Single-layer broadband linearly polarized reflectarray antenna by using phase-delay lines postprint

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Abstract

In this paper, a novel X-band broadband single-layer unit cell with attached phase-delay lines for reflectarray antennas is proposed to overcome the bandwidth limitation of reflectarrays. The unit cell consists of three circular rings, each having a pair of orthogonally positioned gaps, and two identical circular phase-delay lines attached to the outer ring to provide the required reflection phase. Following the unit cell simulation, a large reflection phase range of approximately 600° and an almost linear phase curve are achieved at the center frequency of 10 GHz. Parallel phase curves across different frequencies ranging from 9 GHz to 12 GHz are also obtained. To validate the broadband performance of the proposed unit cell, a 9 × 9 center-fed reflectarray antenna operating in the X-band is designed and simulated. Simulation results show that the designed antenna achieves a 34% 1-dB gain bandwidth, demonstrating a significant improvement in bandwidth compared to previous works. Furthermore, the cross-polarization level is reduced to -40 dB through a mirror-symmetric element arrangement.

Full Text

Preamble

Single-Layer Broadband Linearly Polarized Reflectarray Antenna Using Phase-Delay Lines

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Abstract

This paper proposes a novel X-band broadband single-layer unit cell with attached phase-delay lines for reflectarray antennas to overcome the bandwidth limitations of conventional designs. The unit cell consists of three circular rings, each featuring a pair of orthogonally positioned gaps, with two identical circular phase-delay lines attached to the outer ring to provide the required reflection phase. Simulations of the unit cell demonstrate a large reflection phase range of approximately 600° and an almost linear phase curve at the center frequency of 10 GHz. Parallel phase curves are also obtained across frequencies ranging from 9 GHz to 12 GHz. To validate the broadband performance of the proposed unit cell, a 9 × 9 center-fed reflectarray antenna operating in the X-band is designed and simulated. The results show that the antenna achieves a 34% 1-dB gain bandwidth, representing a significant improvement over previous designs. Additionally, a mirror-symmetric element arrangement effectively reduces the cross-polarization level to −40 dB.

Introduction

Microstrip reflectarray antennas have attracted considerable attention in communication and radar applications due to their numerous advantages [1]. Their low cost, light weight, and planar structure make them an attractive alternative to traditional parabolic reflector antennas and phased array antennas for high-gain applications. In its basic form, a microstrip reflectarray antenna comprises an array of radiating elements printed on a flat surface and illuminated by a space feed. The fundamental design principle involves controlling the phase of the wave reradiated from each element to form a planar phase front in the desired direction. Several phase-shifting mechanisms have been employed to achieve the required reflection phase, including elements with variable size [2], phase-delay lines [3], and element rotation [4].

However, reflectarray antennas suffer from several drawbacks, with narrow bandwidth being the most critical limitation [5]. The bandwidth of a microstrip reflectarray antenna is primarily restricted by two factors: the inherently narrow bandwidth of the microstrip antenna unit cell, and the differential spatial phase delays between the feed and the various elements across the reflectarray aperture. For small and moderate-size microstrip reflectarray antennas, the first factor dominates the bandwidth limitation. To address this issue, numerous techniques have been proposed, including the use of phase-delay line elements [6], thick substrates, multilayered structures [7], and subwavelength techniques [8]. Considering cost and mass constraints, single-layer elements with phase-delay line techniques are particularly attractive. Extensive research has been conducted to improve reflectarray bandwidth using this approach [9, 10]. Previous works have utilized circular patches with two circular phase-delay lines, circular patches with four circular phase-delay lines, and triple circular rings with four quasi-spiral phase-delay lines. Nevertheless, further enhancement of reflectarray bandwidth remains possible. Building upon our prior research on phase-delay line techniques [11], which demonstrated improved bandwidth performance compared to earlier designs, this paper proposes a novel X-band broadband single-layer reflectarray element to further overcome bandwidth limitations.

The proposed element provides a large reflection phase range of approximately 600° and exhibits nearly linear phase response at the center frequency of 10 GHz. The unit cell comprises three circular rings, each with a pair of orthogonally positioned gaps, with two identical circular phase-delay lines attached to the outer ring to provide the required reflection phase. Parallel phase curves across frequencies from 9 GHz to 12 GHz are obtained, which is beneficial for achieving broadband performance. To validate the broadband characteristics of the proposed unit cell, a 9×9 center-fed reflectarray antenna operating in the X-band is designed and simulated in a full-wave environment. The simulation results demonstrate a significant improvement in bandwidth performance compared to previous designs, with the cross-polarization level effectively suppressed below -40 dB through a mirror-symmetric element arrangement [12].

The paper is organized as follows. Section 2 details the properties and analysis of the proposed unit cell. Section 3 presents the simulated results of the designed reflectarray antenna to validate its effectiveness. Finally, Section 4 provides the conclusion.

2. Unit Cell Design and Analysis

The novel reflectarray element, illustrated in Fig. 1 [Figure 1: see original paper], is etched on a 0.8-mm-thick dielectric substrate with a relative permittivity of 3.55 and a loss tangent of 0.0027. A 2-mm-thick air layer is employed to achieve more linear phase responses by separating the dielectric substrate from the metallic ground. As shown in Fig. 1, the unit cell consists of two main parts: an inner multi-resonant structure and outer phase-delay lines.

The inner structure comprises three circular rings, each with a pair of gaps positioned orthogonally. The widths of these gap pairs are denoted as g_i, g_m, and g_o for the inner, middle, and outer rings, respectively, while w_i, w_m, and w_o represent the widths of the three circular rings with corresponding radii R_i, R_m, and R_o. The outer phase-delay lines are connected to the inner structure through two microstrip stubs. The rotation angle θ determines the length of the phase-delay lines, and the required reflection phase for each unit cell is achieved by varying this length. For broadband design, the element spacing is set to 14 mm, which corresponds to 0.467 λ at the center frequency of 10 GHz.

Unit cell simulations are performed using HFSS software with master-slave boundary conditions and Floquet port excitation. The geometric parameters have been optimized to enhance the unit cell performance. Figure 2 [Figure 2: see original paper] depicts the simulated phase response curves as a function of θ at various frequencies. The results show that a phase variation exceeding 600° is achieved at the center frequency of 10 GHz. The phase curves exhibit smooth and linear characteristics with relatively small slopes. Notably, the four reflection phase curves at 9, 10, 11, and 12 GHz remain parallel to each other, with minimal phase deviation between frequencies, which is highly advantageous for broadband performance.

3. Reflectarray Design and Results

To demonstrate the effectiveness of the proposed unit cell, a 9 × 9-element reflectarray antenna is designed and simulated in a full-wave environment. A linearly polarized pyramidal feed horn serves as the space feed, positioned 82 mm above the reflectarray plane. The schematic diagram of the reflectarray antenna is shown in Fig. 3 [Figure 3: see original paper].

The required reflection phases for all unit cells on the reflectarray aperture are calculated at the center frequency of 10 GHz according to equation (1), where k_0 is the propagation constant in free space, d_i is the distance from the feed to the ith unit cell on the reflectarray plane, and (θ_0, ϕ_0) is the designed main beam direction. The phase shifts are calculated for $(\theta_0, \phi_0) = (0^\circ, 0^\circ)$ at 10 GHz, indicating that the main beam is normal to the reflectarray plane. The calculated phase distribution on the reflectarray aperture at 10 GHz is presented in Fig. 4 [Figure 4: see original paper]. Based on these results, the reflectarray model is constructed as shown in Fig. 5 [Figure 5: see original paper], where the elements are arranged in a mirror-symmetric configuration to reduce cross-polarization.

The reflectarray antenna is simulated in a full-wave environment using CST Microwave Studio, and the results are presented below. Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper] show the simulated co-polarized and cross-polarized (X-pol) radiation patterns in the E-plane and H-plane at 9 GHz and 10 GHz, respectively. A peak gain of 20.5 dB is achieved at 10 GHz, corresponding to approximately 50% efficiency. The radiation patterns remain stable across different frequencies. The cross-polarization levels in both principal planes are suppressed below −40 dB, representing a significant improvement for this class of reflectarray antennas. Figure 8 [Figure 8: see original paper] illustrates the simulated gain as a function of frequency, revealing a 1-dB gain bandwidth of approximately 34%, covering the range from 9 GHz to 12.4 GHz. This substantial improvement in bandwidth performance fully demonstrates the effectiveness of the proposed unit cell.

$$\phi_R = k_0 \cdot d_i - k_0 \cdot (x_i \sin\theta_0 \cos\phi_0 + y_i \sin\theta_0 \sin\phi_0)$$

4. Conclusion

A novel single-layer unit cell with attached phase-delay lines has been proposed for broadband reflectarray antenna design, achieving a linear phase response covering approximately 600°. To validate the unit cell' s effectiveness, a 9 × 9 center-fed reflectarray operating in the X-band was designed and simulated in a full-wave environment. The simulation results demonstrate a 34% 1-dB gain bandwidth, confirming improved bandwidth performance compared to previous designs. Additionally, the cross-polarization level is effectively reduced below −40 dB.

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Note: Figure translations are in progress. See original paper for figures.