Design of Novel Microstrip Reflectarray Elements and Their Applications (Postprint)

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

Abstract

A single-layer microstrip reflectarray unit cell featuring a multi-resonant structure is proposed. Its reflection phase characteristics are simulated and analyzed using HFSS, achieving a reflection phase dynamic range of approximately 430° with good linearity. Based on this unit cell, a Ku-band microstrip reflectarray is designed, employing an exponentially tapered slot (Vivaldi) antenna as the feed. Simulation results demonstrate a gain of 27.1 dB at the center frequency, with a half-power beamwidth of 4.96° in both principal planes. The gain variation is approximately 2 dB across the 12–15.5 GHz frequency band, indicating a relatively wide bandwidth. The Vivaldi antenna and reflectarray were fabricated and measured, showing good agreement between the measured and simulated results.

Full Text

Design of a Novel Multi-Resonance Microstrip Reflectarray Element and Its Application

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Abstract

This paper proposes a novel single-layer microstrip reflectarray element featuring a multi-resonance structure. HFSS simulations of its reflection phase characteristics demonstrate a dynamic range of approximately 430° with excellent linearity. Based on this element, a Ku-band microstrip reflectarray was designed using a Vivaldi antenna as the feed. Simulation results show that the antenna achieves a gain of 27.1 dB at the center frequency with a half-power beamwidth of 4.96° in both planes. The gain variation remains within 2 dB across the 12-15.5 GHz band, indicating wideband performance. A prototype comprising the Vivaldi feed and reflectarray was fabricated and tested, showing good agreement between measured and simulated results.

Keywords: microstrip reflectarray, multi-resonance structure, Vivaldi antenna, wideband

Microstrip reflectarray antennas combine the advantages of parabolic reflector antennas and microstrip array antennas. Since their introduction in 1978, they have attracted significant attention and undergone rapid development due to their lightweight, compact size, low cost, ease of manufacturing, conformability with other structures, and integration capability with microstrip circuits. Similar to conventional parabolic reflector antennas, microstrip reflectarrays require no feed network, thereby eliminating parasitic radiation and impedance insertion losses and achieving high radiation efficiency. A microstrip reflectarray consists of a feed source and an array of microstrip radiating elements with phase-shifting capabilities. Under illumination from the feed, each element introduces an appropriate phase shift to the incident wave, enabling the reflected waves to coherently combine in a specific direction and produce a high-gain beam.

Traditional microstrip reflectarray antennas typically suffer from narrow bandwidth, which is influenced by multiple factors including feed bandwidth, element bandwidth, spatial phase delay variations across elements at different positions, and element spacing [1]. Among these, element bandwidth and spatial phase delay are the most critical. An ideal wideband reflectarray element should exhibit reflection phase curves that remain parallel across different frequencies and be independent of the incident wave angle. Proper selection of element configuration and structure can yield such ideal characteristics. While a larger focal-to-diameter (F/D) ratio can mitigate bandwidth limitations caused by spatial phase delay, it compromises feed illumination efficiency, necessitating a design trade-off. Fractal antenna structures exhibit self-similarity that enables multi-frequency operation [2] and increased bandwidth, while their self-loading characteristics further broaden the operating band. Integrating fractal technology with microstrip antenna design offers significant potential for mobile communications, satellite communications, and other wideband applications.

The Vivaldi antenna, proposed by Gibson in 1979 [3], belongs to the class of frequency-independent antennas. It offers an ultra-wide operating bandwidth, good directional radiation characteristics, stable input impedance, simple structure, low cost, and easy planar integration. The antenna comprises a slotline that transitions exponentially from a narrow width at one end to a wide width at the other. Due to its planar structure creating minimal blockage of reflected waves, the Vivaldi antenna serves as an excellent feed for microstrip reflectarrays, effectively solving the feed blockage problem in front-fed configurations.

To transform the spherical wave radiated by the feed into a focused beam, each reflectarray element must provide an appropriate phase shift. Four typical phase compensation methods exist: (1) loading microstrip patches with phase-delay lines of varying lengths [4]; (2) adjusting the size of microstrip reflectarray elements to compensate for spatial phase delays caused by different distances from the feed to each patch [5]; (3) rotating identical circularly polarized microstrip elements by different angles to achieve phase shifts [6]; and (4) loading slots of varying lengths on the patches or ground plane [7]. This work employs the second method—varying element dimensions—to achieve phase compensation.

The proposed single-layer multi-resonance reflectarray element with fractal structure provides both excellent linearity in its reflection phase curve and a phase range of approximately 430°. A microstrip reflectarray utilizing this element was designed and fed by a Vivaldi antenna. Simulation results demonstrate a gain of 27.1 dB at the center frequency with a gain variation of only 2 dB across the 12–15.5 GHz band.

1 Basic Principles of Microstrip Reflectarray

To transform a spherical wavefront into a planar wavefront in a specified direction, the reflection phase curve of the array elements must cover at least 360°. Conventional simple single-layer elements struggle to achieve both the required 360° phase shift and good linearity in their reflection phase curves, particularly near resonant lengths where steep phase slopes result in narrow bandwidth and increased manufacturing sensitivity. While increasing substrate thickness can smooth the reflection phase curve, it reduces the phase range below the 360° requirement. Multilayer stacked patch structures have been used to obtain smooth phase curves exceeding 360° [8], but this approach increases design complexity, manufacturing difficulty, and cost. Single-layer multi-resonance element structures [9] can effectively satisfy both phase range and linearity requirements. For instance, reference [9] achieved a phase range of approximately 380° using a combination of rings and circles. The fractal structure proposed in this paper represents a multi-resonance element that meets phase curve linearity and range requirements while providing wide bandwidth.

As shown in the coordinate system of

, array antenna theory dictates that for a reflectarray radiating in direction (,), the required surface phase distribution is:

$$\phi_i(x_i, y_i) = k_0 \left(d_i - \sin\theta_0(x_i \cos\phi_0 + y_i \sin\phi_0)\right)$$

where k_0 is the free-space propagation constant and (x_i, y_i) represents the center coordinates of the i-th element. The reflection phase of each element equals the incident phase plus its own compensation phase:

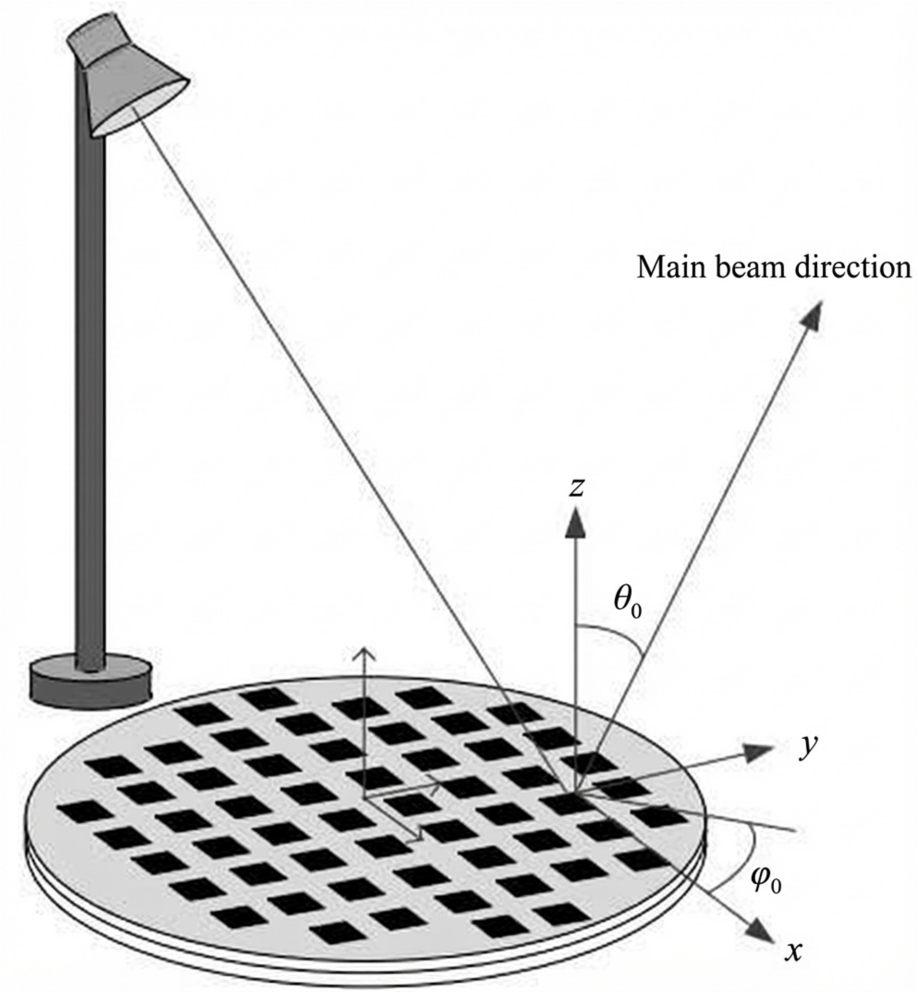

Figure 1: Figure 1

$$\phi_{Ri}(x_i, y_i) = \phi_i(x_i, y_i) + \phi_{di}$$

where d_i denotes the distance from the feed phase center to the i-th patch element, and $\phi_{Ri}(x_i, y_i)$ is the reflection coefficient phase of the i-th element—the required compensation phase.

From equations (1) and (2), the necessary phase shift for each element is:

$$\phi_{di} = k_0 \left(d_i - \sin\theta_0(x_i \cos\phi_0 + y_i \sin\phi_0)\right)$$

Using equation (3), the compensation phase for each element can be calculated, and the element dimensions can then be determined from the element reflection phase curve.

2 Design and Analysis of the Novel Fractal Element

The wideband reflectarray element designed in this work employs a single-layer multi-resonance structure, as illustrated in [FIGURE:2]. This simple configuration facilitates practical implementation. To achieve a large phase shift range and good linearity, an air layer is introduced between the dielectric material and ground plane (implemented using foam material with a dielectric constant close to air in fabrication).

The element features a fractal structure with an outer hexagon side length of a. The dielectric material has a permittivity of $\varepsilon_r = 2.2$, the air layer thickness is h_2, and its dielectric constant is approximately 1.06. The element' s reflection phase is analyzed using the Waveguide Approach (WGA) proposed in reference [10] to obtain the reflection phase curve. Operating in the Ku-band with a grid period $L = 13$ mm, the element' s reflection phase characteristics are simulated using HFSS.

With a varying from 1.5 mm to 6 mm, the effects of different h_1 and h_2 values on reflection phase are analyzed. As shown in [FIGURE:3], both $h_1 = 0.5$ mm and $h_1 = 0.7$ mm yield good linearity and large phase variation ranges, with $h_1 = 0.5$ mm selected for this design. [FIGURE:4] demonstrates the impact of different air layer thicknesses h_2 on the reflection phase curve, revealing a significant influence. When $h_2 = 0$ mm, the reflection phase shows minimal variation, while $h_2 = 3$ mm provides the largest phase variation range with optimal linearity, making it the selected value.

As the element size a increases from 1.5 mm to 6 mm, the phase shift range reaches approximately 430°, satisfying the requirement that microstrip reflectarray elements provide at least 360° of phase range. A comparison of reflection phase curves at the center frequency for hexagonal elements, hexagonal ring elements, and the proposed multi-resonance structure is presented in [FIGURE:5]. The results demonstrate that the designed structure offers both a larger phase variation range and better linearity.

3 Design and Results of the Microstrip Reflectarray

To validate the effectiveness of the proposed element, a Ku-band microstrip reflectarray was designed using the novel unit cell, as shown in [FIGURE:6]. The array has a diameter $D = 325$ mm, dielectric layer thickness $h_1 = 0.5$ mm, $\varepsilon_r = 2.2$, foam layer thickness $h_2 = 3$ mm (dielectric constant 1.06), grid period $L = 13$ mm, feed phase center distance $F = 260$ mm, and focal-to-diameter ratio $F/D = 0.8$. Due to the minimal blockage offered by the Vivaldi antenna’ s planar structure, it is employed as the feed. The fabricated Vivaldi antenna prototype and its measured radiation pattern are shown in [FIGURE:7] and [FIGURE:8].

The simulated radiation pattern of the planar microstrip reflectarray (fed by the Vivaldi antenna) is presented in [FIGURE:9]. At the Ku-band center frequency, the gain reaches 27.1 dB with a half-power beamwidth of 4.96° in both planes. The E-plane (yoz-plane) pattern achieves sidelobe levels of -16 dB, while the H-plane (xoz-plane) achieves -20 dB. Simulated gain patterns at different frequencies are shown in [FIGURE:10], demonstrating a gain variation of approximately 2 dB across the 12–15.5 GHz band, confirming wideband operation.

To verify the practical feasibility of the element and array design, the microstrip reflectarray was fabricated and tested in a microwave anechoic chamber. [FIGURE:11] presents the measured E-plane and H-plane patterns at the center frequency, showing a measured directivity of 27.1 dB. The half-power beamwidths are 5.3° in the E-plane and 4.9° in the H-plane. The minor discrepancies from simulation results are attributed to fabrication tolerances, measurement errors, and the simplified test fixture. Overall, the measured results show good agreement with simulations.

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