

Design of a W-band four-channel dual-polarization waveguide slot antenna (Postprint)

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Abstract

The W-band full-polarization radar detection system is in need of a new type of high-performance antenna feed. The waveguide slot array antenna has the advantages of low profile, high radiation efficiency, and easy access to high gain, and has become the research emphasis in the field of millimeter-wave detection. In order to satisfy the need of developing a full-polarization radar detection system, a W-band four-channel dual-polarization waveguide slot antenna is designed. The results of the simulation and optimization tests show that the antenna has outstanding technical characteristics in dual polarization. The antenna gain is higher than 13 dB, and the cross-polarization level is lower than -34 dB. The bandwidth for VSWR below 1.5 exceeds 2.8 GHz. High isolation of over 50 dB is achieved between different polarization input ports.

Full Text

Design of a W-Band Four-Channel Dual-Polarization Waveguide Slot Antenna

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Abstract

The W-band full-polarization radar detection system requires a new type of antenna feed with excellent performance. The waveguide slot array antenna offers

advantages including low profile, high radiation efficiency, and easy achievement of high gain, making it a research focus in millimeter-wave detection. To meet the needs of developing a complete polarization radar detection system, a W-band four-channel dual-polarization waveguide slot antenna is designed. Simulation and optimization results demonstrate that the antenna exhibits outstanding technical characteristics in dual polarization. The antenna gain exceeds 13 dB, with cross-polarization levels below -34 dB. The bandwidth for $VSWR < 1.5$ is greater than 2.8 GHz, and high isolation exceeding 50 dB is achieved between different polarization input ports.

Keywords: W-band; dual-polarization antenna; four-channel feeding structure; waveguide slot array

INTRODUCTION

Due to significant dielectric losses in the millimeter-wave band, inevitable electromagnetic wave attenuation, and low efficiency of transmission lines, conventional microstrip-fed array antennas can no longer meet the technical requirements for high gain and wide bandwidth at high frequencies. The millimeter-wave detection system urgently requires a new antenna type for these applications.

The waveguide slot antenna offers high radiation efficiency because it does not suffer from dielectric losses, along with advantages of low profile, low transmission losses, and easy achievement of high gain. Thanks to its narrow beam and low sidelobe characteristics, the waveguide slot antenna is widely used in radar antenna systems. In recent years, the Ando & Hirokawa Laboratory at Tokyo Institute of Technology has studied methods to improve waveguide slot antenna performance. By using a full corporate-feeding structure and cross-shaped radiating slots, researchers have successfully operated waveguide slot array antennas in dual-polarization mode in the 60-GHz band with excellent results.

The Beijing Key Laboratory of Millimeter Wave and Terahertz Technology has been developing a W-band full-polarization radar detection system. We previously used a horn antenna as the feed for a W-band dual-polarization Cassegrain antenna. This horn antenna feed features four mutually independent apertures that are linearly polarized subarrays with rotational symmetry, enabling instantaneous synthesis of any polarization wave. Test results showed the Cassegrain antenna gain exceeded 36 dB in the 93 GHz band. To further improve system performance, we propose using a waveguide slot antenna as the Cassegrain feed to leverage its high performance characteristics. To achieve instantaneous full-polarization operation and effective extraction of target multi-polarization information, we propose a four-channel feeding structure combined with a 2×2 radiating element array as the complete antenna structure. HFSS simulation results show this dual-polarization antenna exhibits outstanding characteristics that satisfy the feed requirements for Cassegrain antennas.

II. ANTENNA CONFIGURATION

The antenna structure consists of two main parts: the four-channel feeding structure and the radiating element. Horizontal and vertical polarization waves are fed into the antenna through their respective feeding waveguides. Due to the special feeding structure design, the two polarization waves form a pair of orthogonal magnetic fields in the cross-shaped coupling slot, which are then transmitted into the radiating element located above. TE_{10} and TE_{01} modes are excited by the two polarization waves in the radiating element and eventually radiate into free space through the cross-shaped radiating slot.

A. Four-Channel Feeding Structure

[Figure 2: see original paper] shows the four-channel feeding structure. The structure uses a standard rectangular waveguide size of WR-10 and consists of two horizontal polarization feeding waveguides, two vertical polarization feeding waveguides, four feeding coupling slots, two waveguide transmission layers, and a cross-shaped coupling slot.

The feeding structure positions the two types of polarization ports on different layers. Two horizontal polarization feeding ports are placed in the first layer, while two vertical polarization feeding ports are placed in the second layer. Both types of polarization feeding ports transmit only the dominant TE_{10} mode. The horizontal polarization wave is fed by the horizontal polarization waveguide and transmitted into the horizontal polarization waveguide transmission layer through the feeding coupling slot. It is then coupled into the vertical polarization waveguide layer above through the horizontal polarization coupling slot. Similarly, the vertical polarization wave is coupled into the vertical polarization waveguide transmission layer. The two polarization waves form a pair of orthogonal magnetic field components in the vertical polarization waveguide layer beneath the cross-shaped feeding slot.

Based on the TE_{10} mode magnetic field distribution, the longitudinal magnetic field is very weak at the center of the rectangular waveguide. Therefore, the vertical polarization wave would not be coupled into the horizontal feeding waveguide beneath through the feeding coupling slot, achieving high isolation between the two polarization feeding ports. Finally, the two types of polarization waves are transmitted into the radiating element through the cross-shaped coupling slot.

B. Radiating Element

[Figure 3: see original paper] shows the radiating element structure, which consists of a cross-shaped radiating slot, a quadruple-ridged waveguide, and four cross-shaped coupling slots. The cross-shaped radiating slot and the quadruple-ridged waveguide share the same structural shape to ensure maximum radiation efficiency. The quadruple-ridged waveguide adopts a rotationally symmetric structure, which ensures electromagnetic energy is distributed equally to the

four cross-shaped radiating slots and maintains consistent feeding amplitude. Consequently, both polarization types exhibit identical characteristics.

The cross-shaped coupling slot couples the two orthogonal polarization waves into the quadruple-ridged waveguide, exciting TE₁₀ and TE₀₁ modes. The electric and magnetic field directions of these two modes are orthogonal, as shown in [Figure 4: see original paper]. To realize dual-polarization operation, the cross-shaped radiating slot is formed by a pair of orthogonal rectangular slots, each selecting its respective mode (TE₁₀ or TE₀₁). Due to the orthogonality of the two modes, low cross-polarization levels are achieved.

The radiating element structure has already demonstrated outstanding performance in the 60-GHz band. Based on the principle of frequency scaling used in frequency-independent antennas, the antenna's working performance does not change when the model size is scaled. This means we can proportionally reduce the antenna model size from 60 GHz to 94 GHz to determine the initial parameters, enabling further simulation and optimization.

III. SIMULATION AND OPTIMIZATION

A. Simulation Steps

The antenna simulation and optimization can be divided into the following steps: 1. Optimize the radiating element structure; 2. Optimize the four-channel feeding structure; 3. Combine the optimized radiating element and four-channel feeding structure as the complete antenna structure; 4. Adjust the antenna structure parameter values based on simulation and optimization results.

B. Optimization Methods

The key optimization method is parameter sweep analysis provided by HFSS simulation software. By sweeping parameters one at a time while keeping others unchanged, we can observe and record their respective influence on antenna performance and thus adjust specific structures to optimize overall performance.

IV. RESULTS

To achieve uniform excitation in neighboring radiating slots, the electromagnetic field in the quadruple-ridged waveguide must be symmetric. This can be accomplished by propagating the dominant mode while cutting off higher-order modes generated by the coupling slots. When the quadruple-ridged waveguide under the radiating slots is sufficiently high or low, the higher-order modes can be cut off. The attenuation constant of the TE₁₀ modes through the coupling slots is expressed by:

$$E = E_0 e^{-\alpha t}$$

$$\alpha = \sqrt{\left(\frac{m\pi}{l_c}\right)^2 + \left(\frac{n\pi}{w_c}\right)^2} - k^2$$

where t_c , l_c , and w_c are the height, length, and width of the quadruple-ridged waveguide, respectively, and k is the wave number in free space. In fact, the length and width of the quadruple-ridged waveguide are identical due to the rotationally symmetric structure.

We selected the length and height of the quadruple-ridged waveguide and the spacing between radiating slots as the main optimization parameters. HFSS sweep analyses of each parameter were completed. Based on the effects of parameter sweeps on antenna characteristics, the final structure was determined.

[Figure 5: see original paper] shows the return losses of feeding ports. [Figure 6: see original paper] shows the isolation between different polarization feeding ports. [Figure 7: see original paper] shows the radiation patterns for both polarizations.

The simulation and optimization results are as follows: the peak horizontal polarization gain is 13.54 dB with a 3-dB beamwidth of 42.3° and cross-polarization level below -34 dB; the peak vertical polarization gain is 13.55 dB with a 3-dB beamwidth of 42.2° and cross-polarization level below -35 dB. The average side-lobe level for both polarizations is below -14 dB. The horizontal polarization bandwidth is 2.89 GHz below VSWR 1.5 and 3.5 GHz below VSWR 2. The vertical polarization bandwidth is 3.35 GHz below VSWR 1.5 and 4.14 GHz below VSWR 2. High isolation exceeding 50 dB is achieved between different polarization feeding ports. When both polarization feeding ports operate together, the antenna can synthesize any kind of polarization wave.

The main parameters of the optimized antenna are shown in .

V. CONCLUSION

In this design, we propose a W-band four-channel dual-polarization waveguide slot antenna for employment as the feed of a Cassegrain antenna in a W-band full-polarization radar detection system. The antenna enables instantaneous full-polarization operation and effective extraction of target multi-polarization information. Simulation and optimization results show that the peak gains for both polarizations exceed 13 dB with cross-polarization levels below -32 dB. The bandwidth for both polarizations exceeds 2.8 GHz below VSWR 1.5. High isolation above 50 dB is achieved between different polarization feeding ports.

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