

Design Postprint of a Novel Single-Layer Dual-Band Dual-Polarized Microstrip Reflectarray Antenna

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Abstract

This paper proposes a novel single-layer microstrip reflectarray element featuring a multi-resonant structure, composed of six dipoles placed in parallel with specific spacing. The element exhibits excellent linear polarization characteristics. High-frequency electromagnetic simulation software HFSS is utilized to optimize and analyze the element's parameters, ensuring good linearity of the reflection phase curve within both frequency bands. Based on this element, a dual-frequency dual-polarized offset-fed microstrip reflectarray antenna operating in the X/Ku bands is designed, employing the same pyramidal horn antenna as the feed source for both bands. The reflectarray antenna is fabricated and tested; the results demonstrate good radiation performance at the X-band center frequency of 10 GHz and the Ku-band center frequency of 13.58 GHz. Good agreement between measured and simulated results validates the excellent dual-frequency radiation performance of the reflectarray antenna. The design presented in this paper provides significant reference value for achieving dual-frequency dual-polarization performance in microstrip reflectarray antennas.

Full Text

Design of a Novel Single-Layer Dual-Band Dual-Polarization Microstrip Reflectarray

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Abstract

This paper presents a novel single-layer microstrip reflectarray element featuring a multi-resonance structure composed of six parallel dipoles spaced at a specific interval. The element exhibits excellent linear polarization characteristics. Ansoft HFSS is employed to optimize the element parameters, achieving linear reflection phase curves in both frequency bands. Based on this element, a dual-band dual-polarization microstrip reflectarray antenna operating in X/Ku bands is designed with a single pyramidal horn antenna serving as the feed for both bands. The reflectarray is fabricated and measured, with results demonstrating excellent radiation performance at the center frequencies of 10 GHz (X-band) and 13.58 GHz (Ku-band). Good agreement between measured and simulated results confirms the desirable dual-band radiation performance of the reflectarray. This design offers valuable insights for implementing dual-band dual-polarization performance in microstrip reflectarray antennas.

Keywords: Microstrip reflectarray; Dual-band dual-polarization; Multi-resonance; Offset-fed

1 Introduction

High-gain antennas are increasingly employed in modern applications, with traditional implementations primarily including parabolic reflector antennas and array antennas, both of which suffer from significant drawbacks. Parabolic reflector antennas are bulky, susceptible to wind damage, difficult to transport, and offer limited beam scanning capability [1], while their curved surfaces demand extremely high manufacturing precision. Array antennas, on the other hand, require complex feed networks that introduce substantial transmission losses, making efficiency difficult to maintain. Microstrip reflectarray antennas combine advantages from both approaches, offering lightweight construction, simple fabrication, low cost, easy integration with microstrip circuits, and conformal deployment capabilities, leading to rapid development and widespread adoption in recent years. Additionally, microstrip reflectarrays can achieve high antenna efficiency and facilitate wide-angle beam scanning [2].

Conventional microstrip reflectarray antennas typically suffer from narrow bandwidth [3], making dual-band or multi-band aperture sharing highly desirable. Although existing dual-band dual-polarization reflectarrays have found preliminary applications, achieving a simple single-layer design for two closely spaced frequencies remains challenging. Current approaches for dual-band or multi-band operation in microstrip reflectarrays fall into two main categories:

First, single-layer configurations place both low-frequency and high-frequency elements on the same dielectric layer [4-8]. When the frequency ratio is relatively small, elements can share the same periodicity, but careful design of element geometry and arrangement is required to minimize mutual interference.

However, when frequencies are widely separated (e.g., by a factor of 3-4), selecting appropriate periodicities and element-to-ground spacing becomes problematic. Reference [6] demonstrated triple-band circular polarization operation at 7.1 GHz, 8.4 GHz, and 32 GHz using a single layer with split square rings, cross-shaped dipoles, and split circular rings with embedded dipoles. While single-layer structures avoid shadowing and loss effects from upper layers, they suffer from stronger mutual coupling between different frequency elements.

Second, dual-layer configurations place different frequency elements on separate dielectric layers, either with the low-frequency array above the high-frequency array [9,10] or vice versa [11,12]. Reference [9] proposed a novel element for a 0.5m dual-band right-hand circularly polarized reflectarray, achieving high efficiency and low cross-polarization at 7.3 GHz and 31.75 GHz. Reference [11] implemented L-band and Ka-band operation using a dual-layer structure where the upper high-frequency array's ground plane employed a Frequency Selective Surface (FSS) to reduce its impact on the lower layer. However, dual-layer structures have inherent disadvantages: the upper layer and its ground plane shadow the lower layer, significantly affecting gain; resonant modes excited in the lower layer influence the upper array's gain and sidelobe levels; and dual-layer structures are difficult to align and costly to fabricate. Fractal-based elements have also been used for dual-band or multi-band operation [13-15], leveraging self-similarity and self-loading characteristics. However, these approaches are primarily suitable for widely separated frequency bands and present difficulties for closely spaced dual-band dual-polarization applications.

This paper proposes a single-layer six-parallel-dipole microstrip reflectarray element with a multi-resonance structure. Through parametric analysis, an optimal parameter set is determined, and the element's polarization characteristics are analyzed to verify its feasibility for dual-band dual-polarization operation. Subsequently, a dual-band dual-linear-polarization microstrip reflectarray operating in X/Ku bands is designed, using the same horn antenna to feed both bands in an offset configuration. Simulation and measurement results demonstrate excellent dual-band dual-polarization radiation performance.

2 Basic Principles of Microstrip Reflectarrays

Both microstrip reflectarray and parabolic antennas transform spherical wavefronts from the feed into planar wavefronts through reflection. While parabolic reflectors utilize their geometric curvature to adjust phase, microstrip reflectarrays achieve this by controlling the phase shift introduced by each element to create specific aperture phase distributions. For a reflectarray with beam direction (θ_0, ϕ_0) , the required phase shift ϕ_{Ri} for the i -th element at coordinates (x_i, y_i) is given by:

$$\phi_{Ri} = k_0 [(x_i \cos \phi_0 + y_i \sin \phi_0) \sin \theta_0] \quad (1)$$

where k is the free-space wavenumber. Using equation (1) together with the element reflection phase curves enables determination of each element's parameters in the reflectarray.

[FIGURE:1]

3 Element Design and Analysis

The proposed single-layer six-parallel-dipole element structure and its array arrangement are shown in Figure 2 [FIGURE:2]. X-band and Ku-band elements are interleaved with identical periodicity p . The simple multi-resonance structure makes this element suitable for reflectarray applications, with the operating polarization parallel to the dipole length. The periodicity p is set to 14 mm, corresponding to 0.47λ at 10 GHz and 0.63λ at 13.58 GHz. The substrate has a dielectric constant of 2.25 and thickness $h = 3$ mm. The center two dipoles have length L , while the side dipoles have lengths a_1 and a_2 proportional to L , where $a_1 = kL$ and $a_2 = ka = k^2L$ (k is a constant). All dipoles have width w , and the spacing between adjacent dipoles is d . The Waveguide Approach (WGA) from reference [16] is employed to analyze the element's reflection phase characteristics.

[FIGURE:2]

With L varying from 4 mm to 13.6 mm, the effects of different element parameters (d , w , k) on the reflection phase curves are analyzed in both bands to determine an optimal parameter combination. Figure 3 [FIGURE:3] shows the impact of different d values on the reflection phase curves. The results indicate minimal variation in both bands, suggesting that d has little influence on the reflection phase; $d = 0.5$ mm is selected. Figure 4 [FIGURE:4] presents the effect of different w values. The reflection phase curves vary noticeably with w , and $w = 0.8$ mm provides both large phase range and good linearity at 13.58 GHz and 10 GHz, making it a reasonable choice. Figure 5

illustrates the influence of different k values, which significantly affect the reflection phase curves in both bands, particularly at the higher frequency. Considering linearity and phase range across both bands, $k = 0.7$ is selected.

[FIGURE:3] [FIGURE:4]

With $d = 0.5$ mm, $w = 0.8$ mm, and $k = 0.7$, the element achieves a reflection phase range of approximately 370° at the lower frequency (10 GHz) and about 630° at the higher frequency (13.58 GHz) as L varies from 4 mm to 13.6 mm. This satisfies the reflectarray element requirement of a minimum 360° phase range while maintaining good linearity in both bands.

When the incident wave polarization is orthogonal to the dipole length, the resulting reflection phase curve is shown in Figure 6 [FIGURE:6] (results at 13.58 GHz; similar conclusions hold at 10 GHz). The minimal phase variation with

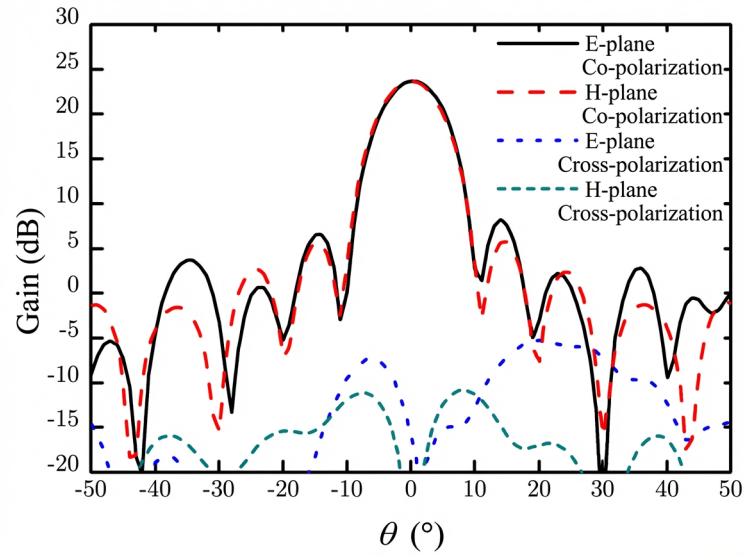


Figure 1: Figure 5

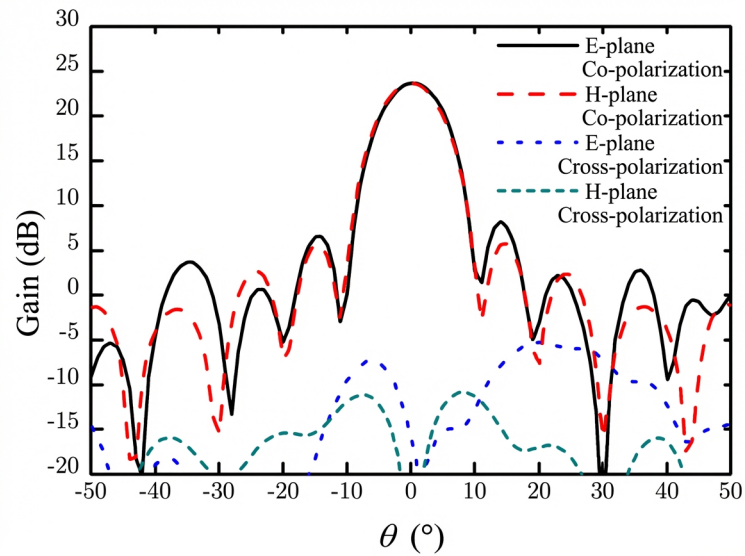


Figure 2: Figure 5

dipole length demonstrates that orthogonally polarized waves have negligible effect, confirming the element's excellent linear polarization characteristics.

[FIGURE:6]

Mutual coupling between elements of different frequency bands is investigated using the model shown in Figure 7

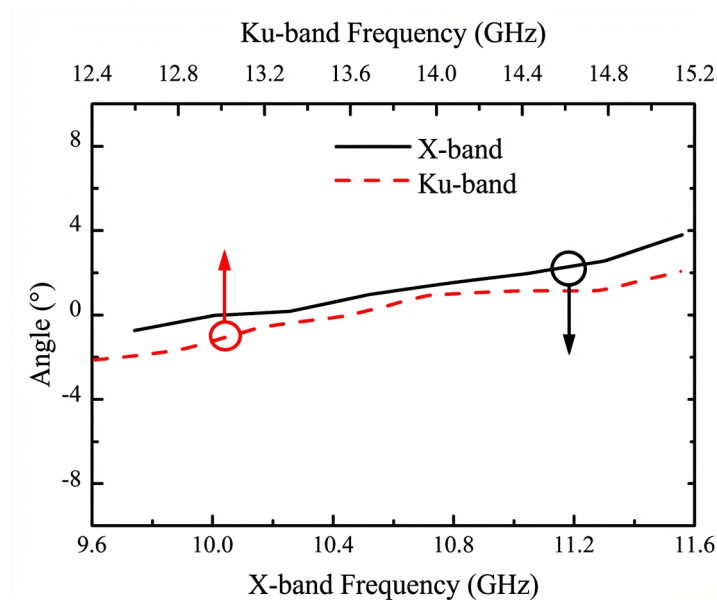


Figure 3: Figure 7

. Figure 8 [FIGURE:8] shows the reflection phase curves of the high-frequency element under the influence of low-frequency elements. The presence and size of low-frequency elements have almost no impact on the high-frequency element's reflection phase curves, indicating minimal mutual coupling. Similar analysis confirms that high-frequency elements likewise have negligible effect on low-frequency elements.

[FIGURE:8]

4 Reflectarray Design and Simulation/Measurement Results

A dual-band dual-linear-polarization microstrip reflectarray operating in X/Ku bands is designed using the proposed element. The antenna structure is shown in Figure 9 [FIGURE:9]. In the X-band, the operating polarization is y-directed with $13 \times 13 = 169$ elements, and the feed phase center is at a vertical distance

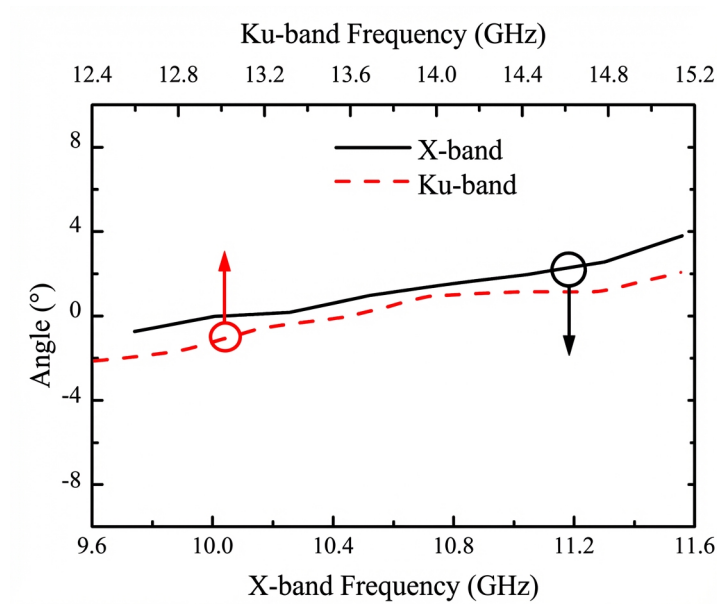


Figure 4: Figure 7

$b = 157.6$ mm from the array. In the Ku-band, the operating polarization is x-directed with $12 \times 12 = 144$ elements, and the feed phase center distance is $b = 145.5$ mm. To eliminate feed blockage, both bands employ offset feeding using a pyramidal horn antenna at an incident angle $q = 30^\circ$, with the main beam directed normal to the array surface (z-axis in Figure 9). The horn's simulated radiation patterns at 10 GHz and 13.58 GHz are shown in Figure 10 [FIGURE:10].

[FIGURE:9] [FIGURE:10]

The simulated radiation patterns at X-band (10 GHz) are shown in Figure 11 [FIGURE:11]. The simulated gain reaches 23.7 dB with the beam accurately pointing to $\theta = 0^\circ$. The E-plane sidelobe level is -15.5 dB with cross-polarization below -29 dB, while the H-plane sidelobe level is -18 dB with cross-polarization below -34.4 dB. Figure 12 [FIGURE:12] shows the simulated patterns at Ku-band (13.58 GHz), achieving 24.7 dB gain with the beam also pointing to $\theta = 0^\circ$. The E-plane sidelobe level is -18.5 dB with cross-polarization below -28.6 dB, and the H-plane sidelobe level is -13.5 dB with cross-polarization below -33.7 dB.

[FIGURE:11] [FIGURE:12]

To validate the design, the reflectarray is fabricated and measured. The measured patterns at 10 GHz and 13.58 GHz are shown in Figures 13 [FIGURE:13] and 14 [FIGURE:14], respectively. The measured results show accurate beam

pointing at $\theta = 0^\circ$ in both bands, with 23.68 dB gain at 10 GHz (E-plane sidelobe -14.8 dB, H-plane sidelobe -17.2 dB, cross-polarization below -26 dB in both planes) and 24.56 dB gain at 13.58 GHz (E-plane sidelobe -19.5 dB with cross-polarization below -30 dB, H-plane sidelobe -13.5 dB with cross-polarization below -26.5 dB). The simulation and measurement results show good agreement, with minor differences in Ku-band E-plane sidelobes attributed to feed misalignment during measurement. Figures 15 [FIGURE:15] and 16 [FIGURE:16] present the measured gain and efficiency versus frequency. The 1-dB gain bandwidth (gain variation < 1 dB) is approximately 12.5% (9.95-11.2 GHz) in X-band with 50.43% efficiency at 10 GHz, and about 12.9% (12.41-14.17 GHz) in Ku-band with 40% efficiency at 13.58 GHz.

Due to the large offset feed angle, slight variations in maximum radiation direction occur across different polarizations and frequencies. Figure 17 [FIGURE:17] shows the maximum radiation direction versus frequency, demonstrating that within the 1-dB gain bandwidth of both bands, the deviation from the $\theta = 0^\circ$ direction is minimal, remaining within $\pm 2.1^\circ$. These results validate the excellent dual-band dual-polarization performance of the proposed reflectarray.

[FIGURE:13] [FIGURE:14] [FIGURE:15] [FIGURE:16] [FIGURE:17]

5 Conclusion

This paper presents a novel multi-resonance single-layer microstrip reflectarray element composed of six parallel dipoles with a simple and easily realizable structure. A dual-band dual-polarization microstrip reflectarray operating in X/Ku bands is designed using this element, with X-band and Ku-band elements interleaved at identical periodicity. A single pyramidal horn antenna feeds both bands in an offset configuration. Simulation analysis demonstrates excellent dual-band dual-polarization radiation performance, and measurements in an anechoic chamber show good agreement with simulations, validating both the element's effectiveness and the antenna's practical feasibility. The design approach and element configuration presented herein provide valuable reference for implementing dual-band dual-polarization performance in microstrip reflectarray antennas.

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