Design of an Electronically Beam-Scanned High-Power Capacity Reflectarray Antenna Based on Liquid Crystals for Airborne Radar Application

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Abstract. In this paper, an electronically beam-scanned high-power capacity airborne radar reflectarray antenna based on liquid crystals is presented. To achieving fast phase-tuning and high-power capacity performances of the airborne radar reflectarray antenna, the thoroughly simulated analysis of the structure of the patch and the position of the bias line is made. The optimized patch is rectangular patch with three rectangular slit, which shows good power capacity performance. And the bias line is placed at the center distance. Simulation shows that the introduction of bias line has little effect on the reflected amplitude and phase of the reflecting unite. A 11×11 airborne radar reflectarray antenna are designed and analyzed. The simulated results show that the power capacity of the reflectarray antenna is about 3.6 MW in air condition and 30° beam-scanning can be obtained. The results verify the electronically beam-scanned and high-power capacity performance of the airborne radar reflectarray antenna. The antenna shows good environmental adaptability and electronically beam-scanning performance.

Keywords: Airborne radar antenna · Electronically beam-scanned · High-power capacity · Reflectarray antenna

1 Introduction

The airborne radar antenna is an important part of a fighter [1–5]. In recent years, with the rapid development of aerospace technology and high-power microwave technology [6], the electromagnetic environment of the battlefield in which fighters located is extremely complex. In order to improve the battlefield survivability of the airborne radar antenna, the antennas should not only meet the basic radiation characteristics requirements, but also meet the high-power capacity performance. In addition, the antenna is also required to have fast beam scanning performance.

Reflectarray antenna has the potential for high-power capacity applications [7]. At the same time, based on the liquid crystals with the thickness of 100 μm, the response time of nematic liquid crystal molecules is within 30 ms [8], the dielectric constant of the liquid

crystal is changed correspondingly. In addition, the available study shows that liquid crystal material has the performance of high-power capacity. Therefore, based on the liquid crystal material, an electronically beam-scanned high-power capacity reflectarray antenna is designed in this paper. The antenna shows good environmental adaptability and electronically beam-scanning performance.

2 Design of Reflecting Unite

The configuration of the proposed reflecting unite is shown in Fig. 1. The radiating antenna is three rectangular slit patch, which forms a sandwich structure with the upper Rogers 5880 dielectric plate layer and the lower liquid crystal material layer. The bias lines at both ends of the patch are connected to the bias line at the bottom of the PCB by the metallized through hole I, and the ground plane by the metallized through hole II. The metallized through hole I is not connected to the ground plane. The positive pole of the DC bias voltage source is connected to the metallized through hole I, and the negative pole is connected to the metallized through hole II. Thereby a bias loop combined with the unite structure is formed. The reflecting unites are arranged in a rectangular grid. In order to obtain relatively good reflecting amplitude and phase response results at normal incidence and 30° oblique incidence, the size parameters of the reflecting unite are optimized and designed, and the optimized key parameters of the patch are shown in Table 1. The unite spacing is 4.5 mm (about 0.53 times the wavelength of the center frequent). The patch thickness is 0.15 mm, the liquid crystal layer thickness is 100 μm, and the upper dielectric plate thickness is 2 mm.

(a) 3D view

(b) Top perspective view
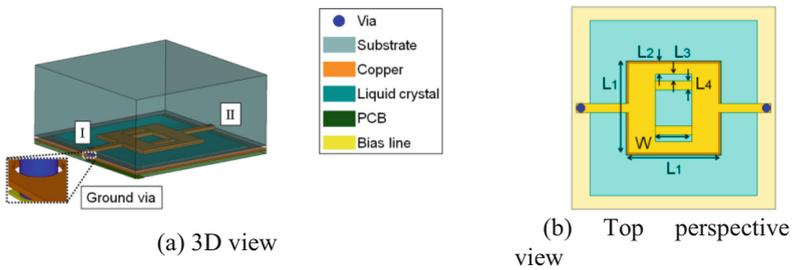
Fig. 1. The configuration of the proposed airborne radar reflecting unite.

Table 1. Optimized parameters.

Parameter	L_1	L_2	L_3	L_4	W
Value (mm)	2.1	0.3	0.15	0.2	0.8

In order to design a reflecting unite with high-power capacity performance, it is necessary to reduce the surface electric field of the radiating patch. The main means to reducing the electric field is to make the electric field distribute over a larger effective

area of the patch. Based on this theory, the simulations of the reflect array unite based on the rectangular patch, the rectangular patch with a rectangular slit and the rectangular patch with three rectangular slit are carried out respectively. The input power is 0.5 W, based on the same liquid crystal materials with dielectric constant and loss tangent (ε = 3.4, tanδ = 0.02), the simulated electric field distributions of reflecting unites with different patch shapes are obtained are shown in Fig. 2. The electric field strength on the surface of the patch is mainly concentrated on both sides of the patch perpendicular to the polarization direction of the excitation electric field, the maximum electric field strength value of the rectangular patch with three rectangular slit unite is relatively lower, which mainly because the effective electric field area of the structure is relatively larger. The reflecting unite based on the patch structure has high power capacity performance.

(a) Rectangular patch   (b) Rectangular patch with a rectangular slit

(c) Rectangular patch with three rectangular slit
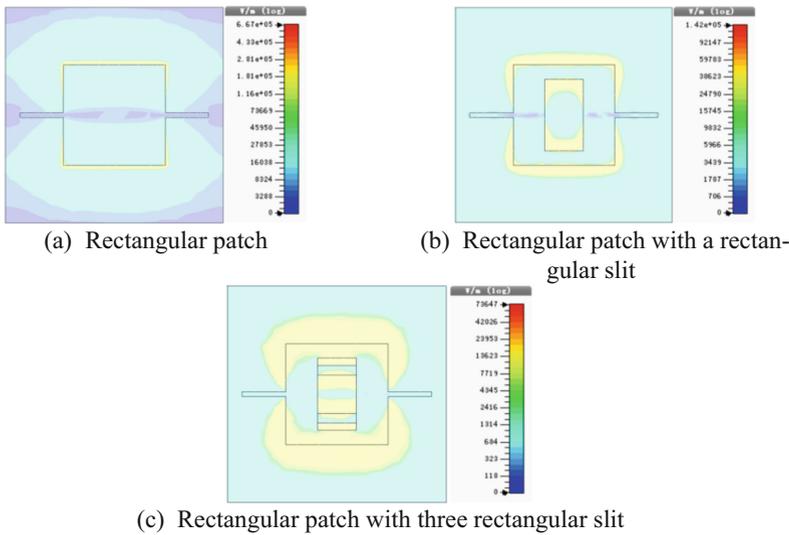
Fig. 2. Electric field distributions of different reflecting unites.

The reflecting unite with high-power capacity needs to load the bias line to connect with the voltage source. As a small structure, the bias line may cause the problem of electric field concentration, thus limiting the power capacity of the reflecting unite. With the goal that the introduction of the bias line has small impact on the power capacity performance of the unite, the position of the bias line is analyzed. For the convenience of analysis, based on the fixed dielectric constant and loss tangent (ε = 3.4, tanδ = 0.02), the unite with no-bias line, with horizontal bias line at the corner of the patch, the unite with horizontal bias line at the 1/4 distance, and the unite with horizontal bias line located at the center distance are simulated and analyzed. The input power is 0.5 W, the obtained electric field distribution on the surface of each patches are shown in Fig. 3. From the electric field distribution, it can be seen that the electric field distribution on the patch surface of the unite where the horizontal bias line is located at the center of the patch is similar to that of the unite without the bias line. As for the unite with the horizontal bias line at the corner and the horizontal bias line at the 1/4 distance, the

introduction of the bias line makes the surface mode of the patch change significantly. The reflected amplitude and phase response results of different unites are shown in Fig. 4. The reflected amplitude and phase response results of the reflecting unite with horizontal bias line located at the center of the patch are consistent with the results of the unite without bias line. According to the above analysis results, placing the horizontal bias line at the center of the patch is the optimal position, which has little effect on the field strength distribution and reflection amplitude-phase response performance of the antenna.

By adjusting the dielectric constant, the change of the dielectric constant caused by the change of the director of the liquid crystal molecules under different applied voltages is simulated. And the reflected amplitude and phase response of the reflecting element under different conditions are simulated and analyzed based on unite cell boundary. The reflecting unite is excited by TM linearly polarized plane wave. The obtained reflected amplitude and phase response results corresponding to different dielectric constants under normal incidence and 30° oblique incidence are shown in Fig. 5. The reflected amplitude and phase response stability is good under under normal and 30° oblique incidence. When the dielectric constant changes from 2.42 to 3.4, the phase compensation of 305° can be achieved, and the reflection amplitude remains greater than −8.6 dB. Under different incident angles, the unite can achieve good reflected amplitude and phase response at the operating frequency of 35 GHz. The reflected magnitude is more than −3 dB among the 35% of the dielectric constant. So for a large antenna arrays, the element loss results are relatively good.

(a) No-bias line   (b) Bias line at the corner of the patch

(c) Bias line at the 1/4 distance   (d) Bias line at the center distance
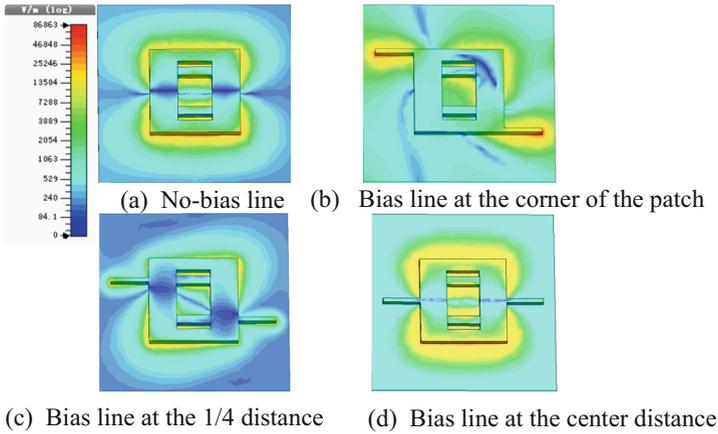
Fig. 3. Electric field distribution on the surface of different patches.

3   Design of Reflectarray

The simulated results of the reflecting unite show that the reflecting unite based on liquid crystal material has stable reflected phase and amplitude response performance. And the unite has the potential for high-power microwave applications. In order to
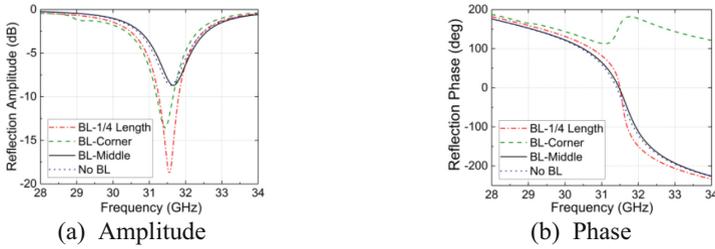
Fig. 4. Reflected phase and amplitude responses of different unites.
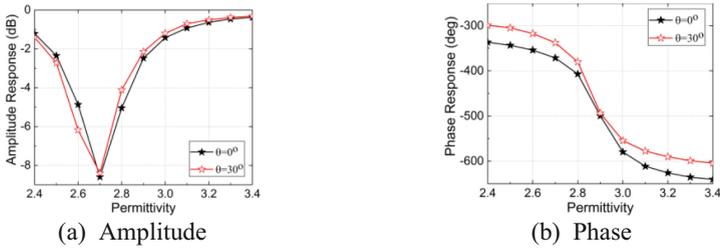
Fig. 5. Reflected phase and amplitude responses under normal and 30° incidence.

verify the above performance, a 11×11 reflectarray antenna is designed with this unite. The reflectarray is fed by a linearly polarized corner cone antenna with 10° offset. The height of the feed was adjusted to meet the requirements of edge tapper of -8 dB. The calculated phase compensation required by each element of the array is shown in Fig. 6. The dielectric constant of each element is adjusted according to the phase response curve of Fig. 5(b). And the full-wave simulation analysis of the reflectarray antenna is performed based on the electromagnetic simulation software.

The simulated results show that the antenna gain with the main beam direction of $(\theta = 10°, \varphi = 0°)$ is 20.7 dB at the operating frequency of 35 GHz. The corresponding aperture efficiency is 28%, and the sidelobe level is -18.1 dB, which achieves better directional beam radiation. Under different beam scanning angles, the 3D pattern and gain results are shown in Figs. 7 and 8. Within the scanning range of 0–40°, the pencil beam radiation pattern is achieved in the specified direction, and the gain variation is about 3 dB, When the main beam is at 20° direction, the antenna achieves the maximum gain of 21.7 dB, and the corresponding aperture efficiency is 35.3%. The relatively good efficiency is obtained.

Taking the main beam direction of $(\theta = 10°, \varphi = 0°)$ as an example, the power capacity performance of the reflectarray antenna is analyzed. The input power is 0.5 W, and the electric field strength distribution of the key part of the reflectarray antenna is shown in Fig. 9. The maximum field strength of the internal patch is 11118 V/m. The internal breakdown threshold of the liquid crystal is 30 MV/m [8], the calculated power capacity is about 3.6 MW. And the maximum field strength on the antenna surface is 750 V/m. Calculated with a breakdown threshold of 3 MV/m in air, the surface power capacity is 8 MW. So the main limitation of the power capacity of the reflectarray antenna
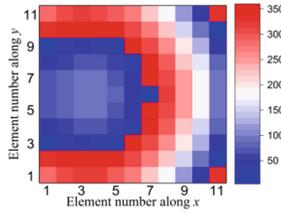
Fig. 6. The phase compensation required by each element
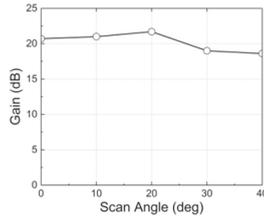
Fig. 7. Gains of different scanning angles.

(a) 0º

(b) 10º

(c) 20º

(d) 30º

(e) 40º
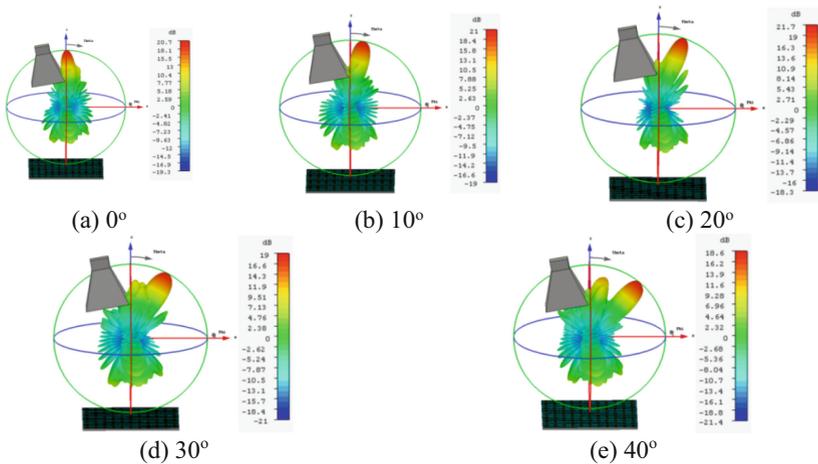
Fig. 8. 3D pattern of different scanning angles.

is on the internal patch, and its power capacity is 3.6 MW. The results show that the reflectarray antenna has high-power capacity performance.

4   Conclusion

In this paper, a electronically beam-scanned high-power capacity airborne radar reflectarray antenna based on nematic liquid crystal is proposed and designed. An innovative reflecting unite is designed with good reflecting amplitude and phase response, and

(a) Internal patch   (b) Antenna surfacE
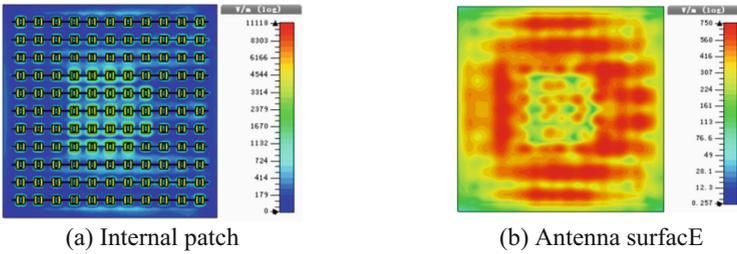
Fig. 9. Electric field strength distribution of the key part of the reflectarray antenna

electric field strength performances. The above performances are basically not affected by the introduction of bias lines. A Ka-band 11×11 reflectarray antenna is designed, and its electronically beam-scanned and high-power capacity performance are verified. The antenna shows good environmental adaptability and electronically beam-scanning performance.

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