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Abstract

A novel single-layer microstrip reflectarray element with fractal structure is proposed. Ansoft HFSS is used to analyze the reflect phase for the fractal element in honeycomb lattice. A 469-element prime focus microstrip reflectarray antenna composed of the proposed fractal elements is designed, manufactured, and measured. The measured gain level of 29.8 dB is obtained at the center frequency of 13.58 GHz with 1-dB gain bandwidth of 15.3%.

Full Text

A Broadband Ku-Band Microstrip Reflectarray Antenna Using Single-Layer Fractal Elements

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ABSTRACT: A novel single-layer microstrip reflectarray element with fractal structure is proposed. Ansoft HFSS is used to analyze the reflection phase for the fractal element in a honeycomb lattice. A 469-element prime-focus microstrip reflectarray antenna composed of the proposed fractal elements is designed, manufactured, and measured. A measured gain of 29.8 dB is obtained at the center frequency of 13.58 GHz with a 1-dB gain bandwidth of 15.3%.

Key words: Reflectarray; honeycomb lattice; broadband fractal structure; single-layer;

INTRODUCTION

The conventional parabolic reflector antenna has been widely used in both military and civilian applications. However, due to increasingly stringent requirements for flexible communication systems, the disadvantages of traditional parabolic reflector antennas—such as heavy weight, large volume, and non-planar structure—have become increasingly apparent. To overcome these limitations, efforts have been made to replace parabolic reflectors with equivalents such as microstrip reflectarrays [1]. A reflectarray antenna consists of an array of microstrip patch elements, each imparting an appropriate phase delay to the incident wave to produce a collimated beam in front of the antenna aperture plane.

The main limitation to reflectarray performance is narrow bandwidth, generally lower than 5 percent and even less for large reflectarrays [2]. The element bandwidth and spatial phase delay dispersion are the two factors limiting reflectarray bandwidth. However, for moderate gain antennas, the element bandwidth appears to be the primary limitation [3]. The bandwidth of the radiating element can be improved through appropriate design of the phase-shifter element. A large F/D ratio is required to ensure that the incident field approximates a plane wave and to minimize spatial phase delay effects. However, larger F/D ratios affect illumination efficiency. Much effort has been made to improve bandwidth [4-9]. In [4], a reflectarray element composed of double crossed loops of variable lengths printed on a conductor-backed substrate demonstrated a 1-dB gain bandwidth of 10% centered at 22 GHz for a fabricated single-layer reflectarray. In [5], significant bandwidth improvement was demonstrated using elements that allow true-time delay. In [6], a novel bandwidth improvement method was proposed that combines the multilayer subwavelength element technique. A method for designing three-layer printed reflectarrays with patches of variable size for broadband operation was presented in [7], yielding significant improvements in bandwidth and gain stability. In [8] and [9], multiresonant elements were used for broadband operation.

In conventional microstrip patch antennas, dual- or multi-frequency operation can be achieved by employing multiple radiating elements, reactively loaded patch antennas, or multi-frequency dielectric resonator antennas [10]. However, these methods increase manufacturing cost and complexity. Fractal-shaped antennas, which combine antenna design theory with fractal geometry, have been proven to possess unique characteristics linked to the geometrical properties of fractals. The microstrip reflectarray combines microstrip antenna design with fractal technology to fully exploit their advantages. The space-filling characteristic of fractal antennas enables miniaturization, while the self-similarity of the antenna structure results in multi-frequency operation that increases bandwidth. The self-loading property also broadens the useful bandwidth [11]. The miniaturization feature of fractal antennas was utilized in [12] to design a miniaturized reflectarray unit cell offering wide-angle scanning capabilities, achieving an improved maximum scan angle of 50° in X-band. Fractal-shaped patch-slot configurations have been studied as reflectarray unit cells in [13], where variable-length slots on the ground plane were used to adjust the phase. It was shown that fractal configurations can reduce the size of the reflectarray unit cell and increase the maximum phase swing.

This paper presents a novel fractal microstrip element on a single-layer substrate. To achieve a larger reflection phase variation range with gentler slope than conventional single-layer elements, an air layer is inserted between the substrate and the ground plane. The novel fractal microstrip element meets the requirements of reflection phase curve linearity and variation range, thereby exhibiting broadband characteristics.

[Figure 1: see original paper]

ELEMENT DESIGN AND PHASE CHARACTERISTICS

The reflectarray presented in this paper is composed of fractal microstrip elements on a grounded substrate. The impedance characteristics of the element vary with its size, enabling adjustment of the reflected electromagnetic wave phase. The configuration of the proposed fractal element is shown in Figure 1. The fractal element is a multi-resonant structure that demonstrates a larger phase range and more linear phase variation than conventional square or circular patches. It consists of two concentric hexagon rings and a hexagon where each side of the inner hexagon equals the adjacent outer hexagon side multiplied by factor k.

Each patch was etched on Rogers RT/duroid 5880 laminates with relative permittivity of 2.2 and thickness h1. The layer between the substrate and ground plane is an air layer with relative permittivity of 1 and thickness h2. L = 13 mm is the lattice period of the element, equivalent to 0.59 wavelengths at 13.58 GHz. To derive the reflection coefficient of the element, simulations were performed using Ansoft HFSS with master-slave boundaries and Floquet ports to model periodic structures. Figure 2 shows the honeycomb lattice model of the fractal element in Ansoft HFSS.

[Figure 2: see original paper]

The phase of the reflection coefficient depends not only on element size but also on the incident angle of the plane wave. When the incident angle is less than 40°, the reflection phase difference between normal and oblique incidence can be neglected [14]. Figure 3 shows the reflection magnitude and phase of the element at 13.58 GHz for different (from 0° to 30°) and (0° and 90°) with h1 = 0.5 mm, h2 = 3 mm, and k = 0.75, where (,) represents the incident wave direction. It can be concluded that and have little influence on reflection magnitude and phase. Furthermore, the incident angles of elements near the reflectarray edge are approximately 30°. Thus, the assumption that elements are excited by a normally incident plane wave is valid in this paper.

[Figure 3: see original paper]

A parametric study was carried out to optimize the element structure for obtaining a smoother reflection phase curve and improved bandwidth. Figure 4 shows the influence of the k factor on phase variations, revealing that k = 0.75 yields better linear reflection phase and sufficient phase variation range. Figures 5 and 6 show the effects of substrate thickness and air layer thickness variations, respectively.

[TABLE I]

[Figure 4: see original paper]

[Figure 5: see original paper]

[Figure 6: see original paper]

Figure 7 shows the phase-size characteristics for different frequencies (12.5–17 GHz) for normal incidence with k = 0.75, h1 = 0.5 mm, and h2 = 3 mm. It can be concluded from Figure 5 that substrate thickness has little influence on the reflection phase curve. Considering manufacturing factors, the substrate thickness was set to 0.5 mm. Figure 6 demonstrates that air layer thickness significantly influences the reflection phase curve, so an air layer thickness of 3 mm was selected for better linear reflection phase and large phase variation range.

Based on the parametric study results, the fractal element with k = 0.75, h1 = 0.5 mm, and h2 = 3 mm represents the optimized design, as summarized in Table I. The reflection phase variation range exceeds 430° as element size varies from 1.5 mm to 6 mm. Reflection phase curves versus element size for different frequencies (12.5–17 GHz) are shown in Figure 7. The reflection phase curves are nearly parallel to each other, indicating the wideband property of the novel fractal element.

[Figure 7: see original paper]

III. REFLECTARRAY DESIGN AND PERFORMANCE

To validate the proposed fractal structure, a prime-focus 469-element reflectarray was designed using the proposed fractal elements as phase-shifting components, and its performance was simulated and measured. The reflectarray diameter D and focal distance F are 325 mm (14.5) and 260 mm, respectively. A pyramidal horn antenna serves as the reflectarray feed. The phase center of the pyramidal antenna is placed at the reflectarray focal point (F), with the illumination level at the reflectarray edges approximately 11 dB below the aperture center level. Figure 8 presents a photograph of the reflectarray prototype. Foam and brackets are used to fix the feed horn. The antenna radiation pattern was measured in a near-field anechoic chamber.

[Figure 8: see original paper]

Figure 9 shows the simulated and measured radiation patterns of the reflectarray antenna for co-polar and cross-polar components in both E-plane and H-plane at the center frequency of 13.58 GHz. As shown in Figure 9, the simulated antenna gain is 30.04 dB at 13.58 GHz with a 3-dB beamwidth of 4.95° in both E-plane and H-plane. The simulated side lobe levels are below -18.8 dB relative to the peak level. The measured gain is 29.8 dB at 13.58 GHz with 3-dB beamwidths of 4.96° in both E-plane and H-plane. The measured side lobe levels are below -18 dB relative to the peak level in both planes. The measured cross-polarization levels are below -35 dB in E-plane and -28 dB in H-plane. The simulation results used actual material properties to match measurement conditions. In practice, the air layer was substituted by a cellular board, and clear epoxy adhesive was used to bond the cellular board and substrate layer.

[Figure 9: see original paper]

Figure 10 shows the measured radiation gain of the reflectarray antenna as frequency varies from 12.58 GHz to 16.58 GHz. It can be concluded that the measured bandwidth, defined by the 1-dB drop in peak gain, reaches 15.3%. The small differences between simulation and measurement results are due to fabrication tolerances and measurement errors. Blockage from the foam and brackets and feed misalignment also contribute to the disagreement between simulations and measurements.

[Figure 10: see original paper]

IV. CONCLUSIONS

A novel fractal microstrip reflectarray element with a single-layer substrate has been proposed and studied. Analysis of the fractal element shows that it can provide sufficient phase variation range with good linear reflection phase and gentle slope. The reflection phase curves at different frequencies indicate that the fractal element possesses broadband properties. A circular reflectarray composed of numerous proposed fractal elements was designed, fabricated, and measured. The measured 1-dB gain bandwidth reaches 15.3%.

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