Liquid Crystal-centric Artificial Intelligence of Things for Urban Scenes and City-scale Public Sector Modernization Towards General Reconfigurability for Artificial General Intelligence and Artificial Superintelligence

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***Abstract*—The landscape of embodied Artificial Intelligence (AI) with liquid crystals (LC) as a hardware solution for sensory and communication capabilities simultaneously is first proposed in this work, targeting an expanded portfolio of devices for city-scale public sectors beyond small-scale indoor applications. The productivity and necessity of using LC are due to its versatility of continuous phase programmability (phase shifters), impedance variability (impedance-tuning adapters), resonance tunability (variable bandpass filters), and polarization changeability (variable polarizers). Furthermore, the stepless tuning (analogue functionality) for high-fidelity, high-resolution spatial/temporal control is highly suitable for explainable and scalable AI. All these functionalities are achievable in low insertion loss and with low-cost, low-power (up to 10 V) electronic biasing, exhibiting the potential of upgrading into Artificial General Intelligence (AGI) and gravitating towards Artificial Superintelligence (ASI) products, solutions and services. This work identifies three cross-domain research activities that integrate AI with LC, drawing on insights gained from our previous research endeavors specific to LC. Additionally, it explores the challenges and strategic roadmaps that support LC-assisted tunability within the contexts of Artificial General Intelligence (AGI) and Artificial Superintelligence (ASI).**

I. Introduction

While the phased array beam steering (PABS) technology has a storied history [1–4], dating back to the early generation of radars [5] for military use cases, and permeating follow-up civil applications in wireless communications, navigations (e.g., maritime), sensing (e.g., agriculture), climate monitoring, in recent decades, its integration in the public sector has just begun to take shape. Public sector use of the PABS technology is on the rise, as driven by the ever-growing civil demand on IoT (internet of things) and AIoT (artificial internet of things) in the smart city landscape, as credibly evidenced in the market projected 582 billion by 2028 in the context of rolling out the next-generation (G) wireless networks (5G and 6G) zeroing in on unlimited and intelligent connections, wherein the remote regimes (e.g., waterways, oceans, space) and the smart cities are intimately connected.

In alignment with the growing public interest in artificial intelligence (AI) and 5G wireless technology—alongside the anticipated transition to 6G networks—particularly in the realm of explainable AI [6–10] and ethical considerations [11], the development of high-performance hardware solutions for radio access networks (RAN) is of paramount importance. Such solutions must be characterized by robustness, controllability, low signal loss, and cost efficiency while ensuring adherence to ethical standards for new services (and facilitating the revenue growth), as illustrated in Fig. 1.

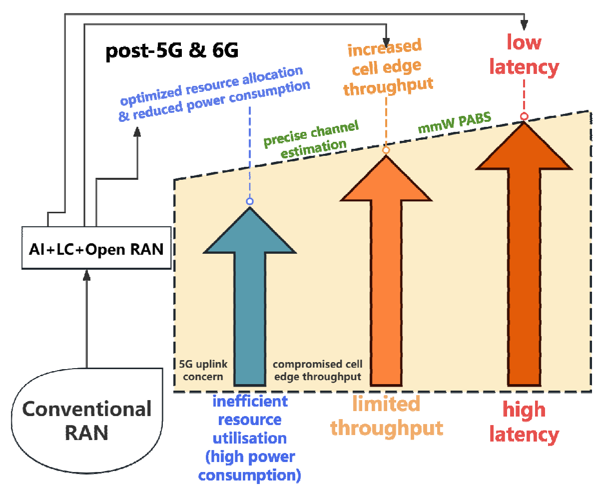

Figure 1. Advancing Radio Access Networks (RAN) through integration of Artificial Intelligence (AI), Liquid Crystals (LC), and Open RAN.

While research and development efforts in AI model training have predominantly centered on data-driven approaches and software solutions within the disciplines of information technology and computer science [12–14], hardware-centric innovations—particularly in reconfigurable hardware solutions—from the perspective of wireless communication and electronic engineering for AI-powered Internet of Things (AIoT) applications remain relatively underexplored. This imbalance has contributed to the underwhelming performance of 5G, which has failed to introduce new services capable of driving revenue growth for network component suppliers, vendors, manufacturers, and operators. Consequently, this shortfall has impeded the

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full-scale deployment of 5G, including the transition to higher-data-rate millimeter-wave (mmW) services.

To address this gap, the present work aims to revolutionize existing wired and wireless communication networks through the development of cost-effective and reconfigurable components for realizing PABS of electromagnetic (EM) waves—particularly in the mmW spectrum—a fundamental technology for 5G and beyond. As depicted in Fig. 2, various approaches can be employed to achieve phase and/or amplitude reconfigurability of EM waves, with a particular focus on mmW [15,16] for next-generation wireless networks.

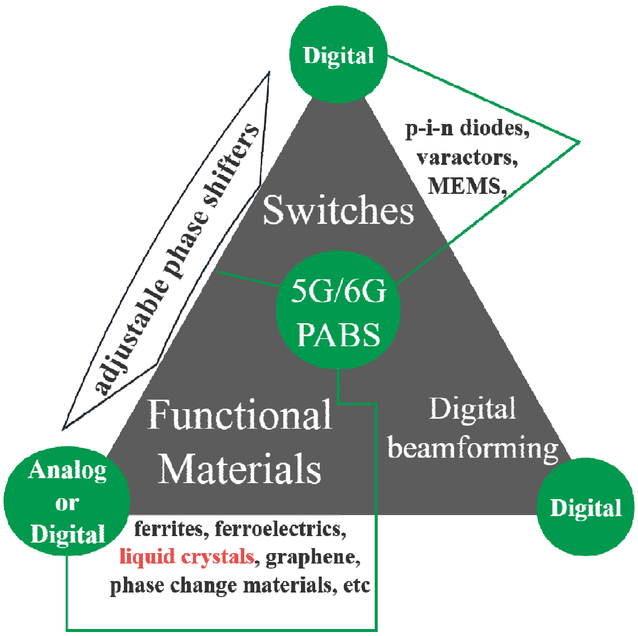

Figure 2. Methods of reconfigurability for 5G and 6G phased array beam steering (PABS), enabling a wide range of modern civil applications, including communications, sensing, navigation, and detection.

II. Synergizing Cross-domain Research Activities

A. *Hazard Perception by Predictive Adaptive Beam Tracking (ABT) with LC-AI*

The inherently continuous beam-steering capability [17,18] of LC-based hardware, when integrated with AI-driven algorithms [19], enables the prediction and identification of previously undetected hazards by analyzing mobility patterns of users or targets. This capability significantly enhances hazard localization, particularly in applications such as autonomous driving within specific urban regions. Notably, this AI-LC integration in the public sector offers fine spatial resolution—a critical advantage—for beam tracking, resulting in lower localization errors. Moreover, the high-resolution capabilities of LC-assisted AI systems improve the quality of training data collection and extraction, thereby enhancing the system's overall explainability.

Beyond transportation and urban safety, LC-enabled adaptive beam tracking (ABT) for AI-powered Internet of Things (AIoT) applications holds considerable potential for the agricultural sector. By enabling targeted intervention, such as the precise application of nutrients and pesticides, this technology can substantially reduce costs while ensuring that only affected plants receive treatment, thereby protecting healthy crops from unnecessary chemical exposure. Additionally, the development of next-generation seismometers based on extremely-low-frequency phased array technology with LC [20,21] represents a promising avenue for advancing geophysical monitoring and early warning systems. These innovations collectively demonstrate the transformative impact of LC-integrated AI across multiple domains, from urban mobility and precision agriculture to environmental sensing and hazard detection.

B. *Smart Power Saving for Sustainability with LC-AI*

In conventional phased array antenna systems, which currently operate without AI assistance, all radiating elements and their associated phase-feeding networks are continuously powered during service. However, by incorporating AI algorithms that can understand and predict user (or target) behaviors in a specific application within an urban environment, the power requirements can be optimized. This can be achieved by selectively deactivating certain portions of the array or transitioning them into standby mode during low-traffic periods, such as specific scheduled times. This approach not only improves energy efficiency and sustainability by reducing power consumption but also extends the lifespan of the hardware, thereby lowering maintenance costs and minimizing downtime. The cost reductions resulting from power savings are expected to play a crucial role in the rollout of 6G networks, where large-scale infrastructures with thousands of antennas and sensors will be required for complex communication-sensing-imaging applications.

In addition to the energy savings achieved at the array scale, local power-saving and stabilization within the LC-based components are equally important. The first approach for insertion loss stabilization was introduced in our LC-based coplanar waveguide (CPW) phase shifters [22] and their variants [23,24]. To evaluate the effectiveness of this approach in a representative application at 79 GHz, a 0–360° differential phase-shifting device was designed and implemented using a CPW PDL topology. This design incorporates two coplanar channels filled with LC, and three different baseline bias voltages for 50 Ω impedance matching (0 V, 1 V, and 5 V) were computationally simulated using identical statistical convergence settings ($\Delta S<0.01$ dB) in HFSS (high-frequency structure simulator). The resulting designs for prototyping, which correspond to different cross-sectional (XS) geometries, were numerically analyzed for the insertion loss (IL) across a bias voltage range of 0 V to 10 V (saturated bias). The maximum (max.) and minimum (min.) values, as well as their deviations, are quantified in Table I.

TABLE I. Evaluation of the Effectiveness of the Impedance Matching-Bias Voltage Baseline Method For An LC-filled Coplanar Waveguide (CPW) PDL (0–360°) at 79 GHz.

Bias voltage for 50 Ω matching	**Simulated Performance Evaluation with HFSS**		
	Max. Insertion Loss (IL)	***Min. IL***	***Max. ΔIL***
5 V-match XS design	7.56497 dB	2.94281 dB	4.62216 dB
1 V-match XS design	6.45103 dB	3.51382 dB	2.93721 dB
0 V-match XS design	6.41491 dB	3.60432 dB	2.81059 dB

Inspired by the simulated insights from the cross-sectional designs, proof-of-concept demos of 0–180° PDL with LC are fabricated. Initial experiments involved perturbing the impedance matching baseline across various biasing voltages (from 0 V to 10 V in 1 V increments), leading to 11 distinct designs with varying cross-sectional (XS) geometries, as selectively illustrated in Figs. 3 and 4. Figure 3 presents the measured insertion loss across the entire biasing voltage range (0 V to 10 V) for each selected design, where impedance matching is optimized at specific bias points. Additionally, Figure 4 identifies the maximum insertion loss (i.e., the minimum S21 value measured) for each design and correlates it with the corresponding bias voltage that optimizes impedance matching. As observed from the results, the 0 V matching baseline (corresponding to a cross-sectional design with 50 Ω matched at the 0 V tuning permittivity state) leads to the minimum value of the max. insertion loss (among the 11 designs as per Fig. 4). This well agrees with the simulated phenomenon shown earlier in Table I, i.e., the 0 V-match XS design works optimally for the AI system integration targeting power saving.

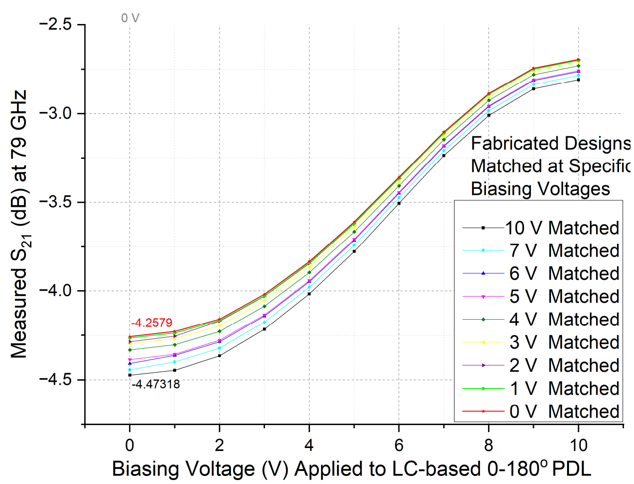

Figure 3. Measured insertion loss across the entire biasing voltage range (0 V to 10 V) for each 0–180° PDL design (with different biasing baseline for 50 Ω match).

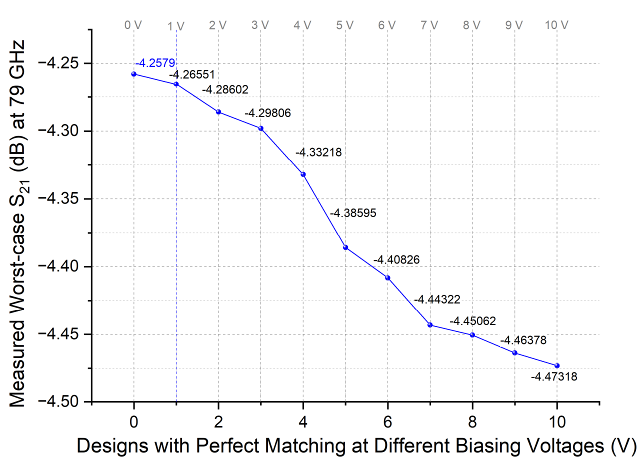

Figure 4. Measured maximum insertion loss (worst-case S21) for eleven designs of 0–180° PDLs (matched at diverse biasing voltages).

However, it is important to note that the transmission line lengths of these fabricated designs are kept constant to achieve the desired 0–180° differential phase shift (DPS) for a specific baseline design, such as matching at 0 V. Consequently, designs with different impedance-matching baselines and biasing voltages may result in a DPS that exceeds or falls short of the intended 180° specification (serving sub-terahertz intelligent reflective surfaces [25] for 6G). This discrepancy introduces inconsistencies when evaluating insertion loss, as designs are compared at a fixed line length, whereas many practical PABS implementations require a max. DPS of exactly 180°. To make a fair comparison, it is necessary to adjust the line length of each design to ensure that the max. DPS is precisely 180°.

Given the adjustment is numerically conducted with a full-wave simulator (e.g., HFSS), it is crucial to analyze the performance variations (characteristic impedance and S-parameters) by running standalone line length models separately (instead of conducting a single scan of the full-length range). Particularly for the DPS evaluation, as indicated by our full-wave computational vulnerability study conducted recently and reported in [26], a single scan of the line length, albeit time-efficient in modelling and data processing, can lead to unambiguity of the phase reference for computing a reasonably explainable DPS. On the other hand, a standalone running approach is time-consuming and memory-hungry (requiring the user to manually establish separate models of different line lengths for performance assessment of each design individually).

With the introduction of AI, the AI-assisted phased reference correction algorithm (development underway based on training from our DPS predictive error patterns obtained so far [26]) will not only address the defects as raised in [26], i.e., providing a more accurate assessment of the performance of the LC-based phase shifters in practical applications, but also enables the power-saving mode in online parameter scanning of the optimum biasing voltage baseline for strategic impedance matching and total insertion loss mitigation.

C. *Interoperable Information Mapping and Screening for Decision-making with LC-AI*

Given the recent limitations of 5G [27,28], public acceptance of AI and the transition to the forthcoming 6G era remain uncertain, particularly among non-specialist audiences. The demand for seamless interoperability between AI and wireless technologies—free from restrictive hierarchical structures and vulnerable to eavesdropping—has become increasingly urgent.

LC technology has shown significant promise in advancing this interoperability by securely enhancing information mapping (as demonstrated by the anti-eavesdropping functionality in the urban senior scenario depicted in Fig. 5) and supporting the evaluation of data accuracy, thus improving data screening processes. In Fig. 5, the LC-based phase delay line demonstrations are electronically controlled through low-voltage, low-power biasing networks (ranging from 0-10 V) with analog-tuning resolutions, enabling the production of highly agile and steerable beams that only target legitimate receivers (users) in urban environments susceptible to eavesdropping, as enabled by the AI-assisted intelligent biasing control for the phased array. By exploiting the unique optical and electronic properties of LC for hardware-software integration, high-quality data can be securely acquired, mitigating risks of interception or eavesdropping. This approach enhances the reliability and transparency of decision-making processes. This capability is particularly crucial in bridging the divide between under-resourced, data-scarce environments and well-equipped, data-rich settings.

Furthermore, LC-based systems enhance data visualization and screening, improving information accessibility across diverse technological and economic landscapes. By mitigating the risks of vendor lock-in, these systems ensure broader applicability and usability of AI-driven insights, effectively making the invisible visible and strengthening the overall quality of data-driven decision-making. Furthermore, the service layer utilizes network slicing to allocate LC-AIoT resources dynamically, where LC tuning parameters (bias-dependent phase and amplitude) become optimization variables in deep learning [29] and federated learning loops [30].

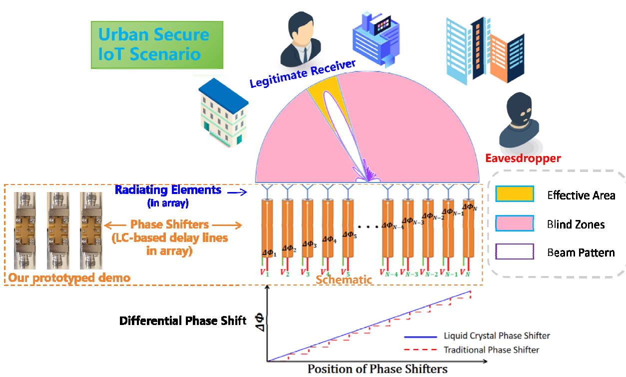

Figure 5. An end-to-end secure urban AIoT framework integrating LC-based phase delay lines (PDL).

III. Challenges and Opportunities for AGI and ASI with LC

Despite the LC-incorporated ascendancy, several challenges remain, including the need for faster response times, enhanced material stability, and seamless integration with AI-driven network architectures to ensure optimal performance in next-generation wireless communication systems. The severity of each challenge is rated on a scale from 1 to 5 as depicted in Fig. 6.

Arguably, the future of intelligent systems lies in seamless integration—where advanced materials (e.g., LCs), adaptive algorithms, and contextual services converge. The service layer leverages these capabilities through federated learning [30], where distributed LC-AIoT nodes on the edge collaboratively refine models without centralized processing.

Looking further ahead, as Artificial General Intelligence (AGI) demands embodiment, the proposed LC matrices could pioneer morphable hardware—smart reconfigurable surfaces enabled by electro-responsive LC elastomers that shift texture/stiffness to mimic human touch, or optical arrays that self-optimize for neural network vision tasks.

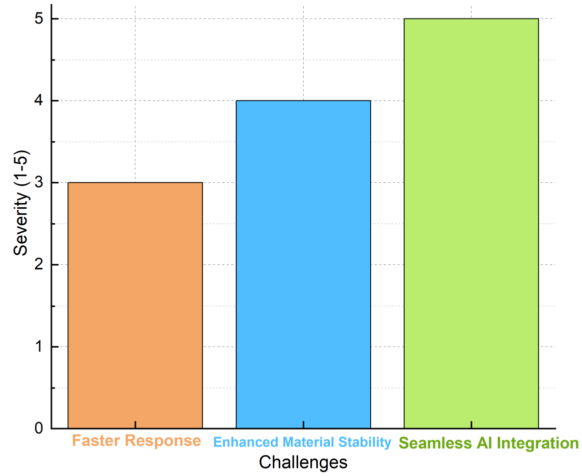

Figure 6. Projected challenges for envisioned combination of LC and AI.

Pushing the operating frequency further for constructing optical neural networks, LC-based tunable waveguides can implement reconfigurable photonic circuits, enabling real-time, low-latency inference. Here, the software layer integrates physics-aware AI [19], treating LC material dynamics as differentiable parameters in neural network training—effectively merging hardware properties with algorithmic learning.

For Artificial Superintelligence (ASI) and its cosmic-scale computational demands, LC's quantum potential (room-temperature qubits) might unlock energy-efficient three-dimensional (3D) processing architectures [31]. Room-temperature macroscopic quantum effects in certain LC phases [32] could lead to novel computing paradigms. Moreover, LC's mesophases [33,34] with self-aligning properties enable fault-tolerant photonic computing. The service dimension here involves autonomous diagnostics [35], i.e., LC-based nano-sensors for monitoring system integrity and triggering self-reconfiguration before failure. In this regard, LC is by no means just a material—it's the bridge between silicon [25], synapse [36], and service [18]. The next-generation intelligence stack won't just compute; it'll adapt, perceive, and serve—all in one crystalline blink.

Although proponents of AGI and ASI advocate for the pursuit of knowledge free from political interference, public acceptance and support from local authorities remain uncertain, particularly during the ongoing 5G rollout, where network capabilities often outpace available services [18,37]. This discrepancy raises significant challenges for integrating emerging hardware technologies—such as LC-based solutions—into AI-native networks to fulfil the AIoT vision. For many, AI and its ethical considerations remain an opaque "black box" [6,10], largely due to the lack of explainability in training data processing and extraction. This suggests the urgent need for demonstration experiments and real-world testing of LC-enabled AI use cases to enhance transparency and foster broader acceptance. Moreover, skepticism surrounding the slow response speed of LC-based reconfigurable devices in ultra-fast-switching applications persists, given the limited empirical evidence on LC's temporal deployment. Addressing these concerns necessitates advancements in LC chemistry (and new physics) to enhance reorientation speeds, thereby reinforcing confidence in its viability for unlocking high-speed AI-driven applications.

Arguably, to mainstream LC-based reconfigurable devices and fully realize the potential of next-generation (5G and beyond) communication systems and beyond, it is imperative to develop strategies that maximize performance while maintaining adaptability in an evolving technological landscape. This necessitates breakthrough innovations in LC-based phase shifters, optimizing their tuning range and energy efficiency to ensure that future communication systems are not only high-performing but also environmentally sustainable. The coaxial-accommodating method for LC PDLs is excellent in electromagnetic shielding as compared to planar inverted microstrip line (IMSL) and CPW, but the coaxial one reduces the tuning range significantly due to the difficulties [22] in producing the pre-alignment layer and performing the mechanical treatments on the radial surface of the core line as well as the housing conductor, both structured in a cylindrical manner [23]. The strip line [38], featuring planar arrangement of the substrates and the core line, and at the same time maintaining the substantial advantages of an enclosed structure (like the coaxial ones), may bridge the gap and tip the balance in realizing this vision.

A critical issue arising from the currently oversimplified perception of AI-LC integration is the overestimation of system capabilities, which may lead to unrealistic expectations and hinder practical deployment (drawing the lessons learned from the current disappointment on 5G). One promising solution lies in digital twinning [39–41] and virtual prototyping, enabling rigorous simulation and validation of LC-based AI systems before large-scale implementation. These tools can provide valuable insights into real-world performance, bridging the gap between theoretical models and empirical deployment. Beyond advancements in proprietary systems, the demand for software-defined radio (SDR) and open-source radio access network (RAN) [42–44] paradigms is growing louder than ever. AI-driven RAN (AI-for-RAN) frameworks can further enhance adaptability and efficiency, ensuring seamless integration of LC-based reconfigurable hardware within future wireless communication infrastructures.

IV. Concluding Remarks

This work establishes a clear framework and a set of strategic pathways toward achieving standardized phase reconfigurability using liquid crystals (LC) for high-spatial-resolution beam steering, with a particular focus on its applications in Artificial General Intelligence (AGI) and Artificial Superintelligence (ASI) within the public sector. By integrating LC-based hardware with AI-driven algorithms, this study highlights the potential of these technologies to enhance network performance, improve decision-making transparency, and support emerging AIoT applications. Arguably, LC exhibits dynamic reconfigurability (in phase and amplitude) at low power, making them ideal for AIoT edge applications. LC's electro-optical tunability, when combined with 5G's ultra-reliable low-latency communication and 6G's sub-terahertz reconfigurable surfaces, is envisaged to create a synergistic triad of responsive matter, edge intelligence, and autonomous services, i.e., leveraging LC-enabled technology as a unifying platform for AIoT, AGI, and ASI.

However, the successful deployment of LC-based devices in next-generation (5G/6G) networks requires high-granularity temporal planning to justify their adoption and drive a widespread infrastructure upgrade. Without a structured and well-defined implementation roadmap, the transition risks inefficiencies and setbacks that could impose high costs on network operators and stakeholders. To mitigate these challenges, a unified framework must be established, ensuring that deviations from standardized deployment strategies do not lead to unnecessary delays or resource misallocation. Furthermore, the integration of digital twinning and virtual prototyping will be instrumental in refining LC-based technologies before large-scale rollout, allowing for iterative optimizations and enhanced predictive modelling. Similarly, the advancement of software-defined radio (SDR) and open-source radio access network (RAN) paradigms will foster greater interoperability, reducing dependency on proprietary systems and accelerating innovation in AI-native networks.

By addressing these challenges and leveraging cutting-edge advancements in LC chemistry, AI-driven RAN, and phase-shifting optimization, this work provides a foundational roadmap for unlocking the full potential of LC-based reconfigurable devices beyond the wireless communication landscapes, i.e., LC technology is not merely a passive component but an active participant in the intelligence value chain. By unifying responsive hardware, adaptive algorithms, and autonomous service layers, LC-based systems can underpin AIoT's edge adaptability, AGI's embodied cognition, and ASI's ultra-efficient computation. Future research shall explore LC-embedded neuromorphic architectures, quantum LC phenomena, and self-sustaining service frameworks to realize this vision.

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