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Design of a Wideband Single-Layer Reflectarray Antenna Using Slotted Rectangular Patch With Concave Arms

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ABSTRACT A novel single-layer slotted rectangular patch with concave arms is proposed for wideband reflectarrays. The broadband characteristic is realized by combining both bandwidth enhancement techniques, i.e. using multi-resonant element and slotted rectangular patch element. By placing a pair of concave arms beside the slotted rectangular patch, additional resonance is introduced for an improved phase range and linearity. The element is optimized for a rather linear phase range covering 360°, resulting in a broadband behavior. Key geometrical parameters are studied to apprehend its working principle. Employing the novel unit cell, a reflectarray with 25° offset-fed, and constituting 23×23 elements with 0.3λ element periodicity at 10 GHz, is simulated and measured. Good agreement is obtained between the simulation and the measurement. The proposed reflectarray features a wide measured 32% 1-dB gain bandwidth and a maximum aperture efficiency of 65%. Furthermore, the measured side-lobe and cross-polarization levels are 20 dB and 32 dB at 10 GHz, respectively.

INDEX TERMS Slotted rectangular patch, single-layer, wideband, reflectarray antenna, subwavelength, concave arms.

I. INTRODUCTION

Reflectarray antenna has appealing features of low-mass, low-cost and simple fabrication and deployment [1]–[3]. Despite of the narrowband performance, it is found that for small or moderate size reflectarrays, this shortcoming can be remedied by enhancing the element behavior [4]. A great deal of research efforts has been therefore made to design wideband elements, such as using phase delay lines [5], [6], four arm spiral element [7], fractal element [8], true-time delay lines [9], and subwavelength element [10]. Furthermore, the bandwidth can also be enhanced by employing multi-resonant element [11], [12]. By adopting multi-resonant structure, additional resonances are introduced and improved phase linearity and range can be realized.

On the other hand, it is interestingly found that a rectangular patch etched with slots is recently reported for wideband reflectarrays [13]. By changing the lengths of the slots etched within the rectangular patch, a linear phase curve is obtained, leading to a wide measured 1-dB gain bandwidth of 24%. However, it is noticed that although the phase slope is linear, the phase range is about only 330°, less than 360° as required. Therefore, it would be interesting to combine the two bandwidth improvement approaches, i.e. multi-resonant structure and slotted rectangular patch structure, for an increased phase range as well as a broadened bandwidth.

In this paper, a novel element comprising single-layer slotted rectangular patch with concave arms is presented for wideband reflectarray antennas. The concave arms, which are also used in a miniaturized ultrawideband antenna design [14], are introduced here to produce an extra resonance for an increased phase response and enhanced bandwidth. By placing a pair of concave arms beside the slotted rectangular patch and optimizing the critical design parameters, the element can offer a rather linear phase response ranging 360°. The proposed element combines the advantages of both multi-resonant element designs in [11], [12] and slotted rectangular patch design in [13], therefore demonstrating a superior performance. A 25° offset-fed reflectarray consisting of 529 proposed unit cells with periodical spacing

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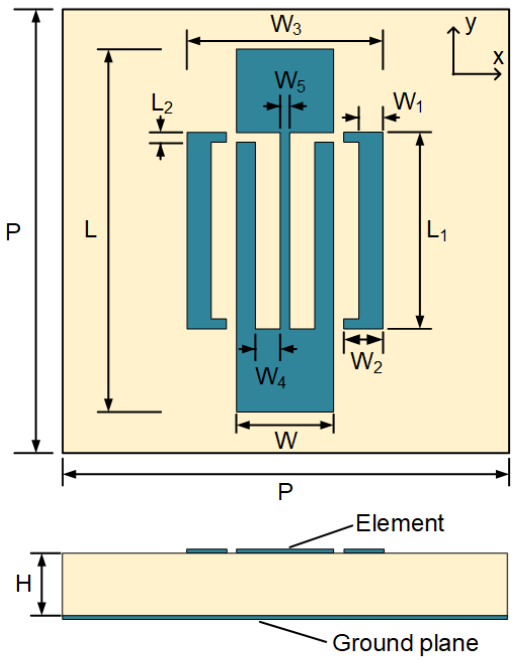

FIGURE 1. Configuration of the unit cell.

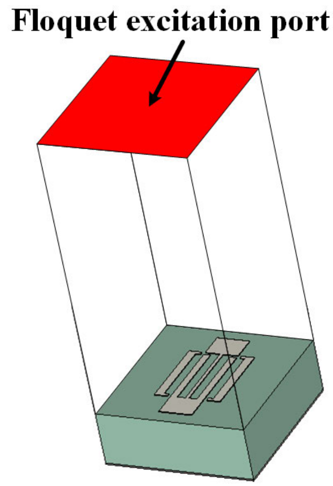

FIGURE 2. Simulation setup of the unit cell.

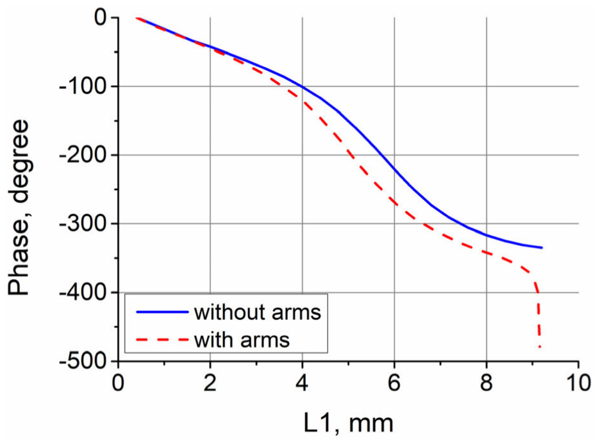

FIGURE 3. Reflected phase curves against the length L_1 at 10 GHz for the slotted patch with and without concave arms.

of 0.3λ at 10 GHz is simulated and developed. The experiment agrees the simulation well and a wide 32% 1-dB gain bandwidth with a maximum aperture efficiency of 65% is obtained. In addition, side-lobe and cross polarization levels are also good, which are in the ranges of 20 dB and 32 dB at 10 GHz, respectively. Compared with recently reported works, this design exhibits a greatly improved performance.

II. DESIGN AND ANALYSIS OF UNIT CELL

Fig. 1 illustrates the configuration of the proposed unit cell. A slotted rectangular patch and a pair of concave arms are printed on the upper side of a F4BM substrate whose thickness and dielectric constant are 3.175 mm and 2.2, respectively, while a ground is printed underneath the substrate. The design features a single-layer structure and no extra air layers are required. The elements have a periodicity of P in x- and y-directions, respectively. A pair of concave arms are placed beside the slotted patch and their length is proportional to the length L_1 of the slots embedded within the rectangular patch, while the variation of phase is obtained by changing the length L_1.

The structure is designed at 10 GHz and simulated by CST Microwave Studio, as shown in Fig. 2. The Floquet port excitation and periodical boundaries are adopted to consider the inter-elemental coupling. Under a normal plane wave incidence, the unit cell is simulated in a rectangular waveguide where the front and back surfaces are set as perfect electrical conducting walls and the left and right surfaces are set as perfect magnetic conducting walls.

As a starting point, the unit cell with a grid spacing of P =11 mm and slotted patch length L =8 mm, is initially simulated and analyzed to comprehend the operating mechanism of the proposed structure. Fig. 3 illustrates the reflected phases of the slotted patch with and without concave arms. For a single slotted patch, the phase swing is only about 330°, less than 360° as required by typical reflectarray element designs. By placing a pair of concave arms beside the slotted patch, a ''knee'' shaped curve with an extended phase span is observed. This is owing to the additional resonance introduced by the concave arms and the interaction between the slotted patch and the concave arms. Furthermore, the concave arms also provide additional degree of freedom to optimize the element performance, such as phase span and linearity, for a wideband operation. However, it is noticed in Fig. 3 that although the phase range is increased by introducing the concave arms, the linearity of the phase is poor. Therefore, the unit cell should be optimized for a linear phase response covering 360°.

It is seen in simulations that while several geometric parameters affect the element performance, the unit cell periodicity P, the length of slotted patch L, and the proportional

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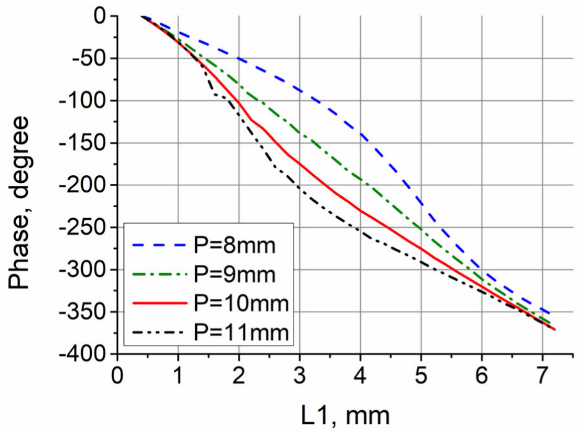


FIGURE 4. Reflected phase curves against the length L_1 at 10 GHz for different periodicity P of the element.

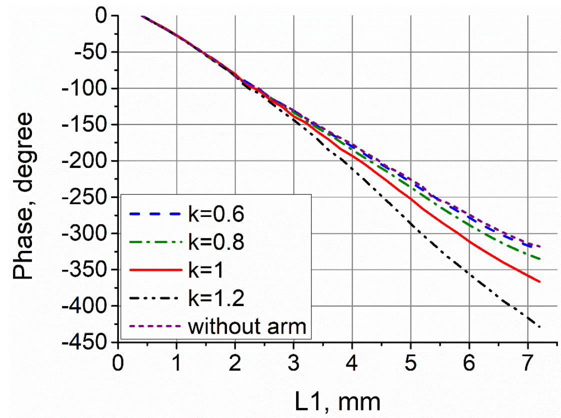


FIGURE 6. Reflected phase curves against the length L_1 at 10 GHz for different ratio k between the lengths of concave arms and the lengths of slots.

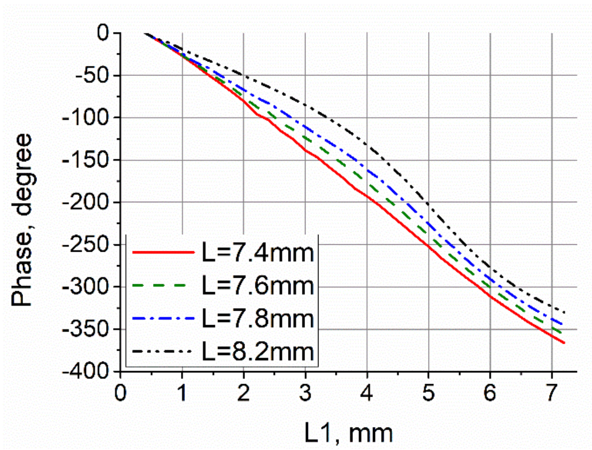


FIGURE 5. Reflected phase curves against the length L_1 at 10 GHz for different L of the element.

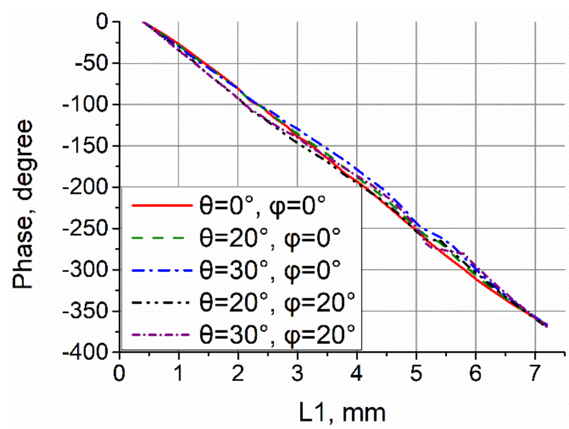


FIGURE 7. Reflected phases of the unit cell for various incident wave angles.

ratio k between the lengths of concave arms and the lengths of interior slots within the patch, present the most influence on the reflected phase. Fig. 4 shows the effect of unit cell grid spacing P on the reflected phases. As previously mentioned, the element linearity can be enhanced by using subwavelength elements [10]. It is noticed in Fig. 4 that by reducing the periodicity P from 11 mm to 9 mm, the phase linearity is improved whereas the phase range is hardly changed. However, when the periodicity P decreases to 8 mm, the phase linearity deteriorates and the phase span is also reduced. Therefore, the unit cell periodicity of 9 mm, i.e. 0.3λ at 10 GHz, is chosen for a satisfactory behavior.

Fig. 5 exhibits the effect of slotted patch length L on the reflected phases. As can be observed in Fig. 5, when L decreases, the linearity of reflection phase curve is improved and the phase range is also increased. A linear phase curve covering 360° is achieved with an optimal L value of 7.4 mm.

Fig. 6 plots the reflected phase with different proportional ratio k between the lengths of concave arms and the lengths of slots. It is evident that the reflection phase range varies with different ratio k. With the increase of k, the phase span also increases. Note that although the curve of k =1.2 features a wider phase span, its calculated linearity is inferior compared to the curve of k =1. Therefore, taking both phase linearity and range into account, i.e. the phase slope as linear and smooth as possible, and the phase range with a 360° coverage, k =1 is chosen as an optimal value. In this case, concave arms have an equal length with slots.

The impact of various incident wave angles on reflected phase is also analyzed, as depicted in Fig. 7. It is apparent that the variation of reflection phases is negligible for the incident wave angle up to 30°.

Table 1 shows the proposed unit cell dimensions and Fig. 8 plots the reflected magnitude and phase of the unit cell versus L_1 with final geometric dimensions at 10 GHz. It is evident that a rather linear phase ranging 360° with a high reflected magnitude near 0 dB is obtained.

The unit cell reflected phases against L_1 for various frequencies are illustrated in Fig. 9. It is noticed that the phases feature a linear response and less sensitive with frequency variation, indicating a wideband operation.

TABLE 1. Geometric parameters of the unit cell.

Parameters	Value
P	9 mm
L	7.4 mm
L_2	0.2 mm
W	2 mm
W_1	0.5 mm
W_2	0.8 mm
W_3	4 mm
W_4	0.5 mm
W_5	0.2 mm

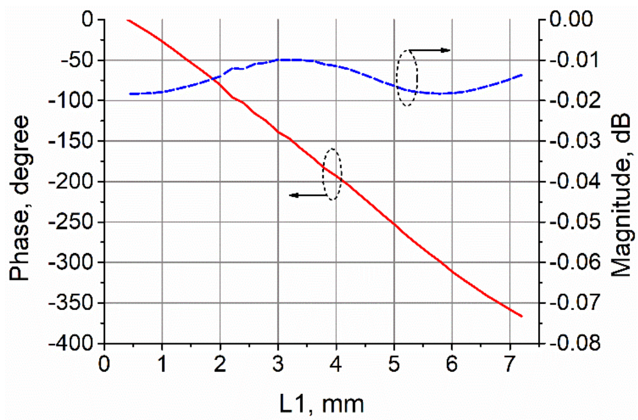


FIGURE 8. Reflected magnitude and phase against L_1 of the unit cell with final geometric dimensions at 10 GHz.

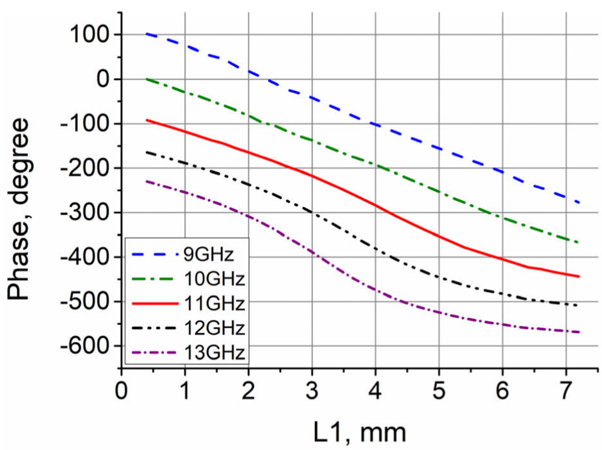


FIGURE 9. Reflected phases against L_1 of the unit cell for various frequencies.

III. REFLECTARRAY IMPLEMENTATION AND RSULTS

A pyramidal horn antenna is employed to illuminate the reflectarray with an offset angle of 25° and the vertical distance between the horn and the array is set to 148 mm for a satisfactory aperture efficiency. In this study, an offset feed of 25° is used to decrease the blockage effect and a specular reflection is also utilized to produce a main beam at $\theta_b = 25°$, $\varphi_b = 0°$. The proposed reflectarray contains 529 elements and the elements are mirror symmetrically arranged against the x-direction for the cross polarization reduction. The entire reflectarray system including the feed horn and the reflectarray aperture was modelled and simulated by CST Microwave Studio where the mutual coupling effects have been taken into account by the full-wave simulation.

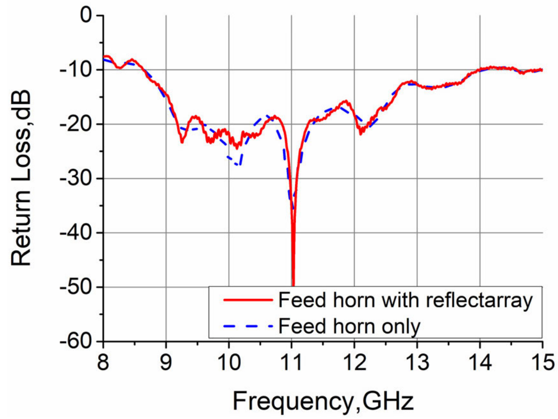
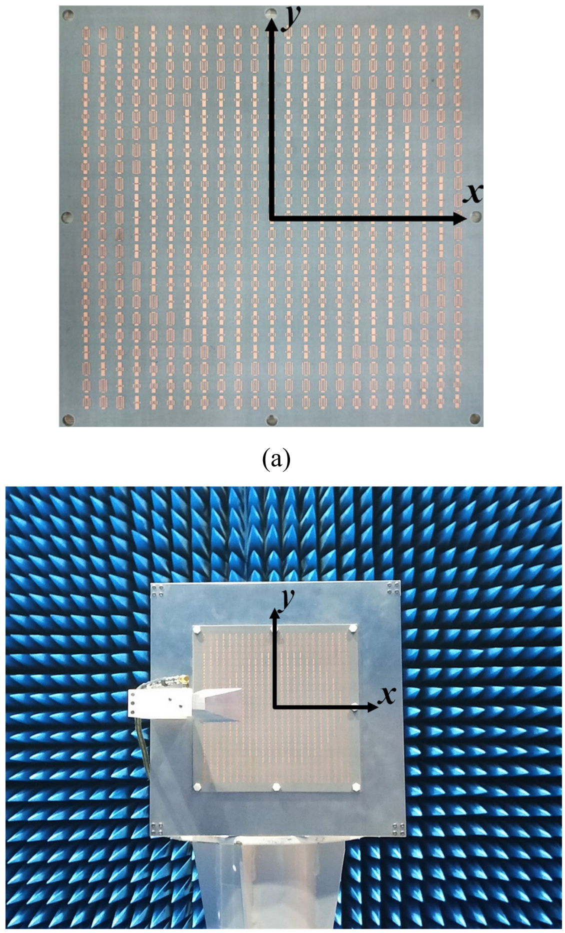


FIGURE 10. Return losses of the single feed horn and the feed horn with reflectarray.



(a)

(b)

FIGURE 11. (a) Proposed reflectarray prototype, and (b) measurement setup.

Fig. 10 plots the measured return losses of the single feed horn and the feed horn with reflectarray aperture. It is shown

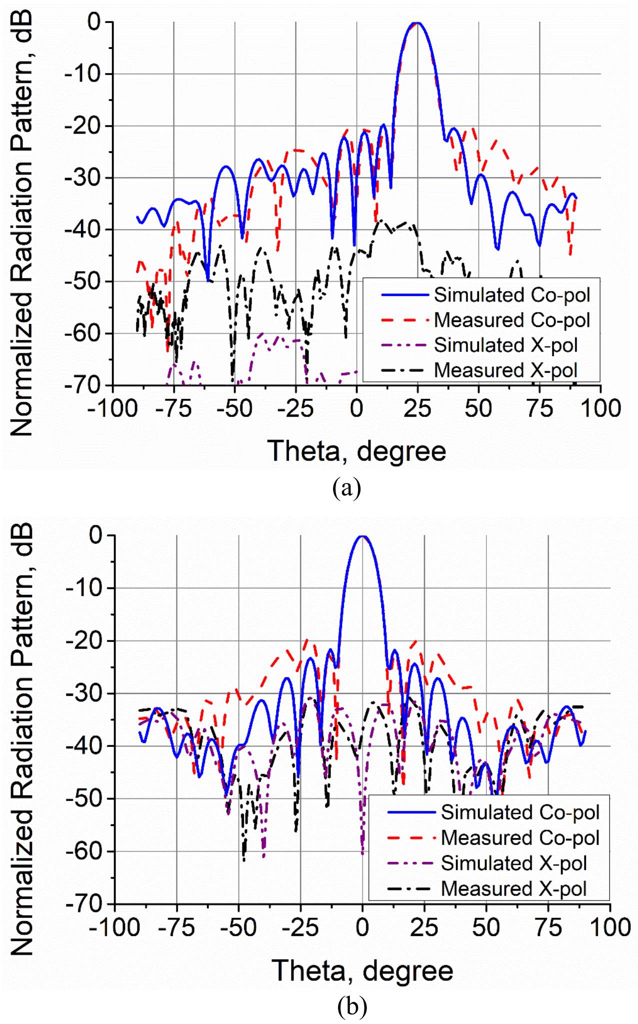


FIGURE 12. Simulated and measured normalized radiation patterns of the antenna at 10 GHz. (a) *E*-plane and (b) *H*-plane.

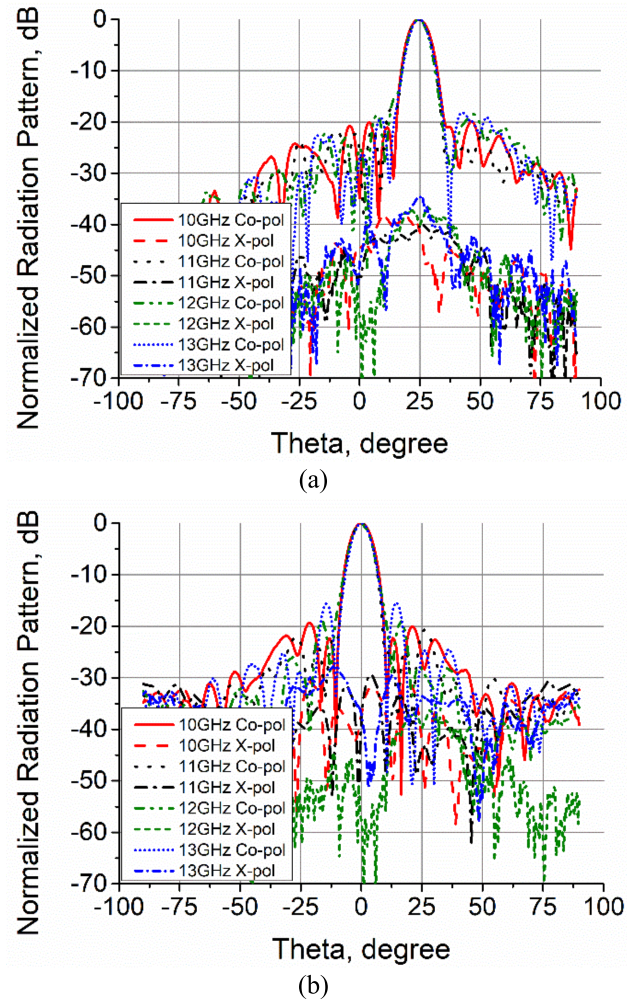


FIGURE 13. Measured patterns of the antenna at different frequencies in (a) *E*-plane and (b) *H*-plane.

that the two curves are nearly overlapped to each other and a good matching is obtained across the band.

Fig. 11 (a) displays the prototype of the array and the antenna radiation properties such as gain and patterns were tested in a far-field range inside an anechoic chamber, as shown in Fig. 11 (b).

Fig. 12 displays the simulated and measured normalized *E*- and *H*-plane radiation patterns of the antenna at 10 GHz. Note that the *E*-plane is *x*-*z* plane and the *H*-plane is the plane that forms a 25° angle with *y*-*z* plane. It is noticed that the simulations and measurements agree reasonably well. The slight discrepancies are owing to fabrication tolerances and measurement errors. The main lobe shows up at 25° as designed. The measured side lobe levels in *E*- and *H*-planes are 20 dB down from the maximum of the main lobe. It is also seen that the measured cross polarization levels are below 32 dB near the main beam in both the *E*- and *H*- planes.

Fig. 13 presents the measured radiation patterns at different frequencies in both *E*- and *H*-planes, respectively. It is seen that the patterns in *E*-plane are constant across the band with the main lobes occurring at 25°. In the *H*-plane, the radiation patterns also remain generally stable for various frequencies. With the increase of frequency, the patterns become slightly degraded with both side-lobe level and cross polarization level elevated. Generally speaking, a satisfactory performance in terms of main lobe directions, side-lobe and cross polarization levels, is realized.

The simulated and measured gain and aperture efficiency of the reflectarray are shown in Fig. 14. It is seen that the measured results and simulated results again agree reasonably well. The measured gain is 25.7 dBi at 10 GHz, equivalent to an aperture efficiency of 65%. In addition, the proposed reflectarray exhibits a measured 1-dB gain bandwidth of 32%, which spans from 10.5 GHz to 14.1 GHz, demonstrating its broadband operation. Note that the center frequency of the 1-dB gain bandwidth is shifted from designed 10 GHz to about 11.3 GHz. This is mostly owing to the antenna's electrical size increases with the rise of frequency. Furthermore, the feed horn phase center errors,

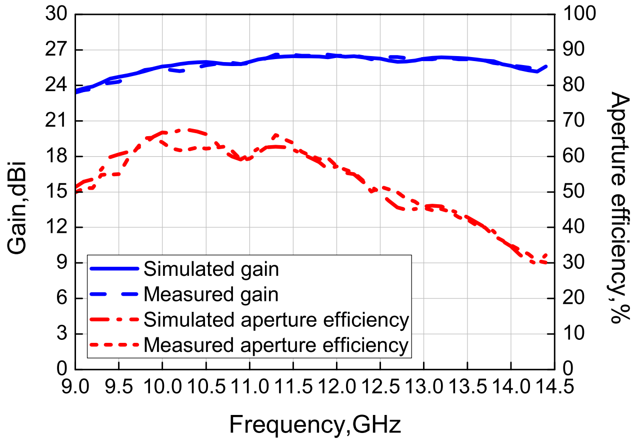


FIGURE 14. Simulated and measured gain and aperture efficiency of the reflectarray.

TABLE 2. Comparison of proposed antenna behavior with various reported works.

Ref.	[7]	[11]	[12]	[13]	**Proposed**
Center Frequency (GHz)	13.58	13.5	15	10	**10**
Gain Bandwidth (%)	28.7 (1-dB)	17 (1-dB)	33.52 (1-dB)	23 (1-dB)	**32 (1-dB)**
Additional Air Layer	No	Yes	No	No	**No**
Cross-Pol Level (dB)	<-27.5	<-27	<-27.4	< -26	**< -32**
Sidelobe Level (dB)	<-20	<-25	<-13.4	<-19	**<-20**
Aperture Efficiency (%)	60.2	66	64.1	67	**65**

misalignment errors, manufacture tolerances, and imperfect measurement surroundings may also result in the deviation.

A comparison of the proposed reflectarray with various reported designs is shown in Table 2. It is noticed that compared with multi-resonant element designs in [11], [12], and slotted rectangular patch design in [13], the proposed design features a superior or comparable behavior in terms of aperture efficiency, side-lobe / cross polarization level, and gain bandwidth. This performance improvement is the result of combining the both bandwidth enhancement approaches.

IV. CONCLUSION

A novel single-layer slotted rectangular patch with concave arms is proposed for wideband reflectarrays. By introducing a pair of concave arms beside the slotted rectangular patch, additional resonance is generated for an improved phase range and linearity. The variation of phase is obtained by changing the lengths of the slots embedded within the patch and the element can achieve a rather linear reflected phase response covering 360°. The designed reflectarray is for a 25° off-broadside radiation at 10 GHz. The measured data exhibits that a wide 1-dB gain bandwidth of 32% with a peak aperture efficiency of 65% is realized. In addition, the side-lobe and cross polarization levels are also satisfactory, which are 20 dB and 32 dB at 10 GHz, respectively.

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