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Design of Three-Element Circular Polarization Antenna Array Based on Sequentially Rotated Feed Technique

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Abstract: Circularly polarized antennas are used in communications between ground stations and satellites to achieve reliable communication links. The right-hand circular polarization and left-hand circular polarization are two types of circular polarization in satellite communications, they are used to support uplink and downlink communications. Circularly polarized antennas are used also in radar system for target detection, tracking and identification. The "three-element circularly polarized microstrip array antenna" is designed to produce left-handed circular polarization, make its size compact, make its bandwidth wider than 3.7–4.2GHz and achieve high gain. Circular polarization element antenna and three-element circularly polarized microstrip array antenna are designed and simulated in software HFSS, and the circular polarization element antenna is manufactured and tested in anechoic chamber. For circular polarization element antenna and three-element circularly polarized microstrip array antenna, the study analyzed these parameters: AR, S(1,1), VSWR, bandwidth, normalized impedance, gain and realized gain, radiation efficiency. After optimized, the study get the required results of them.

Keywords: Circularly polarized antenna; Array antenna; Microstrip patch antenna; Satellite communication

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1. Introduction

The concept of the microstrip patch antenna was first proposed in 1953, but at that time, the engineering association did not think that the appearance of microstrip antennas would be important. During the 1950s and 1960s, only a few people studied microstrip antennas in depth [1].

With the development of microwave integration technology and the use of various low-consumption dielectric materials, the fabrication of microstrip antennas has been supported in terms of technology. However, with the development of space technology, antenna elements with smaller height and width are needed. The first practical microstrip antennas appeared in 1970. In 1979, an international conference was held at the

University of New Mexico and microstrip antennas were discussed [2].

In 1981, the IEEE published an academic thesis about microstrip antennas. Gradually, microstrip antenna technology has been known and more people have begun to study microstrip antenna, so the research of microstrip antenna has developed rapidly, and gradually, new forms and new properties of the microstrip patch antenna have been studied [3].

2. Principle and technology of the microstrip patch antenna

2.1. The principle of radiation

The radiation is generated in the area between the edge of the patch and the ground. Lewin was the first person to study discontinuous radiation of microstrip antennas. This technique was based on the flowing current in the conductor. The approach taken can be used to know the effect of the radiation on the quality factor of the microstrip resonators. In this process, the aperture field is formed by the open end of the microstrip and the ground. Using this strategy, the effect of the radiation on the quality factor can be described as the formula of operating frequency, the size of the resonator, the thickness of the substrate, relative dielectric constant [4].

2.2. Analysis method of the microstrip patch antenna

2.2.1. Method of the transmission line model

The method of the transmission line model is only suitable for rectangular microstrip patch antennas. **Figure 6** is the structure of a rectangular microstrip antenna, the length of patch $l = \lambda/2$, λ is the wavelength in medium, the width of the patch is w. For simplify the calculation, set the coordinate system as follows: the z-axis and the y-axis are located on the ground, and the z-axis is along the direction of the gap [5].

2.2.2. The method of cavity model

The method cavity model is a cavity between patch and ground as the lossy resonant cavity that is surrounded by the magnetic walls, above and below are electric walls. The main loss of the cavity is the radiation loss of the edge gap [6]. First, the method of cavity model was used to solve the field in the cavity and equivalent magnetic flow at the edge was obtained from the tangential component of the edge of the electric field. From the equivalent magnetic current, one can calculate the radiation field. The method of cavity model is used for many regular-shaped microstrip patch antennas [7].

2.3. Feeding method of microstrip antenna

For the microstrip line feeding method, the feeder line and patch are on one plane, so one of the advantages of microstrip line feed is that the production is simple. However, the feed line also generates radiation, which can affect the directional pattern of the antenna and gain. Because the input impedance of the microstrip patch antenna is related to the position of feed point, by selecting the position of the feed point, can achieve the impedance matching of antenna with the feed line [8].

2.4. Circular polarization antenna

2.4.1. Principle of circular polarization antenna

Circular polarization antennas are antennas that can radiate or receive circular polarization waves. Circular polarization wave has the following five principles.

Circular polarization is an instantaneous rotating field, and radiation in the field is the same. From its direction of propagation, the shape of the endpoint trajectory of the wave's vector of instantaneous electric field is a circle. When the vector of the instantaneous electric field along the direction of propagation and rotates in left-handed, that's left-handed circularly polarized wave. When the vector of the instantaneous electric field along the direction of propagation and rotates right-handed, that's a right-handed circularly polarized wave [9].

Circular polarization waves can be considered as two parts of linearly polarized waves with equal amplitude, the two parts of polarized waves are orthogonal in time and space. So, the principle of achieving the circularly polarized antenna is: two parts of the orthogonal linearly polarized electric field are generated in the space, making the amplitudes of two polarized waves are same, and there is a 90° difference in the direction of amplitude [10].

Any polarized waves can be considered as two parts of circularly polarized waves that have opposite directions. The linearly polarized waves can be considered as two parts of circularly polarized waves that have opposite directions and the same amplitude. The circular polarization antenna can receive any polarization waves, any polarized antenna can receive the radiated circular polarization wave. That's why circularly polarized waves are commonly used in electronic reconnaissance [11].

3. Design and simulation

3.1. The background and purpose of design

The designed antenna array consists of three circularly polarized elements. The antenna can be used in the downlink frequency band (3.7–4.2 GHz) of satellite communication. The polarization method is left-handed circular polarization.

This antenna was designed, calculated, simulated, and optimized for achieving circular polarization, miniaturization, high bandwidth, and high gain. The circular polarization element antennas and circular polarization antenna array are designed and simulated in HFSS software. Also, the circular polarization element antenna was fabricated and its performance was tested in the anechoic chamber [12].

3.2. The stages in design

There are 3 stages in the design, as shown below (**Figure 1**).

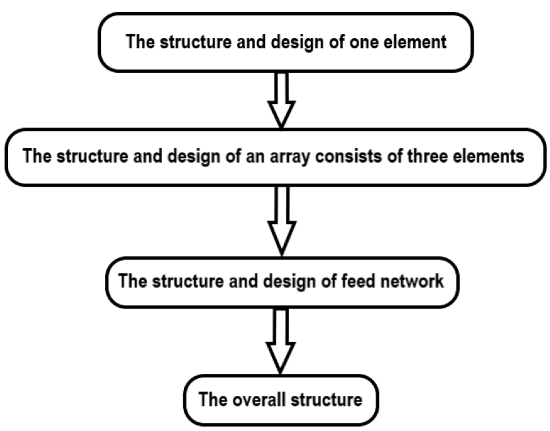


Figure 1. The stages in design.

3.3. The structure and design of the CP element antenna

For achieving the circular polarization, geometric perturbation was used to slot the selected circular patch resulting in the excitation of two degenerate modes with a phase difference of 90 degrees.

To achieve high bandwidth and miniaturization, a parasitic patch is added on top of the main radiation patch. The size of the upper parasitic patch should be a little smaller than the lower main radiation patch. The purpose of using parasitic patches is to add a new resonance point. Each patch has only one resonance point. According to f_r, the resonance point can be found. The upper parasitic patch is a high-frequency resonance point, and the lower main radiation patch is a low-frequency resonance point. By adjusting the radius of the main radiation patch r_1 and parasitic patch r_2, two resonance points are close to each other to achieve the purpose of broadening the bandwidth [13].

3.4. Matching three CP element antennas

First design and simulate an ideal model composed of three elements, determine the initial distribution of the three elements, and check the simulation results of S(1,1), impedance and gain.

In the designed antenna array, the distance between the three element antennas and the origin point is the same, and the array radius is 30 mm, by adjusting the spacing between the three antenna elements, we can know there is almost no antenna coupling and grating lobe.

3.5. The structure and design of the feed network

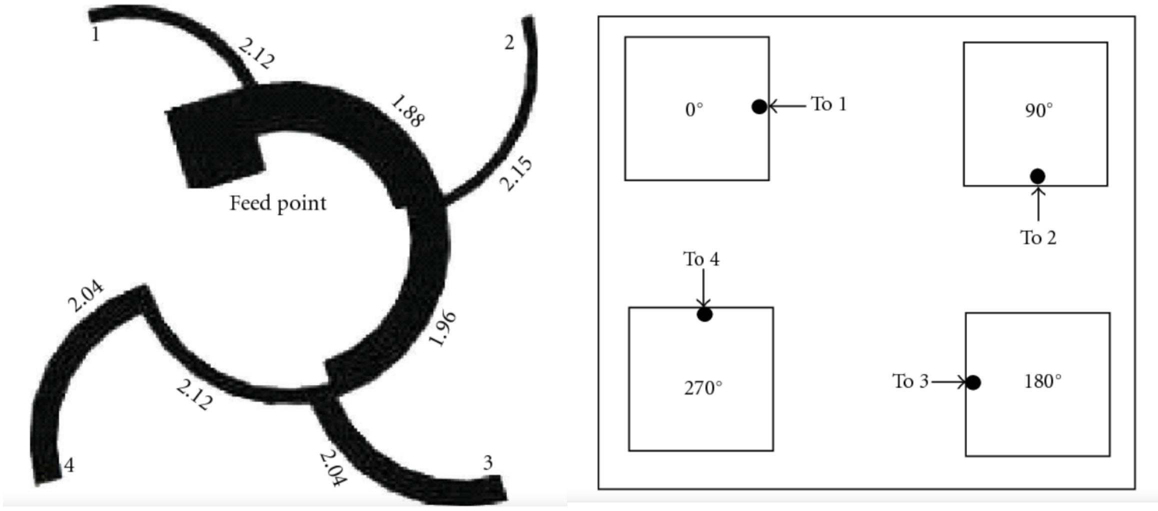
3.5.1. Introduction to the sequential rotation feed technology

For the designed three-element antenna array, the feed method is sequential rotation feed technology (SRFT). This method is used for feeding circularly polarized antennas, especially in array antennas. The purpose of this technology is to achieve high-performance circularly polarized radiation through a specific feeding method, optimizing the bandwidth, axial ratio and gain of the antenna [14].

In sequential rotating feed technology, the feed network is designed to feed each radiating element in the array one by one. The phase difference of each radiating element is a certain angle. In this design, the antenna array is composed of three radiating elements, so the phase difference between the three radiating elements is around 120°.

Through this sequential phase rotation feeding method, a stable circularly polarized wave can be formed in the radiation direction of the antenna array. In this design, my antenna produced left-hand circularly polarized waves.

In **Figure 2A** and **Figure 2B**, it is a 2*2 circularly polarized antenna array with sequential rotation feed, the sequence of feeding is 1,2,3,4; because of this cp antenna array is composed of four radiating elements, so the phase difference between four radiating elements is 90°.



(A) Four-port Sequential Rotation Feed (B) 2*2 Circularly Polarized Antenna Array

Figure 2. 2*2 Circularly Polarized Antenna Array with Sequential Rotation Feed [15].

3.5.2. Introduction to the feed network

The dielectric substrate of the feed network is Rogers RT/duroid 5880 (0.75mm thick) with a tangent loss of 0.0009 and a relative dielectric constant of 2.2. Each antenna element uses the same feeding method of back-feed. The feed point is located close to the edge of the patch. Placing the feed point close to the edge of the patch results in a longer current path, which increases the electrical size but allows for a smaller physical size, thus achieving miniaturization [15].

The feed network consists of a conversion line and transmission line, **Figure 3** shows two λ/4 conversion lines and three Z_0 impedance transmission lines, conversion lines are used to convert to Z_0 impedance from the output port to the input port, transmission lines are used to transmit Z_0 impedance from input port to output port. To design the feed network the method of Wilkinson unequal power divider is used, as shown in **Figure 3**.

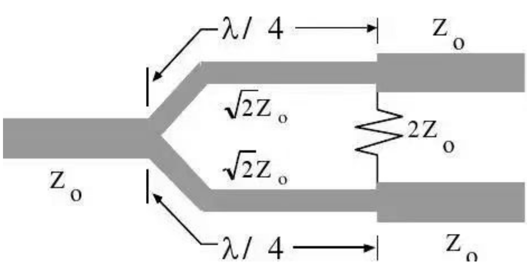


Figure 3. λ/4 Conversion Line and Z_0 Transmission Line [16].

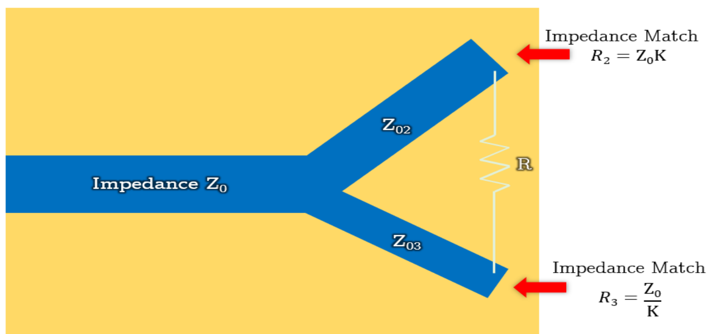


Figure 4. Wilkinson Unequal Power Divider [16].

$$Z_{03} = Z_0\sqrt{\frac{1+K^2}{K^3}} \tag{40}$$

$$Z_{02} = K^2 Z_{03} = Z_0 \sqrt{K(1 + K^2)} \tag{41}$$

$$R = Z_0 \left(K + \frac{1}{K} \right) \tag{42}$$

Z_0 is the characteristic impedance of port 1, Z_{02} is the characteristic impedance of port 2, Z_{03} is the characteristic impedance of port 3. In this study, my designed antenna consists of three elements, so there are three output ports and one input port. The input impedance is input from one port, converted by Wilkinson unequal power divider and fed into the three ports of each unit antenna. The three element antennas are spaced 120 degrees apart from each other and the power divider should provide a phase difference of 120 degrees between outputs. The distance between the three feed points is equal to each other, the distance between each other is 58 mm [16].

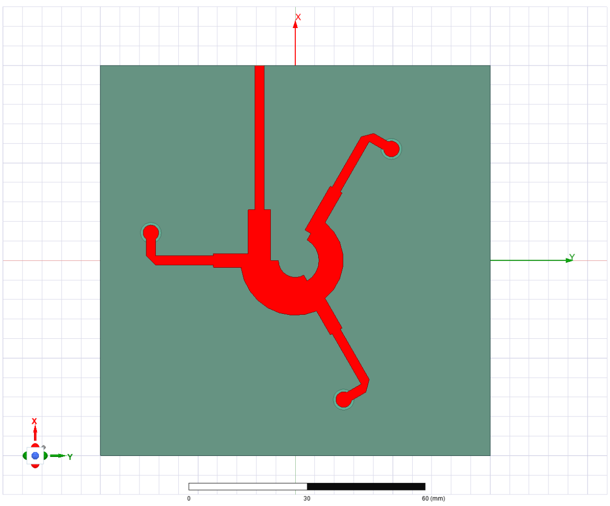


Figure 5. The Designed Feed Network (bottom view).

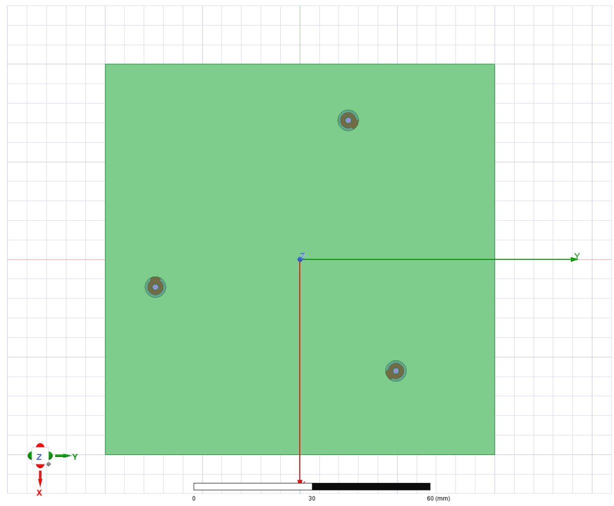


Figure 6. The Designed Feed Network (top view).

3.5.3. Simulation results of the feed network

From the diagram of the power ratios of the three-element antennas as shown in **Figure 6**, it can observed that after simulation and optimization, in the frequency band of 3.70–4.20 GHz, the port 4 is 0–0.4dB lower than port 3 and 1.1–1.7dB lower than port 2, the port 3 is 0.9–1.3dB lower than port 2; we can know the power is assigned from port 1 to port 2, port 3, and port 4 are close to the same level [17].

In the simulation result, the phase difference between the element antennas is not exactly 120°; as shown in **Figure 5** and **Figure 6** the phase difference between port 2 and port 3 is 90°–108°, the phase difference between port 3 and port 4 is 120°–133°, this indicates that there are factors affecting the phase difference, for example:

(1) The design of the feed network: Different feeding techniques, such as direct feeding, series feeding, and parallel feeding, lead to varying phase delays, affecting phase uniformity and circular polarization performance.

(2) The spacing between element antennas: Too close spacing can lead to mutual coupling effects, causing inconsistencies in phase and amplitude. Proper spacing can reduce mutual coupling and improve phase

uniformity.

(3) The properties of substrate material: The electrical characteristics of the substrate material, such as dielectric constant and loss tangent, also affect the phase difference. Different material properties result in different propagation speeds and phase delays, impacting the overall performance of the antenna array.

4. Conclusion

For the circularly polarized element antenna, from measurement results of S-parameter S(1,1), axial ratio, Z-parameter Z(1,1), gain, and radiation efficiency, the bandwidth is broadened by adjusting the resonance points of the main radiation patch and the parasitic patch, the circularly polarized element antenna can work fine in the 3.70–4.20GHz frequency band and achieved left-handed circular polarization. The designed aluminum frame had a good impact on the gain of the CP element antenna and the main lobe is clear.

Disclosure statement

The author declares no conflict of interest.

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