# A Novel Design for Reconfigurable Intelligent Surfaces (RIS) with Thin Liquid Crystal Layer for Wireless Communications

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**Abstract**
This paper proposes a proof-of-concept design for RIS made with liquid crystal (LC) and Corning glass for wireless communication applications. The proposed RIS concept consists of the specially designed copper-coated glass substrates and liquid crystal materials that were filled in between two glass substrates. The LC layer exists between the upper and lower Corning glass sheets, and it is 20 µm thick. Although the 20 µm cell-gap is very thin compared to the operating frequency (it is more than 100 µm in previous research), more than the 180° phase difference was achieved by applying 10 V in the designed frequency band. Our proposed concept can improve wireless communication coverage by reflecting incident electromagnetic waves in the desired direction to secure a propagation path by simply changing the alignment of LC molecules under different driving voltages. Also, conventional LCD manufacturing technology can significantly reduce costs and support larger-sized capabilities compared to incumbent semiconductor-based electronics and printed circuit board (PCB) processing.

**Author Keywords**
Liquid crystal; reconfigurable intelligent surface; beam steering; reflector; 5G; mmWave; Ka-band; glass-embedded; driving voltage;

## 1. Introduction

Using mmWave bands as a carrier frequency for 5G/6G communication offers a high data throughput, a massive connectivity, and a low latency. However, the mmWave communication also suffers higher path loss and small coverage area due to its short wavelength and straightness characteristics [1], [2]. High gain phased array antennas have been proposed to overcome a significant attenuation from the mmWave bands and to compensate for the propagation loss.However, gain for the phased array antenna is saturated due to the feeding network with base stations and the restricted space with mobile devices [3]. This method of using antennas not only has its own limitations, but it also cannot form a communication link when there are obstacles between the base station and mobile terminals.

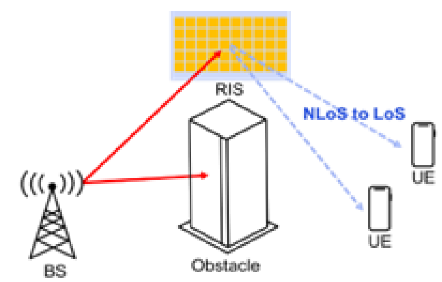



**Figure 1.** Active RIS operation concept

To solve this, many studies are being published to secure the line-of-sight for a signal improvement with reconfigurable intelligent surfaces (RIS) to create a new communication link between the base stations and the users [4]. Figure 1 shows the basic concept of the RIS for the next generation wireless communication system. Recently, RIS for beyond 5G and 6G wireless communication is being studied to expand coverage through an active control of a signal reflection toward desired directions [5]. To achieve the tunability of RIS, [5] proposed the pin diode driven RIS. The unit-cell with a PIN diode required multiple diodes to obtain multi-bits (> 2-bits) beam-steering functions. Multiple DC lines and vias increase the design complexity of this structure.

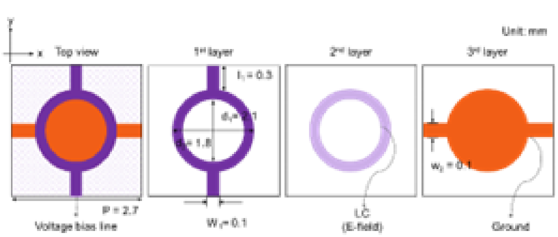
To alleviate the shortcomings of conventional RIS using semiconductor-based devices, researchers[6-9] have proposed reconfigurable mmWave devices based on liquid crystal (LC). These referenced papers are studies where researchers controlled the reflection angle by changing the reflection phase of the unit-cells. They used the change in the dielectric constant according to the difference in the LC voltage. In this way, LC RIS can reduce manufacturing costs and is advantageous for scaling up procedures.

From a performance point of view, LC RIS has the properties of a continuous shifting phase and a stable performance according to the frequency (diodes and varactors have frequency limitations). However, conventional active RIS designs typically require a thick cell-gap (greater than 100 μm) to ensure suitable dielectric anisotropy. This requirement can lead to several issues, including slow response times, alignment problems, high driving voltages, manufacturing challenges, and more. It is imperative to develop a new principle for an active LC RIS device that can operate with a smaller cell-gap.

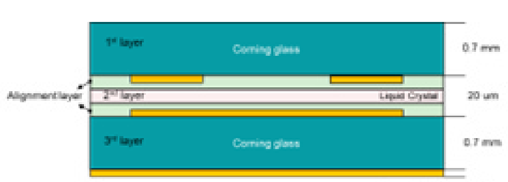
This research proposed the active LC RIS with the 20 μm-thick cell-gap to get a fast response time. The proposed active LC RIS validated the phase variation for a 1-bit quantized unit-cell (up to 190°) according to the driving voltages from 0 to 30 V with the full-wave simulation (based on the dielectric constant of LC), and according to the measurement. Based on the proposed small cell-gap active LC RIS, we can control the desired reflection angles to secure the mmWave propagation path with the line-of-sight.

## 2. LC RIS Design

Figure 2 illustrates the unit-cell structure of the proposed physical dimension for the LC RIS. The area of the proposed unit-cell for RIS is 2.7 × 2.7 mm2 which forms a ring 2.1 mm in diameter (see Figure 2(a) for the detailed physical dimension) to resonate at Ka-band. The unit-cell structure is composed of two 700 um-thick Corning glass sheets surrounding LC (20 μm-thick, GT7-29001, Merck) and two electrode layers (600 nm-thick, copper). The LC material used is for RF application, where the dielectric constant and loss tangent of the LC variation is altered from 2.46 to 3.53 and from 0.0064 to 0.0116, respectively. This varies according to the strength of perpendicular electric fields within the LC cell that is proportional to the amplitude of voltages. Based on the unit-cell design, the proposed RIS was made with the periodic 48 × 48 unit-cells with a total area of 150 × 150 mm$^2$. The period of the proposed unit-cell is 2.7 mm (roughly λ/4), the same as the width of the unit-cell. To drive the LC between two glass sheets by driving voltages, the lines are designed on the top and bottom glass layers. The top line is connected along the y-axis while the bottom line is orthogonally located along the x-axis. With the designed line configuration, the equal voltage is applied along the x-axis when the top lines and the bottom lines are connected to voltages and ground planes, respectively.



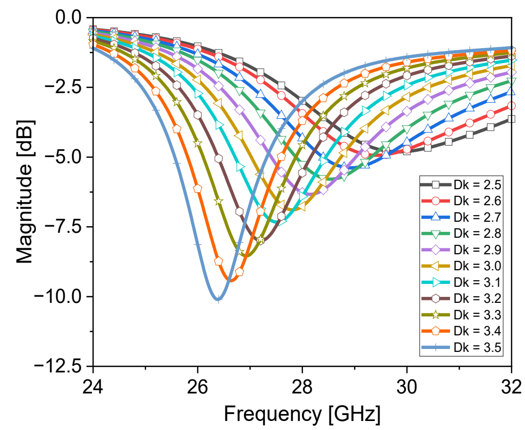

(a)



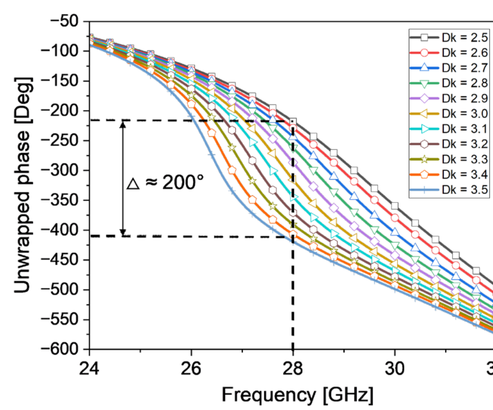

(b)

**Figure 2.** Physical dimension of the proposed unit-cell structure of LC RIS (a) top view (b) side view

The designed unit-cell was simulated using a commercial full-wave simulation tool. The reconfigurable frequency responses of the unit-cell were obtained by a periodic boundary condition analysis using dielectric constant variation (from 2.5 to 3.5) of the nematic liquid crystal. The goal of the unit-cell design is to achieve the phase shift range of the reflection coefficient over 180° for a 1-bit quantized unit-cell, and for beamforming. Figure 3(a) shows the magnitude of reflection of the proposed unit-cell design. Since the unit-cell for the proposed RIS was designed for 1-bit quantization beamforming, it was optimized with the lowest reflection loss at each dielectric constant, with the 180° phase difference, and with the smallest difference in reflection loss between the two states.




(a)




(b)

**Figure 3.** Simulated results of the RIS unit-cell with the variation of the dielectric constant (a) magnitudes of S11 in dB scale (b) phases of S11 in degree

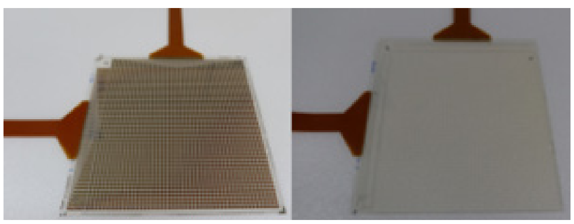
Figure 3(b) shows the reflection phases of the proposed unit-cell design according to the dielectric constant variation of the encapsulated LC. As a result, while the dielectric constant increased from 2.5 to 3.5, a change in the reflection phase by more than 200° was confirmed at 28 GHz.

**Table 1.** Comparison of reconfigurable reflectors using LC

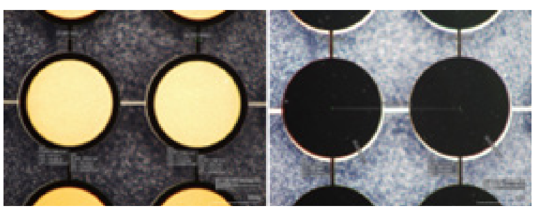
| Ref. | [6] | [7] | [8] | Our work |
|---|---|---|---|---|
| Dk of LC | 2.5-3.5 | 2.65-3.6 | 2.46-3.53 | 2.46-3.53 |
| Substrate | TLY-5/FR4 | Glass | Glass | Glass |
| Phase range | 260° | 128° | 278° | 190° |
| LC cell-gap | 250 μm | 8 μm | 200 μm | 20 μm |

## 3. Fabrication and experiments

Figure 4 shows the fabricated LC RIS samples. The left side of Figure 4(a) shows the copper-based LC RIS which satisfied RF performance at the target frequency band. The figure on the right is a sample made of transparent electrodes (ITO, indium thin oxide), and it was fabricated to confirm the LC behavior. There are FPCBs for the voltage input on the left and top side of Figure 4(a). The dimensions were measured through an optical microscope as shown in Figure 4(b). This confirmed that the fabricated samples matched the designed physical dimensions. The overall physical dimensions of the electrodes are within an acceptable range tolerance.



(a)



(b)

**Figure 4.** (a) Photographs [Left: with copper, Right: with ITO] and (b) polarized optical microscope images of fabricated active LC RIS samples

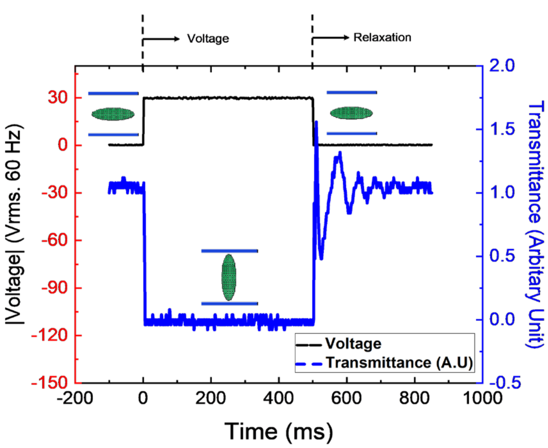
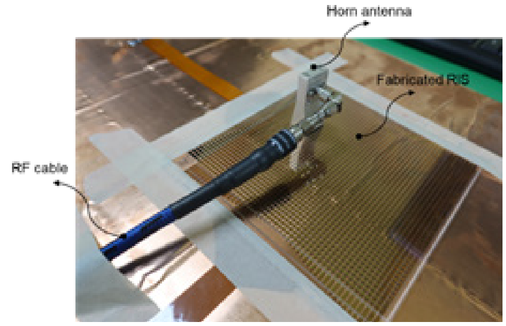
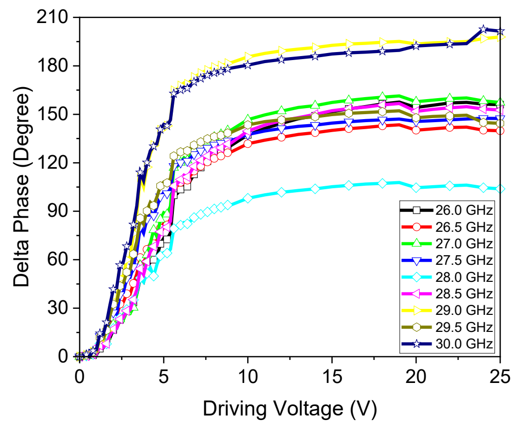



**Figure 5.** Response time of the proposed active LC RIS device

In Figure 5, we present a comprehensive analysis of the turn-on/off response times for our proposed LC RIS device, comparing it to a conventional LC RIS device with the 100 μm-thick cell-gap. The conventional device exhibits a prolonged total response time of 20 seconds, primarily relying on slow relaxation mechanisms during turn-off. In contrast, our innovative design, featuring a cell-gap reduced to one-fifth of the conventional thickness (approximately 20 μm), achieves an exceptional total response time of just 130 ms.




(a)




(b)

**Figure 6.** Fabricated RIS sample measurement (a) photograph of the test setup for reflection coefficients (b) measured the dynamic range of phase variation according to different voltages

The magnitude and phase of the RIS reflection coefficient were measured using PNA network analyzer (Keysight, N5224B).
Unlike the simulation, to measure an RF performance of the unit-cell, the horn antenna (see Figure 6(a)) operating in the mmWave band was contacted to the top of the RIS. The horn antenna acts as a sensor and is connected to an RF cable to transmit signals to the PNA network analyzer. Through the relationship between transmitted and reflected signals, the frequency response characteristics according to voltage changes were measured. To estimate the maximum tunability of reflection phases, voltages were increased by up to 25 V (AC, 60 Hz) to all lines on the top glass while all lines on the bottom glass are connected to ground for a reference level. The measured variation range of the reflection phase is up to 190° at the 29 GHz with the almost saturated voltage of 10 V. Although there is a slight difference in the operating frequency band, the target phase variation was obtained with the fabricated RIS sample.

## 4. Conclusion

In this paper, the active LC RIS with the 20 μm-thick cell-gap was proposed, designed, fabricated, and validated. To achieve the 20 μm-thick cell-gap that can be manufactured using the conventional display fabrication process, we proposed and simulated the 1-bit quantized unit-cell with a 180° difference in the reflection phase. The fabricated RIS sample was evaluated to estimate the response time and the phase tunability for the reflective beam-steering. As for the response time measurement, up to 25 V were applied to the ITO sample. The measured on switching time was 6 ms and the off time was 130 ms, which was consistent with the simulation. Furthermore, to validate the phase tunability of the fabricated RIS with copper, the phase change was measured while varying voltages from 0 to 25 V. As a result of the measurement, a phase difference capable of the 1-bit quantization (180° phase difference) was obtained using the fabricated RIS sample.

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