM mode converters, supporting multiplexing and demultiplexing for high-dimensional quantum communication and data transmission, which securely addresses the increasing demand for data transmission capacity.

In free-space optical communication, atmospheric turbulence can degrade OAM beam integrity. LC phase shifters, integrated into adaptive optics systems, can correct (compensate for) the wavefront distortions in real-time, preserving the phase structure of OAM beams and enhancing signal robustness. LC phase shifters can achieve fine control over the helical phase front of OAM beams, enabling the dynamic tuning of topological charge. This capability is valuable for applications in OAM-based imaging, such as optical tweezers [53] or super-resolution microscopy [54], where precise control of angular momentum is required. The integration of LC technology with diffractive optical elements (e.g., spiral phase plates or q-plates [55][56]), can yield miniature devices suitable for 6G mobile and satellite communication systems.

Advances in LC technology have enabled their integration with metasurfaces [57], which can enhance phase modulation capabilities. This hybrid approach can lead to highly efficient and scalable devices for generating complex OAM states or implementing tailored phase profiles. Since phase accuracy is highly sensitive to the beam formed and hence the OAM quality, experimental investigations should be in place for bridging the gap between academic research and practical implementation. However, the ideating and designing phase of the LC THz benefits from simulations, for which the computational vulnerabilities can be referred to [52][58].

A summary of the research and development opportunities for LC-OAM are depicted in Fig. 5 below, with unlimited opportunities open to discussion.

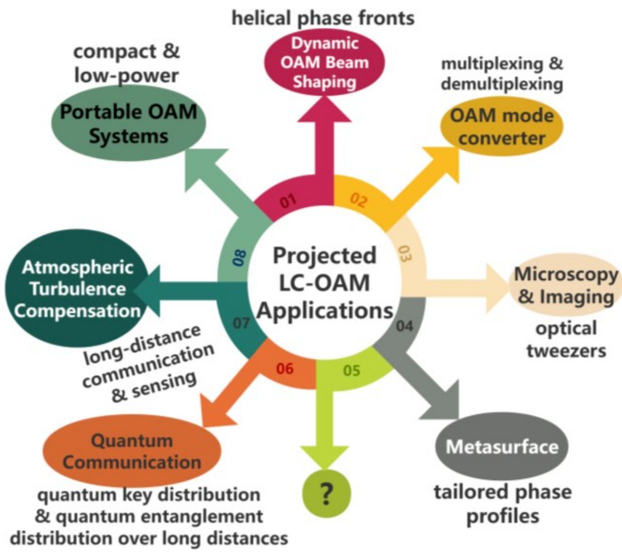

Fig. 5. Identifying a comprehensive collection of potential applications of LC-based OAM.

C. *EMCON and Frequency Hopping with LCs*

LC-based metasurfaces and phased arrays can be employed to control the direction and shape of mmWave and THz beams. The resulting dead zones (low-observable operation modes) create regions of radio silence or emissions control (EMCON), effectively mitigating the risk of eavesdropping. This concept is illustrated in Fig. 6, which exemplifies a maritime application scenario where LC-based phase-shifting networks are installed onboard. Analogue to smart LC films used for privacy windows, LCs can be employed to create "privacy windows" that selectively block or permit mmWave and THz radiation. By dynamically controlling the transparency of these windows, LCs can serve as a physical barrier, preventing unauthorized access to sensitive areas or information.

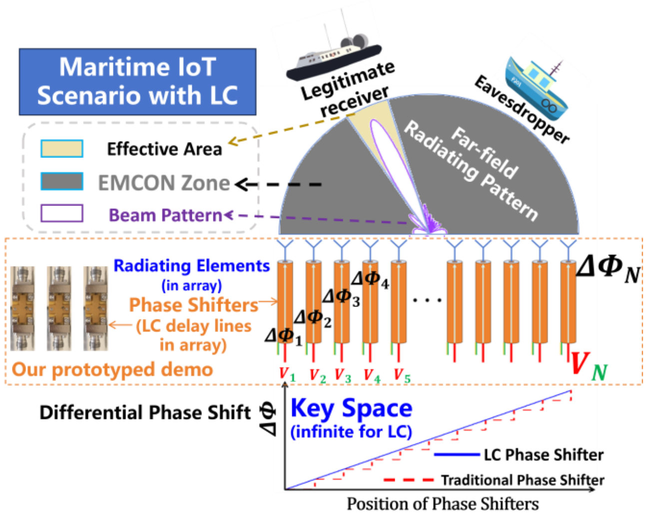

Fig. 6. LC-based phased array for EMCON in maritime applications featuring minimized detectability or maximized signal focus.

Beyond the extensive capabilities enabled by LC-based phase-shifting mechanisms, LC devices also facilitate rapid switching between different frequency channels. This technique, known as frequency hopping, is widely utilized in secure communication systems to complicate interception and decoding by eavesdroppers.

An engineering implementation integrating LC-based continuously reconfigurable filter technology is illustrated in Figs. 7 and 8, with its frequency response depicted in Fig. 9. The device features a tunable notch between two LC biasing states and is structured as an inverted microstrip line (IMSL) with a quarter-wavelength shunt stub. The resonance frequency shifts continuously from 65.8 GHz to 60 GHz (highlighted in the green region for the frequency hopping regime) as the bias voltage increases from 0 V to its saturation level, corresponding to a dielectric constant variation from 2.5 to 3.3 in the V-band.

The IMSL geometry design is as per the LC thickness of 0.1 mm (i.e., the spacing between the inverted microstrip core line and the grounding metal plane), the core line width of 0.1616 mm, and the core line length of 1 mm (for the signal transmitting path). This arrangement is for impedance matching (50 ohms) at the saturated bias state of the LC (i.e., the mmW polarization in line with the LC directors, yielding the LC permittivity of 3.3 in maximum).

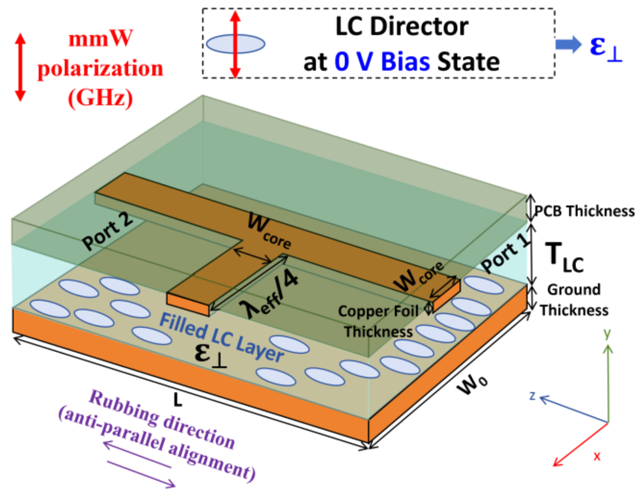

Fig. 7. Geometry of our LC-filled reconfigurable notch filter (LCs biased at 0 V), with T_{LC}=0.1 mm, W_{core}=0.1616 mm, main line length L =1 mm, and 50 Ω matched at the LC-saturated bias state).

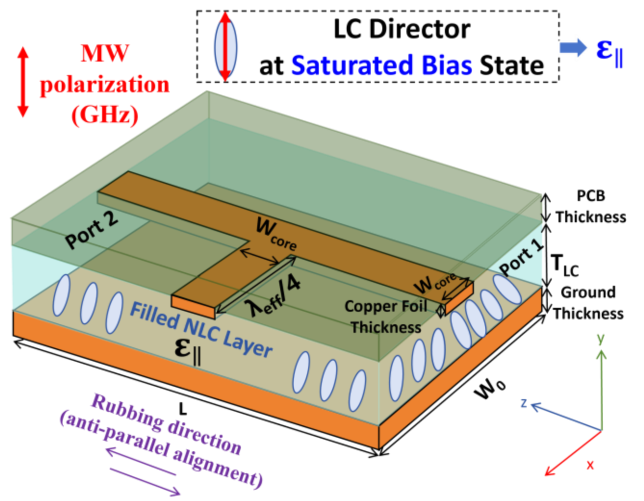

Fig. 8. Geometry of our LC-filled reconfigurable notch filter (LCs biased at saturated voltage), with T_{LC}=0.1 mm, W_{core}=0.1616 mm, main line length L =1 mm, and 50 Ω matched at the LC-saturated bias state).

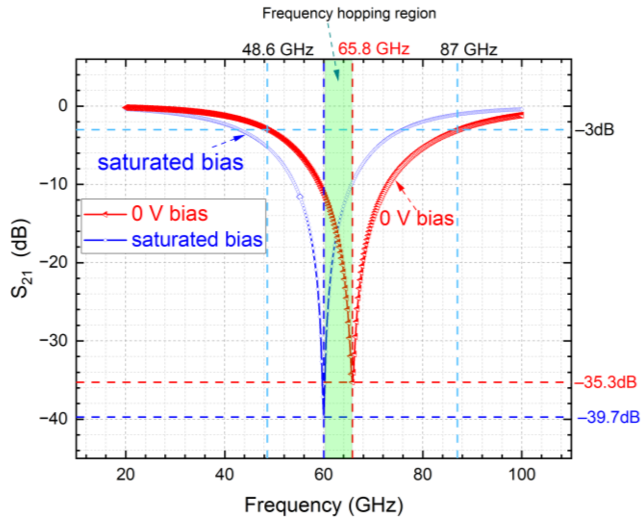

Fig. 9. Frequency response of the LC-based reconfigurable filter device (Figs. 7 and 8), featuring measurable changes in the continuously tunable notch for frequency hopping applications.

III. Challenges and Roadmap

This paper strives to identify the roadmap of leveraging LCs for bolstering 6G network security. As the discourse on 6G security intensifies, the role of LCs moves from being peripheral to central. Yet, like all potential solutions, it necessitates rigorous testing, validation, and development to be deployed effectively. The identification of technical challenges in scalability, calibration, response time and power consumption are crucial. Accordingly, solutions to overcome these obstacles are proposed to ensure the practical realization and desirably efficient implementation of LC-based security-targeting systems.

A. Tuning Agility and Susceptibility to Biasing Attacks

It is important to note that external stimuli, such as biasing fields (e.g., electric, magnetic, or temperature fields), play a crucial role in the reconfigurability of LC-based tunable devices, including phase shifters and filters, as discussed above. However, the response time of LCs, and the associated latency, remains a critical performance concern. Specifically, how the response time of LCs—including delay and transient effects—impacts the phase of round-trip reflection is an area that has received limited investigation.

Existing studies lack empirical substantiation, as they often fail to provide sufficient experimental data or credible sources to validate their hypotheses. Addressing these limitations requires a fundamental shift in the molecular design of future LCs. In addition to optimizing for reduced insertion loss and a miniaturized device footprint, the chemical composition of next-generation LCs must differ significantly from that of currently used materials to mitigate performance constraints arising from molecular mechanisms.

Given the strong dependence of device functionality on external stimuli, LC-based systems are inherently susceptible to perturbation-based attacks, a concern that can be framed within the context of cryptographic security and cryptanalysis. The biasing networks employed for tuning LCs, as illustrated in Fig. 10, are vulnerable to various forms of adversarial manipulation, depending on the biasing method used. This study is the first to highlight such security risks. Potential attackers or eavesdroppers could exploit these vulnerabilities by inducing substantial variations in ambient temperature, thereby disrupting the LC response. Such perturbations could lead to significant phase drifts or, in extreme cases, system malfunction, posing a considerable threat to the reliability of LC-based communication systems.

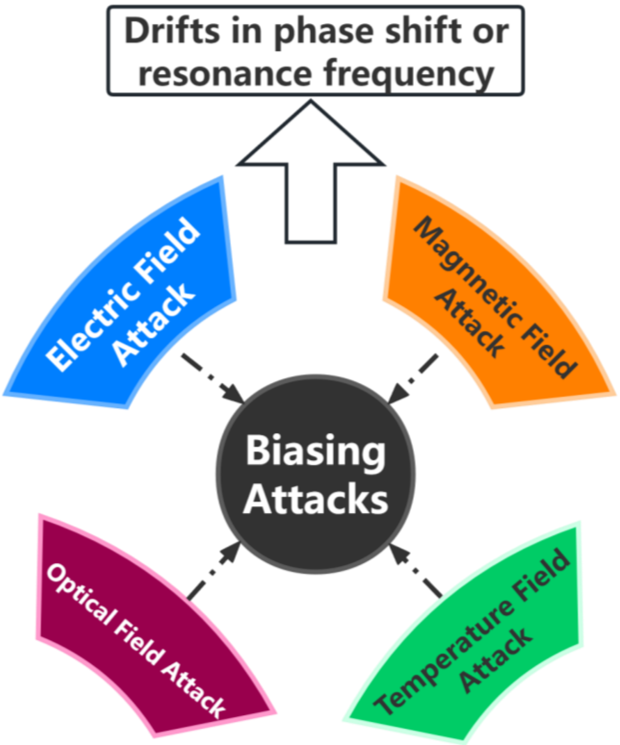

Fig. 10. Non-negligible susceptibility of biasing attacks identified for LC-based delay line phase shifters and notch-variable filters.

B. Incorporating Data-centric Approach, Life-cycle Assessments and Protocols for 6G

The classic LC-MW and LC-mmW devices' modelling approaches are arguably based on coupling the nano-to-micro-to-millimeter multi-scale problem, which has posed difficulties in analytical solutions, necessitating innovative computational methods. Physics-informed machine learning (PIML) [59][60] is one of the candidates for the solving method that takes insights from limited data and the underpinning physics. The work reported in [59] studies into the applicability of PIML with LC for the first time. Once decent data (both simulated and experimental) is available, future work should incorporate physics-informed (to ensure interpretability of the model's predictions) machine learning to streamline the design, performance characterization and optimization workflow (which was time-consuming in the past due to the complicated interplay between multiple influential factors including but not limited to the anisotropic material properties [27][29] and the deployed device's geometries [61–63]), hence reducing the cost and complexity of the technology.

To demonstrate the technological, economic, and environmental performance of the LC-aided network security system at a commercial scale, process modelling and life cycle assessments (for both the LC-based hardware and the software suits to control the LC-enabled units) will need to be performed. Notably, the integration of LC technology with existing communication protocols and network infrastructure must be carefully evaluated, given the limited availability of experimental prototypes and commercial off-the-shelf solutions. Arguably, LCs must seamlessly integrate with standardized networking technologies to ensure compatibility and interoperability. This includes addressing challenges such as synchronization, protocol overhead, and data synchronization between multiple LC-RIS units in large-scale deployments. Efficient protocols and algorithms specifically designed for LC-enabled networks need to be in place to address these challenges and maximize the network speed. Distributed Analytics for Adaptation Beam steering systems can leverage decentralized machine learning models trained collaboratively across nodes, enabling adaptive steering decisions based on real-time data.

In addition to the network-reconfiguring speed, user experiences in terms of reliability (robustness) are vital in determining the success of LC-enabled 6G deployments. Users expect reliable, high-quality connections that deliver consistent performance. Accordingly, LCs and LC-RIS must ensure seamless handovers between different communication nodes, especially in mobile scenarios (e.g., space IoT in Fig. 3 and maritime IoT in Fig. 6), to maintain uninterrupted connectivity. The handover process should arguably be transparent to users, avoiding disruptions or degradation in the service quality.

C. Integration with Decentralized Technologies

In addition to the hardware bottom-up approach (e.g., using a coaxial one) for attacks-immunity, decentralized distributed ledger technologies (DLT) [64], e.g., blockchain [65] and decentralized key management (secure directional communication beamforming can use keys distributed and managed via a DLT network), can be synergized in the biasing control manipulation of LC-based reconfigurable devices to address the aforementioned centralized vulnerabilities of malicious attacks. This new combination is particularly promising for emerging adaptable 6G use cases, including autonomous systems, IoT [33][66], and ultra-reliable low-latency communications [67].

Additionally, from the lens of authentication and access [68], e.g., blockchain can store and manage unique device identities of antenna elements fed by variable phase shifters or tunable delay lines. When LC beam steering dynamically directs signals, DLTs ensure only authenticated devices (radiating elements and the feeding phase shifters) can receive or decode the signal, enhancing security. Smart contracts can automate this access control, authorizing beam alignment only for devices meeting pre-defined criteria (e.g., location, credentials, or resource availability). Beam steering resources, e.g., the specific reconfigurable frequency bands (actioned by LC-filled variable filters), and the reconfigurable power levels (realized by LC-based attenuators) can be tokenized, enabling a decentralized marketplace where devices negotiate for resource access (i.e., token-based resource access).

The LC-based bias-voltage-dependent beam-steering adjustments (e.g., phase state changes, user-specific beam directions) can be logged on a distributed ledger. The tamper-proof beam logs ensure transparency and traceability, helping detect malicious activities (e.g., beam hijacking or jamming attempts) with ease. From the parlance of secure updates and patching, LC-based beam-steering systems can use decentralized networks to verify and distribute firmware or algorithm updates securely, protecting against supply chain attacks. Reward mechanisms for cooperative behavior could be identified, i.e., nodes participating in collaborative beamforming or resource optimization could earn rewards, encouraging decentralized cooperation.

A DLT framework can facilitate coordination between multiple beamforming units (e.g., across base stations or edge devices). This enables dynamic collaboration for optimal beam alignment without relying on a central authority. In this LC-based collaborative beamforming landscape, distributed nodes can use consensus mechanisms to decide optimal beam directions, improving resource allocation and load balancing in dense network environments. With the service rollout of beyond-5G/6G, LC-based DLT-incorporated adaptive network monetization can be envisioned with transparent usage-based billing for the beam steering services. By way of illustration, IoT devices or edge nodes could pay micropayments for specific beamforming services. The integration opportunities of LCs and DLTs are summarized in Fig. 11 below.

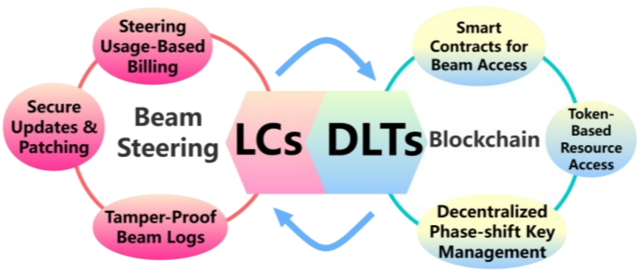

Fig. 11. New proposal on LCs synergized with DLTs for enhanced 6G network security (roadmap and vision).

D. Public Acceptance for Sustainability

The successful deployment of LC-based technologies in 6G network security relies not only on technological advancements in devices and materials, but also on public acceptance and regulatory endorsement. Despite the potential of LC-driven solutions to enhance physical-layer security and adaptive communication, their widespread adoption may face skepticism, particularly given the challenges observed during the 5G rollout, where infrastructure development has often struggled to keep pace with service demands. This disparity has led to concerns regarding the feasibility and reliability of emerging hardware-driven security paradigms in next-generation networks.

A key challenge in gaining public trust lies in the perceived opacity of LC-integrated security mechanisms, particularly when combined with AI-driven threat mitigation strategies. The complexity of LC-based reconfigurable hardware, coupled with AI-enhanced security protocols, may contribute to concerns regarding explainability, reliability, and unintended vulnerabilities. Furthermore, as security threats evolve, the need for transparent, verifiable, reasonably predictable, ethical, and standardized implementation of LC-based solutions becomes increasingly critical to ensuring both technical credibility and societal acceptance.

To bridge this gap, demonstration experiments (e.g., the space IoT shown in Fig. 3, the maritime scenario illustrated in Fig. 6), real-world testbeds (e.g., an LC-RIS experimentation in the urban landscape shown in Fig. 4), and interdisciplinary collaborations are essential in validating the effectiveness of LC-based security technologies. Engaging with industry stakeholders, policymakers, and the general public through awareness campaigns and regulatory discussions will further facilitate acceptance and adoption. Ultimately, the integration of LC-based techniques in 6G security must not only achieve stringent performance standards [69–72] (e.g., addressing vulnerabilities such as those identified in [73][74] and meet established security benchmarks [75–79]), but also align with broader societal and ethical considerations to ensure a sustainable and trust-driven deployment.

IV. Conclusion

The call for information security echoes louder than ever. Expected to succeed 5G within the next decade, 6G promises to deliver data speeds surpassing one terabyte per second, ultra-low latency, and ubiquitous connectivity rolling out at high-frequency millimeter-wave (mmWave) towards terahertz (THz). With applications ranging from autonomous vehicles and augmented reality to remote medical procedures, the possibilities are awe-inspiring. However, as we look toward this future, we must also confront the vulnerabilities and security threats that come with it. The exponential growth in data transmission and the proliferation of connected devices will undoubtedly attract the attention of malicious actors. Eavesdropping, data breaches, and cyberattacks pose severe threats to both personal privacy and national security. Traditional encryption methods in legacy wireless networks may not suffice in the face of quantum computing and increasingly sophisticated hacking techniques.

Liquid crystal (LC)-enabled reconfigurable devices, capable of tuning phase, amplitude, and polarization, serve as catalysts for the advancement of mmWave reconfigurable networking technologies to address the growing demand for increased capacity and bandwidth. The significance of LC-based approaches for 6G network security is well recognized. However, the fundamental principles governing these approaches—and, consequently, the strategies to enhance their reliability, robustness, and scalability—remain inadequately explored. Therefore, this study undertakes an in-depth investigation into LC-enabled security mechanisms, elucidating their potential and addressing the associated challenges.

As we venture into the uncharted territory of 6G, it is imperative to remain vigilant against the accompanying security challenges. The dynamic and adaptive nature of LCs aligns well with the ever-evolving threat landscape, offering a promising frontier for securing communication channels and representing a paradigm shift in network security. Breakthroughs demand experimental testing and fail cycles. The transition to the standardization of the 6G ecosystem will not be without its trials.

Last but not least, while the exploration journey into LCs can enhance security against eavesdropping in mmWave and THz communications, they should be part of a broader security strategy that includes encryption, authentication, and other security measures. The specific implementation and effectiveness of LC-based security measures would depend on the system details and the threat model being addressed, for which further understanding of the current landscape and challenges faced, performing life cycle and techno-economic analysis are needed to harness this potential fully.

REFERENCES

[1] Tataria H, Shafi M, Molisch A, Dohler M, Sjöland H, and Tufvesson F, "6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities," Proceedings of the IEEE, vol. 109, no. 7, pp1166-1199, 2021.
[2] Li J, "Roadmap of 6G Reconfigurable Intelligent Surfaces with Nematic Liquid Crystals: Fundamentals, State-of-the-Art, and Challenges," Proceedings of the IEEE/IFAC 10th International Conference on Control, Decision and Information Technologies, pp802-807, 2024.
[3] Li J, and Li H, "Finite-element Adaptive Meshing Statistics of Liquid Crystal Coaxial Phase Shifters for mmW Electronics and THz Photonics Beyond Display: A Comparative Study," Photonics Letters of Poland., vol. 16, no. 3, pp40-42, 2024.
[4] Kürner T, and Priebe S, "Towards THz Communications - Status in Research, Standardization and Regulation," Journal of Infrared, Millimeter, and Terahertz Waves, vol. 35, no. 1, pp53-62, 2013.
[5] Elayan H, Amin O, Shihada B, Shubair R, and Alouini M, "Terahertz Band: The Last Piece of RF Spectrum Puzzle for Communication Systems," IEEE Open Journal of the Communications Society, vol. 1, pp1-32, 2020.
[6] Li H, and Li J, "Advancing Microscale Electromagnetic Simulations for Liquid Crystal Terahertz Phase Shifters: A Diagnostic Framework for Higher-Order Mode Analysis in Closed-Source Simulators," Micro, vol. 5, no. 1, pp3, 2025.
[7] Alsharif M, Kelechi A, Albreem M, Chaudhry S, Zia M, and Kim S, "Sixth Generation (6G) Wireless Networks: Vision, Research Activities, Challenges and Potential Solutions," Symmetry, vol. 12, no. 4, pp676, 2020.
[8] Suraci C, Pizzi S, Molinaro A, and Araniti, G, "Business-Oriented Security Analysis of 6G for eHealth: An Impact Assessment Approach," Sensors, vol. 23, no. 9, pp4226, 2023.
[9] Kim N, Kim G, Shim S, Jang S, Song J, and Lee B, "Key Technologies for 6G-Enabled Smart Sustainable City," Electronics, vol. 13, no. 2, pp268, 2024.
[10] Li J, Li H, Xiao Y, Jiang P, Wang S, and Guo Z, "Generalization of Impedance Characterization Methods for Liquid Crystal-Embedded Tunable Transmission Lines and Applied Study into Guard Band Redundancy Evaluation," Engineering Letters, vol. 33, no. 2, pp374-381, 2025.
[11] Li J, and Li H, "Susceptibility to Low-Frequency Breakdown in Full-Wave Models of Liquid Crystal-Coaxially-Filled Noise-Shielded Analog Phase Shifters," Electronics, vol. 13, no. 23, pp4792, 2024.
[12] Kazmi S, Hassan R, Qamar F, Nisar K, and Ibrahim A, "Security Concepts in Emerging 6G Communication: Threats, Countermeasures, Authentication Techniques and Research Directions," Symmetry, vol. 15, no. 6, pp1147, 2023.
[13] Vuppala S, Biswas S, and Ratnarajah T, "An Analysis on Secure Communications in Millimeter/Micro-Wave Hybrid Networks," IEEE Transactions Communication, vol. 64, no. 8, pp3507-3519, 2016.
[14] Tripi G, Iacobelli A, Rinieri L, and Prandini M, "Security and Trust in the 6G Era: Risks and Mitigations," Electronics, vol. 13, no. 11, pp2162, 2024.
[15] Li J, "Vulnerabilities Mapping based on OWASP-SANS: A Survey for Static Application Security Testing (SAST)," Annals of Emerging Technologies in Computing, vol. 4, no. 3, pp1-8, 2020.
[16] You I, Kim J, Pawana I, and Ko Y, "Mitigating Security Vulnerabilities in 6G Networks: A Comprehensive Analysis of the DMRN Protocol Using SVO Logic and ProVerif," Applied Sciences, vol. 14, no. 21, pp9726, 2024.
[17] Mahmoud H, Ismail T, Baiyekusi T, and Idrissi M, "Advanced Security Framework for 6G Networks: Integrating Deep Learning and Physical Layer Security," Network, vol. 4, no. 4, pp453-467, 2024.
[18] Luo J, Wang F, Wang S, Wang H, and Wang D, "Reconfigurable Intelligent Surface: Reflection Design Against Passive Eavesdropping," IEEE Transactions on Wireless Communications, vol. 20, no. 5, pp3350-3364, 2021.
[19] Vaishnavi K, Khorvi S, Kishore R, and Gurugopinath S, "A Survey on Jamming Techniques in Physical Layer Security and Anti-Jamming Strategies for 6G," Proceedings of the 2021 28th International Conference on Telecommunications, pp174-179, 2021.
[20] Koeberle M, Hoefle M, Gaebler A, Penirschke A, and Jakoby R, "Liquid Crystal Phase Shifter for Terahertz Frequencies with Quasi-Orthogonal Electrical Bias Field," Proceedings of the 2011 International Conference on Infrared, Millimeter, and Terahertz Waves, pp1-1, 2011.
[21] Li J, "Challenges and Opportunities for Nematic Liquid Crystals in Radio Frequency and Beyond," Crystals, vol. 12, no. 5, pp632, 2022.
[22] Li J, "Design Margin of Millimeter-wave Ultra-wideband 0-180° Analog Delay Line with Insertion Loss Less Than 2 dB," Proceedings of the 2023 16th UK-Europe-China Workshop on Millimetre Waves and Terahertz Technologies, pp1-3, 2023.
[23] Bošnjaković D, Sebastián N, and Drevenšek-Olenik I, "Magnetically Tunable Liquid Crystal-Based Optical Diffraction Gratings," Polymers, vol. 12, no. 10, pp2355, 2020.
[24] Li J, "All-optically Controlled Microwave Analog Phase Shifter with Insertion Losses Balancing," Engineering Letters, vol. 28, no. 3, pp663-667, 2020.
[25] Li J, "Tunability Dependence of All-Optical Liquid Crystal Delay Line on Laser Polarization and Incidence Angle," Photonics Letters of Poland, vol. 15, no. 4, pp51-53, 2023.
[26] Li J, "Optically Steerable Phased Array Enabling Technology Based on Mesogenic Azobenzene Liquid Crystals for Starlink Towards 6G," Proceedings of the 2020 IEEE Asia-Pacific Microwave Conference, pp345-347, 2020.
[27] Li J, "Low-loss tunable dielectrics for millimeter-wave phase shifter: from material modelling to device prototyping," IOP Conference Series: Materials Science and Engineering, vol. 892, 012057, 2020.
[28] Li J, and Li H, "Effective Dielectric Constant Benchmark of 60 GHz Liquid Crystal-Filled Coaxial Delay Line," Proceedings of the 2024 IEEE International Conference on Computational Electromagnetics, pp1-3, 2024.
[29] Li J, and Chu D, "Liquid crystal-based enclosed coplanar waveguide phase shifter for 54-66 GHz applications," Crystals, vol. 9, no. 12, pp650, 2019.
[30] Li J, and Li H, "Frequency Ripples Reduction in Differential Delay Time of Liquid Crystals Coaxial Delay Lines," Proceedings of the 2024 IEEE INC-USNC-URSI Radio Science Meeting (Joint with AP-S Symposium), pp154-155, 2024.
[31] Li J, and Li H, "Liquid Crystal Coaxial Phase Shifter Designs at 0.3 THz," Proceedings of the 5th China and International Young Scientist Terahertz Conference, Volume 2. Springer Proceedings in Physics, vol. 401, pp147-151, 2024.
[32] Li J, "Towards Fabrication of High-tuning-range Liquid Crystals High-aspect-ratio Coplanar Waveguide Phase Shifter by LIGA, DRIE and Laser Ablation," Proceedings of the 2023 Cross Strait Radio Science and Wireless Technology Conference, pp1-3, 2024.
[33] Li J, and Li H, "Computationally Sampling Surface and Volume Current Densities of Liquid Crystal Non-Planar Phase Shifters for Low-Loss 5G IoT and 6G AIoT," Proceedings of the 2024 IEEE International Conference on Omni-layer Intelligent Systems, pp1-6, 2024.
[34] Li J, "Experimental Characterization of Patterned Electrodes and Shaped Substrates for A Liquid Crystals Phase Shifter at V Band," Proceedings of the IEEE 15th International Conference on Microwave and Millimeter Wave Technology, pp1-3, 2023.
[35] Li J, "Millimetre-wave beam steering with analog-resolution and minimised distortion based on liquid crystals tunable delay lines with enhanced signal-to-noise ratios," Proceedings of SPIE, Millimetre Wave and Terahertz Sensors and Technology XIII, vol. 11541, 115410H, 2020.
[36] González-Coma J, Nocelo López R, Núñez-Ortuño J, and Troncoso-Pastoriza F, "Beacon-Based Phased Array Antenna Calibration for Passive Radar," Remote Sensing, vol. 17, no. 3, pp490, 2025.
[37] Li J, "Bias Tees Integrated Liquid Crystals Inverted Microstrip Phase Shifter for Phased Array Feeds," Proceedings of the IEEE EPS 21st International Conference on Electronic Packaging Technology, pp1-5, 2020.
[38] Jones J, "The fiftieth anniversary of the liquid crystal display," Liquid Crystals Today, vol. 27, no. 3, pp44-70, 2018.
[39] Jaroszewicz L, and Bennis N, "Liquid Crystal Optical Devices," Crystals, vol. 9, no. 3, pp523, 2019.
[40] Li J, "Wideband PCB-to-Connectors Impedance Adapters for Liquid Crystal-Based Low-Loss Phase Shifters," Proceedings of the 50th European Microwave Conference, pp546-549, 2021.
[41] Huang X, Zhu D, Zhou Z, Chen K, Zheng G, Chen P, Lu Y, and Li Z, "Tiger Amulet inspired high-security holographic encryption via liquid crystals," Nanophotonics, vol. 12, pp1787-1795, 2023.

[42] Li J, "From Liquid Crystal on Silicon and Liquid Crystal Reflectarray to Reconfigurable Intelligent Surfaces for Post-5G Networks," Applied Sciences, vol. 13, no. 13, pp7407, 2023.
[43] Grunwald R, Jurke M, Liebmann M, and Bock M, "Orbital Angular Momentum Encoded Beam Tracking and Wavefront Sensing," Journal of Lightwave Technology, vol. 41, no. 7, pp2017-2024, 2023.
[44] Yang H, Zheng S, He W, Yu X, and Zhang X, "Terahertz orbital angular momentum: Generation, detection and communication," China Communications, vol. 18, no. 5, pp131-152, 2021.
[45] Djordjevic I, "Multidimensional OAM-based secure high-speed wireless communications," IEEE Access, vol. 5, pp16416-16428, 2017.
[46] Yuan R, Liu Y, Tan Q, Ge J, Cheng P, and Guo Q, "An All-Liquid-Crystal Strategy for Fast Orbital Angular Momentum Encoding and Optical Vortex Steering," IEEE Journal of Selected Topics in Quantum Electronics, vol. 28, no. 5, pp1-6, 2021.
[47] Li J, "Optically Inspired Cryptography and Cryptanalysis: A Survey and Research Directions," Proceedings of the Emerging Technologies in Computing, Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol. 332, pp98-110, 2020.
[48] Li J, "An Efficient Mixed-signal Dielectric-partitioning Model of Liquid Crystals based Shielded Coplanar Waveguide for Electronically Reconfigurable Delay Lines Design," Proceedings of SPIE, Integrated Optics: Design, Devices, Systems and Applications VI, vol. 11775, 1177519, 2021.
[49] Kumar R, Gupta S, Wang H, Kumari C, and Korlam S, "From Efficiency to Sustainability: Exploring the Potential of 6G for a Greener Future," Sustainability, vol. 15, 16387, 2023.
[50] Olaleye T, Ribeiro P, and Raposo M, "Generation of Photon Orbital Angular Momentum and Its Application in Space Division Multiplexing," Photonics, vol. 10, pp 664, 2023.
[51] Naseri H, PourMohammadi P, Melouki N, Ahmed F, Iqbal A, and Denidni T, "Generation of Mixed-OAM-Carrying Waves Using Huygens' Metasurface for Mm-Wave Applications," Sensors, vol. 23, pp2590, 2023.
[52] Li H, and Li J, "Advancing Microscale Electromagnetic Simulations for Liquid Crystal Terahertz Phase Shifters: A Diagnostic Framework for Higher-Order Mode Analysis in Closed-Source Simulators," Micro, vol. 5, no. 1, pp3, 2025.
[53] Cronin-Golomb M, "Editorial on Optical Tweezers for the 15th Anniversary of Micromachines," Micromachines, vol. 15, pp1522, 2024.
[54] Nandi S, Caicedo K, and Cognet L, "When Super-Resolution Localization Microscopy Meets Carbon Nanotubes," Nanomaterials, vol. 12, pp1433, 2022.
[55] Rubano A, Cardano F, Piccirillo B, and Marrucci L, "Q-plate technology: a progress review [Invited],"Journal of the Optical Society of America B, vol. 36, ppD70-D87, 2019.
[56] Marrucci L, "The q-plate and its future," Journal of Nanophotonics, vol. 7, no. 1, 078598, 2013.
[57] Shih Y, Lin X, Silalahi H, Lee C, and Huang C, "Optically Tunable Terahertz Metasurfaces Using Liquid Crystal Cells Coated with Photoalignment Layers," Crystals, vol. 11, pp1100, 2021.
[58] Li J, and Li H, "Assessing Vulnerabilities in Line Length Parameterization and the Per-Unit-Length Paradigm for Phase Modulation and Figure-of-Merit Evaluation in 60 GHz Liquid Crystal Phase Shifters," Symmetry, vol. 16, no. 10, pp1261, 2024.
[59] Li J, "Machine Learning and Digital Twinning Enabled Liquid Crystals mm-Wave Reconfigurable Devices Design and Systems Operation," Proceedings of the IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications, pp1-3, 2023.
[60] Li J, "Physics-Informed Machine Learning Assisted Liquid Crystals µWave Phase Shifters Design and Synthesis," Proceedings of the Emerging Technologies in Computing, Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol. 538, pp3-13, 2023.
[61] Li J, "Novel Partially-Shielded Coplanar Waveguide with Metasurfaces for Liquid Crystals Tunable Delay Lines Beyond 67 GHz," Proceedings of the 2022 IEEE Conference on Antenna Measurements & Applications, pp1-4, 2022.
[62] Li J, "Dissipative Analysis of Liquid Crystal-loaded Passive Reconfigurable Transmission Line Components with Filled Vias at 60 GHz," Proceedings of the IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization, pp48-50, 2023.
[63] Li J, "Rethinking Liquid Crystal Tunable Phase Shifter Design with Inverted Microstrip Lines at 1–67 GHz by Dissipative Loss Analysis," Electronics, vol. 12, no. 2, pp421, 2023.
[64] Soltani R, Zaman M, Joshi R, and Sampalli S, "Distributed Ledger Technologies and Their Applications: A Review," Applied Sciences, vol. 12, pp7898, 2022.
[65] Saari A, Junnila S, Vimpari J, "Blockchain's Grand Promise for the Real Estate Sector: A Systematic Review," Applied Sciences, vol. 12, 11940, 2022.
[66] Li J, and Zhou H, "Impact of Radial Grounding Model Granularity on Directivity of 433 MHz Monopole Antennas with Flat and Inclined Radials for ISM IoT Applications," Annals of Emerging Technologies in Computing, vol. 9, no. 1, pp44-57, 2025.
[67] Marinšek A, Delabie D, De Strycker L, and Van der Perre L, "Physical Layer Latency Management Mechanisms: A Study for Millimeter-Wave Wi-Fi," Electronics, vol. 10, pp1599, 2021.
[68] de Almeida M, and Canedo E, "Authentication and Authorization in Microservices Architecture: A Systematic Literature Review," Applied Sciences, vol. 12, pp3023, 2022.
[69] Li J, and Li H, "Liquid Crystal Technology for IoT and Beyond: Advancements and Future Directions," 2025 IEEE/IFAC International Conference on Control, Automation, and Instrumentation (IC2AI), Beirut, Lebanon, pp1-5, 2025.
[70] Li J, and Li H, "Reconceiving Impedance Matching and Mismatching to Mitigate Bias-Drift in Insertion Loss of Liquid Crystal Phase Delay Lines," Photonics Lett. Pol., vol. 17, no. 1, pp35-37, 2025.
[71] Siddiky M, Rahman M, Uzzal M, and Kabir H, "A Comprehensive Exploration of 6G Wireless Communication Technologies," Computers, vol. 14, pp15, 2025.
[72] Li J, and Li H, "FEM Solution Database for Liquid Crystal GHz and THz Coaxial Phase Shifters in Digital Twinning," 2024 IEEE Virtual Conference on Communications (VCC), NY, USA, pp1-5, 2025.
[73] Li J and Li H, "Passive-active crosstalk beyond low-frequency breakdown in mathematical-physical models of liquid crystal phase shifters at low-frequency applications," IET Conference Proceedings, vol. 2024, 30, pp592-596, 2025.
[74] Li J, "Will 'Liquid-Crystal-Based Floating-Electrode-Free Coplanar Waveguide Phase Shifter With an Additional Liquid-Crystal Layer for 28-GHz Applications' Work?" Engineering Letters, vol. 31, 2, pp 820-824, 2023.
[75] Khairul I, Noor R, Nur M, Ghazali S, and Md J, "Smart Cities' Cybersecurity and IoT: Challenges and Future Research Directions," IAENG International Journal of Computer Science, vol. 51, no. 7, pp725-737, 2024.
[76] Li J, "Introductory Chapter: Establishing New Life in Terahertz Reconfigurability," Journey Into Terahertz Radiation - Exploring the Invisible Frontier, IntechOpen, 2025.
[77] Scalise P, Boeding M, Hempel M, Sharif H, Delloiacovo J, and Reed J, "A Systematic Survey on 5G and 6G Security Considerations, Challenges, Trends, and Research Areas," Future Internet, vol. 16, no. 3, pp67, 2024.
[78] Goranin N, Hora S, and Čenys H, "A Bibliometric Review of Intrusion Detection Research in IoT: Evolution, Collaboration, and Emerging Trends," Electronics, vol.13, no. 16, pp3210, 2024.
[79] El M, "Enhancing Communication Networks in the New Era with Artificial Intelligence: Techniques, Applications, and Future Directions," Network, vol. 5, no. 1, pp1, 2025.

Jinfeng Li (M'20) is a Microwave Engineering Scientist, a specialist in novel reconfigurable RF devices, as well as an authority on liquid crystals-based microwave and millimeter-wave technology. He received the B.Eng. degree (1st class) in electrical and electronics engineering from the University of Birmingham and Huazhong University of Science & Technology, in 2013, the MPhil degree in nuclear energy from the University of Cambridge, in 2014, and the Ph.D. degree in liquid crystals microwave and millimeter-wave electronics engineering from the University of Cambridge, in 2019.

From 2019, he joined the University of Southampton as a research fellow, Imperial College London as a visiting research fellow, and Nuclear Futures Institute (Bangor University) as a research associate. He is currently an Assistant Professor with the Beijing Key Laboratory of Millimeter Wave and Terahertz Technology as well as the Advanced Research Institute of Multidisciplinary Science at Beijing Institute of Technology. He is also an Adjunct Professor at the Key Laboratory of Short-Range Radio Equipment Testing and Evaluation, Ministry of Industry and Information Technology and Terahertz Science Application Center (TSAC). In the past ten years, his research experiences include (1) microwave and millimeter-wave beam steering and tunable devices based on liquid crystals for 5G/6G, inter-satellite communications, and radio astronomical instrumentation; (2) wireless surface acoustic wave sensors antenna array for monitoring the

structural integrity of LNG tanks; (3) light water reactor thermal hydraulics facility and instrumentation development in North Wales; (4) optical fiber based multi-phase flow characterization; (5) computational modelling of nuclear reactor core using Monte Carlo and deterministic methods for nuclear energy policy decision-making; (6) motor drives of multilevel multicell inverters for fuel economy and sustainable cities; (7) application security and sentiment analysis of big data for stock market forecasting; (8) contact tracing and health informatics for COVID-19 (cited by PNAS and Lancet Public Health). He has edited two books (1. Advances in Sentiment Analysis - Techniques, Applications, and Challenges, ISBN: 978-0-85014-060-6; 2. Journey Into Terahertz Radiation - Exploring the Invisible Frontier, ISBN: 978-1-83634-113-0), authored or co-authored over 80 journals and conference papers.

Prof. Li was a recipient of the IET Award, the AP Jarvis Prize (highest final-year-project honour in University of Birmingham), the AETiC Highly Cited Article Award 2023, and three Best Paper Awards at IEEE, IOP and IET conferences, respectively. He was a Cambridge Trust Scholar, Speaker at IEEE AP-S/URSI 2024 and the 50th & 46th European Microwave Conferences, Emerging Technologist with Barclays UK, Editorial Board member of three Science Citation Index journals, TPC and Session Chair of seven IEEE conferences, including IEEE ISAP (27th International Symposium on Antennas and Propagation), IEEE 15th International Conference on Microwave and Millimeter Wave Technology (ICMMT 2023), IEEE/IFAC 10th International Conference on Control, Decision and Information Technologies (CoDIT 2024), IEEE COINS 2024, IEEE VCC 2024, IEEE SNAMS 2019, and 5th China and International Young Scientist Terahertz Conference etc. He was elected Senior Member of the China Institute of Communications (CIC), Top 1% Reviewer on Publons (Web of Science), Reviewing Expert for the China Academic Degrees and Graduate Education Development Center, Grants Reviewer for the National Natural Science Foundation of China (NSFC), Newton Prize (£1m fund) reviewer for the UK National Commission for UNESCO, and Grants Reviewer for the Health and Social Care Delivery Research (HSDR) fund from National Institute for Health Research (NIHR), UK.

Prof. Li is also an award-winning Concert Pianist and Composer with over 20 piano recitals across China and the UK (2004 - now). Prof. Li was elected National-level Young Talent in 2023. He teaches four undergraduate modules including (1) States of the Arts in Liquid Crystals Millimeter-wave Technology for 6G; (2) Frontiers and Progress of Electrical and Computer Engineering; (3) States of the Arts in Piano; and (4) Frontiers of Electronic Science and Technology. He and his student won the Best Paper Award at IET GEn-CITy 2024.

Haorong Li is pursuing a postgraduate degree in microwave and terahertz engineering at Beijing Institute of Technology under the supervision of Prof. Jinfeng Li who leads the Liquid Crystal Millimeter-wave Technology Group. Haorong received the Special Scholarship from the School of Integrated Circuits and Electronics and was awarded the Excellent Postgraduate Student title at Beijing Institute of Technology in 2024. He won the Best Paper Award (Student) at IET International Conference on Green Energy, Computing and Intelligent Technology (GEn-CITy 2024).