Design of a millimeter wave helical reflectarray antenna with high power handling capacity

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Abstract. A millimeter-wave high-power handling capacity circularly polarized shared-aperture transceiver reflectarray antenna is proposed and designed. The short helical reflection antenna is proposed to be the reflectarray element. The 360° phase shift can be achieved by rotating the helical element. A flat-top shaped beam shared-aperture transceiver array antenna feed is designed to improve the efficiency and power capacity of the reflectarray antenna. The reflectarray with the aperture size of 49.5 \times 49.5 \text{ mm}^2 is designed and simulated. The full-wave simulation results show that at center frequency of 30 GHz, the gain of the antenna is 22.5 dB with the efficiency of 57.8%, and the axis ratio is 0.8 dB. In the range of 26 to 34 GHz, the reflection coefficient is lower than -17.8 dB, with the relative bandwidth of 26.7%. The 1-dB gain bandwidth is 19.4%. Under air condition, the power capacity of the element antenna is 898 W, and the power capacity of the reflectarray antenna is 19.2 kW.

1. Introduction

In millimeter-wave satellite communication systems, antennas are generally required to have high gain and high power capacity. As one of the core components of the millimeter wave system, the millimeter wave antennas can provide high gain in a compact physical size, which is the reason for the extensive researches [1]. The existing researches on millimeter wave satellite communication antennas are mainly focusing on the active phased array antennas [2-5]. The constrained feed is applied to this kind of antenna. The beam scanning can be realized by electronic control with high speed. However, due to the use of constrained feed, the bandwidth of the antenna is generally between 1-2%, and the output power of the element is in the order of hundreds of milliwatts. With the development of millimeter-wave military and civilian satellite communication systems, the demand for millimeter-wave antennas with broadband, high power handling capacity has become increasingly prominent.

Reflectarray antenna is another kind of array antenna using spatial feed. The antenna has the performance of high power capacity for that it can distribute the energy radiated from the antenna feed to each reflectarray element. At the same time, the broadband reflectarray antenna can be achieved with a reasonable design of the antenna element [6-7]. Introducing reflectarray antenna into the field of millimeter-wave satellite communications is expected to improve the bandwidth and power capacity of millimeter-wave civilian satellite communications antennas. In this paper, a millimeter-wave high-power handling capacity shared-aperture transceiver helical reflectarray antenna is proposed and designed. The beam-forming of the array feed is studied to improve the efficiency and power capacity of the reflectarray antenna. Firstly, a short helical reflectarray element is designed, and the reflection amplitude and phase responses, and the power capacity of the element are analyzed. Then, the flat-top
shaped beam for the array feed are given. Finally, the radiation performance, available bandwidth, and power capacity of the helical reflectarray antenna are analyzed.

2. Design of reflectarray element

The structure of the proposed reflectarray element is shown in figure 1. It consists of a metal helix supported by an axis. In order to obtain a good reflection amplitude and phase responses, the parameters of the element are optimized. The height of the feed point of the helical is 1.1 mm, the radius of the helix is 2.2 mm, the wire diameter of the helix is 0.66 mm, the circumferential angle is 250°, and the pitch of the helix is 0.43 mm. The operating center frequency is 30 GHz, and the element spacing is 5.5 mm.

![Figure 1. Structure of the proposed reflectarray element.](image)

The amplitude and phase responses of the proposed element is analyzed firstly. The reflected phase can be adjusted by rotating the helical around the axis. Based on the infinite array method, the element is simulated and analyzed. The reflected amplitude and phase responses corresponding to different rotation angles under normal incidence and 30° oblique incidence are shown in figure 2. At the center frequency of 30 GHz, the reflected phase responses can satisfy 360° phase compensation. And the phase response under normal incidence is consistent with that under 30° oblique incidence. The co-polarized reflected amplitude is greater than -0.2 dB, and the cross-polarized amplitude is less than -14 dB. The good reflected amplitude and phase responses are mainly attributed to the all-metal structure of the element, which avoid dielectric loss. Under different incident angles, the element can achieve relatively stable reflected amplitude and phase responses.

![Figure 2. Simulated (a) phase and (b) amplitude responses under normal and 30° incidence.](image)
The power capacity performance of the reflectarray element is analyzed then. At center frequency of 30 GHz, the electric field strength distribution of the reflectarray element is shown in figure 3. The maximum electric field strength is 70801 V/m, mainly concentrated on the turn of the helix. Based on the breakdown field strength in air of 3 MV/m, the calculated power capacity of the reflectarray element is 898 W.

3. Design of array antenna feed
The helical antenna can directly radiate the circularly polarized wave and the phase of the radiated wave can be adjusted by rotating each helical antenna element. The flat-top shaped beam can make the energy uniform for each reflectarray element so that the antenna efficiency and power capacity of the reflectarray antenna are improved. At the same time, adding an integrated transceiver device to the input end of the feed network can make the reflectarray antenna system realize the shared-aperture performance. Based on the above theoretical analysis, a two concentric rings array antenna feed composed of 18 helical antenna elements is designed as shown in figure 4. In order to make the array antenna feed radiate the flat-top beam, the input amplitude and phase of the elements in the two rings are optimized basing on the particle swarm optimization algorithm [8]. The array antenna feed can be divided into two groups, namely, the elements in inner ring and outer ring. Correspondingly, there are four parameters, namely, the amplitudes and phases of the two rings are optimized. The obtained amplitudes and phases are shown in table 1. The simulated far-field pattern of the two orthogonal planes are shown in figure 5. The 3-dB beam widths on both orthogonal planes are 62.5°. The beam with flat-top and good rotation symmetry is achieved.
| Amplitude | Phase |
|-----------|-------|
| 0.7       | 121°  |
| 0.3       | 260°  |

4. **Reflectarray design and performance**

In order to verify the performance of the above reflectarray element, a reflectarray antenna with the aperture size of 49.5 mm is designed. The above-mentioned helical array antenna feed is used to feed the reflectarray. The required phase compensation of each element is determined using the ray tracing theory. The rotation angle of each helical antenna element is adjust based on the phase response curves in Fig. 2. Full-wave simulations of the reflectarray antenna are carried out.

The radiation performance of the reflectarray antenna is analyzed. At 30 GHz, the radiation patterns of the reflectarray antenna in two orthogonal planes are shown in figure 6. The antenna gain is 22.5 dB with the corresponding aperture efficiency of 57.8%, and the axial ratio is 0.8 dB. In the two orthogonal planes, the sidelobe levels are lower than -14.4 dB, the cross-polarization levels are lower than -23.4 dB, and the -3 dB beam-widths are 10.3 deg. The beam rotation symmetry is good. The antenna gains and reflection coefficient at different frequencies are shown in figure 7. The reflection coefficient is below -17.8 dB over the entire frequency band, and the maximum gain of 22.8 dB is obtained at 31.8 GHz. The antenna gain is stable for different frequencies, which contribute to the broadband performance. According to the array theory, the radiation patterns of the reflectarray antenna under different scanning angles are shown in figure 8.

![Figure 4. Configuration of the array antenna feed.](image)

![Figure 5. Flat-top shaped pattern of the array antenna feed.](image)

![Figure 6. Simulated radiation patterns on (a) Phi=0° and (b) Phi=90° planes at 30 GHz.](image)
Within the scanning angle of 40°, the antenna gain is reduced by 1 dB. And the pencil beam radiating in the specified direction is accurately achieved. The above results indicate that the reflectarray antenna has good radiation performance, phase control performance and broadband performance.

The power capacity of the proposed reflectarray antenna is analyzed. At the center frequency of 30 GHz, the electric field distribution of the reflectarray is shown in figure 9. The maximum field strength is 15286 V/m, which is mainly concentrated on the corner of the helical. Taking the breakdown threshold of air condition as 3 MV/m, the calculated power capacity of the reflectarray is 19.2 kW. The results verify the high power handling capacity performance of the millimeter wave reflectarray antenna.
5. Conclusion
In this paper, a millimeter-wave high-power handling capacity shared-aperture transceiver helical reflectarray antenna is proposed. The proposed reflection element consists of a short helix. Simulation results show that the power capacity of the element is 898 W under air condition. A reflectarray antenna consisting of 81 elements is simulated. The full-wave simulations show that the 1-dB gain bandwidth is about 19.4%. In the range of 26 to 34 GHz, the reflection coefficient is lower than -17.8 dB, with the relative bandwidth of 26.7%. The power capacity of the reflectarray antenna is 19.2 kW under air condition. The beam-scanning performance of the antenna is also verified. The proposed millimeter wave reflectarray antenna is proved with the performance of broadband, phase adjusted and high power handling capacity and provides a new antenna form for the research and application of the millimeter wave military and civilian satellite communications antenna.

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