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Beam Scanning Microstrip Leaky Wave Antenna Design Based on Liquid Crystal

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Abstract—A novel beam scanning microstrip leaky wave antenna based on liquid crystal material is proposed in this paper. Based on the dielectric anisotropy of the liquid crystal, the main beam angle of the antenna pattern can be easily adjusted with the changing of external bias voltages. Good agreement between simulated and measured results is found for the presented leaky wave antenna. Both the simulation and test frequencies of the antenna are set at 12 GHz. Besides, the measured data show that when the dielectric constant of the liquid crystal changes from 2.4 to 2.52, about 10 degrees tuning range of the main beam angle is achieved.

1. INTRODUCTION

In recent years, due to the important property of dielectric anisotropy, liquid crystal materials have been widely used in the microwave field as tunable devices. Compared with traditional microwave tunable devices [1, 2], microwave devices based on crystal materials can achieve miniaturization, high integration and easy regulation [3]. Moreover, many scholars have studied the application of liquid crystals in the microwave field, including reconfigurable antennas [4], phase shifters [5], and filters [6]. A substrate integrated waveguide (SIW) leaky wave antenna was presented in [8]. Generally, an SIW leaky wave antenna has disadvantages of high cost, high profile, and complicated feeding structure. Instead of SIW antenna, a beam scanning leaky wave antenna based on liquid crystal material is proposed in this paper. It has low cost, low profile, and the feed is simple too. Furthermore, there are almost no articles on microstrip leaky wave antenna based on liquid crystal materials. Therefore, the design in this paper has certain significance for other microstrip leaky wave antennas based on liquid crystal materials.

2. DESIGN PRINCIPLE

A schematic diagram of a microstrip leaky wave antenna is shown in Figure 1, in which the dielectric constant of the substrate is represented by ε_r, and W and L denote the width and length of the radiation patch, respectively. Besides, h means the thickness of the dielectric substrate.

The expression of far radiation field of the microstrip leaky wave antenna is:

$$E_\phi = f(r,\theta,\phi)\frac{\exp[-j(\beta_z-\beta_0\cos\theta)L]-1}{\beta_z-\beta_0\cos\theta} \tag{1}$$

$$H_\theta = -E_\phi/120\pi \tag{2}$$

$$f(r,\theta,\phi) = \frac{\beta_0 U\exp(-j(\beta_0 r)}{\pi r}\times\cos\left(\beta_0\frac{W_e}{2}\sin\theta\cos\varphi\right)\sin\theta \tag{3}$$

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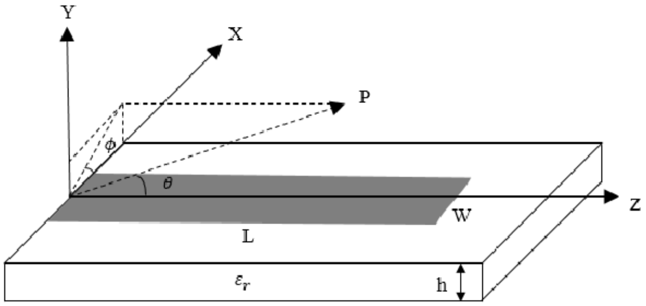


Figure 1. Structure of microstrip leaky wave antenna.

where U is the voltage between the two magnetic currents, and W_e is the equivalent width of microstrip line. Formula (3) does not consider the loss of the antenna and is corrected by the alternative Formula (4), in which k_Z is the propagation constant along the z direction. At the same time, the reflection is taken into account. Assuming that the terminal of the microstrip leaky wave antenna is an open circuit, the expression of the far radiation field can be modified as:

$$E_\phi = f(r,\theta,\phi)\frac{\exp[-j(k_z-\beta_0\cos\theta)L]-1}{k_z-\beta_0\cos\theta} - \exp(-2jk_zL)\frac{\exp[j(k_z+\beta_0\cos\theta)L]-1}{k_z+\beta_0\cos\theta} \tag{4}$$

When the leakage phase constant β_z satisfies $\beta_z < k_0$, it works in the first higher order mode. The main beam direction $\theta_m = 90^\circ - \theta$, and the expression is:

$$\theta_m = \arcsin\left(\frac{\beta_z}{k_0}\right) \tag{5}$$

The leakage propagation constant can be expressed as following [7]:

$$\begin{aligned} k_z &= \beta_z - j\alpha_z = (\omega^2\mu\varepsilon_r - k_x^2)^{1/2} && (6)\\ \exp(jk_xW) &= -(k_x-\omega\mu y_w)/(k_x+\omega\mu y_w) && (7)\\ y_w &= \frac{h}{120\lambda} + j\frac{k_0\varepsilon_r\Delta L}{120\pi} && (8) \end{aligned}$$

Among them, ΔL is the equivalent extension of the antenna patch width brought by the terminal opening effect, and y_w is the radiation admittance. From Formula (8), it can be concluded that the factors affecting the antenna radiation direction are radiation patch width W, relative permittivity ε_r, dielectric substrate thickness h, and equivalent extension of the antenna length ΔL. When the frequency is fixed, it is difficult to change W, h. But by filling the liquid crystal into the microstrip leaky wave antenna, the phase of the 1 order spatial harmonics of the antenna can be changed with the change of electric field. Therefore, the antenna achieves the function of beam scanning with the change of dielectric constant of liquid crystal.

3. ANTENNA DESIGN AND MEASUREMENTS

Figure 2 shows the antenna structure [9], which consists of dielectric substrate, radiation patch, liquid crystal, and metal ground layer. A feeding microstrip line and a bias circuit are designed on the first layer of dielectric substrate. The feeding microstrip line is connected with the patch on the lower surface through the metal through hole so that the voltage is evenly loaded on both ends of the liquid crystal easily. A substrate of Rogers 4350B with thickness 0.254 mm is used for designing this kind of antenna. Generally, for the choice of liquid crystal material, it is necessary to test its specific characteristics, and the measurement method can be found in [10]. The dielectric constant of the liquid crystal selected in this paper is varied from 2.4 to 2.52 when changing bias voltages from 0 V to 16 V. The dielectric constant remains unchanged when voltage is bigger than 16 V.

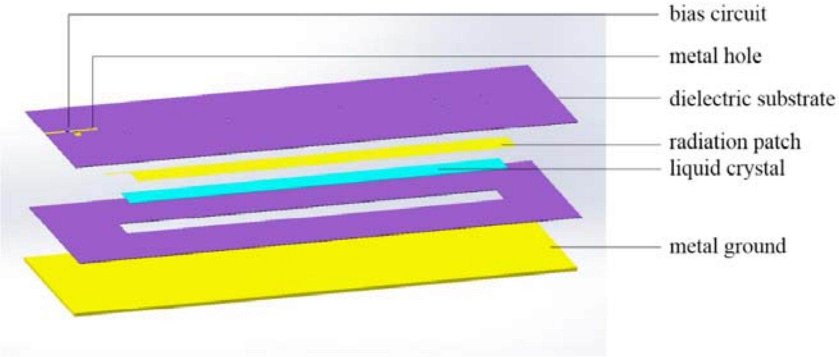
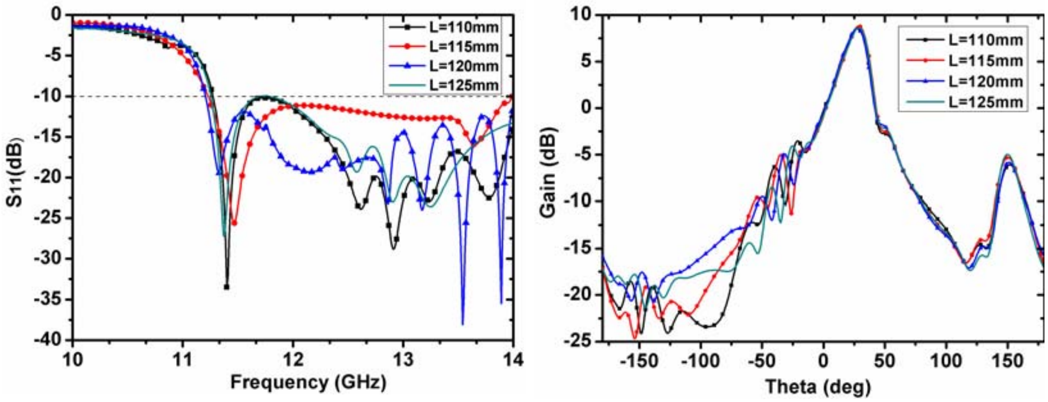
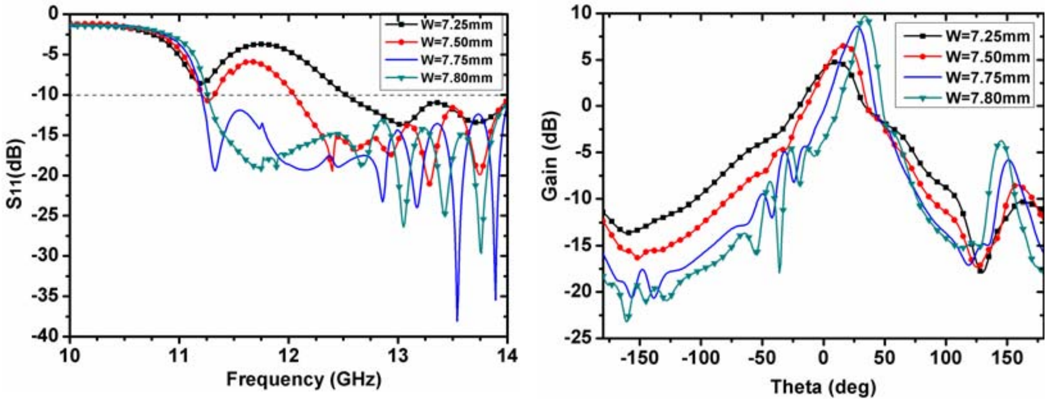


Figure 2. Structure of liquid crystal-based microstrip leaky wave antenna.



(a) (b)

Figure 3. (a) Influence of different radiation patch length L on S_{11} and (b) on Gain.

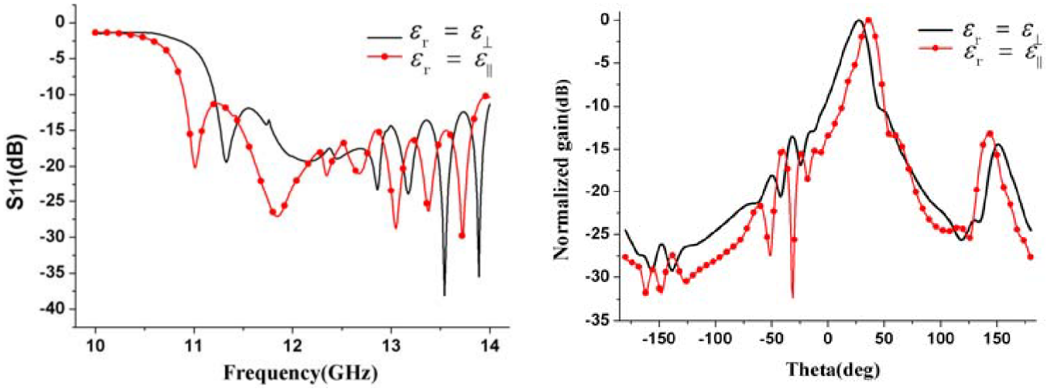


(a) (b)

Figure 4. (a) Influence of different radiation patch width W on S_{11} and (b) on Gain.

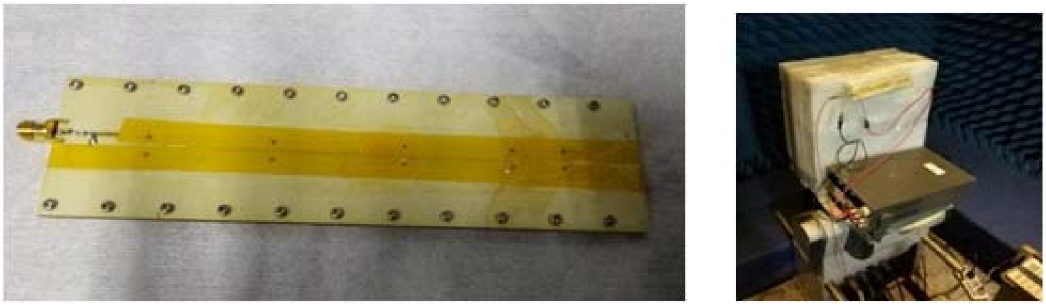
Figure 3 shows that different radiation patch lengths L have little effect on S_{11} and gain of the antenna when L is greater than 110 mm and less than 125 mm. However, W has great influence on antenna gain and bandwidth shown in Figure 4. Therefore, with the consideration of bandwidth and gain the parameters are set as $W = 7.8$ mm and $L = 120$ mm.

Figure 5(a) depicts the final simulated results at 12 GHz in two states. When the dielectric constant of the liquid crystal is switched from $\varepsilon_{\perp}$ to $\varepsilon_{\parallel}$, the operating bandwidth of is broadened from the original



(a) (b)

Figure 5. Simulation results at 12 GHz. (a) Simulated results of S parameter. (b) Simulated results of normalized gain.



(a) (b)

Figure 6. Antenna's physical map and test environment. (a) Physical map. (b) Test environment.

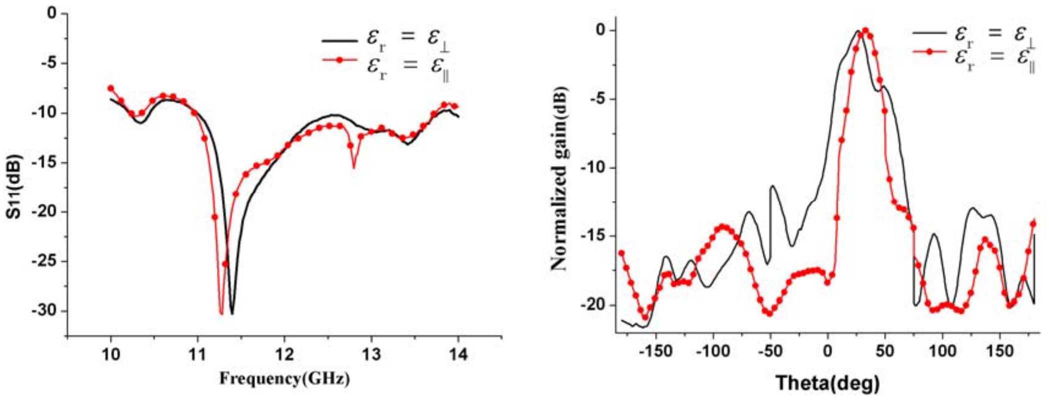
11.2 GHz–14 GHz to 10.9 GHz–14 GHz.

Figure 5(b) describes the simulation results of the normalized E-plane pattern of the liquid crystal microstrip leaky-wave antenna at 12 GHz. When the dielectric constant of the liquid crystal is switched from $\varepsilon_\perp$ to $\varepsilon_\parallel$, maximum radiation direction of the antenna is changed from 28 to degrees to 36 degrees. The change range is 8 degrees. The physical map of the fabricated liquid crystal microstrip leaky wave antenna and the test environment are shown in Figure 6.

The liquid crystal microstrip leaky wave antenna was tested at 12 GHz, and the normalized E-plane radiation pattern is shown in Figure 7. The two extreme states of the liquid crystal were measured, and the corresponding bias voltages were at 0 V and 16 V. Because the dielectric of the liquid crystal is unchanged when the applied voltage is bigger than 16 V, the parameters of S_{11} and gain remain fixed when the bias voltage is greater than 16 V.

Figure 7(a) displays reflection coefficients of the antenna under the two states of different dielectric constants. It can be seen that when the bias voltage is adjusted from 0 V to 16 V, the dielectric constant of liquid crystal is switched from $\varepsilon_\perp$ to $\varepsilon_\parallel$, and the working frequency is from 11 GHz to 14 GHz. The bandwidth is relatively stable, and the change of the dielectric constant of the liquid crystal has little effect on the S-parameter of the antenna. It should be noted that Figure 7(a) is not very consistent with Figure 5(a). The main reason is that the simulation only changes the dielectric constant of liquid crystal material, but not consider many practical influence factors, such as the tightness of liquid crystal packaging. However, the bandwidths of the two diagrams str basically the same.

Figure 7(b) shows the measured results of E-plane normalized gain of the antenna at 12 GHz. In practical tests, the maximum radiation direction of the antenna changes from 25° to 35°, which means that the maximum radiation direction of the antenna is tuned 10 degrees, and there is a better



(a) (b)

Figure 7. (a) Measured results of s parameter. (b) Measured results of normalized gain.

consistency compared with simulation results.

At last, the gain and radiation efficiency are simulated and tested. The simulated values of the gain and radiation efficiency are 8.6 dB and 0.6; however, the tested values are 8.1 dB and 0.55, respectively, when dielectric constant of LC is 2.4. When dielectric constant of LC is 2.52, the simulated and tested values of the gain are 9.63 dB and 8.82 dB. The simulated radiation efficiency is 0.57, and the tested value is 0.52. The differences of gain and efficiency between the simulation and measurement are caused by the fact that the complex dielectric constant is not easy to be tested correctly.

4. CONCLUSION

A liquid crystal microstrip leaky wave antenna is designed and tested in this paper. The antenna operates stably at 11 GHz–14 GHz, which has a wider bandwidth. Besides, the test results are in good agreement with the simulation ones. At 12 GHz, we can see that the direction of the maximum radiation direction can be changed from 28° to 36° in simulated results. In the measured results, the maximum radiation direction can be changed from 25° to 35° with bias voltages from 0 V to 16 V. This design has been tested only in 12 GHz. Actually, other frequency points of the operate bandwidth also have the function of beam scanning. At the same time, when forming an array of leaky wave antennas or changing liquid crystal materials with larger dielectric permittivity changing range, the performance and application scenarios of this kind antenna will be better.

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