Liquid Crystal Based Reflectarray for Reconfigurable Intelligent Surface Applications

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Abstract: In this Letter, a reconfigurable reflectarray (RA) based on liquid crystal (LC) electric controlling property at Ka band is presented. The innovation focuses on measuring the phase steering ability of the whole LC RA with a structure of 4-finger under plane wave incidence and application on the actual scene, which can steer scattering wave to blind spots, not just play a role of EM launcher, but also an relay. Results show the LC RA can steer phase continuously to 213° with bias voltages and beam steering to different directions and different areas are achieved. This work introduces a LC RA as RIS that can steer scattered beam to increase receiving power at spot, which can be an application of RIS on wireless communication.

Keywords: Reflectarray, liquid crystal, coverage improvement, reconfigurable intelligent surface

Classification: Antennas and propagation

References

[1] C. Ge, S. Xia, Q. Chen, and F. Adachi, "A graph coloring-based interference coordination algorithm for cluster-wise ultra-dense RAN," *IEICE Communications Express*, Vol.10, No.2, 99–104, Feb 2021.

[2] C. Pan, Ren H, Wang K, et al., "Reconfigurable Intelligent Surfaces for 6G Systems: Principles, Applications, and Research Directions," *IEEE Communications Magazine*, vol. 59, no. 6, pp. 14-20, June 2021.

[3] X. Cao, Q. Chen, T. Tanaka, M. Kozai and H. Minami, "A 1-bit Time-Modulated Reflectarray for Reconfigurable Intelligent Surface Applications," *IEEE Transactions on Antennas and Propagation*, *Early Access*, doi: 10.1109/TAP.2022.3233659.

[4] G. Zhou, C. Pan, H. Ren, P. Popovski and A. L. Swindlehurst, "Channel Estimation for RIS-Aided Multiuser Millimeter-Wave Systems," *IEEE*

DOI: 10.1587/comex.2023SPL0014
Received January 27, 2023
Accepted February 22, 2023
Publicized March 03, 2023

Transactions on Signal Processing, vol. 70, pp. 1478-1492, 2022.

[5] D. Fukuda, A. Luckhurst, *Physical Properties of Liquid Crystals Nematics*, INSPEC, The Institution of Electrical Engineers, London, United Kingdom, 2001.

1 Introduction

With the demand of massive data and rapid communication speed, the sixth-generation (6G) wireless networks come to the public gradually, due to the tight spectrum resources, commercial companies and academic scholars divert attention to mm wave band and try to apply millimeter wave antenna in wireless communication system[1], but the physical properties of Wave-particle duality of electromagnetic waves and diffraction of electromagnetic waves at high frequency build barriers in the wireless channel to users and lower the signal noise ratio in communication. [2]

For the weakness of millimeter wave penetration into the wall, reconfigurable intelligent surface is being widely studied [2,3,4] as a possible solution to the end users at high-frequency wireless communications owing to their reconfigurabilities such as controlled-direction beam, multibeam and beam forming, such a steering property of beam can be used in programmable transmitters or receivers to further strengthen the signal to the users in need and guide the electromagnetic wave transmitting to the desired districts.

In this letter, a LC-based reconfigurable RA is designed, simulated, fabricated, and the manufactured model can achieve a continuous phase shift of 213° under bias voltage. Then the reconfigurable RA is utilized as a RIS to control the reflected wave to a certain area. Here the experiment simulates real application scenarios to make up for blind spot, the beam towards different areas or two areas can be achieved, which is more valuable for some application Scenario.

The rest of this communication is organized as follows. In Sect. 2, a 4-finger LC RA element is proposed and its performance is simulated, we also do an experiment of reflection properties under plane wave illumination and reconfigurabilities with bias voltage. Then, in Sect. 3, the reconfigurabilities of beam from this LC RA is shown. At last, Sect. 4 summarizes this communication and gives conclusions.

2 Design and Experimental Validation of the Reconfigurable LC RA

RAs always use the resonant element to steer the phase of reflected wave, steer the unit variables which change the resonant state will adjust the reflection phase, we choose the RA patch structure and steer the relative permittivity of LC with bias voltage, thus phase steering can be achieved. As for the beam of RA, through array synthesis theory, if we control the bias voltage of each channel properly, continuous phase of each RA channel can change the direction of reflected waves.

2.1 Design of LC RA

Since LC is a kind of anisotropic material and has a rod-like molecule which will change the direction of the molecule's axis under quasi-static field, the relative permittivity ε_r will change at the same time. The resonant conditions change, which will cause the phase change compared with the non-bias state. when the unit is not biased, the ε_r of LC layer can be expressed [5] by

$$\overline{\overline{\varepsilon}}_{r,\perp} = \overline{\overline{\varepsilon}}_r(Vp = 0) = \begin{bmatrix} \varepsilon_{r,\parallel} & 0 & 0 \\ 0 & \varepsilon_{r,\perp} & 0 \\ 0 & 0 & \varepsilon_{r,\perp} \end{bmatrix} \tag{1}$$

The LC molecules don't rotate when bias voltage is low until the bias increases to a voltage Vth that is large enough to rotate the LC molecules (Fig. 1(c) and (d)). When the biased voltage is added to alter the LC molecule to its full bias state, the inhomogeneous condition can be described with tensor, so the calculated by equation (2) can be used to make simulations and LC RA design.

$$\overline{\overline{\varepsilon}}_{r,\parallel} = \overline{\overline{\varepsilon}}_r(Vp \gg Vth) = \begin{bmatrix} \varepsilon_{r,\perp} & 0 & 0 \\ 0 & \varepsilon_{r,\perp} & 0 \\ 0 & 0 & \varepsilon_{r,\parallel} \end{bmatrix} \tag{2}$$

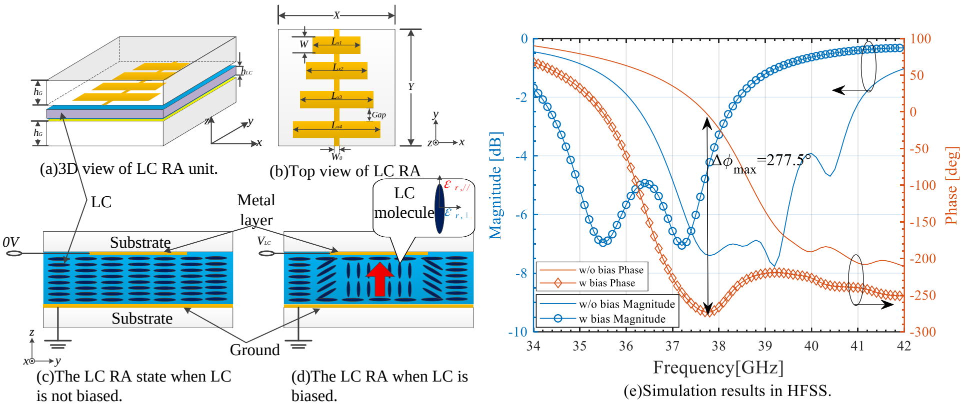
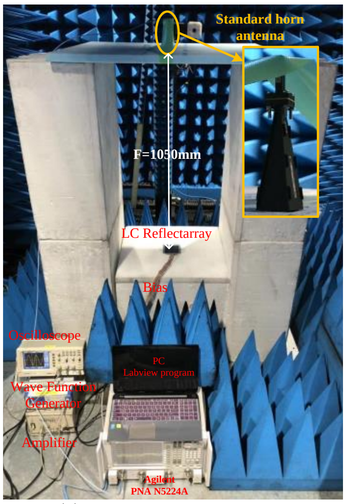


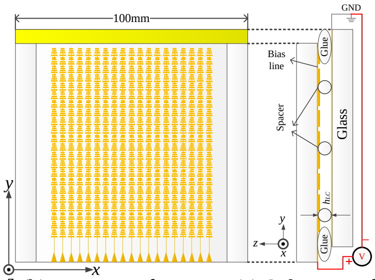
Fig. 1. Simulation model of LC RA and its performance.

The designed LC RA unit and marked variables are shown in Fig. 1(a) and 1(b), this model is simulated in the software HFSS with periodic structure and floquet mode, LC is simulated with the expression of equation (1) and (2) with value of $\varepsilon_{r,\perp}$ = 2.6 and $\varepsilon_{r,\parallel}$ = 3.2, and tanδ = 0.023, value of the variables are optimized by PSO algorithm, but considering the manufacturing error, the variables are finally revised. A pairs of parallel quartz glass (ε_r = 3.78, tanδ = 0.0001) with thickness of h_G = 0.6 mm, metal films on glass surface are manufactured as the physical support for the patch structure of RA unit. The top view of the designed 4-finger unit is shown at Fig. 1(b) and the lengths are marked: the period of the RA unit are $X = Y$ = 4.0 mm, the lengths of the resonant dipoles are L_{x1} = 2.2 mm, L_{x2} = 2.3 mm, L_{x3} = 2.4 mm, L_{x4} = 2.5 mm, and the width of each dipole is W = 0.6 mm, there is a variable distance Gap = 0.4 mm, between each dipole, the bias line has a width of W_0 = 0.4 mm, thickness of LC layer is set h_{LC} = 0.1 mm.

The resonant numerical data with full bias state and without bias are plot in Fig. 1(e), it can be seen that resonant frequency without bias is 40.20 GHz and the reflection coefficient reaches -7.95 dB; at the full bias state, the reflection coefficient increase a little to -7.46 dB and resonant frequency shift to lower frequency at 36.48 GHz; the phase of scattering field from the LC RA at full bias state shift to smaller value compared with the phase without bias, here a -287.5º is caused when LC change the state.

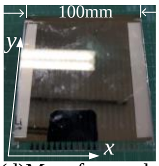


(a)Experiment scene.



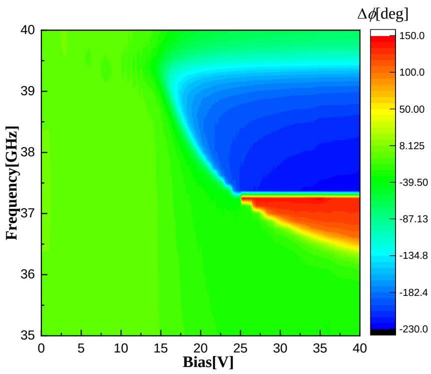
(b)Top view of the RA model.

(c) Side view of LC RA

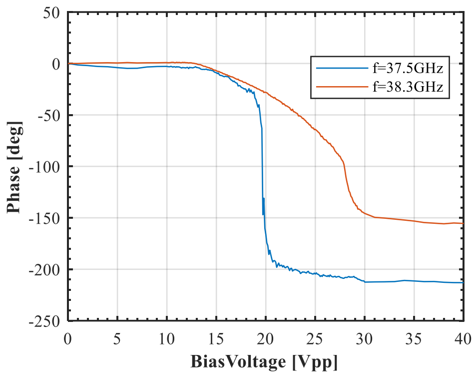


(d)Manufactured RA model.

(e)Element of RA.



(f)Phase steering map with bias at different frequencies.



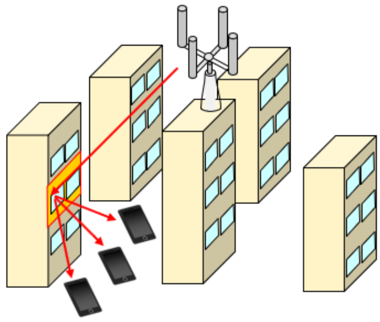
(g)Phase-voltage curve at two special frequencies f = 37.50 GHz and f = 38.30 GHz.

Fig. 2. Measurement of the LC RA under plane wave illumination.

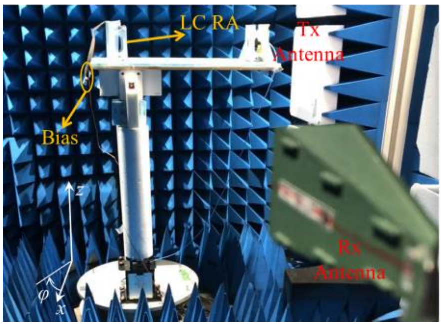
2.2 Reconfigurabilities and Measurements

The experiment for measuring the steering phase of LC RA is shown in Fig. 2(a), manufactured model consists of 21×19 elements (Fig. 2(d) and 2(e)) is placed on the plastic foam under which are radio absorbers. A standard horn antenna is placed perpendicularly on the top of foam structure with E plane parallel to the direction of dipole and the distance from horn antenna to the LC RA is F = 1050 mm which can guarantee the far field region of antenna. The LC RA is placed on the platform made of plastic foam and all electrodes are connected to all the bias lines, the same voltage is connected to bias lines. Scattered field is measured by the horn antenna and is analyzed by Agilent PNA N5224A. To control the ε_r of LC RA, a steering system is designed: A LabVIEW program is coded on the PC, which can control the Wave function generator to output voltage signal with different magnitudes and frequencies. Using an amplifier, enough voltages are attained, the output voltages from the amplifier are biased to channels of LC RA. In this way, LC can be controlled accurately. The voltage steering process starts from 0V to 40V(Vpp) with steps of 0.02V and scattered field is measured.

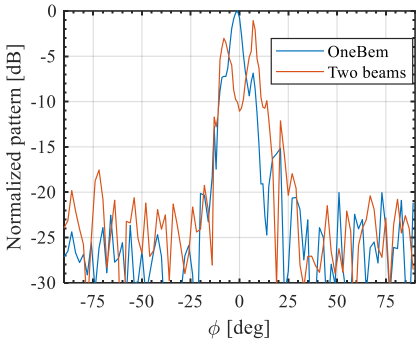
The steering phase conditions of the model at different frequencies are shown in Fig. 2(f). The phases keep still at all frequency points when the voltages start to increase slowly, and phase starts to change at high frequency when bias voltage reaches 10V slowly. At frequency band f > 37.34 GHz, when the bias voltage increases over 10V, the phase of LC RA start to shift, and with bias increase, the phase change starts to decrease. At a certain frequency point of band f < 37.34 GHz, when the voltage increases over 10V, $\triangle\phi$ starts to increase with the voltage increase. Two Phase-bias curves are shown in Fig. 2(g), at f = 37.50 GHz, the phase curve has larger phase steering scale of 213 ° compared with the curve of 156 ° at f = 38.30 GHz, but it is steeper and may be difficult to control beam.



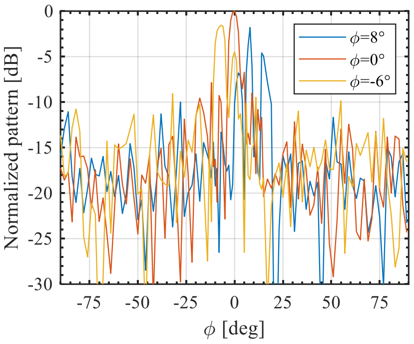
(a)The application scene of RIS.



(b) Measure the scattered beam of RIS.



(c)Steered beam of LC RA at 37.50 GHz.



(d)Steered beam of LC RA at 38.30 GHz.

Fig. 3. Simulate the application of RIS and measure the scattered beam under plane wave illumination.

3 Application of LC RA as RIS

The application of LC RA for making up for blind spots in crowded builds is shown in Fig. 3(a). The steering beams of the LC-based RA feed by the horn antenna have been measured for several voltage controlling schemes and at the design frequency of 37.50 GHz and obvious response frequency 38.30 GHz. Fig. 3(b) shows a photograph of the radiation pattern measurement for reconfigurable LC RA feed by horn antenna in the anechoic chamber, the RA is placed at the center of the rotation platform supported by plastic foam, the bias lines are connected to voltage controlling module, with different bias voltages applied to the RA electrodes according to the amplitude and phase of scattering field, the beam will be controlled. And the feed horn antenna with aperture 36.2 mm × 24.4 mm is placed 800.0 mm from the LC RA, and far field (>327.6mm@37.50 GHz) is guaranteed at Ka band, thus plane wave can be approximated, and this condition can simulate the plane wave illumination.

The beam steering characters have been shown in Fig. 3(c) and 3(d), at f = 37.50 GHz, there is a beam towards 0º when no bias is applied to the RA, while two beams towards -8º and 7º will be generated when there is a proper bias voltage applied to the electrodes of the RA with optimal algorithm, but not too beautiful beams can be obtained. At f = 38.30 GHz, there will be a beam tilt 8º, 0º and -6º when proper bias voltages applied to the RA, this beam steering ability at 38.30 GHz is better than 37.50 GHz. Because the phase steering curve of 38.30 GHz is smoother than 37.50 GHz, which will make the phase steering easier and more accurate. In this scheme, blind spots may be erased.

4 Conclusion

A reconfigurable LC RA unit 4-finger working at Ka band is designed, and a practical measurement of RA under plane wave incidence are proposed. A 21×19 elements LC RA models is fabricated and measured by the controlling system. The measured results show the LC RA has a stable and continuous phase steering ability of 213º. Reconfigurable patterns of one beam and two beams can be observed at f = 37.50 GHz, tilt beam at 8º, 0º and -6º can also be generated at f = 38.30 GHz. Thus the blind spots in crowded buildings may be erased in the future wireless communication.

Acknowledgments

The authors are grateful to Mr. Fujisawa of Tohoku University, Japan for the information and knowledge of liquid crystal properties. This research was supported by the Ministry of Internal Affairs and Communications in Japan (JPJ000254).