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# Design of Beam Steerable Reflectarray with Liquid Crystal

Xiaotong LI† Hiroyasu SATO† Hideo FUJIKAKE‡ and Qian CHEN†

† Department of Communications Engineering, Graduate School of Engineering, Tohoku University 6-6-05 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi, 980-8579 Japan

‡ Department of Electronic Engineering, Graduate School of Engineering, Tohoku University 6-6-05 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi, 980-8579 Japan

E-mail: † li.xiaotong.r4@dc.tohoku.ac.jp

**Abstract:** In this study, we present a novel reconfigurable reflectarray (RA) operating in the millimeter wave band, utilizing a two-finger element comprising electrically biased liquid crystal (LC). Our approach incorporates an orthogonal bias network, enabling changes in the equivalent relative permittivity of the liquid crystal. As a result, we achieve reflection phase control along both the $x$ and $y$ directions, facilitating beam steering in both the E-plane and H-plane. The LC RA consists of a 10×10 array of 2-finger units, with a standard horn antenna placed at an oblique angle for feeding. Through array synthesis and full wave simulation, we calculate the radiation pattern, and our results demonstrate successful beam scanning in both the E-plane, spanning from -25° to 25°, and H-plane, ranging from 0° to 42°. This study represents a significant advancement in the field of LC RAs compared to previous research, as it offers a simpler scheme for achieving beam scanning in both planes. The introduction of the orthogonal bias network and the utilization of two-finger elements provide enhanced control over the phase and direction of the reflected waves, enabling more versatile and efficient beam steering capabilities.

**Keywords** Reconfigurable, Reflectarray, Liquid crystal, Beam scan

# 液晶を用いたビーム制御可能なリフレクタアレイの設計

李 暁彤† 佐藤 宏康† 藤掛 英夫‡ 陳 強†

† 東北大学大学院工学研究科　通信工学専攻　〒980-8579 宮城県仙台市青葉区荒巻字青葉 6-6-05
‡ 東北大学大学院工学研究科　電子工学専攻　〒980-8579 宮城県仙台市青葉区荒巻字青葉 6-6-05

E-mail: † li.xiaotong.r4@dc.tohoku.ac.jp

**あらまし**　本研究では，液晶を用いたミリ波帯リコンフィギュアブルリフレクトアレーの直交バイアスネットワークを提案する．アレー素子の反射位相を変化させるにはアレー素子毎に異なるバイアス電圧を液晶に印加してそれぞれ比誘電率を変化させる必要がある．そこで，グランド面において $x$, $y$ 両方向に設けられた直交バイアスネットワークを構築することで，E 面と H 面の両方におけるビーム走査を実現している．液晶リフレクトアレーは，オフセット給電ホーンアンテナ，およびユニットセルが 2 個のダイポール素子で構成された 10×10 周期アレーで構成されている．アレーファクタおよび全波シミュレーションを用いた放射パターンを評価し，E 面では-25°～25°，H 面では 0°～42°のビーム走査が可能であることが示されており，両平面においてビームを走査するための簡便なスキームを提供している．

**キーワード**　リコンフィギュラブル，リフレクトアレイ，液晶，ビームスキャン

## 1. Introduction

The use of reconfigurable reflectarrays (RAs) to achieve dynamic control over reflected beams has garnered significant attention, with LC-based electromagnetic technology being a popular choice for implementation. Previous designs of LC RAs mainly relied on thin-line electrodes to connect the patch layer, which limited their beam steering capabilities to a single plane [1]-[2]. Although some solutions were proposed to achieve beam steering in two orthogonal planes [3], they required numerous bias lines, making the implementation complex and challenging.

However, a breakthrough was achieved with a new scheme [4] that utilized subarrays and bias line control to achieve beam shift in both the E-plane and H-plane, representing a significant improvement in LC RA technology. Building upon this concept and conducting a thorough investigation of liquid crystal molecule



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distribution in a three-dimensional environment, our study proposes a simpler and more practical approach to achieve beam steering in both planes. This is accomplished by employing discrete ground and cross bias conditions, eliminating the need for numerous bias lines and making it more feasible for engineering applications.

Our study presents a novel and simplified approach to achieve beam steering in both the E-plane and H-plane using LC RAs. By utilizing discrete ground and cross bias conditions, we can achieve versatile and dynamic control over the reflected beams, enhancing the practicality and efficiency of LC-based reconfigurable RAs for various engineering applications.

## 2. Unit design

In this study, we use a 2-finger structure (shown in Fig.1) as the basic unit of the LC RA. The LC RA unit consists of five layers: the top layer is made of quartz glass with a relative dielectric constant of $\varepsilon_{r1}$ = 3.78 and a loss tangent of tanδ = 0.002. The second layer is the patch layer, followed by the sealed LC layer, the fourth layer is the metalized ground layer with a slot to separate the ground part, and the bottom layer is also made of quartz glass. The parameters chosen for the LC RA unit are as follows: $h_G$ = 0.6mm, $X$ = 0.4mm, $G$ = 3.95mm, $L_{x1}$ = 1.95mm, $L_{x2}$ = 2.2mm, $h_{LC}$ = 0.25mm, Gap = 2.0mm, $W$ = 0.3mm, $W_0$ = 0.2mm.The liquid crystal used in the design is LC-BYE7, its material parameters are used as follows: relative dielectric constant changes from $\varepsilon_{r,}$ = 2.1 to $\varepsilon_{r,//}$ = 3.2, loss tangent varies from $\tan\delta_{\perp}$ = 0.014 to $\tan\delta_{//}$ = 0.004.

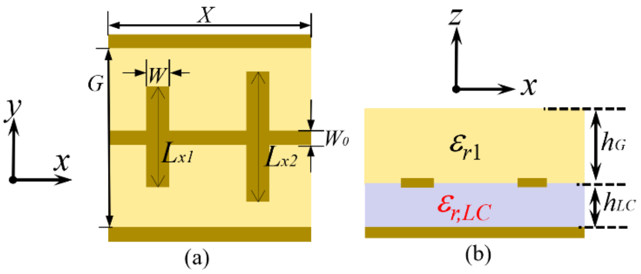
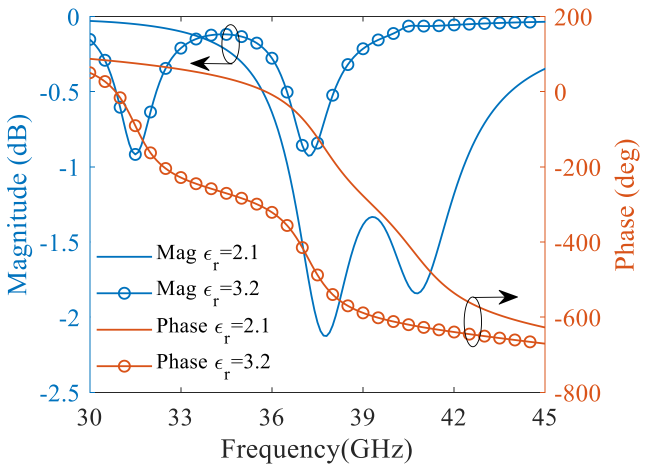
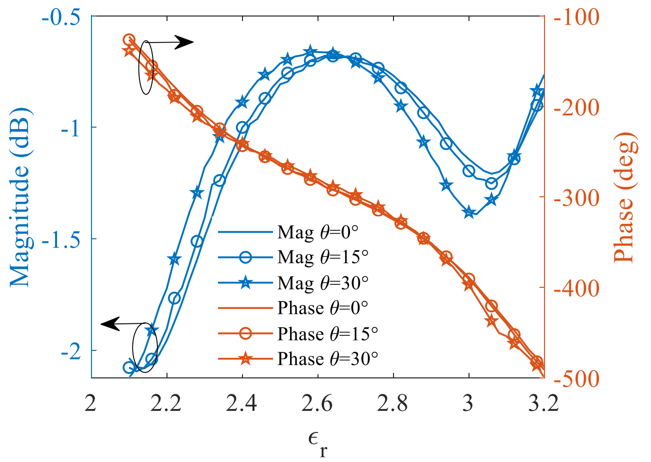



Fig.1. Numerical Analysis Model (Unit Cell). (a)Top view. (b) Side view

With bias voltage increasing, the relative increase and the reflection coefficient is shown in Fig. 2(a), with the increase in bias voltage, the return loss changes from -0.25 dB to -2.10 dB within the frequency band of 33.0 GHz to 42.0 GHz. This indicates relatively low loss compared to other LC RAs, making it an efficient and effective design for millimeter wave communication. At the target frequency point of 37.5 GHz, as depicted in Fig. 2(b), the magnitude of the scattering field varies from -2.1 dB to -0.6 dB with the changing state of the LC due to the increase in relative permittivity. The phase, on the other hand, decreases from -123° to -488°, resulting in a phase steering scale of over 360°. This ability to achieve a phase steering range of more than 360° is highly desirable for reconfigurable RAs, as it allows for flexible beam steering and control of the reflected waves. Even when the incident angles vary from 0° to 30° with respect to the -z axis, the magnitude of the reflected wave remains above -2.2 dB, and the phase change still exceeds 360°. This demonstrates the excellent performance and robustness of the proposed LC RA design, making it suitable for a wide range of practical applications. Overall, the results show that the LC RA design achieves a large phase shift range, low loss, and stable performance, making it a promising solution for RA design.




(a)




(b)

Fig.2. Simulation results of LC RA. (a)Γ VS frequency. (b) Γ VS relative permittivity of LC when biased at different incident angle.

## 3. LC RA integration and bias scheme for controlling radiation pattern

### 3.1. Construction of the LC RA LC properties under DC bias voltage

Traditional LC RAs do rubbing along one direction, which allows the LC molecules to rotate in one plane (Fig. 3(a) and 3(b)). We separate the ground layer of the RA with slot along direction *x*, and the patch layer of the RA is discretized with slot along direction *y*. Apply different voltages to different parts of ground $x_1$, $x_2$, $x_3$, …, $x_m$ relative to patch layer, different relative permittivity of LC in the RA unit appears (like Fig. 3(c)), so the RA unit can achieve phase controlled along direction x; apply different voltages to different parts of ground $y_1$, $y_2$, $y_3$,…, $y_n$ relative to patch layer, different relative permittivity of LC in the RA unit is obtained (like Fig. 3(d)), so the RA unit can achieve phase controlled along direction *y*.

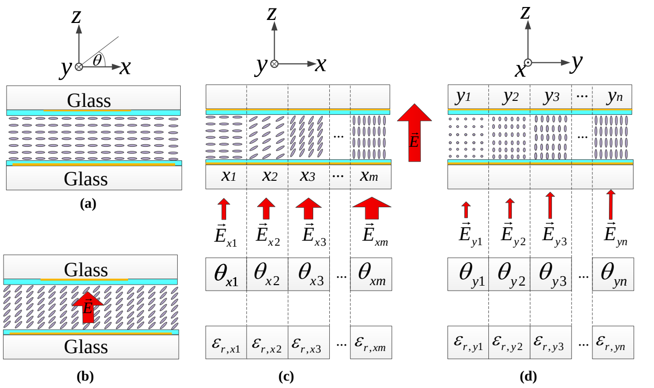



Fig. 3. LC properties under DC voltage steering when glass is alignment along *x* direction. (a) Initial state of LC molecules w/o bias. (b) State of LC molecules w bias when rubbing is along *x*. (c) Relative permittivity distribution in *xOz* plane as different bias is added along *x*. (d) Distribution of $\varepsilon_r$ in *yOz* plane as different bias is added along y.

### 3.2. Construction of the LC RA

In this LC RA system, the coordinate origin is set at the center of the RA, with direction x aligned along the bias lines of the patch layer, and direction y aligned along the dipole of the RA unit. To address the issue of obstacles, a standard horn antenna operating at the Ka band with a gain of 24.0 dBi is used as the feed. The horn antenna is positioned at coordinates (0.00, -34.64, 40.00) mm, providing an oblique incidence angle of 30° with a polarization of the TM mode, as illustrated in Fig. 4(a).

The LC RA consists of a 10×10 element array, and it has an aperture size of 40mm with an F/D ratio of 1.38. This configuration ensures a high aperture efficiency, which is crucial for optimizing the performance of the system.

With this setup, the LC RA is capable of achieving beam steering in both the E-plane and H-plane, enabling dynamic control of reflected beams. The LC RA's ability to independently control elements and achieve two-dimensional beam scanning makes it a versatile and powerful tool for various applications in millimeter-wave communication systems.

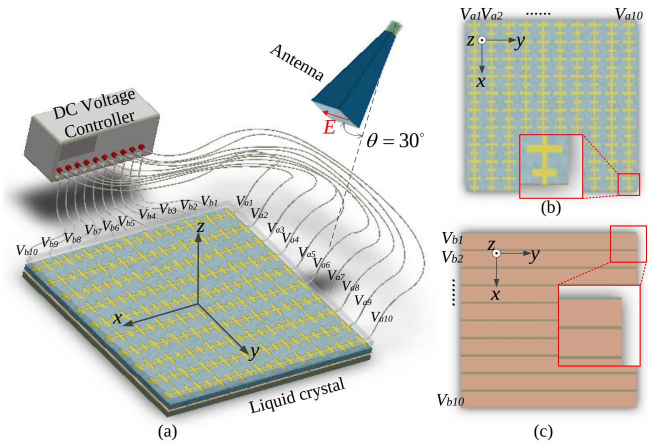


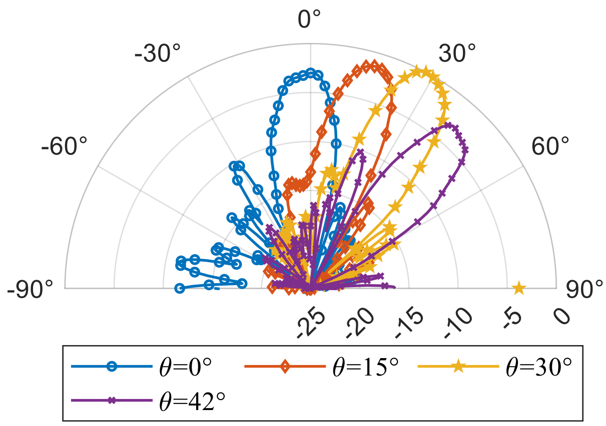

Fig.4.Geometry of the reconfigurable LC RA system. (a)3D view of LC RA system with orthogonal bias line. Top view of the LC RA: (b)Voltages can add different values along direction *y*. (c)Slots along direction *y* discrete the ground into sections and voltages can add different values along direction *x*.

### 3.3. Construction of the LC RASteer beam at H-plane and E-plane for LC RA

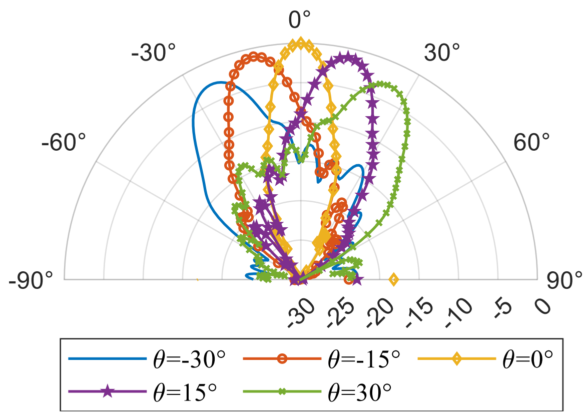
The incident wave from the feed antenna to the RA is approximated by cosine q pattern and the induced current can be obtained, the radiation pattern of the LC RA can be calculated by the array synthesis, pattern of RA is a product of RA element pattern and array pattern. To steer beam at H-plane, progressive phase distributed on the plane *xOz* is needed, so a scheme is provided: the voltage electrodes connected to the patch are the same value $V_a$, and the ground layers are biased with different voltages $V_{b1}$, $V_{b2}$, $V_{b3}$, …, $V_{b10}$, the phase of reflected wave from each column along direction *x* will be controlled, so the phase center of reflected wave will shift along direction *x*. And the beam can be steered in E-plane from 0° to 42° relative to *z* axis(Fig. 5(a)) when maximum radiation intensity decrease 3.0 dB. When the electrodes connected to ground are biased the same voltage $V_b$, the ground layers are biased with different voltages $V_{a1}$, $V_{a2}$, $V_{a3}$, …, $V_{a10}$, orthogonal beam steering can be achieved, the steered beam at E-plane can cover from -30° to 30°.

### 3.4. Comparison with other surface structures

The incident wave form the feed antenna to the RA is approximated by cosine q pattern and the induced current can be obtained, the radiation pattern of the LC RA can be calculated by the array synthesis, pattern of RA is a product of RA element pattern and array pattern. To steer beam at H-plane, progressive phase distributed on the plane *xOz* is needed, so a scheme is provided: the voltage electrodes connected to the patch are the same value $V_a$, and the ground layers are biased with different voltages $V_{b1}$, $V_{b2}$, $V_{b3}$, …, $V_{b10}$, the phase of reflected wave from each column along direction *x* will be controlled, so the phase center of reflected wave will shift along direction *x*. And the beam can be steered in E-plane from 0° to 42° relative to *z* axis(Fig. 5(a)) when maximum radiation intensity decreases 3.0 dB. When the electrodes connected to ground are biased the same voltage $V_b$, the ground layers are biased with different voltages $V_{a1}$, $V_{a2}$, $V_{a3}$, …, $V_{a10}$, orthogonal beam steering can be achieved, the steered beam at E-plane can cover from -30° to 30°.




(a)




(b)

Fig.5. Beam scanning of LC RA. (a) H-plane. (b) E-plane

## 4. Conclusion

A development of LC RA unit of 2-finger with discrete ground and a DC bias scheme of orthogonal bias electrodes reconfigurable LC RA are proposed in this article. By applying orthogonal bias voltages to these electrodes, precise control over the phase of the LC RA is achieved in two directions. Consequently, it becomes possible to steer the aperture phase on the LC RA, enabling beam steering in both the E-plane and H-plane. To validate the proposed design, a pyramid horn antenna operating at the Ka band is employed as the primary feed. A 10x10-element LC RA is designed, and the radiation pattern is calculated using array synthesis with consideration of element radiation properties. Experimental results demonstrate that at target frequency 37.5 GHz, the LC RA successfully achieves beam scanning in two orthogonal directions: E-plane scanning ranging from -30° to 30°, and H-plane scanning from 0° to 42°.


## 5. Acknowledgment

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