Development of Beam Steerable Reflectarray with Liquid Crystal for Both E-Plane and H-Plane

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ABSTRACT

In this paper, a reconfigurable reflectarray (RA) with two-finger element composed of electrically biased liquid crystal (LC) at millimeter wave band is proposed. An orthogonal bias-network is proposed and developed, which can result in changes in the equivalent relative permittivity of the liquid crystal, and reflection phase along direction x and direction y can be realized, thus beam steering at both E plane and H plane can be achieved. The LC RA is composed of \(10 \times 10\) elements of 2-finger unit, a standard horn antenna is obliquely placed as feed, and radiation pattern is calculated by array synthesis and full wave simulation. It is found that beam scan at both E plane and H plane can be achieved. Compared with former researches of LC RA, this work introduces a simple scheme to achieve beam scan for LC RA at both E plane and H plane.

INDEX TERMS
reconfigurable, reflectarray, liquid crystal, beam scan

I. INTRODUCTION

Reflectarrays have attracted increasing attention over the past years because of their unique properties: low loss due to the absence of a corporate feed, ease of fabrication, planarity and low weight and lower cost [1],[13]. Reconfigurability, a generally highly desirable feature, would increase their versatility even more. The previous works on RAs are mainly focused on the unit design [2]-[5] and generating a fixed pattern optimized by algorithm [6]-[11]. Many of these works are about influence of unit parameters on phase change and fixed element distribution on the array [2]-[10].

Recently, efforts are devoted to the realization of dynamically reconfigurable reflection units [11]. In fact, based on the known properties of changing reflection phase with different methods on RA, dynamically controllable reflected wave gets the most notice [1]. In the field of real-time control, various technologies especially electronic control approaches to realize reconfigurability are getting more and more attention, such as ferroelectric thin films, varactor diodes [13], RF MEMS [14]-[17], mechanical rotation [14], LC [18]-[25] and so on. However, loss of ferroelectric films at millimeter wave band can not be ignored. Besides the high costs, MEMS and diodes integrated on RA also have the problem of assembling. Contrarily, LC is low cost and easily integrated to antennas and microwave devices with planar structures, which is suitable to be assemble to the RA. As a result, studies of LC applications on RA technology at millimeter wave have increased a lot[26]-[30].

The LC RA usually uses the material properties that can change relative permittivity by adding quasi-static electric field to the electrodes [22], [35]. When different voltages are applied to the Patch layer of RA relative to the ground, phase with different values of reflected wave from the RA is achieved.

The previous design of the LC RA unit mainly used thin-line electrodes to connect the patch layer [21]-[25], so these RA can just steer beam in one plane [21]. A solution to achieve beam steer at 2 orthogonal planes is proposed in
reference [36], but it needs many bias lines, another scheme is came up to achieve beam shift at E plane and H plane with concept of subarray and the control of bias lines [37], which is a significant improvement of LC RA. Based on the idea of bias lines and detailed investigation of distribution of liquid crystal molecules in a three-dimensional environment, this paper proposes a simpler solution to achieve beam steering at both E plane and H plane by discrete ground and cross bias condition, which is more practical in engineering.

This article is organized as follows: Section II presents the multi-resonant RA unit structure 2-finger and discrete ground, explains the working principles, the ability of this RA unit to change the phase and amplitude of the reflected wave is discussed, and the characteristics of the reflected wave changing with the liquid crystal state under a certain incident angle is mimicked. Section III introduces the bias network and principles that can steer LC molecules at two directions, which change the phase of RA at both E plane and H plane, this application on array that can achieve beam steering by analysis of both array synthesis and full wave synthesis, the performance of the LC RA (Beam scanning at both E plane and H plane) with different bias conditions are shown. Section IV concludes this paper.

II. DESIGN OF LC RA ELEMENT

Here a 2-finger structure shown in Figure.1 is used as unit of LC RA. This multi-resonant element application in LC RA unit is firstly presented in [28], which can achieve reflection phase change, this structure exhibits excellent performance of reflection phase variation more than 330° within a broad frequency. In this work, Particle Swarm Optimization(PSO) is applied to develop and optimize the parameters of this structure to achieve larger phase shift range over 360° and relative high reflection coefficient, which is used as basic indexes for RA element design. The liquid crystal used in the design is LC-BYE7, its material parameters are used as follows [35], [36]: relative dielectric constant changes from $\varepsilon_{||} = 2.1$ to $\varepsilon_{\perp} = 3.2$, loss tangent varies from $\tan\delta_{\parallel} = 0.014$ to $\tan\delta_{\perp} = 0.004$. 

This element uses traditional sandwich structure shown in Figure. 1, there are five layers in the structure of LC RA unit: the top layer is the quartz glass( $\varepsilon_r = 3.2$, $\tan\delta = 0.002$), the second layer is the patch layer, the third layer is the sealed LC, the fourth layer is the metalized ground layer, the bottom layer is also quartz glass. The parameters of the LC RA are marked at the Figure. 1(a) and Figure. 1(b), by simulation of electromagnetic software Ansys HFSS and optimization algorithm, proper values of the parameters are chosen in the TABLE I, different from the original model 2-finger structure presented in [28], a slot on the bottom metal layer of glass is attached to separate the ground in the direction $y$ which is orthogonal to the path layer.

| Variable | Numerical Values (mm) | Variable | Numerical Values (mm) |
|----------|-----------------------|----------|-----------------------|
| $h_G$    | 0.60                  | $h_{LC}$ | 0.25                  |
| $X$      | 4.00                  | $Gap$    | 2.00                  |
| $G$      | 3.95                  | $W$      | 0.30                  |
| $L_{a1}$ | 1.95                  | $W_0$    | 0.20                  |
| $L_{a2}$ | 2.20                  |          |                       |

In simulation model of HFSS, the metal layer is chosen as the same material properties as copper with thickness of 5um, which is numerically greater than the skin depth at the target frequency 37.5 GHz, and the polyimide of 0.9 um along direction $x$ is attached on the surface of the glass, which can guarantee the inital directions of the rod-shaped LC molecules( Figure. 1(c) and (d)), and the incident wave travelling along -$z$ directions would respond differently when LC is biased with different quasi-static voltages. To mimic the procedure of bias voltage applied to the LC, linear variation of LC changing from $\varepsilon_{||} = 2.1$, $\tan\delta_{\parallel} = 0.014$ to $\varepsilon_{\perp} = 3.2$, $\tan\delta_{\perp} = 0.004$ is applied in the simulation model at frequency band from 30 GHz to 48 GHz. The simulation results are shown in Figure. 2, the magnitude of the reflected wave from RA is shown in Figure. 2(a), the return loss changes from -0.25 dB to -2.1 dB at the band from 33 GHz to 42 GHz, which is relatively low loss compared with other LC RAs. The phase is shown in Figure.
2(b), the phase steering scale of more than 360° is achieved at the frequency band from 37.2 GHz to 38 GHz.

![Magnitude of Reflection Coefficient](image1)

**Figure 3.** Magnitude and phase of Reflection Coefficient from LC RA with different incident angle at frequency 37.5 GHz

![Phase of Reflection Coefficient](image2)

**Figure 2.** Simulation of Reflection Coefficient from LC RA unit in floquet mode when different bias voltage is applied

At the target frequency point 37.5 GHz, the magnitude and phase steering conditions of LC RA are presented in Figure 3, the magnitude of scattering field varies from -2.1 dB to -0.6 dB within the changing state of LC, and phase decrease from -123° to -488° as the relative permittivity increase, the phase steering scale is over 360° and can be utilized in the reconfigurable RA. Even when the incident angle is 0-30° with respect to the -z axis, the amplitude of reflected wave is still above -2.2 dB, and the phase change is numerically greater than 360°, which is a good index for RA design.

**III. LC RA INTEGRATION AND BIAS SCHEME FOR CONTROLLING RADIATION PATTERN**

**A. LC PROPERTIES UNDER DC BIAS VOLTAGE**

To achieve the stable reconfigurable performance, the directions of LC molecules should be guaranteed to keep the relative permittivity in a certain value (Figure 4(a)), so rubbing procedure is needed. Usually, polyimide is used as alignment film to cover the metal-side surface of glass [21]. Complicated heating process and rubbing procedure are required, here rubbing along direction x is chosen, which allows the LC molecules to rotate with an angle \( \theta \) relative to axis x in the \( xOy \) plane (Figure 4(b)). So if the ground layer of the RA is separated with slot along direction x, apply different voltages to different parts of ground \( y_1, y_2, y_3, \ldots y_n \) relative to patch layer, different relative permittivity of LC in the RA unit appears (like Figure 4(c)), so the RA unit can achieve phase controlled along direction x; if the patch layer of the RA is discretized with slot along direction y, apply different voltages to different parts of ground \( y'_1, y'_2, y'_3, \ldots y'_n \) relative to patch layer, different relative permittivity of LC in the RA unit is obtained (like Figure 4(d)), so the RA unit can achieve phase controlled along direction y.

![Initial state of LC molecules](image3)

(a) Initial state of LC molecules w/o bias

![State of LC molecules w/ bias when rubbing is along x](image4)

(b) State of LC molecules w bias when rubbing is along x

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different values form DC voltage module connected to patch layer are set to the ground are set controlled in two mutually orthogonal directions (as shown row, thus the phase of reflected wave from RA can be connected in one line, the phase of RA can be controlled by different bias lines would occupy to much space on the surface of the limitations that just one line can be controlled by bias voltage. Even though some papers present some scheme of bias to achieve unit controlled more than one direction, however, it needs complex bias layout and with the number of units increasing, more bias lines are need. More bias lines would occupy to much space on the surface of the substrate surface of RA, which is destructive to the electromagnetic properties and performance of RA.

Based on the works and ideas from previous scholars, the electrode is integrated on one line to connect the bias line, the phase of RA can be controlled by different bias voltages, this paper proposes a scheme of electrode connection: the finger structure are connected in one row, thus the phase of reflected wave from RA can be controlled in two mutually orthogonal directions (as shown in Figure. 5): when the voltage electrodes connected to the ground are set \( V_{b1} = V_{b2} = V_{b3} = \cdots = V_{bn} \), the voltage electrodes form DC voltage module connected to patch layer are set different values \( V_{d1}, V_{d2}, V_{d3}, \cdots, V_{d1b} \), so the phase of RA element can vary in direction y, if the voltage electrodes connected to the patch layer are the same \( V_{d1}=V_{d2}=V_{d3}=\cdots=V_{d_n} \), and the discrete ground sections are biased with different voltages \( V_{bl}, V_{b2}, V_{b3}, \cdots, V_{b1n} \), the phase of RA element will change in direction x.

**B. DESIGN OF BIAS NETWORK FOR LC RA**

To achieve the reconfigurable performance, Static driving voltage is usually used in the control LC modules because of its the stability and low-cost, so it is also common in LC RA. The LC RA usually connect the unit cell with a bias line in one direction, which is convenient for control, but this scheme to control the unit has limitations that just one line can be controlled by bias voltage. Even though some papers present some scheme of bias to achieve unit controlled more than one direction, however, it needs complex bias layout and with the number of units increasing, more bias lines are need. More bias lines would occupy to much space on the surface of the substrate surface of RA, which is destructive to the electromagnetic properties and performance of RA.

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Considering the orthogonal bias network scheme, a RA with $10 \times 10$ elements is presented, where just 2 groups bias lines and total number 20 are distributed in both upper layer and the ground plane layer. By proper bias of one group electrodes the same voltage and another group with different values, orthogonal phase steering can be achieved thus beam steering at both E plane and H plane can be achieved.

C. RADIATION PATTERN OF THE LC RA

The coordinate origin locates at the center of RA, direction $x$ is along bias lines of patch layer, direction $y$ is along the dipole of RA unit. When a standard horn antenna working at Ka band with gain of 24 dBi is used as the feed and locates at the coordinate $(0, -34.64, 40)$ mm, which could provide a incident wave from $30^\circ$ with polarization of TM mode(Figure. 5(a)). In this condition, the radiation condition from antenna to RA at 37.5 GHz is shown in Figure. 6. Magnitude is shown in Figure. 6(a). the magnitude on the edge of RA is -11 dB which is an acceptable value for aperture antenna. Since the normal form of horn antenna aperture is in $xOz$ plane and the E plane of the feed is along the direction $y$, the co-polarization of the incident wave is direction $y$. Once the incident field componentes on the aperture of each element are computed, the reflected fields for each element in RA can be obtained by the generalized scattering matrix, which relates the field components of incident field and reflected field in periodic structure.

$$
\begin{bmatrix}
E^\text{ref}_x (m, n) \\
E^\text{ref}_y (m, n)
\end{bmatrix}
= 
\begin{bmatrix}
\Gamma_{xy} & \Gamma_{xy} \\
\Gamma_{yj} & \Gamma_{yj}
\end{bmatrix}
\begin{bmatrix}
E^\text{inc}_x (m, n) \\
E^\text{inc}_y (m, n)
\end{bmatrix}
$$

(1)

Phase of reflected wave of RA just has a phase shift of the space phase delay $\phi_k$, $\phi_k = \phi_{psd} + \phi_{0}$. The phase of RA element can be used to calculate the pattern in the subsequent radiation pattern.

When the electrodes are biased with DC voltage with different values, the reflected wave from LC RA unit of different columns or rows will change with different phase $\phi_{LC}$,

$$
\phi_{LC,mn} = -k_0R_{mn} + \phi_{0} + \phi_{i,mn}
$$

(3)

With array synthesis, the phase of one column or one row RA can be modulated by DC voltage, considering the radiation Pattern of 2-dimensional RA is summation of reflected wave from each element,

$$
\vec{E}(\hat{u}) = \sum_{m=1}^{M} \sum_{n=1}^{N} A_{mn} (\hat{u}) \hat{I} (\vec{r}_{mn})
$$

(4)

$$
\hat{u} = \hat{x} \sin \theta \cos \varphi + \hat{y} \sin \theta \sin \varphi + \hat{z} \cos \theta
$$

(5)

Here M is the number of column array along direction $x$, N is the number of row array along direction $y$; $m$ and $n$ are the orders of the LC RA along direction $x$ and $y$; $A$ is the RA element pattern function, using a scalar approximation of cosine $q_e$ model for the RA unit; The element excitation $I(r_{mn})$ is caused by the incident field and response properties of LC,

$$
A_{mn} (\theta, \varphi) = \cos^{q_e} (\theta) e^{\gamma(i_{mn})}
$$

(6)

$$
I_{mn} = E_{y} \Gamma_{yj} q_e^{\gamma_{psd}}
$$

(7)

Thus, the directivity $D$ can be calculated by the definition and beam is shown in Figure. 7. The 3D polar pattern is shown in Figure. 7(a), the H plane is $xOz$ plane, and E plane is at $yOz$ plane which inclined by $30^\circ$ relative to the $yOz$ plane. The normalized E plane and H plane of the pattern are presented in Figure.7 (b), from which the maximum radiation at $\alpha=30^\circ$, $\varphi=0^\circ$ can be observed, the sidelobe level of E plane and H plane is -23 dB and -12.5 dB, both of them are good indexes for antennas.

**FIGURE 6.** Space phase distribution on the RA at frequency 37.5GHz when horn antenna is used as feed.

The space phase of the incident wave on each RA element can be obtained by the following equation

$$
\phi_{psd} = -k_0R_i
$$

(2)

$R_i$ is the Euclidean distance from the phase center of the horn antenna to the RA element $i$, $k_0$ is the free space wave number, and the space phase distribution is shown in Figure. 6(b). Since all the elements of LC RA are the same, the
D. STEER BEAM AT H PLANE AND E PLANE FOR LC RA

To steer beam at E plane, progressive phase distributed on the plane perpendicular to $z'$ is needed, so a scheme is provided: the voltage electrodes connected to the ground are the same value $V_a$, and the patch layers are biased with different voltages $V_{a1}$, $V_{a2}$, $V_{a3}$, …… $V_{a10}$, the phase of reflected wave from each row along direction $x$ will be controlled, so the phase center of reflected wave will shift along direction $y$, an example of progressive phase difference of $-60^\circ$ and $60^\circ$ for RA are shown in Figure. 8(a) and (b), thus the phase front will be steered in E plane, so progressive phase difference along $y$ will result in the beam direction normalized to the equal phase front (Figure. 9(a)). The same requirements happen for the beam steering at H plane, but with a symmetrical DC bias scheme: that the patch layers are biased with the same value $V_a$, the ground are biased with different voltages $V_{b1}$, $V_{b2}$, $V_{b3}$, …… $V_{b10}$, the phase of reflected wave from each row along direction $x$ can be changed according to the controlled $V_{b}$, so the phase center of reflected wave will shift along direction $x$, a comparison of progressive phase difference of $-60^\circ$ and $60^\circ$ along direction $x$ at the RA aperture are shown in Figure. 8 (c) and (d), thus the phase front will be steered in H plane, so progressive phase difference along $x$ will result in the beam direction normalized to equal the phase front (Figure. 9(b)). The prescribed relative permittivity of LC can be obtained by interpolation solution from Figure. 3(b), when relative permittivity is decided the magnitude respond can also be attained from Figure. 3(a).

When the electrodes on one side are biased the same voltage and steer voltage in the other side, orthogonal beam steering can be achieved, the performance of the LC RA can be computed by the array synthesis approach described in the former section. And the calculated beams of the different bias conditions are shown in Figure. 10, the Figure. 10(a) exhibit the beam scanning properties at E plane, from the figure, beam scanning angle $\theta$ relative to the axis $z'$ can cover from $-30^\circ$ to $30^\circ$, with the scanning...
angle increasing from center of E plane $\theta'$, the side lobe starts to increase, when it reaches to -13.0 dB, maximum radiation intensity decreased to -3.0 dB, beam width also increases; Figure. 10(b) exhibits the beam scanning properties at H plane, from which beam scans from 0° to 42° in yOz plane, with the scanning angle increasing from center of H plane $\theta$=30°, the side lobe also increases, when the scanning angle reaches to $\theta$=0°, maximum radiation intensity decreased to -3.0 dB, however the beam width decrease and side lobe increase to -10 dB due to the asymmetric position of feed antenna, and when the scanning angle reaches $\theta$=42°, the maximum radiation intensity decrease to -3.0 dB, side lobe increase to -10 dB, beam width increases.

**FIGURE 10. Beam scanning of LC RA**

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