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Communication

From Liquid Crystal on Silicon and Liquid Crystal Reflectarray to Reconfigurable Intelligent Surfaces for Post-5G Networks

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Abstract: This communication aims to address the recent surge of interest in reconfigurable intelligent surfaces (RISs) among both academic and industrial communities, which has largely neglected the historical developments of two other underpinning technologies, i.e., liquid crystal on silicon (LCOS) and liquid crystal reflectarray antenna (LCRA). Specifically, this communication focuses on the state of the art of LC-RIS, highlighting the unique features of this newly raised enabling technology for post-5G (6G) networks and comparing it to LCOS, which operates at different frequencies and is suited to different use cases. Drawing on insights from existing knowledge of LCOS and LCRA, opportunities and challenges are explored for LC-RIS's technical advancements in enhancing the coverage, capacity, and energy efficiency of wireless networks. In particular, the development status and roadmap of LC-RIS in China is reviewed.

Keywords: electromagnetics; intelligent reflecting surface; liquid crystal; liquid crystal on silicon; phased array; reconfigurable intelligent surface; RIS; reflectarray; 5G; 6G

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1. Introduction

While 5G [1] is a significant improvement over 4G, 6G (albeit in an early conceptualization stage) is envisioned to take wireless technology to the next level, offering even faster speeds (from 100 Gbps to 1 Tbps) [2], lower latency (as low as 1 µs) [3], wider coverage (access to remote areas by satellite internet [4]), and more advanced capabilities (combining THz and optical frequencies [5]).

One of the key challenges in expanding wireless coverage is the limited range of high-frequency radio waves that are used for 5G and 6G. Signal transmission in the THz and millimeter-wavelength ranges experiences significant attenuation and may be entirely obstructed by obstacles present in the propagation environment. To overcome this, one approach being explored is the use of low earth orbit (LEO) satellites [6] to provide global coverage and low-latency connectivity. SpaceX and Amazon are already launching large-scale satellite constellations for internet connectivity with expanded coverage. Alternatively, researchers are exploring new technologies such as "mirrors"-based intelligent reflecting surfaces (IRSs) [7,8], which employ software-controlled mirrors (a host of passive reflecting elements) to reflect and focus radio signals (pencil beam) to a desired direction, thereby enhancing the signal strength and reducing interference, allowing them to penetrate obstacles and extend coverage. These surfaces are usually static and do not have the ability to change their reflection properties.

To obtain additional capability of dynamically changing reflection properties in response to the wireless environment, the concept of reconfigurable intelligent surface (RIS) was introduced in recent years [9–12]. RISs can be programmed to change the phase and amplitude of reflected waves, which allows them to actively manipulate the direction and strength of the reflected signals, making them more flexible and adaptable than mirror-based IRSs. The concept of RIS was first introduced in [9], entitled "Smart radio environments empowered by reconfigurable AI meta-surfaces: an idea whose time has come", by Marco Di Renzo et al. The paper [9] presents the preliminaries and potential applications of RISs, which are surfaces made of an array of tunable elements that can reconfigure the propagation of electromagnetic waves. Since then, RIS has become an active area of research, and numerous studies have been conducted to investigate its capabilities and potential uses [10–14]. For most cases, metasurface is utilized as a relay that reflects the signal from the source toward the destination to enhance the signal-to-noise ratio.

This communication points out the fact that the concept of RIS is arguably not new if being viewed from the angle of liquid crystal reflectarray (LCRA), which has been established for more than two decades [15], and liquid crystal on silicon (LCOS), which has existed even earlier for more than three decades [16,17], of which people who are dedicated only to the field of microwave engineering might not be fully aware.

Technically, the main principle and major functionalities are transferable among LCRA, LCOS, and the emerging RIS, but they differ in their operating frequencies and corresponding use cases (illustrated in Figure 1), which will be discussed in Section 2. The main obstacles preventing liquid crystals (LCs) from dominating (or creating) the RIS concept earlier (in another word, to facilitate the conceptualization of RIS for an earlier exposure) are due to the inherent challenges (bottleneck) of LC-based phase-shifting technology, which will be specified in Section 3. This semi-technical review provides a novel perspective on the evolution and potential of RIS technology, leveraging insights from previous LC-based reconfigurability research to inspire new developments in this field.

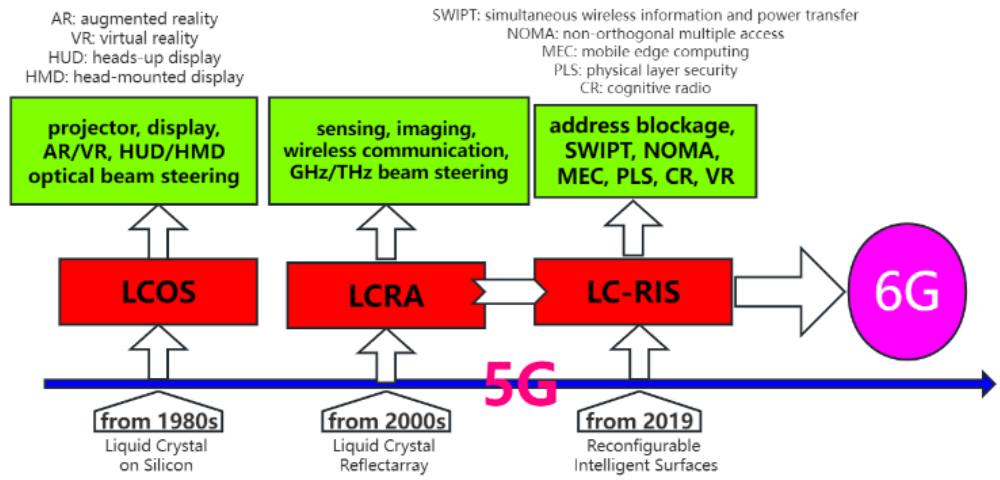

Figure 1. Technological progression of LCOS, LCRA, and LC-RIS.

2. Status of RIS and LC-RIS

2.1. Methods to Achieve RIS Inspired by LCRA and LCOS

Current approaches to realize RIS are categorized in Figure 2. Interestingly, the technological candidates identified here are mostly identical with those used to achieve microwave and millimeter-wave phase shifters [18], except for digital/programmable metamaterials [19] and software-controlled metasurfaces [9,12]. Extensive research and excellent reviews on these candidates have been presented in previous publications on LC-based phase shifters [20] and phased array beam steering [21], which agree with our argument that the "new" concept of RIS could arguably be seen as being driven by LC, more specifically by LC phase shifters based on phased array [22] or LC reflectarray [23,24].

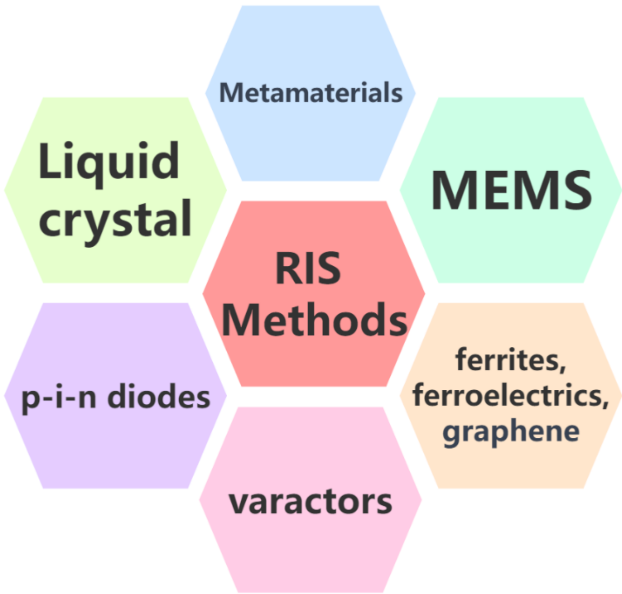

Figure 2. Methods to construct RIS.

Liquid crystal on silicon (LCOS) technology [25–28] has been in existence for several decades, and it is primarily used in display technology. LCOS works by reflecting light off a mirror coated with a layer of liquid crystals that can be electrically controlled to change the angle of the reflected light to generate high-resolution images. LCOS displays are known for their high brightness, contrast, and color accuracy, making them suitable for a wide range of applications, including projectors, head-mounted displays, and augmented reality devices. While LCOS can modulate light waves, its performance in modulating microwaves or radio waves is limited due to the size of the liquid crystal pixels and the operating frequency range. However, LCOS technology has recently been leveraged to drive the emergence of LC-RIS.

LC-RIS, on the other hand, uses a surface coated with an array of small liquid crystal pixels that can be individually controlled electronically to manipulate the phase, amplitude, and polarization of incident electromagnetic waves (including radio waves, microwaves, millimeter waves, THz, and light waves), producing customized wavefronts that can be used to redirect, reflect, or scatter incoming signals in real time and, thus, exhibiting potential applications in wireless communication (by enabling more efficient and secure transmission of data), as well as radar and imaging systems. Numerous examples of RIC-aided networks are illustrated in [14]. Arguably, the emergence of RIS has provided a new way to think about displays and communication systems. RIS technology has the potential to revolutionize the way we interact with our environment and improve many aspects of our lives. As the research in this area continues, we can expect to see even more exciting applications of RIS technology in the future.

2.2. Advantages of LC-RIS vs. RIS with Other Methods

First, from traditional mirror-based IRS to the emerging RIS, technological evolution represents a leap from uncontrollable to controllable (reconfigurable). Second, from p-i-n diode or MEMS-based switches to LC-enabled reconfigurable techniques, RIS is undergoing a revolution from digitally controlled steps (bringing undesired phase quantization effects) to continuously tuned beamforming (analogue control with ultra-high spatial resolution), i.e., the long-lasting challenges of discrete phase-shift levels posed by traditional switch-based technologies can be fully addressed by LC phase-shifting network-based antenna array beam steering. The achievable tuning resolution (spatial) is infinitely fine in theory. Table 1 presents a comparison of the potential performance of LC-based RIS and other mechanisms.

Table 1. Selective performance indicators of diverse phase-shift mechanisms for constructing RIS.

Technology	Phase-Shift Resolution	Power Consumption	Insertion Loss (in GHz)	Response Speed
LC phase shifters	Analog tuning (stepless)	Low for transmission line. Moderate for waveguide.	Low for waveguide. Low/moderate for transmission line.	Slow (milliseconds to seconds)
Semiconductors and MEMS phase shifters	Digital tuning (binary)	Relatively moderate	High/moderate	Fast (nanoseconds to microseconds)
Ferrite and ferroelectric phase shifters	Digital tuning (binary)	Relatively high	High	Moderate (microseconds to milliseconds)

Lower insertion loss (in the microwave and millimeter-wavelength ranges) [29] is another strength of LC against semiconductors and MEMS. In terms of ferrites and ferroelectrics, high power consumption and high insertion loss remain unaddressed; hence, they are not the optimal solutions for RIS.

Concerning the entire costs, LC-filled units are relatively easy to manufacture and have been widely used in display technology for decades. As a result, they are readily available at a low cost, making them an attractive option for RIS applications. Contrarily, metamaterials require more complex and expensive manufacturing processes, and their properties are fixed once they are fabricated. This means that they are not as flexible or adaptable as LCs.

Furthermore, LCs are compatible with a wider range of frequencies than many metamaterials. This makes them more versatile and allows them to be used in a broader range of ultra-wideband applications, e.g., by placing LC-RIS surfaces in strategic locations, such as buildings, vehicles, or outdoor environments, they can be used to reflect, refract, or absorb electromagnetic waves to enhance signal strength and mitigate interference. This can help to improve the overall performance of wireless communication systems in terms of data rates, reliability, and latency.

Another area where LC-RIS can be applied in 6G is in enabling intelligent signal processing. By controlling the phase of reflected waves, LC-RIS can be used to create complex electromagnetic wave patterns that can be used to encode information. This can be used to create new types of communication systems that are more efficient and reliable than existing systems.

3. Challenges of LC-RIS and Future Outlook

All three technologies (LCOS, LCRA, and LC-RIS) rely on the unique properties of liquid crystal materials, which can be continuously manipulated by applying a low-frequency electric field. They are also all capable of reconfiguring their properties in real time, making them useful for a variety of applications in communication, sensing, and imaging. However, there are several technical hurdles (illustrated in Figure 3) that must be overcome to realize their full potential. These drawbacks are attributed mainly to the use of LC, more specifically to the intrinsic properties of LC, as discussed below.

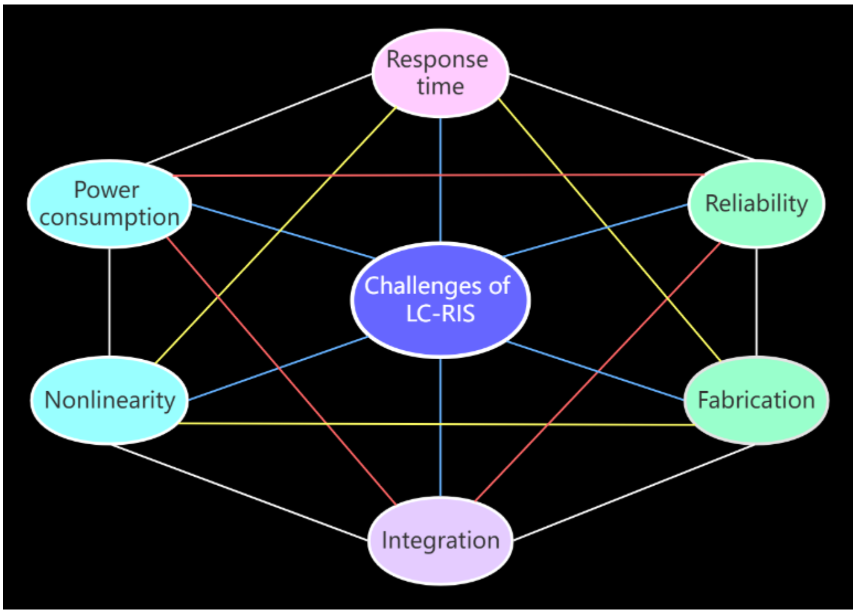

Figure 3. Challenges of LC-RIS.

Firstly, LC materials in nematic phase typically have relatively slow response times (in seconds or milliseconds) compared to other materials, e.g., semiconductors (in microseconds). This can limit the speed at which an RIS can operate, particularly for mission-critical and agile applications. To address this challenge, researchers are exploring various techniques to improve the response speed of LC-based reconfigurable components. One approach is to use materials with faster response times, e.g., ferroelectric LC [26]. Another approach is to optimize the design of RIS to reduce the thickness of the LC layer without compromising the insertion loss significantly. Additionally, recent advances in integrated circuits and digital signal processing [30] have enabled the use of sophisticated algorithms to control RIS and compensate for the slower response times of LC materials. By carefully designing the control algorithms, it is possible to achieve high performance even with slower response times.

Secondly, the response of LC materials to electric (or magnetic) field is largely nonlinear [31], which makes it difficult to predict the exact behavior of an RIS in response to a given input signal. This nonlinearity can lead to distortion and signal degradation, which can affect the overall performance of the RIS.

Promisingly, a LC-based 66 GHz enclosed coplanar waveguide phase shifter reported by [18] achieves a linear phase shift–voltage response between the threshold bias voltage (4 V) and the saturated bias voltage (10 V) in the experiments. Although the response is not fully linear between 0 V and 20 V, the effective tuning range achieves linearity for the first time. The performance is only slightly impacted by the nonlinearities that occur below the Fréedericksz transition voltage (4 V) and above the saturation voltage (10 V).

Upgrading further to the RIS panel level, an LC-RIS must be carefully designed and optimized to achieve the desired performance. This requires precise control over the material properties, the geometry of the RIS elements, and the operating conditions. Additionally, an RIS must be able to adapt to changing environmental conditions, such as variations in temperature and humidity; this is a quintessential multi-physics problem requiring structural, thermal, and electrical performance analysis of LC via numerical simulation. Powering LC units for an RIS can also be a significant challenge, particularly for large-scale applications. Efficient power management strategies [32] must be developed to minimize energy consumption while maintaining the desired performance (for which low-maintenance, self-learning calibration algorithms are technically demanding). Arguably, real-time digital twins and efficient algorithms governing the aforementioned tasks are highly sought after for LC-RIS's self-learning control and optimization.

The manufacturing of RIS using LC technology can still be challenging in today's miniaturized high-throughput workflows, especially when it comes to achieving the necessary precision and uniformity across the entire surface. This can affect the overall performance and reliability of RIS, presenting the same challenge faced by LCOS [28].

Furthermore, an LC-RIS must be able to integrate with existing wireless communication systems seamlessly. This requires additional development of low-loss (radiation-free) interfaces [33] and protocols that can facilitate communication between LC-based RIS and other devices, e.g., antennas and transceivers. It remains to be seen how the total cost of LC-RIS can compete with other technology-based RIS or not.

Notably, physics-aware machine learning [34] and artificial intelligence (AI) technologies, which can operate both at the link- and system-levels, are envisaged to have a significant impact on the design of LC-RIS communication systems across all layers of the communication architecture. The trends of cognition and self-organization, smart spectrum access, operation of the physical and medium access layers up to resource allocation and network organization are all envisaged to be further accelerated by these technologies. Although AI does not produce new physics, leveraging it can greatly accelerate the rollout of LC-RIS in the post-5G roadmap, unlocking new frontiers of knowledge and innovation. For example, new applications that combine sensing, positioning, imaging, and mobility with communication capabilities will be made available with ease.

Last but not least, the long-term reliability of RIS based on LC technology is still not fully understood, and more research studies are needed to identify potential failure mechanisms (as researchers have identified for LCOS [35]) and develop strategies to mitigate them. This is particularly important for mission-critical applications, e.g., in aerospace and defense. For a network targeted with embedded trust in such a situation, security should be in place at all levels, including the physical layer [36].

4. Development Roadmap of the LC-RIS Industry in China

The LC-RIS industry in China faces several challenges, e.g., low market share (due to insufficient awareness of LC's advantages), weak competitiveness (due to export control of high-end LC-device making instrument), small industry scale (only a few companies specialized in LC microwave have emerged in recent years), and dependence on imported high-end scientific instruments (as mentioned above). However, the potential for growth in the industry is enormous, and there is a vast scope for development.

To address these challenges, it is essential to focus on key core issues and overcome relevant technical barriers. This can be achieved by promoting the localization of key core components and enhancing the technological capabilities of the industry. The government should play a crucial role in guiding the industry's development, while enterprises should take the lead in driving innovation and growth. To be more specific, both national and local scientific instrument companies (specializing in LC technology and microwave/THz techniques) should be encouraged to jointly play a vital role in the development of the LC-RIS industry by investing in research and development; fusing LC displays, LCOS, and LCRA with RIS; enhancing their technological capabilities; and expanding their market share in comparison to other rapidly growing RIS counterparts, such as multifunctional tunable metamirrors [37] and metasurfaces [38,39].

To achieve the goal of commercializing the LC-RIS industry in China, it is essential to adopt a targeted approach and provide appropriate support to different segments of the industry. This can be achieved by providing financial support to scientific instrument projects and promoting innovation and development. The industry should also focus on achieving industrialization and scaling up the application of scientific instruments. Finally, it is crucial to invest in the development of high-level scientific instrument talents (in LCOS, LCRA and RIS) to ensure the long-term growth and sustainability of the LC-RIS industry.

With joint efforts, the establishment of a scientific innovation system that integrates industry, academia, research, and application, as well as the cultivation and development of a group of large-scale comprehensive LC-based microwave enterprises, China's LC-RIS industry can certainly achieve a transformation from the current “following” position to “keeping pace” with the future and eventually leading the field. This requires the collaboration of various stakeholders, including the government, industry, academia, and research institutions, to promote the development of LC-RIS and their applications. The cultivation of talent and the promotion of innovation are also crucial in this process. Through these efforts, China can enhance its competitiveness in the global LC-RIS market and contribute to the advancement of science and technology.

Here, at the Beijing Key Laboratory of Millimeter Wave and Terahertz Technology, School of Integrated Circuits and Electronics, Beijing Institute of Technology (BIT), one of our over-arching goals is to bridge the gaps of LC-RIS in a few pressing applications facing our civilization. By combining the specialism of producing scalable, portable, and affordable LC tunable devices [20] with the well-established state of the art in large-scale phased antenna array, antenna miniaturization techniques [40], and metasurfaces [41,42], we are developing in-house code and new experimental prototypes for producing quality-assured LC-RIS embedded with sensing capabilities [43], thereby paving the way for the implementation of digital twins of future LC-RIS-enabled post-5G [44,45] and 6G systems, while delivering new knowledge of RIS science and education.

5. Concluding Remarks

This communication aims to draw academic and industrial attention on the recent surge of research interest in reconfigurable intelligent surfaces (RIS), which inception has occurred a few years ago but without acknowledging the backbone technologies that originated from a few decades ago, i.e., liquid crystal on silicon (LCOS) and liquid crystal reflectarray antenna (LCRA). As such, a host of valuable insights can be drawn from existing knowledge in LCOS and LCRA, thus inspiring the technical realization of LC-RIS for 6G networks.

By leveraging LC pixels to control the phase of reflected waves continuously, the potential applications of LC-RIS technology are vast, e.g., improving wireless communication systems (including 5G and beyond) and imaging systems (cameras and sensors) and building smart homes and smart cities with intelligent surfaces that can adapt to changing environmental conditions. Therefore, it is also expected that LC technology will gain more global traction due to the expanding portfolio of the “new” RIS concept and the booming RIS industry. Overall, the new paradigm for a future internet roadmap with LC-RIS will require collaboration and innovation not only within the academia but also across a wide range of stakeholders, including governments, industry, and civil society.

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