Progress In Electromagnetics Research C, Vol. 73, 65–73, 2017

Single-Layer Dual-Band Dual-Linear-Polarization Reflectarray Antenna with Different Beams for Each Band

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Abstract—A novel single-layer unit cell structure is proposed to design a dual-band dual-linear-polarization reflectarray antenna with different beams for X and Ku bands. The unit cell structure is composed of a circular ring and two cross bow-tie structures combined by a circular patch. Five tunable geometric parameters can be optimized to achieve the required phase distributions of the reflectarray antenna with independent radiation patterns for each band which is a challenge for single-layer linearly polarized reflectarrays. Besides, the proposed unit cell structure has the ability to meet the demand of dual-polarization applications. A 301-element center-fed reflectarray with an octagon-shape aperture operating at X and Ku bands is designed, manufactured and measured to verify the dual-band performance of the proposed unit cell. The measured results show that the object of achieving different beams at different frequencies is realized with good radiation patterns at both designed frequencies. Besides, the similar radiation patterns for both linear polarizations are also achieved at both bands.

1. INTRODUCTION

Recently, microstrip reflectarray technology has attracted wide attention in many communication and radar applications due to its various advantages [1]. Its low cost, light weight and planar structure make it an alternative high gain antenna to traditional parabolic reflector antenna and phased array antenna. In its basic form, a microstrip reflectarray antenna is composed of an array of radiating elements printed on a flat surface, which are illuminated by a feed. The main principle for designing a reflectarray antenna is to control the phase of the wave reradiated from the radiating elements to form a planar phase front in the desired direction. Several methods have been used as the phase shift mechanism to obtain the desired reflecting phase, such as using element with variable size [2], phase delay line [3], and element rotation [4].

However, there are some drawbacks associated with reflectarray antennas, among which, narrow bandwidth is the most outstanding one [5]. Despite the narrow bandwidth performance, reflectarray antennas are well suited for dual-band demands in some special cases. In recent decades, several techniques have been proposed to achieve dual-band performance for reflectarray antennas, such as single-layer multi-resonance structures [6], multilayer structures [7–10] and frequency selective surface (FSS)-backed structures [11–13].

Furthermore, dual-band reflectarray antennas, which can maintain two different and independent radiation patterns for each operating band, are needed in some applications. In [14], Shaker and Cuhaci proposed an antenna system that is composed of a Ka-band FSS-backed reflectarray and a Ku-band conventional reflector. The FSS-backed reflectarray is designed in such a way that it is transparent in the operating band of the conventional reflector placed under the reflectarray slab. As a result, the hybrid antenna system has easily achieved two different and independent radiation patterns for each operating band. Besides, a new antenna system was reported in [13] for simplicity, in which the

Received 31 January 2017, Accepted 28 March 2017, Scheduled 10 April 2017
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conventional reflector is replaced by a ground-backed reflectarray antenna with lower surface profile and smaller antenna mass. For further improvement, the two reflectarray antennas were substituted by one reflectarray antenna with two layers, each of which can operate independently in its operating band and there was less interference between the two layers [8–10]. Then, a single-layer dual-band circularly polarized reflectarray was proposed, which is composed of an array of dual-resonance structures [15]. In this design, the phase responses at two bands are well isolated to achieve different beams for each band. In consideration of smaller antenna mass and cost, reflectarray antenna with single layer is desirable. However, the reflecting phase of linearly polarized single-layer dual-resonance structure cannot be tuned independently at two different frequencies due to the mutual coupling inside the unit cell. As a result, it is hard to realize mutually independent radiation patterns at each operating band. In our previous work [16], an approach is proposed to design a single-layer dual-band linearly polarized reflectarray antenna with different beams for each band. However, the desired phase distributions cannot be fully achieved, which leaded to phase errors and thus degraded the radiation performances.

In this paper, a novel unit cell, composed of a circular ring and two cross bow-tie structures combined by a circular patch, is proposed to design a single-layer dual-band dual-linear-polarization reflectarray antenna which can maintain two independent radiation patterns in X and Ku bands, respectively. There are five geometrical parameters which can be tuned to compensate the phase shifts at the designed frequencies so as to achieve different radiation patterns simultaneously, which is different from the techniques mentioned in [8] and [15]. Compared with our previous work [16], a wider reflecting phase range for both frequencies is achieved and simultaneously satisfied the designed phase distribution at two designed center frequencies, which can efficiently reduce the phase errors. Besides, the proposed unit structure can satisfy the demand of dual-polarization applications. Finally, a 301-element center-fed reflectarray forming an octagon-shape aperture operating at X and Ku band is designed, manufactured and measured for verification. The measured results have shown better radiation performances at the two designed frequencies.

The paper is organized as follows. Section 2 introduces the novel dual-band single-layer unit structure. In Section 3, we present the design approach as well the measured results. Finally, section 4 presents the conclusion of this study.

2. UNIT CELL DESIGN

Figure 1 depicts the proposed single-layer unit-cell structure working at X and Ku bands for dual linear polarizations. As one can see, the proposed unit cell consists of a circular ring and two cross bow-tie structures, which are orthogonally placed and combined by a circular patch. The unit cell is etched on a 0.81-mm-thickness Rogers 4003 grounded substrate with relative permittivity (ε_r) of 3.38 and loss tangent of 0.0027. The spacing of the unit cell is set to be $L = 8\,\mathrm{mm}$, which is equivalent to 0.27 wavelength at 9 GHz and 0.35 wavelength at 13 GHz. The outer radius of the circular ring R_o is optimized for wide linear phase range at both 9 GHz and 13 GHz, and an optimum value of $R_o = 3.4\,\mathrm{mm}$ is obtained for all unit cells, which also determines the minimum limit of both frequency bands. Thus, abrupt geometry variations for adjacent unit cells in the traditional reflectarrays can be avoided [17] which is good for achieving almost equal mutual coupling between adjacent unit cells, especially for compact reflectarrays.

As shown in Figure 1, there are five tunable geometrical parameters to control the reflecting phases at 9 GHz and 13 GHz:

(1) The inner radius of the circular ring R_i, which is the main parameter used to control the reflecting phase for both bands and make sure that 9 GHz and 13 GHz fall in the range of lower and upper bands respectively.

(2) The gap between the circular ring and the cross bow-tie structure W_i, which affects the mutual coupling between the circular ring and the cross bow-tie structure.

(3) The angle of the cross bow-tie structure Ang, which mainly control the reflecting phase for the upper band.

(4) The radius for the fan section of the cross bow-tie structure r_0, which is represented by parameter M, R_i and W_i via $r_0 = (1 - M/2) \times (R_i - W_i)$. M should be limited in the range of $0 < M < 1$ to avoid structure overlapping and distortion.

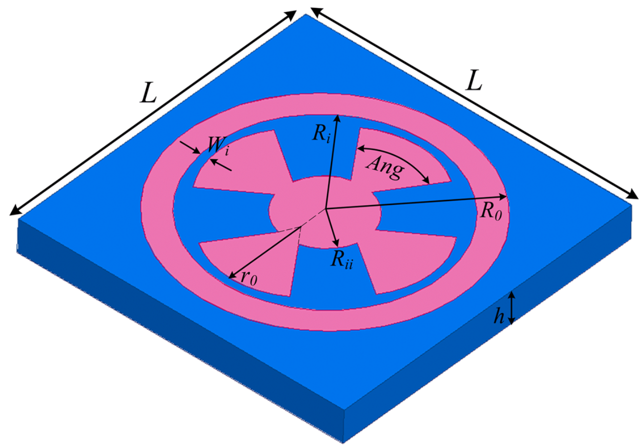

Figure 1. Unit cell structure of the reflectarray antenna.

(5) The radius of the inner circular ring R_{ii}, which connects the cross bow-tie structure and is represented by parameter M, N, R_i and W_i via $R_{ii} = (N/2 + M/2) \times (R_i - W_i)$. N should be limited in the range of $0 < N < 1$ for the same reason above.

To investigate the phase responses of the unit cell with different configurations, an infinite array model is built in HFSS using master-slave boundary condition and Floquet port excitation. Then, the parameter sweeping is carried out by tuning the values of R_i, W_i, Ang, M, and N for the unit cell as given in Table 1.

Table 1. Geometrical parameters and their sweeping ranges.

Parameters	R_i (mm)	W_i (mm)	Ang (deg)	M	N
Ranges	1.6 : 0.1 : 3.2	0.1 : 0.1 : 0.5	30 : 1 : 75	0.1 : 0.1 : 0.6	0.1 : 0.1 : 0.6

Figure 2 shows the influence of these five parameters on the phase response curves at both two bands, from which we can see that the phase response mainly varies with the value of R_i for both 9 GHz and 13 GHz. Parameters W_i, Ang, M and N also have effect on the phase responses at both two frequencies, which means more possible reflecting phases can be realized to simultaneously satisfy the desired reflecting phases for the designed radiation patterns at two bands. Besides, the reflecting phases can be tuned in a wider range for 13 GHz than that for 9 GHz by varying the value of W_i, Ang, M and N. We thus obtain the reflecting phases of the unit cell for all the configurations (R_i, W_i, Ang, M and N). Figure 3 shows the achievable reflecting phases of the proposed unit cell at both bands, and each point (p_1, p_2) in the blue area indicates one of the achievable unit-cell configurations (R_i, W_i, Ang, M and N), where p_1 and p_2 are the corresponding achievable reflecting phases ranging from $-180°$ to $+180°$ at 9 GHz and 13 GHz, respectively. The blue area occupies more than 80% of the entire region, i.e., $-180° \sim +180°$ for both frequencies, which means most of reflecting phases required for the designed reflectarray can be fulfilled by properly adjusting the configuration parameters of R_i, W_i, Ang, M and N for each unit cell of the reflectarray. Compared with our previous work [16], the achievable reflecting phase range is significantly broadened, which helps to achieve better radiation performances when designing a dual-band reflectarray antenna with two mutually independent radiation patterns at each operating band.

Figure 4 shows the effect of polarization of the incident wave on the phase responses for normal incident. As we can see, the phase responses of the unit cell for both TE and TM polarization of incident wave are almost the same, and their difference is less than 0.5°, so good dual-linear-polarization property is demonstrated.

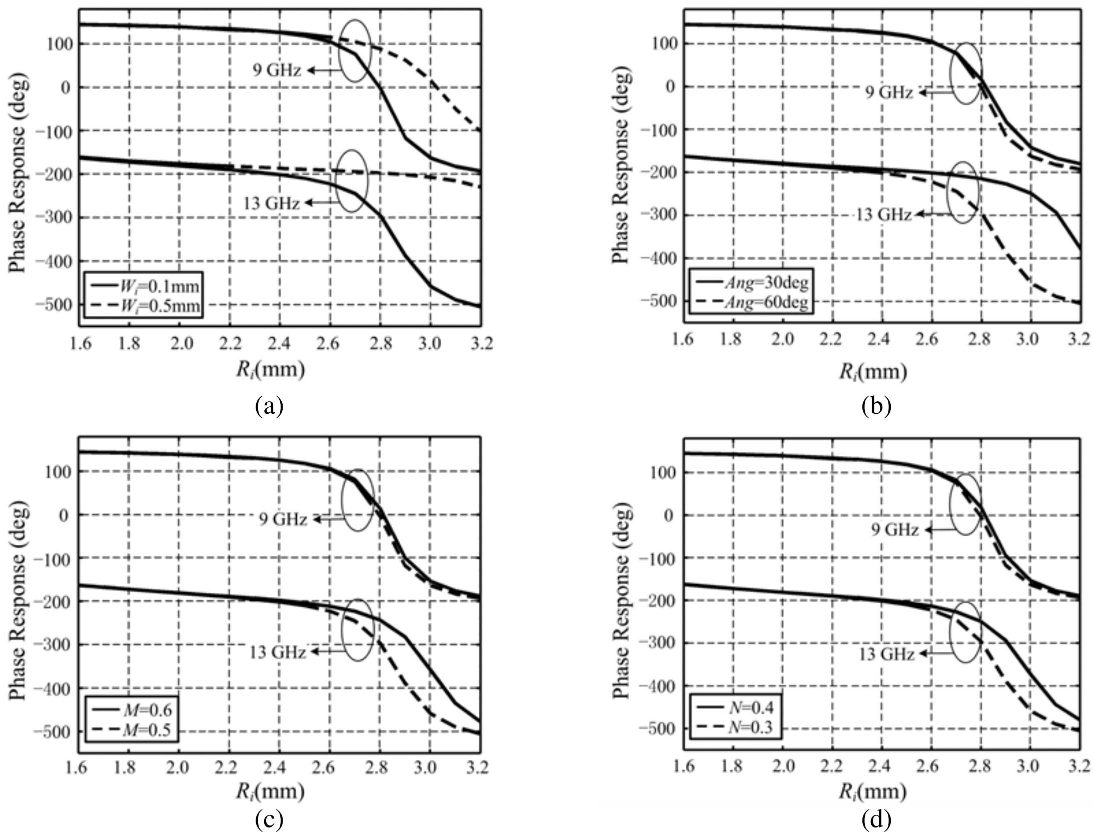

Figure 2. Reflecting phases of the unit cell at 9 GHz and 13 GHz, respect to R_i (a) for different values of W_i ($Ang = 60\,\text{deg}$, $M = 0.5$, $N = 0.3$), (b) for different values of Ang ($W_i = 0.1\,\text{mm}$, $M = 0.5$, $N = 0.3$), (c) for different values of M ($W_i = 0.1\,\text{mm}$, $Ang = 60\,\text{deg}$, $N = 0.3$), (d) for different values of N ($W_i = 0.1\,\text{mm}$, $Ang = 60\,\text{deg}$, $M = 0.5$).

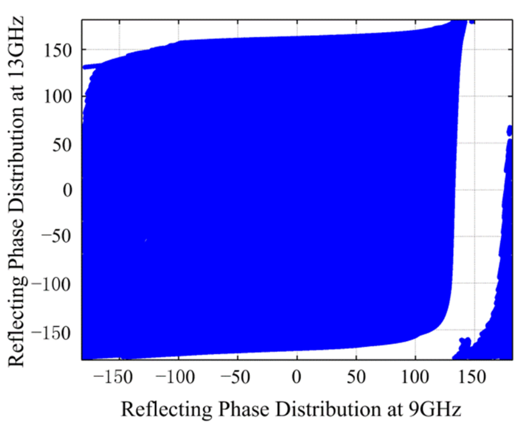

Figure 3. Achievable phase distribution of 9 GHz versus that of 13 GHz.

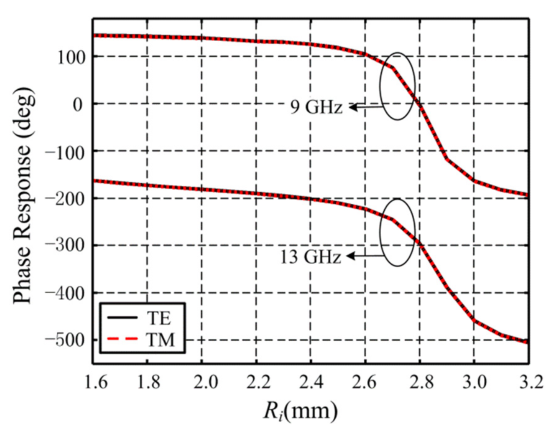

Figure 4. Phase responses for different polarizations of the incident wave for normal incident ($W_i = 0.1\,\text{mm}$, $Ang = 60\,\text{deg}$, $M = 0.5$, $N = 0.3$).

3. REFLECTARRAY DESIGN AND RESULTS

3.1. Design Principle

Generally, the reflecting phases of linearly polarized single-layer dual-resonance structure are hard to tune independently at two different frequencies due to the mutual coupling inside the unit cell. As a result, it is hard to maintain mutually independent radiation patterns at each operating band. Here, we present an approach to solve the problem for our proposed unit cell.

At the first step, the required phase distributions for each unit cell on the reflectarray plane at 9 GHz and 13 GHz are calculated, respectively, according to Eq. (1)

$$\phi_R = k_0 \times (d_i - (x_i \cos\varphi_0 + y_i \sin\varphi_0)\sin\theta_0) \quad (1)$$

where k_0 is the propagation constant in free space, d_i the distance from the phase center of the feed to the position of the ith unit cell on the reflectarray plane (x_i, y_i), and (θ_0, φ_0) the designed main beam radiation direction of the reflectarray antenna. Here, a 301-element center-fed reflectarray with an octagon-shape aperture with diameter of 152 mm operating at X and Ku bands is designed, and the main beam radiation directions are designed to be $(\theta_0, \varphi_0) = (18°, 0°)$ for 9 GHz and $(\theta_0, \varphi_0) = (25°, 180°)$ for 13 GHz, respectively, with the same feed position for both frequencies. In this design, a feed of pyramid horn is chosen and positioned, which is linearly polarized. The designed feed horn can operate at both X and Ku bands and it is positioned 123 mm right above the center of the reflectarray plane with focus-to-diameter (F/D) ratio of 0.8 providing proper illumination with −10 dB tapering on the edge of the reflectarray plane. The schematic diagram of the designed dual-band reflectarray antenna is shown in Figure 5.

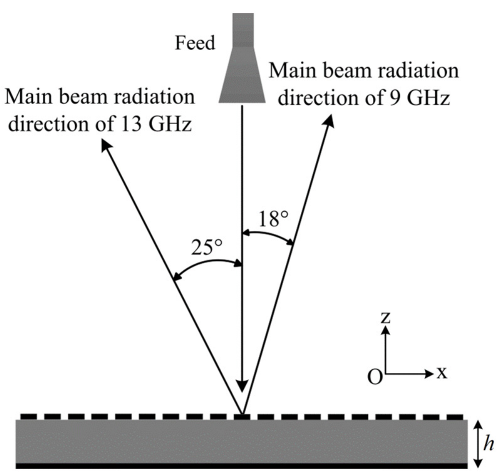

Figure 5. Schematic diagram of the designed reflectarray antenna.

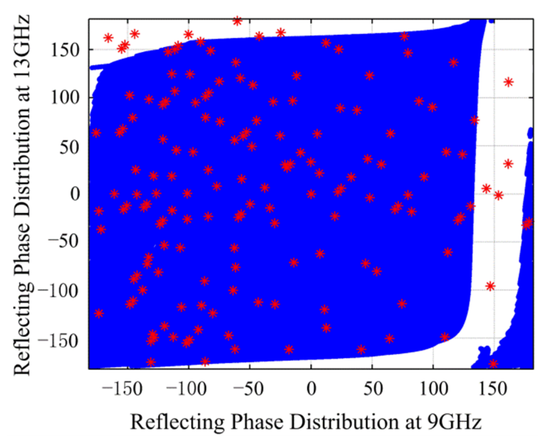

Figure 6. Required reflecting phases for both 9 GHz and 13 GHz.

The required reflecting phases of all the unit cells at both 9 GHz and 13 GHz are shown in Figure 6, and the red star points (p_1, p_2) represent all the required unit cells on the reflectarray plane, where p_1 and p_2 are the corresponding required reflecting phases ranging from −180° to +180° at 9 GHz and 13 GHz, respectively. There are only 160 red star points shown in Figure 6, in consideration of the symmetry about the x-axis. Figure 7 and Figure 8 plot the required phase distributions of the reflectarray aperture at 9 GHz and 13 GHz, respectively.

At the next step, the most appropriate unit cell configurations on the reflectarray aperture are determined through an optimization process. As can be seen from Figure 6, only 8% of red star points are outside the blue area causing phase errors during the design, i.e., those required phase shifts for these unit cells are unachievable simultaneously for both 9 GHz and 13 GHz. Most suitable configurations should be found out among the database shown in Figure 3 to match the desired phase shifts at the

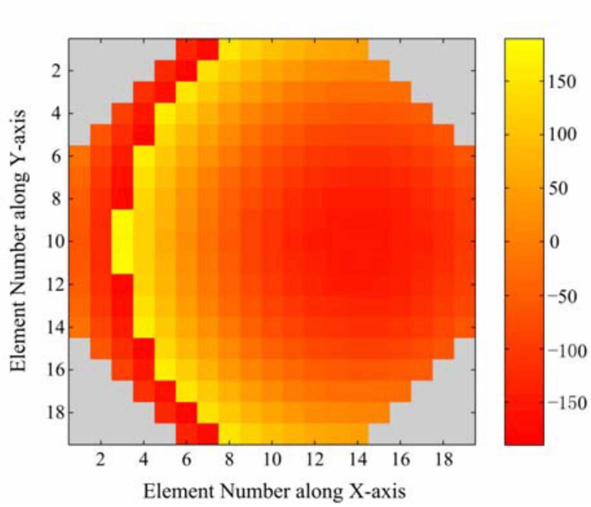

Figure 7. Required phase distribution of the designed reflectarray aperture at 9 GHz.

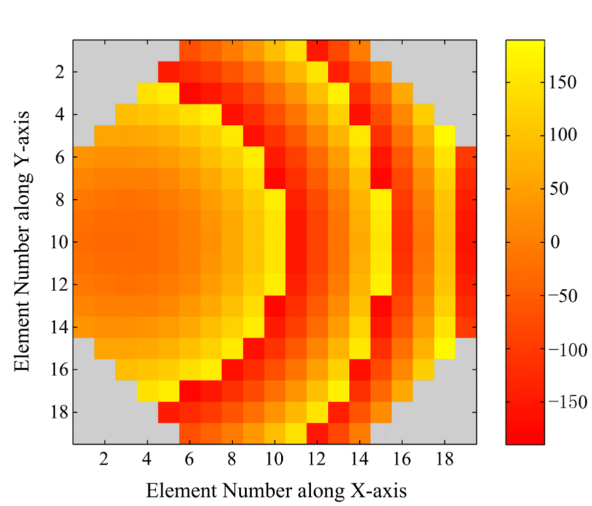

Figure 8. Required phase distribution of the designed reflectarray aperture at 13 GHz.

upper and lower frequencies concurrently [18]. Due to the inevitable phase errors, the candidates that produce the best phase shifts at both frequencies are selected by minimizing the following error function:

$$e(m,n) = \sum_{i=l,u} \left| \Phi^{desired}(f_i)(m,n) - \Phi^{achieved}(f_i)(m,n) \right| \tag{2}$$

where (m,n) represents the number of the unit cell in two-dimension of the reflectarray surface; $\Phi^{achieved}$ (f_u) and $\Phi^{achieved}$ (f_l) are the achievable phase shifts of the upper and lower frequencies; $\Phi^{desired}$ (f_u) and $\Phi^{desired}$ (f_l) are the calculated phase shifts of the upper and lower frequencies. In practice, the error function introduced in Eq. (2) is tested for all unit cell configurations as shown in Figure 3 and the unit cell configurations with lowest errors are chosen as the optimum elements. A simple MATLAB code is developed to find the optimum elements for all the unit cells on the reflectarray plane.

3.2. Results

Finally, the center-fed dual-band reflectarray antenna working at X and Ku bands is successfully designed and fabricated, which aims to achieve mutually independent radiation patterns for each band. The fabricated reflectarray is octagon-shaped with diameter of 152 mm and 301 elements, as shown in Figure 9, where the fiberglass is utilized to support the feed horn and the relfectarray plane in order to decrease blocking effect in the measurement system.

The fabricated reflectarray antenna is measured in an anechoic chamber. In order to investigate the effect of the incident polarization, the antenna is tested in both X (horizontal) and Y (vertical) polarizations by rotating the feed horn. The measured E-plane co-polarization normalized radiation patterns for X and Y polarization incident wave at designed frequencies of 9 GHz and 13 GHz are plotted in Figure 10 and Figure 11, respectively. As we can see that, the main beam directions are around (18°, 0°) for 9 GHz and (25°, 180°) for 13 GHz with a deviation less than 0.5°, which agreed well with our design goal. Besides, the radiation patterns of X and Y polarizations have similar performances. The measured gains of the designed dual-band reflectarray antenna are 18.9 dBi at 9 GHz and 23.9 dBi at 13 GHz for X polarization, and 18.6 dBi at 9 GHz and 23.76 dBi at 13 GHz for Y polarization. At 9 GHz, the E-plane SLL (side lobe level) is measured below −14.6 dB for both X and Y polarizations while at 13 GHz, the E-plane SLL is below −19.2 dB for X polarization and −18.6 dB for Y polarization. Our proposed dual-band unit cell and design approach for a dual-band dual-linear-polarization reflectarray antenna with different beams at X and Ku bands are thus validated with better performances than our previous work obtained [16].

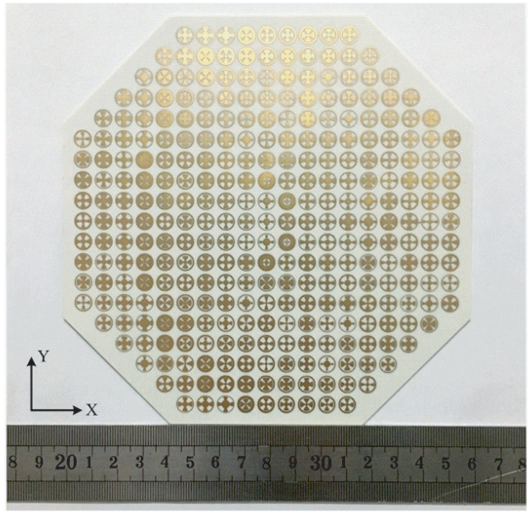

Figure 9. Prototype of the fabricated reflectarray.

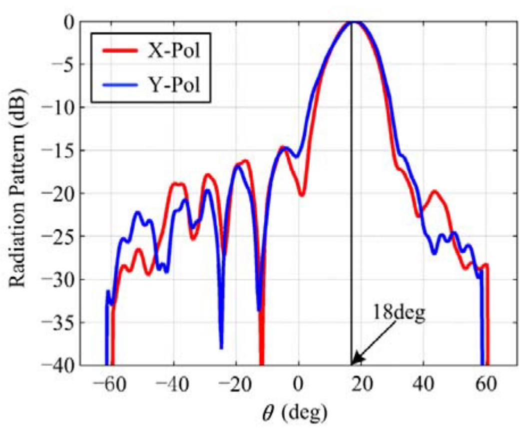

Figure 10. Measured co-polar E-plane radiation patterns for X and Y polarizations at 9 GHz.

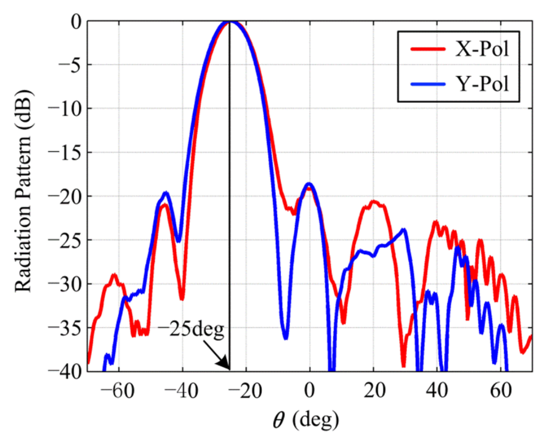

Figure 11. Measured co-polar E-plane radiation patterns for X and Y polarizations at 13 GHz.

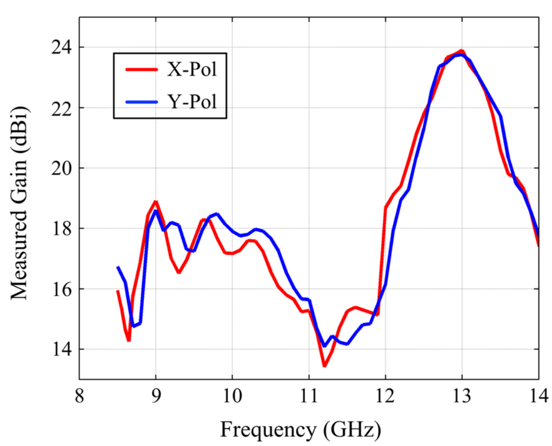

Figure 12. Measured gains versus frequencies.

The measured gains of both X and Ku bands versus frequencies for both X and Y polarization incident waves are presented in Figure 12 showing a similar performance for X and Y polarization incident waves, i.e., the dual-linear polarization property of the designed dual-band reflectarray antenna is demonstrated.

4. CONCLUSION

This paper has presented a novel single-layer unit cell structure for designing a dual-band dual-linear-polarization reflectarray antenna with different beams at X and Ku bands. The unit cell structure is composed of a circular ring and two cross bow-tie structures combined by a circular patch. The reflecting phase distributions at both bands are achieved over 80% of the entire region ($-180° \sim +180°$ for both frequencies), which means the dual-band property is posed. Besides, our proposed unit cell can be used for both orthogonal linear polarizations. A 301-element center-fed reflectarray with an octagon-shape aperture operating at X and Ku bands is designed, manufactured and measured to show the dual-band performances of the proposed unit cell. The measured results show that our target for realizing different beams at different frequencies is achieved. The measured main beam directions are around (18°, 0°) for 9 GHz and (25°, 180°) for 13 GHz, respectively, with a deviation less than 0.5° as expected. Besides, good radiation performances at both designed frequencies are also obtained with similar radiation patterns for both linear polarizations achieved at both bands.

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