A Novel Single-Layer Unit Structure for Broadband Reflectarray Antenna Postprint

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Date: 2017-03-10T00:00:00+00:00

Abstract

A novel X-band single-layer unit cell structure with enhanced bandwidth for linearly polarized microstrip reflectarray antenna is proposed. The unit-cell structure is composed of two circular rings, each with a pair of gaps which are orthogonally placed, and two identical phase-delay lines attached to the outer circular ring. With this novel structure, a linear phase response ranging about 550° is achieved by varying the length of the phase delay line. An offset-fed reflectarray antenna composed of 277 elements forming an octagon-shape aperture is designed, fabricated, and measured to verify the broadband characteristic of the proposed unit cell. Measurement results show that 20% 1-dB gain bandwidth is realized. Besides, the maximum gain at 10 GHz is about 26.38 dBi, which means about 51.3 % efficiency is achieved. At the same time, the side lobe level and cross polarization for E-plane are also measured which are below −17.5 dB and −26 dB, respectively.

Full Text

Preamble

Abstract–A novel X-band single-layer unit cell structure for broadband linearly polarized microstrip reflectarray antennas is proposed. The unit-cell structure comprises two circular rings, each with a pair of orthogonally placed gaps, and two identical phase-delay lines attached to the outer circular ring. With this novel structure, a linear phase response spanning approximately 550° is achieved by varying the length of the phase-delay line. An offset-fed reflectarray antenna composed of 277 elements forming an octagon-shaped aperture is designed, fabricated, and measured to verify the broadband characteristic of the proposed unit cell. Measurement results demonstrate a 20% 1-dB gain bandwidth. Additionally, the maximum gain at 10 GHz is approximately 26.38 dBi, corresponding to about 51.3% efficiency. Meanwhile, the side lobe level and cross-polarization for the E-plane are measured to be below −17.5 dB and −26 dB, respectively.

Index Terms–Reflectarray antenna, single-layer unit cell, bandwidth enhancement, phase delay lines.

I. Introduction

Microstrip reflectarray technology has attracted considerable attention for many applications, such as communication and radar systems, due to its compelling advantages [1]. However, microstrip reflectarray antennas also suffer from several disadvantages, particularly narrow bandwidth. Two main factors restrict the gain bandwidth of microstrip reflectarray antennas: first, the inherently narrow bandwidth of microstrip antenna unit cells; second, the differential spatial phase delay between the feed source and unit cells on the reflectarray plane.

The first factor is more significant for bandwidth limitation in small and medium-size reflectarray antennas [2]. Numerous methods have been presented to enhance the bandwidth performance of radiating unit cells for reflectarray antennas in recent years, among which applying unit cells with wide-range linear phase responses is a very effective approach [3]. Several methods exist to achieve linear phase responses, such as using multi-layer structures [4], thickening the substrate, and attaching phase-delay lines [5]. To reduce fabrication errors and cost, single-layer broadband reflectarrays have been proposed using multi-resonant elements, achieving 24% 1-dB gain bandwidth [6].

However, this approach requires thick substrate to obtain linear phase responses, leading to unavoidable increases in mass and cost. Additionally, thick substrate results in a smaller linear phase range. Consequently, element dimensions must be varied significantly to achieve a sufficiently wide range of linear phase responses, introducing potential phase errors due to increasingly complex mutual coupling and difficulty in controlling fabrication tolerances.

In recent years, many researchers have focused on the phase-delay line approach, as it can easily achieve a large linear phase range using thin substrate without requiring elements of significantly varied size [5], [7], [8], [9]. However, the bandwidth performance reported in these works remained limited, as the parallelism of the phase response curves versus phase-delay-line length for the presented elements was insufficient, which unavoidably restricted the expansion of the operating frequency band.

In this letter, a linearly polarized single-layer unit-cell structure is proposed to enhance the bandwidth performance of reflectarray antennas. The proposed element structure consists of an inner resonant structure composed of double split rings and two phase-delay lines. The double split rings were first proposed for dual-band circularly polarized reflectarrays [10], where they rotate independently to obtain different reflection phases. In our work, the double split rings are fixed with optimized dimensions to provide linear phase responses versus frequency. This approach yields parallel phase response curves versus the phase-delay-line length. A 277-element offset-fed reflectarray with an octagon-shaped aperture operating in X-band is designed, fabricated, and measured to validate the broadband characteristic of the proposed unit-cell structure. Measurement results demonstrate a 1-dB gain bandwidth of over 20%. The measured peak gain at 10 GHz is approximately 26.38 dBi, corresponding to about 51.3% efficiency.

II. Unit Cell Design

Fig. 1 [FIGURE:1] depicts the designed single-layer unit-cell structure, which was proposed in our previous work [11]. The unit cell consists of two circular rings, each with a pair of orthogonally placed gaps, and two identical phase-delay lines attached to the outer circular ring for phase shifting. w_i and w_o represent the widths of the inner and outer rings, respectively, and the corresponding gaps are g_i and g_o. w_s and L_s denote the width and length of the stubs that connect the phase-delay line to the outer circular ring. The length of the identical phase-delay lines is represented by its rotation angle θ in degrees. The unit-cell size is [missing] wavelength in free space. Unit cells are etched on a dielectric substrate (d_t) of 1.5 mm thickness with relative permittivity $\varepsilon_r = 3.48$, and a 2-mm-thick air layer (d_s) separates the substrate layer from the metallic ground to achieve smoother phase response.

TABLE I lists the final designed element geometry parameters.

To investigate the phase response of the unit cell and optimize the structure geometry parameters, an infinite array model is built in HFSS simulation software, employing Floquet port excitation and master-slave boundary conditions. The operating principle of our proposed element can be described as follows. To obtain linear phase responses versus frequency, the geometric parameters of the double split-ring structure are optimized to resonate at 10 GHz. Additionally, the width (w_s) and length (L_s) of the stub must be optimized to achieve good matching between the phase-delay lines and the double split-ring structure. In this way, the reflection phase curves versus the lengths of the phase-delay lines at different frequencies have a high probability of remaining parallel, thus enabling wideband performance.

The phase response curves versus the length of the phase-delay line at frequencies of 9, 10, 11, and 12 GHz are plotted in Fig. 2 [FIGURE:2], where θ represents the length of the phase-delay lines. As can be seen, a linear and smooth reflection phase curve spanning approximately 550° is achieved at 10 GHz. Parallel phase curves across different frequencies are also obtained. It is worth noting that the reflection phases vary linearly with smaller slopes and in parallel with each other when the phase-delay line lengths (θ) range from 60° to 180°, demonstrating superior broadband performance compared to the unit cells in [5], [7], [8], [9].

To further explore the broadband property of the proposed unit cell, different unit cells with orthogonal gaps, parallel gaps, and without gaps are investigated, with results presented in Fig. 3 [FIGURE:3]. This figure shows how the reflection phases for elements with 0° phase shift vary with frequency [12]. The phase-delay line lengths (θ) for these three unit cells with 0° phase shift are $\theta = 35°$, 40°, and 70°, respectively. It is observed that these three unit cells exhibit different frequency performance for reflection phases. When frequency changes, the unit cell with orthogonal gaps shows the smallest phase variation across the operating frequency band of 8–12 GHz. Therefore, the bandwidth performance of the reflectarray elements can be significantly enhanced by adding orthogonal gaps.

III. Reflectarray Antenna with Proposed Unit Cell

In this section, an X-band offset-fed reflectarray with diameter $D = 285$ mm is designed, manufactured, and tested to validate the broadband feature of the novel unit-cell structure.

The required reflection phases for all unit cells on the reflectarray plane are calculated at 10 GHz according to (1), where k_0 represents the propagation constant in free space, d_i is the distance between the phase center of the feed source and the center of the ith unit cell on the reflectarray plane, and (θ_0, ϕ_0) is the designed main beam radiation direction. Here, to avoid feed blockage, a 10° offset-fed design is selected for the reflectarray antenna to produce a main beam in the specular reflection direction, which means (θ_0, ϕ_0) is set to $(10°, 0°)$. An X-band pyramidal horn with linear polarization is utilized as the feed source, and the distance between the feed source and the reflectarray center is designed to be 225 mm, corresponding to a focus/diameter (F/D) ratio of 0.79. The unit cell phase responses are designed to compensate for the spatial phase delays between the feed source and reflectarray unit cells.

Fig. 4 [FIGURE:4] shows the designed phase distribution on the aperture at 10 GHz, and Fig. 5

shows a photograph of the fabricated reflectarray composed of 277 unit cells forming an octagon-shaped aperture. As can be further seen from Fig. 5, the unit cells are arranged in a mirror-symmetric configuration to reduce cross-polarization [7]. Fig. 6 [FIGURE:6] shows the measurement setup, where a fiberglass support is utilized to hold the feed horn while minimizing feed blockage.

Fig. 7 and Fig. 8 [FIGURE:8] show the measured co-polarization and cross-polarization (X-pol) radiation patterns at frequencies within the 1-dB gain band for the E-plane and H-plane, respectively. As can be seen, a gain of approximately 26.38 dBi is achieved at 10 GHz, corresponding to about 51.3% efficiency. The measured cross-polarization levels of both principal planes (E-plane and H-plane) are suppressed below −26 dB across the operating frequency band, benefiting from the special element arrangement design. Additionally, the realized side lobe levels for both principal planes are −17.5 dB and −15 dB at 10 GHz, respectively. Both Fig. 7 [FIGURE:7] and Fig. 8 demonstrate good broadband performance, as the measured radiation patterns within the 1-dB bandwidth remain stable.

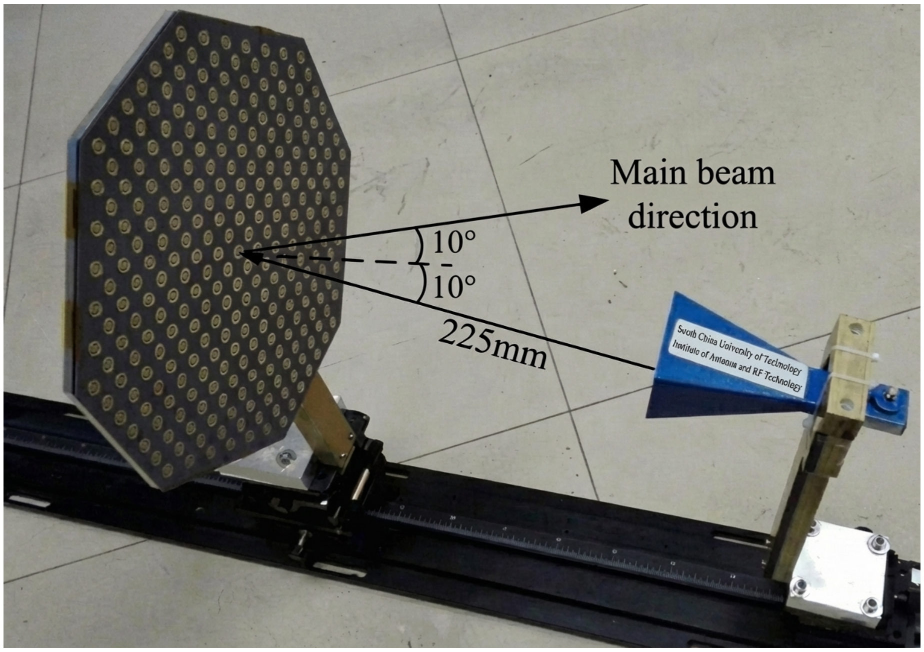

Figure 1: Figure 5

Fig. 9 [FIGURE:9] plots the measured gain curve against frequency, showing that the 1-dB bandwidth is approximately 20% (9.74-11.8 GHz) while the 3-dB bandwidth is about 28% (9.55-12.35 GHz). A drastic gain drop occurs when the frequency falls below 9.8 GHz, primarily due to the narrow operating band of the feed horn. In fact, the phase center of the feed horn can deviate at frequencies below 9.8 GHz, resulting in significant phase errors. Additionally, the wider beamwidth of the feed horn at lower frequencies also decreases antenna efficiency, particularly for our offset-fed reflectarray configuration. These two factors are the main reasons why the actual central frequency deviated from 10 GHz to approximately 10.8 GHz. Some ripples can also be observed on the measured gain curves, which result from multiple reflections between the feed horn, reflectarray plane, and the probe. Besides, system measurement errors can also lead to this phenomenon.

The measurement results of Fig. 9 demonstrate that an obvious improvement in gain bandwidth performance is achieved compared to previous works [5], [7], [8], [9], as described in TABLE II.

IV. Conclusion

A novel single-layer unit cell with phase-delay lines is proposed for reflectarray antennas with enhanced bandwidth performance. The geometry dimensions of the double split rings and the lengths of the phase-delay lines are optimized to achieve parallel phase responses across a wide frequency range. A 277-element offset-fed reflectarray with an octagon-shaped aperture operating in X-band is designed, fabricated, and measured. The measurement results showing a 20% 1-dB gain bandwidth demonstrate significantly improved bandwidth performance compared to previous reflectarrays using phase-delay lines. It should be noted that although our current 1-dB gain bandwidth is smaller than that reported in [6], our approach can be easily extended to further enhance bandwidth by adding an additional gapped ring to the resonant structure. In fact, a 36.3% 1-dB gain bandwidth has been achieved using this method, with these new results addressed in another paper.

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Fig. 7. Measured co-polar and cross-polar radiation patterns of E-plane.

Fig. 8. Measured co-polar and cross-polar radiation patterns of H-plane.

Fig. 9. Measured gain versus frequency.

TABLE II COMPARISON OF THE BANDWIDTH PERFORMANCE WITH PREVIOUS WORKS ON ANTENNAS USING PHASE-DELAY LINES

Reference	Center Frequency (GHz)	1-dB Gain Bandwidth (%)	3-dB Gain Bandwidth (%)	Polarization
[5]/[7]				Linear
				Linear
				Circular
				Linear

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