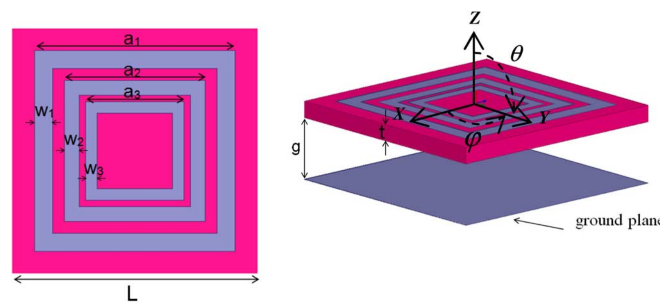
A High-Efficiency Ku-Band Reflectarray Antenna Using Single-Layer Multiresonance Elements

A. Vosoogh, K. Keyghobad, A. Khaleghi, and S. Mansouri

***Abstract*—A broadband single-layer reflectarray antenna composed of multiresonance square-rings elements is presented. The element is optimized to provide a linear phase curve and wide-enough phase variation. To avoid feed blockage, an offset feed configuration is used, and wave incident angle is considered to determine the appropriate element parameters that provide desirable phase shift on the antenna surface. The aperture efficiency of the antenna is maximized by optimizing feed position and characteristics. A 480-element antenna is fabricated and measured. The measured results show 1-dB gain bandwidth of 17% and radiation efficiency of 66% at 13.5 GHz center frequency.**

***Index Terms*—Multiresonance square-rings elements, offset feed, reflectarray.**



(a) (b)

Fig. 1. Geometry of multiresonance square-rings element.

I. Introduction

A REFLECTARRAY antenna is an array of flat reflective elements with adjusted phases to compensate the different phases associated with different path lengths from illuminating feed. This feature compromises the advantages of conventional parabolic reflectors and phased array antennas. Similar to a parabolic antenna, the illuminating feed structure of a reflectarray antenna provides a high efficiency for a large aperture since there is no insertion loss as in phased array antennas. Also, these antennas can utilize the benefit of a phased array antenna to achieve a counter beam-shaping by using a phase synthesis technique. Other major advantages of the reflectarray antenna are its planar structure, easy manufacturing, and small volume [1].

The major limitation of the reflectarray antenna is its narrow bandwidth. For reflectarrays with moderate sizes, this mostly arises from bandwidth limitation of radiating elements [1]. Elements with linear phase response can be used to improve antenna bandwidth. This linearization could be done by using phase delay lines [2], slotted ground [3], stacked patches [4], etc. One of the most efficient approaches to achieve a linear phase response is by using elements with multiple resonances [5]–[7]. In [6], several multiresonance unit cells were studied, and their phase curves were investigated. A reflectarray antenna using double-square-rings element is manufactured in [7], which provides wider bandwidth than usual square elements.

In this letter, we used multiple resonance structures to form an optimized triple-square-rings element. This feature can lead to a linear phase curve with dynamic range of phase variation of more than 500°. Also, in order to avoid feed shadow effect, an offset feed configuration is implemented.

Since, in most reflectarray designs, a unit-cell phase response considering normal incident wave is used to perform phase compensation on reflectarray surface, an illuminating feed in offset configuration could result in higher incident angles and disqualify the phase shifts of each element determined by normal incident angle. Thus, the incident wave angle also is considered to derive the phase response of each element in the reflectarray surface more precisely. A prototype reflectarray antenna is manufactured and tested for Ku-band. The element structure and feed position have been optimized to achieve the maximum efficiency.

II. Unit Cell Design

The configuration of the proposed unit cell is shown in Fig. 1. It consists of three concentric square rings where each side of the inner ring is equal to the side of the outer ring multiplied by the factor of S. These elements are etched on a substrate with permittivity of 2.2 and thickness of 0.75 mm. An element spacing of 11 mm (about 0.5λ) is used to avoid grating lobes. To obtain a smoother phase curve, an air gap (g) is considered between the substrate and the ground. To derive phase curve characteristics of the element, simulations are analyzed using Ansoft HFSS electromagnetic simulation software that uses master–slave boundaries and Floquet ports to model periodic structures.

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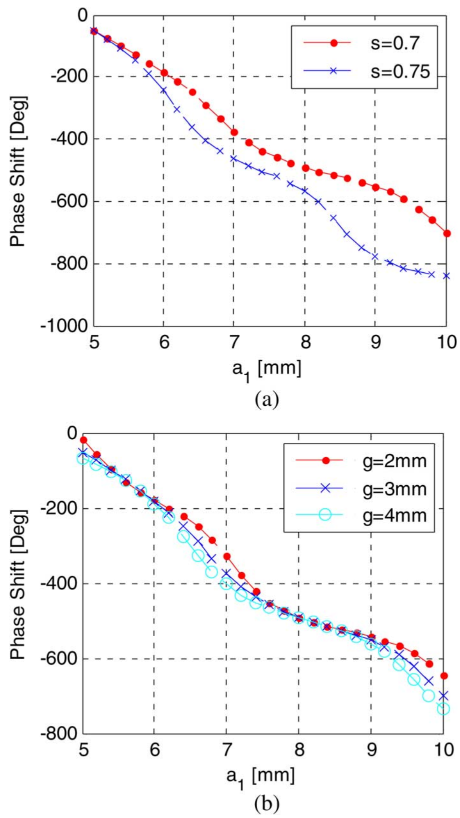

Fig. 2. Phase curve of unit cell for different (a) S factors for $g = 3$ mm and (b) air gaps for $S = 0.7$ at 13.5 GHz center frequency.

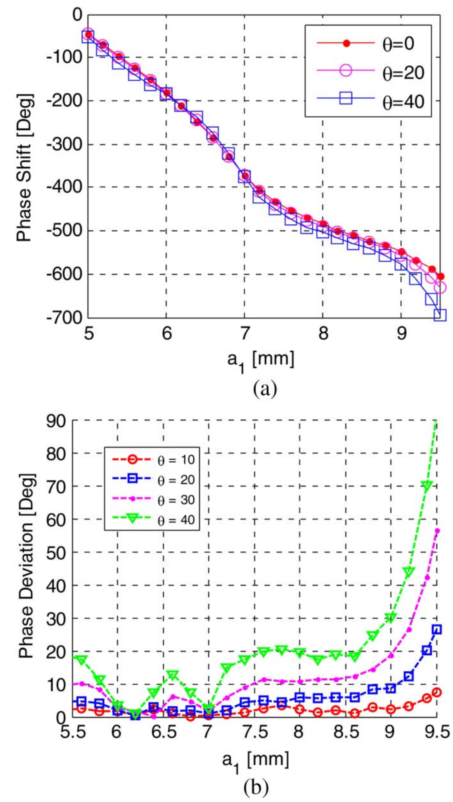

Fig. 3. (a) Phase curve of unit cell at 13.5 GHz for different θ and (b) phase deviation of phase curves with different θ from phase curve with $\theta = 0$, $S = 0.7$, and $g = 3$ mm.

TABLE I
UNIT CELL GEOMETRY

a_2	a_3	w_1	w_2	w_3	S	L (mm)	g (mm)	t (mm)
$S \times a_1$	$S \times a_2$	$0.09 \times a_1$	$0.7 \times w_1$	$0.7 \times w_2$	0.7	11	3	0.75

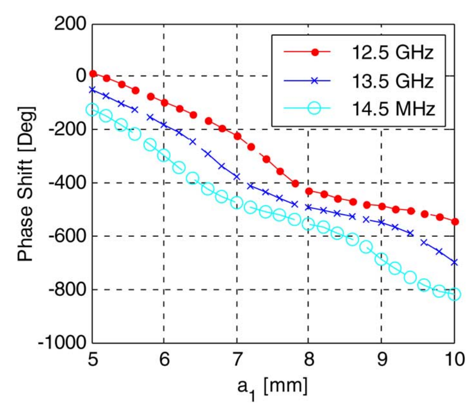

Fig. 4. Phase curve versus a_1 for three different frequencies (12.5, 13.5, and 14.5 GHz) with $S = 0.7$ and $g = 3$ mm.

A parametric study is carried out to evaluate bandwidth performance and optimize element structure leading to a smoother phase curve. Fig. 2 shows the influence of S factor and air gap on phase variations. It can be concluded that a factor of 0.7 [Fig. 2(a)] and an air gap of 3 mm [Fig. 2(b)] leads to the most linear phase curve among studied values, while a_1 varies from 5 to 10 mm to provide the required phase. The final optimized values of various effective parameters are depicted in Table I.

To define the appropriate element presenting exact phase shift on reflectarray surface, the wave incident angle has been considered. As shown in Fig. 3(a), the variation of wave incident angle with respect to broadside direction, θ, affects the phase variations. This causes a phase deviation up to 90°, mostly in larger incident angles and bigger sizes of unit cell as illustrated in Fig. 3(b).

In Fig. 4, the phase response against a_1 is plotted for three different frequencies at 12.5, 13.5, and 14.5 GHz. It can be seen that these curves are approximately parallel to each other. These characteristics show that the differential phase shifts are invariant versus frequency in this band, which leads to a wider bandwidth.

III. DESIGN AND SIMULATION

An offset feed reflectarray antenna is designed to maximize the antenna efficiency by reducing the feed blockage. Increasing the offset angle reduces the feed blockage, but introduces reduction of the aperture efficiency due to the nonappropriate aperture illumination. It was shown that the aperture efficiency of an offset feed reflectarray maintains almost constant with offset angle increases until the angle of 25° is achieved, in which the efficiency drops about 1% [8]. To have the antenna radiation pattern at the broadside direction, in the offset configuration, the antenna efficiency is reduced due to the specular reflections from the ground plane, which is not at the same direction [9].

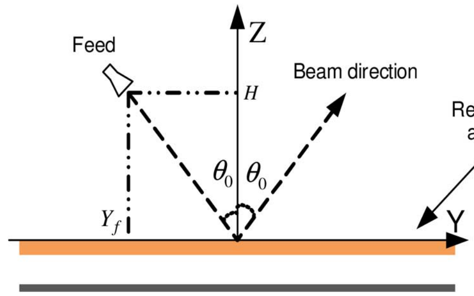

Fig. 5. Schematic diagram of the reflectarray antenna.

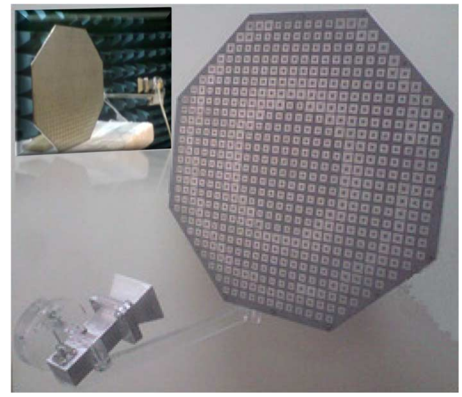

Fig. 6. Reflectarray antenna prototype.

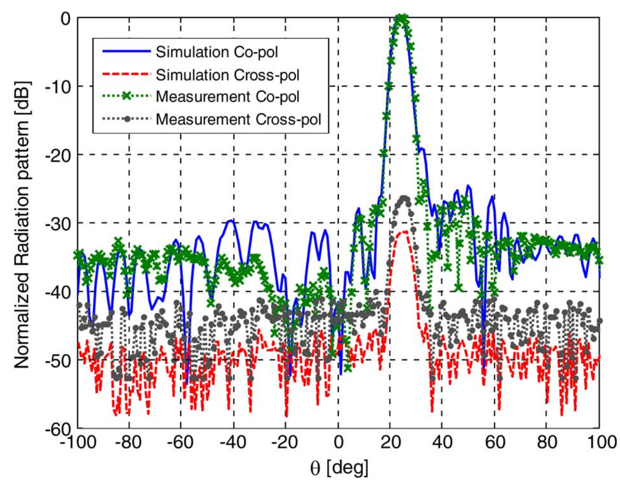

Fig. 7. Normalized simulated and measured radiation pattern of reflectarray antenna for copolar and cross-polar components at 13.5 GHz.

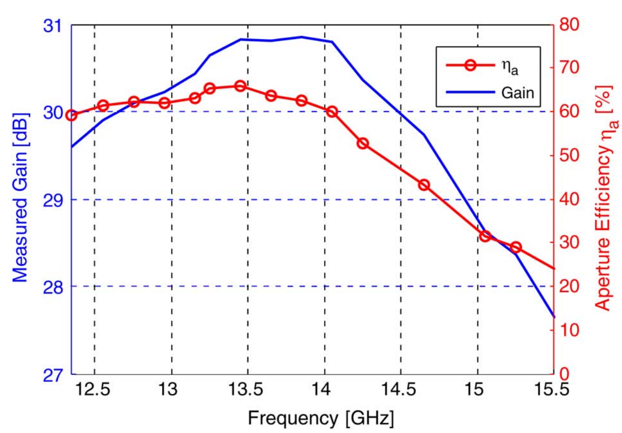

Fig. 8. Measured radiation gain and efficiency of reflectarray antenna composed of triple-square-ring element.

Since these specular reflections are not directed toward the main beam direction, energy in these structures is wasted. To overcome this disadvantage, the main beam direction of the antenna is oriented toward offset mirror angle.

The schematic design of reflectarray antenna is illustrated in Fig. 5. The feed antenna is located at $x = 0, y = -H \tan \theta_0$, $z = H$, where θ_0 is the offset angle and H is the height of the feed. A linearly polarized pyramidal horn antenna is used as the illuminating feed. The relative antenna parameters are optimized according to parametric study in [8], as $H/D = 0.75$, $\theta_0 = 25$, $q = 7.5$, in which D is the antenna diameter and q is the feed specification defined as $\cos^q \theta$. Note that, in this configuration, the illumination level at the reflectarray edges is about 12 dB below the level at the aperture center.

A reflectarray antenna consisting of 480 elements is designed to operate at the center frequency of 13.5 GHz. The array aperture is a hexagonal-shaped surface with diameter of 32 cm. To direct the main beam in a given direction (θ_0, φ_0), the phase shifts have been induced at each element according to [1]

$$\phi_R = k_0(d_i - (x_i \cos \varphi_0 + y_i \sin \varphi_0) \sin \theta_0) \tag{1}$$

where k_0 is the propagation constant in vacuum, d_i is the distance from the phase center of the feed to ith unit cell in the reflectarray surface, and H is the height of the feed. The phase distribution on the reflectarray surface is extracted using (1), and the related element dimensions are obtained from Fig. 3(a) according to the look angle.

The antenna simulation is accomplished using the full-wave time-domain solver of CST Microwave Studio. In total, there were 700e6 mesh cells that are reduced to 15e6 by using subgrid method of the software. This can run on a normal fast PC. The antenna is fabricated on an RT5880 with thickness of 0.7 mm. The fabricated antenna is shown in Fig. 6. The radiation pattern of the antenna is measured in the far-field anechoic chamber. Fig. 7 shows the measured and the simulated patterns for the copolar and cross-polar components at the center frequency of 13.5 GHz.

The designed antenna has 3-dB beamwidth of 5.3° with the sidelobe level of 28 dB. The measured antenna main beam is directed toward 24° from broadside direction. The small difference with simulation is due to the feed alignment and the measurement errors. This is in a good agreement with simulation.

The measured antenna gain versus frequency is depicted in Fig. 8. The measured antenna gain is maximum at 13.5–14 GHz with the gain of 30.8 dB. The 1-dB gain bandwidth of about 17% is achieved. The measured antenna aperture efficiency is also depicted in Fig. 8. As shown, the aperture efficiency of 66% can be calculated at 13.5 GHz considering the antenna aperture size. This efficiency is significantly enhanced compared to the previous design [7] with two concentric square rings that has provided a simulated and measured radiation efficiency of 34.3% and 12.5%, respectively [7]. This performance enhancement is the result of using offset configuration, feed adjustment, element optimization, and phase compensation induce on each element by considering the wave incident angles.

IV. Conclusion

An optimized triple-square-rings element is used to fabricate a broadband single-layer reflectarray antenna with linear phase curve and more than 500° phase variation for Ku-band. To allocate the accurate element with appropriate phase shift on reflectarray surface, the incident wave angle form feed is considered to design the antenna. The measurement result shows 1-dB bandwidth of about 17%. Using offset configuration, a gain of 30.8 dB and radiation efficiency of 66% at the center frequency of 13.5 GHz is achieved by optimizing relative antenna parameters including the ratio of H/D and offset angle.

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