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Broadband and High Efficiency Single-Layer Reflectarray Using Circular Ring Attached Two Sets of Phase-Delay Lines

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Abstract—A new single-layer element structure for broadband operation is presented. The element is composed of a circular ring attached two sets of phase-delay lines with the opposite direction of rotation. The demission of circular ring is fixed, and about 460° reflection phase range is achieved by varying the length of the phase-delay lines. Using the proposed element, a 381-element single-layer linearly polarized reflectarray is designed, fabricated and measured. A gain of 27.5 dB is measured at 13.58 GHz with 3-dB beamwidth of about 6.8°, and the corresponding aperture efficiency is 57.3%. Good radiation performances are also achieved at other frequencies. Measured results show 1.5-dB and 3-dB gain bandwidth of 47.8% (13.58–20.08 GHz) and 64% (12.08–20.78 GHz) with the center frequency of 13.58 GHz respectively, which demonstrates excellent broadband performance. Besides, high aperture efficiencies (more than 50%) are achieved in a wide frequency range (12.08–17.08 GHz). Low cross polarization and sidelobe levels are also achieved in the frequency band.

1. INTRODUCTION

Reflectarray antenna is put forward as a substitute for the conventional parabolic reflector antenna for its merits, such as flatness, easy fabrication, low cost, lightweight and beam-scanning capability [1]. However, the greatest shortcoming of a reflectarray is the narrow bandwidth, which is mainly caused by the narrow bandwidth of elements. Many approaches have been introduced to enhance the bandwidth of reflectarray in recent years.

Multilayer structure is an effective way for improving the bandwidth of reflectarray [2]. However, the extra manufacture complexity and increased cost introduced by the configuration cannot be neglected. Single-layer multi-resonant elements structure is frequently used for bandwidth expanding [3–5]. A combination of cross and rectangle loops (triple-resonant structure) with thick substrate was proposed to achieve linear reflection phase curve and a broadband single-layer reflectarray using the element was designed to achieve 1-dB gain bandwidth of 24% [3]. However, thick substrate will increase the weight and cost of antenna. With the exception of multilayer and multi-resonant structure, using true-time delay (TTD) lines [6] and subwavelength technology [7, 8] also can broaden the bandwidth of reflectarray. A novel double square meander-line rings element with subwavelength lattice period ($\lambda/5$) was proposed in [8]. An X-band reflectarray was developed to verify the validity of the element and the measured results showed the 1.5-dB and 3-dB gain bandwidths are 18% and 32% respectively. However, for most reflectarray elements, smaller element lattice period will lead to decreased reflection phase range and extend the reflection phase errors. Using element with phase-delay lines is another way to achieve broadband performance of reflectarray [9, 12]. In [9], a single-layer disk element with phase-delay lines is proposed. A reflectarray is presented using the element and 3-dB gain bandwidth

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of 18% was obtained. However, due to the non-self symmetry of the element, the cross polarization performance of the reflectarray is very poor. In [10], a new way for arrangement of phase-delay elements was proposed to reduce the cross polarization levels. However, the bandwidth performance of the above reflectarray with phase-delay line element is still limited.

In this paper, a novel single-layer element structure is presented to be used as reflectarray cell for wideband operation. The element is composed of a circular ring loaded by two sets of phase-delay lines. By varying the length of the phase-delay lines, large range linear reflection phase curves with less steep have been obtained. Based on the proposed element, a single-layer offset-fed reflectarray with octagonal aperture is fabricated and tested. Measured gain of 27.5 dB with aperture efficiency of 57.3% is obtained at the center frequency of 13.58 GHz. The frequency range of measured gain larger than 26.5 dB, which is 1 dB smaller than the gain at center frequency, is from 12.58 GHz to 20.58 GHz. The 1.5-dB and 3-dB gain bandwidths are about 47.8% (13.58–20.08 GHz) and 64% (12.08–20.78 GHz) with the center frequency at 13.58 GHz respectively. The aperture efficiencies of the reflectarray are larger than 50% over a wide frequency range.

2. ELEMENT DESIGN AND PHASE CHARACTERISTICS

The structure of the proposed element is shown in Fig. 1. As we can see, the element is composed of a circular ring attached by two sets of phase-delay lines with two opposite direction of rotation. A dielectric material with relative permittivity (ε_r) of 2.25 and thickness (h_1) of 1 mm is used to sustain the element. The element lattice period (L) is 10 mm, which corresponds to $0.45\lambda_0$ (λ_0 is the wavelength in the free space) at the center frequency of 13.58 GHz. Between the dielectric substrate and the ground plane, a 2 mm-thick air layer (h_2) is added in order to smooth the reflection phase curve.

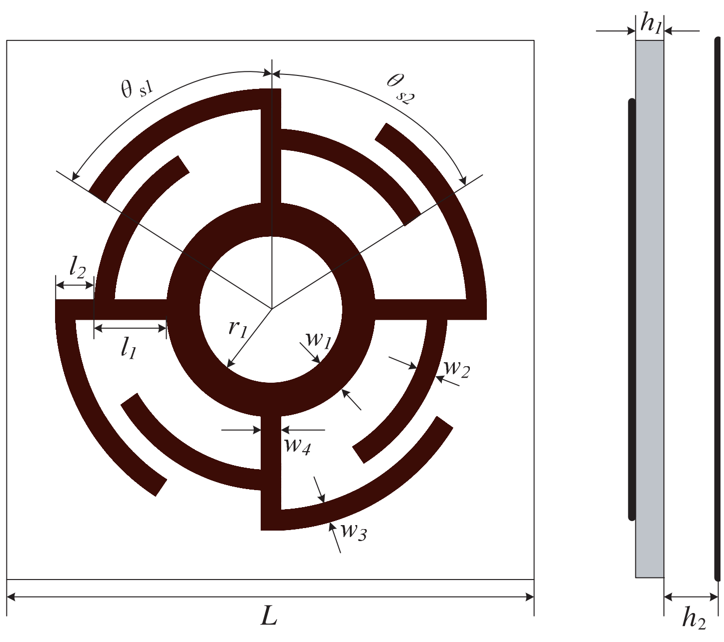


Figure 1. Structure of the proposed element.

To achieve the reflection phase curves of the proposed element, the commercial software of HFSS is used to simulate the infinite array approach. The inner radius (r_1) and width (w_1) of the circular ring are optimized to obtain linear reflection phase curves. The values of l_1, l_2, w_2, w_3 and w_4 are optimized to achieve good matching between the phase-delay lines and the circular ring. The reflection phase of the element can be controlled by varying the length of the phase-delay lines, and the length of the phase-delay lines change with the value of the θ_{s1} and θ_{s2}. For simplicity, θ_{s1} and θ_{s2} are set to be the same value of θ_s, which ranges from 2° to 85°. Table 1 depicts the final optimized parameters of the element.

Table 1. Element geometry.

Parameter	Value	Parameter	Value
$\theta_{\mathbf{s1}}$	θ_s	$\mathbf{w_1}$	0.5 mm
$\theta_{\mathbf{s2}}$	θ_s	$\mathbf{w_2}$	0.3 mm
L	10 mm	$\mathbf{w_3}$	0.3 mm
$\mathbf{r_1}$	1.1 mm	$\mathbf{w_4}$	0.3 mm
$\mathbf{l_1}$	1.1 mm	$\mathbf{h_1}$	1 mm
$\mathbf{l_2}$	0.6 mm	$\mathbf{h_2}$	2 mm

Different elements only with inner phase-delay lines, only with outer phase-delay lines and with inner and outer phase-delay lines are studied in Fig. 2, and their reflection phase curves are shown. The results show that element with inner and outer phase-delay lines has larger range and better linear reflection phase curve, which indicates greater potential for broadband operation. Effects of different incident angles on reflection phase and magnitude of the element in TE mode are presented in Fig. 3. One can draw from the figure that the reflection phase and magnitude curves are insensitive to the incident angle. Besides, the reflection magnitude for different incident angles is larger than -0.05 dB.

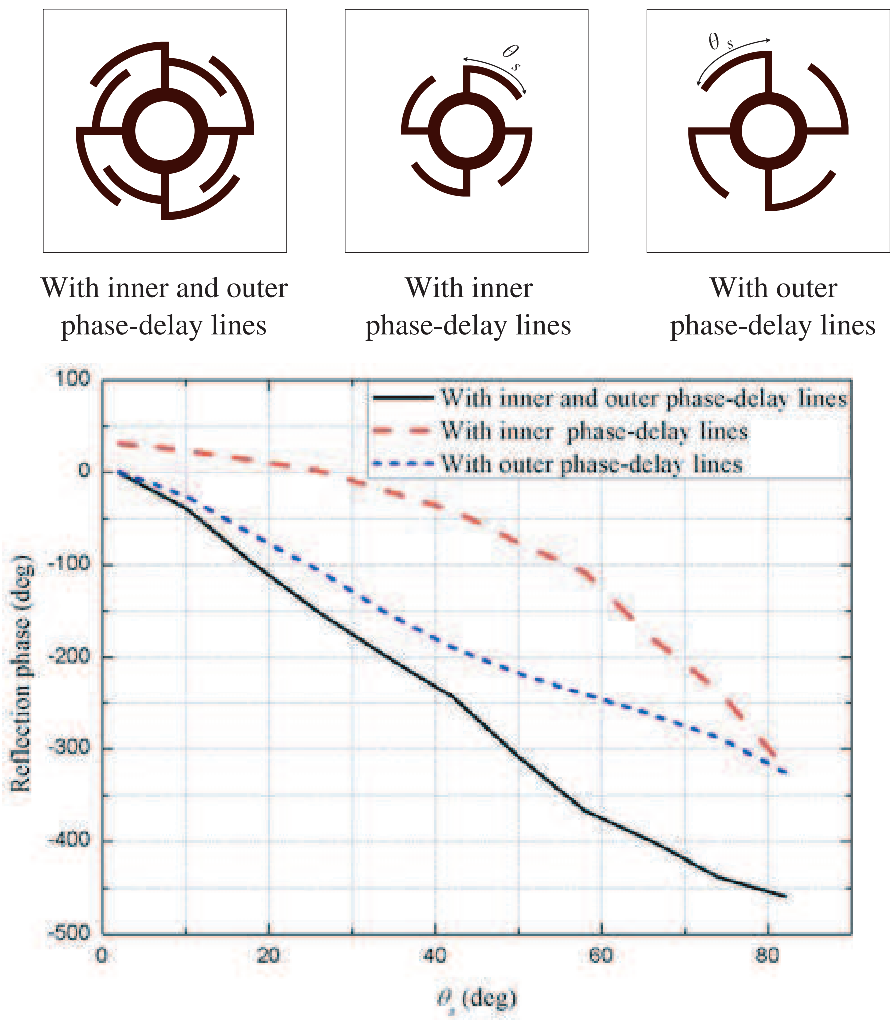


Figure 2. Reflection phase curves for different elements.

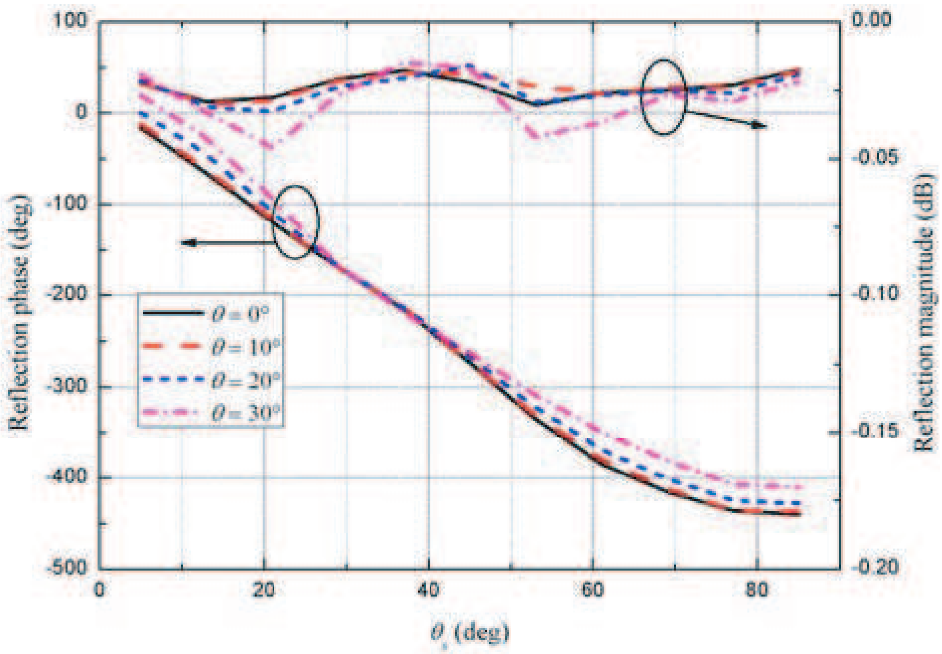


Figure 3. Reflection phase and magnitude versus the length of phase-delay lines for different incident angles (TE mode).

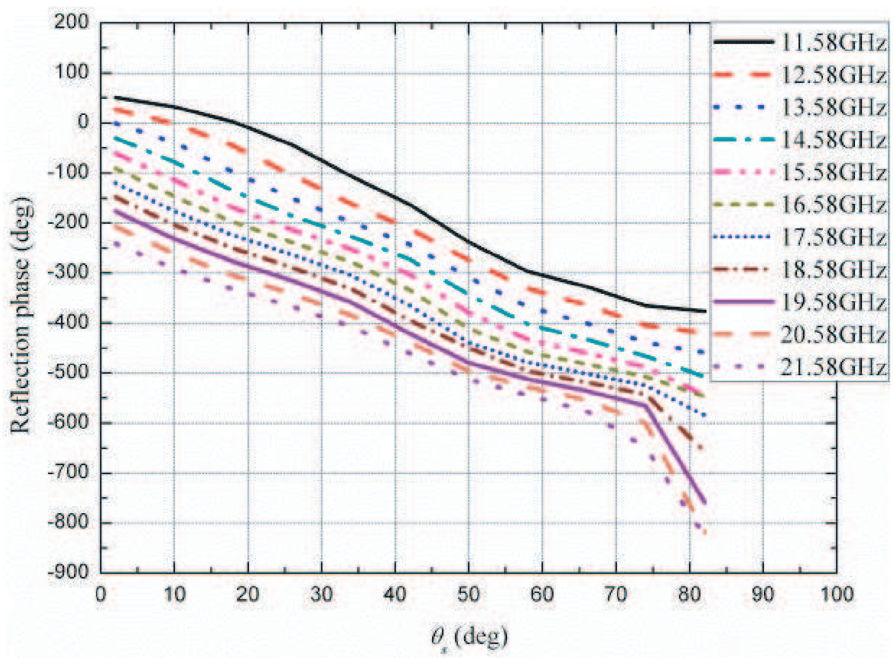


Figure 4. Reflection phase versus the length of phase-delay lines for different frequencies.

Figure 4 shows the reflection phase curves versus the length of phase-delay lines over a very wide frequency range of 11.58–21.58 GHz. As can be seen, about 460° reflection phase range is obtained at center frequency of 13.58 GHz. The reflection phase curves for different frequencies are parallel to each other with good linearity, which indicates the wideband property compared with the conventional elements. To further explain the broadband feature of the element, reflection phase curves versus frequency for different lengths of phase-delay lines is investigated and presented in Fig. 5. It can be

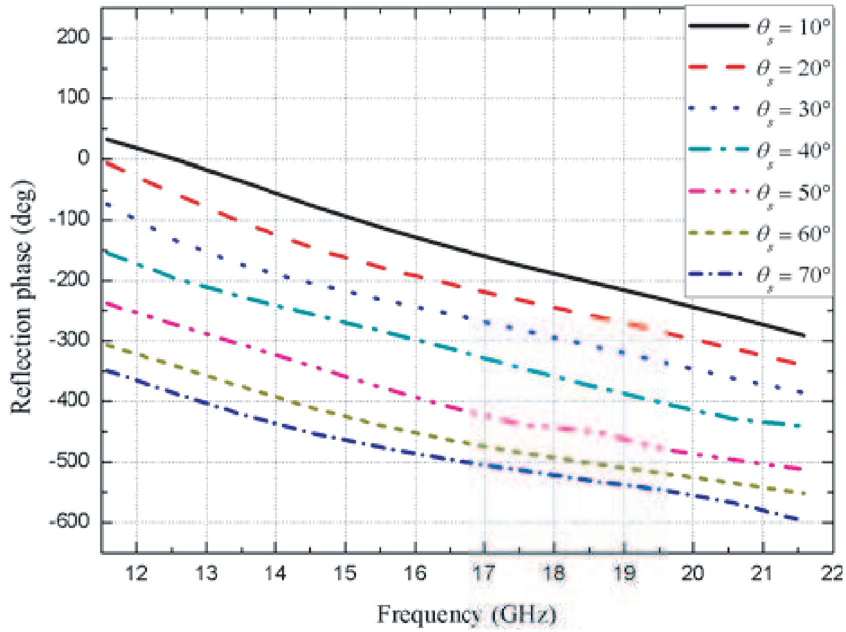


Figure 5. Reflection phase versus frequency for different lengths of phase-delay lines.

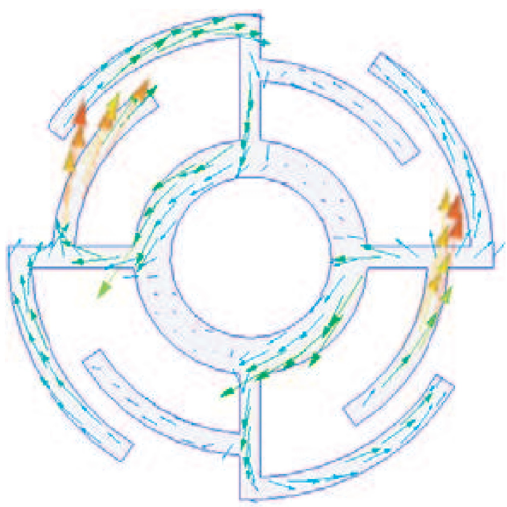


Figure 6. The surface current distribution on the element structure at 13.58 GHz.

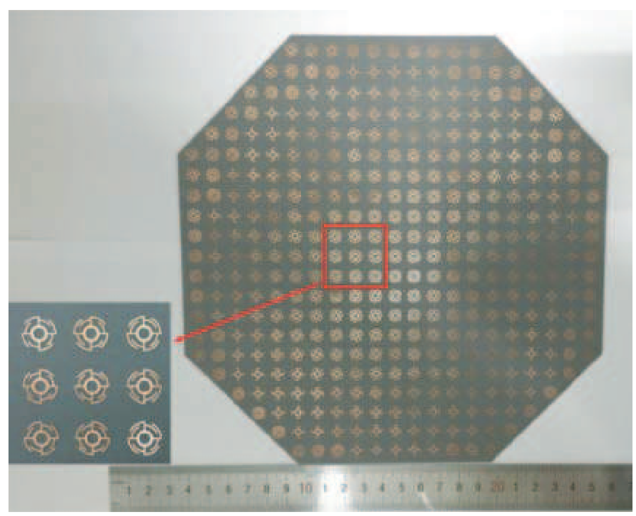


Figure 7. Prototype of the reflectarray and element arrangement.

seen that for different lengths of phase-delay lines, the reflection phase curves are parallel to each other with small phase variation over the very wide frequency band of 11.58–21.58 GHz. Fig. 6 displays the surface current distribution at center frequency of the proposed element structure, which clarifies the mechanism of broadening the bandwidth.

3. REFLECTARRAY DESIGN AND PERFORMANCE

A linearly polarized offset-fed reflectarray with octagonal aperture is designed and fabricated. The photograph of the reflectarray and element arrangement is presented in Fig. 7. As we can see, the elements are placed in a mirror symmetric configuration for further reducing the cross polarization levels [10]. The reflectarray's aperture size (D) and focal distance (F) (distance between the phase center of feed and reflectarray center) both are set to 210 mm, which demonstrates an F/D ratio of 1. The incident field coming from the feed at an angle of incidence of ($\theta_i = 15°$, $\varphi_i = -90°$), and the main beam points to ($\theta_b = 15°$, $\varphi_b = 90°$). A Ku-band linearly polarized pyramidal horn whose pattern is modeled by $\cos^{8.3}\theta$ is used for illuminating the reflectarray. The simulated gain of feed horn antenna is 15.2 dB, and the 3-dB beamwidth are 34° and 31° for the E-plane and H-plane, respectively. The illumination taper at the edge of aperture are about −8.7 dB at 13.58 GHz. The illumination ($\eta_i = 83.7\%$) and spillover ($\eta_s = 84.7\%$) efficiencies can be estimated according to [1]. The reflectarray is simulated by the integral equation method of HFSS. NSI planar near-field system is used for testing the radiation performances of the reflectarray prototype.

Measured and simulated co-polar and cross-polar radiation patterns of the reflectarray at 13.58 GHz are shown in Fig. 8. As presented in Fig. 8, the beam pointing is in accordance with the pre-designed

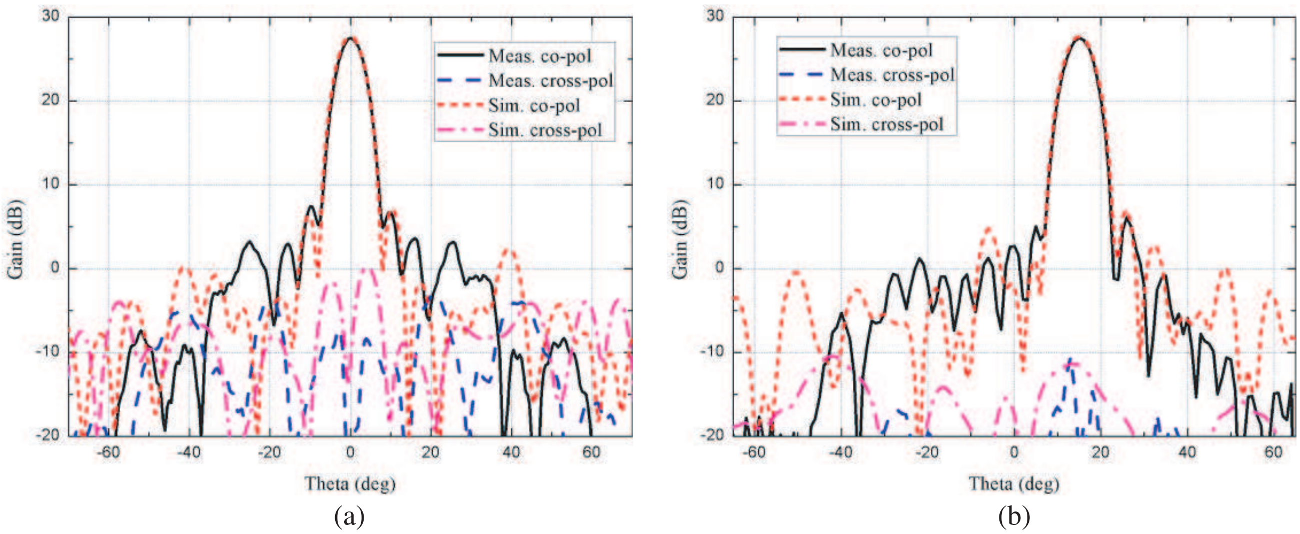


Figure 8. Measured and simulated co-polar and cross-polar radiation patterns of the reflectarray at 13.58 GHz. (a) E-plane ($\varphi = 90°$). (b) H-plane ($\varphi = 0°$).

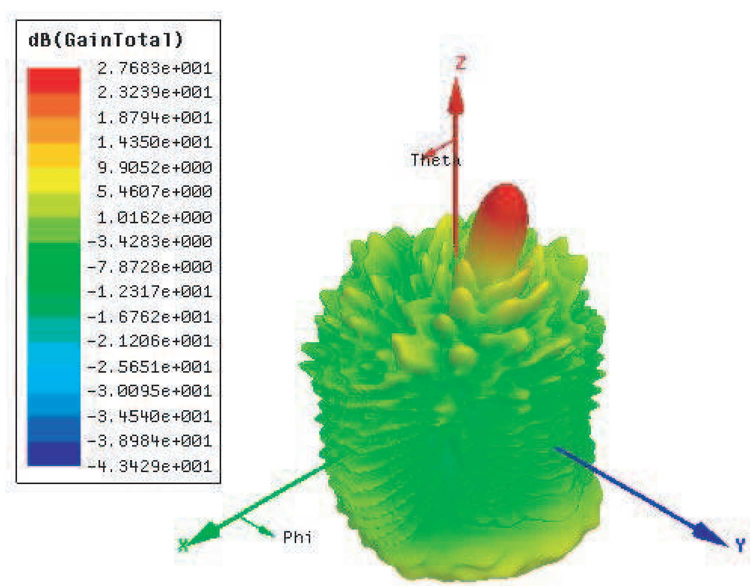
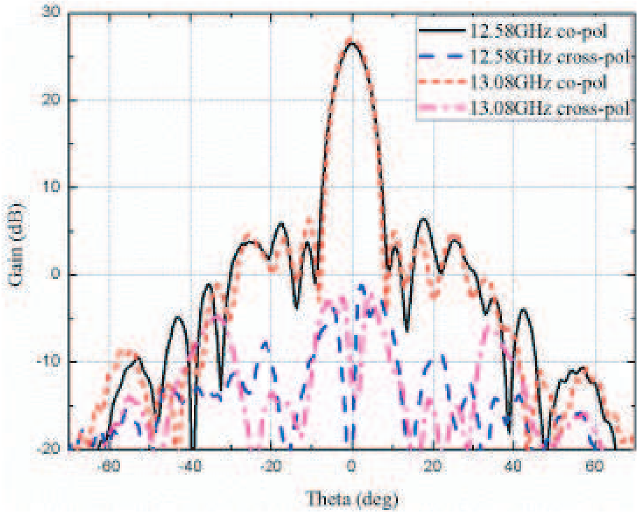
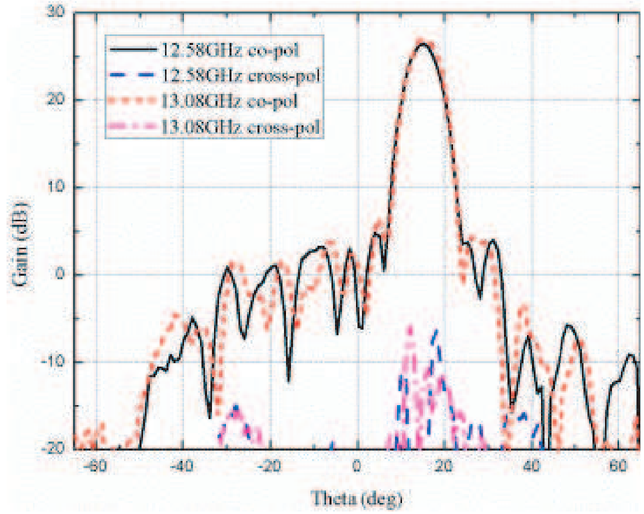


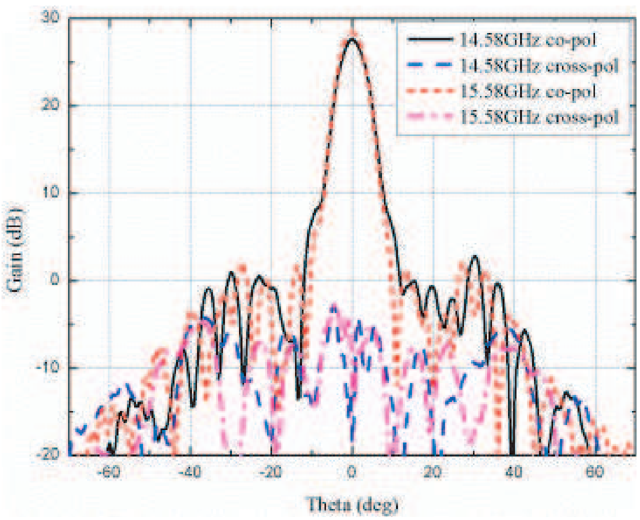
Figure 9. Simulated 3D radiation pattern of the gain at 13.58 GHz.


12.58GHz co-pol
12.58GHz cross-pol
13.08GHz co-pol
13.08GHz cross-pol
Gain (dB)
Theta (deg)

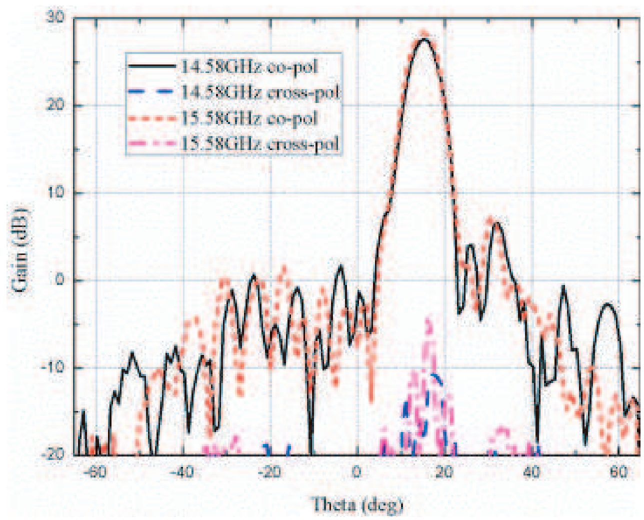
(a)


12.58GHz co-pol
12.58GHz cross-pol
13.08GHz co-pol
13.08GHz cross-pol
Gain (dB)
Theta (deg)

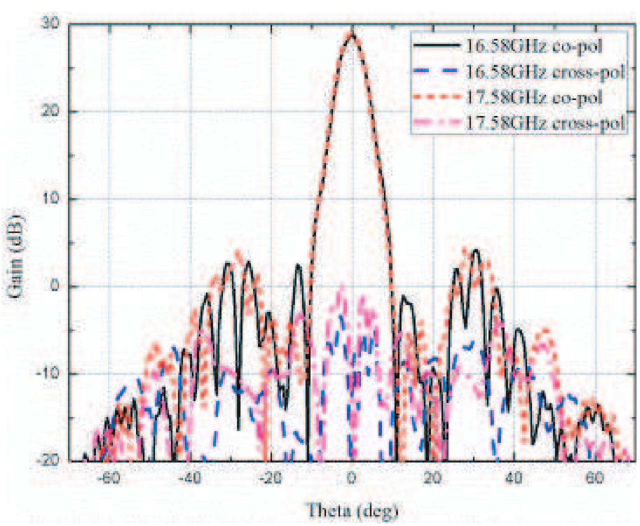
(b)


14.58GHz co-pol
14.58GHz cross-pol
15.58GHz co-pol
15.58GHz cross-pol
Gain (dB)
Theta (deg)

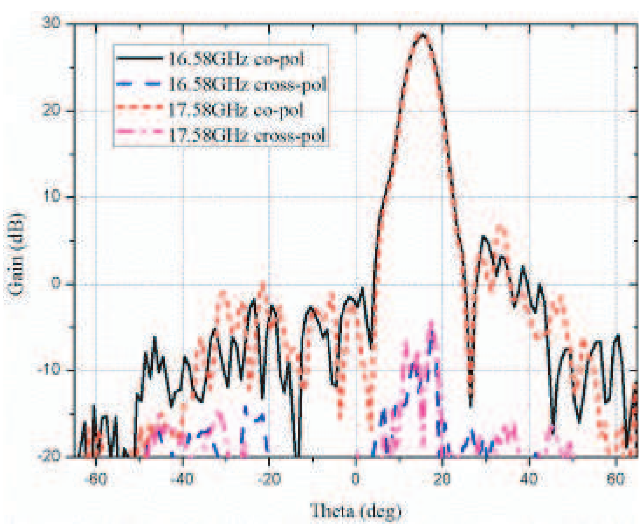
(c)


14.58GHz co-pol
14.58GHz cross-pol
15.58GHz co-pol
15.58GHz cross-pol
Gain (dB)
Theta (deg)

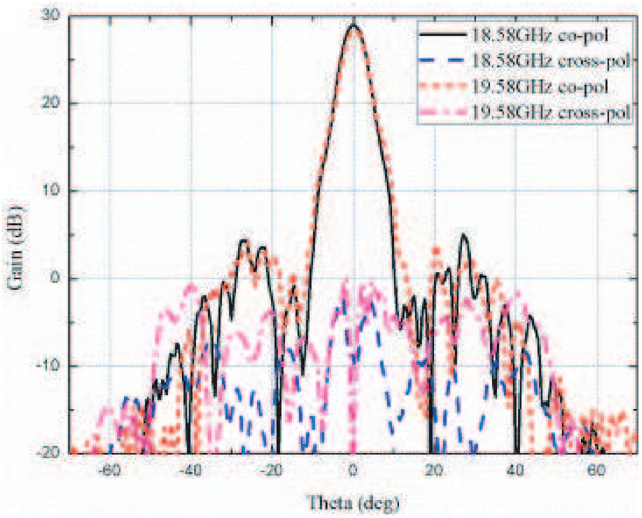
(d)


16.58GHz co-pol
16.58GHz cross-pol
17.58GHz co-pol
17.58GHz cross-pol
Gain (dB)
Theta (deg)

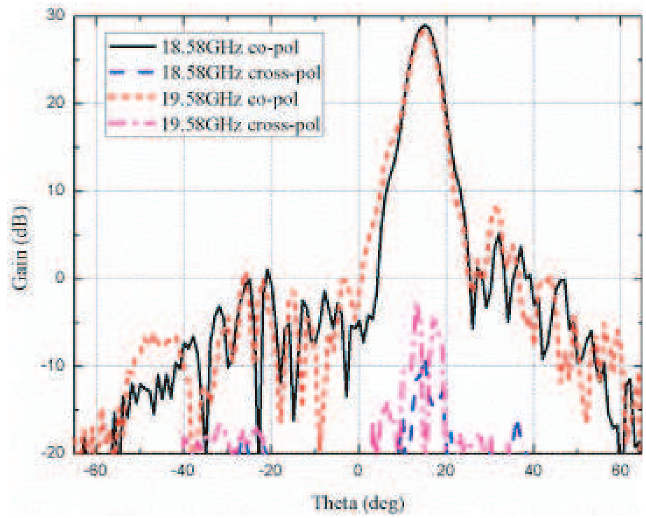
(e)


16.58GHz co-pol
16.58GHz cross-pol
17.58GHz co-pol
17.58GHz cross-pol
Gain (dB)
Theta (deg)

(f)



(g)



(h)

Figure 10. Measured co-polar and cross-polar radiation patterns of the proposed reflectarray at different frequencies. (a) (c) (e) (g) E-plane. (b) (d) (f) (h) H-plane.

direction. A gain level of 27.5 dB with 3-dB beamwidth of about 6.8° and aperture efficiency of 57.3% is achieved at center frequency of 13.58 GHz. Both in E- and H-planes, the side lobe and cross polarization levels are below −20 dB and −27.5 dB, respectively. Fig. 9 shows the simulated 3D radiation pattern of the gain at the center frequency of 13.58 GHz.

Figure 10 depicts the measured co- and cross-polar radiation patterns for several different frequencies (12.58–19.58 GHz) in E- and H-planes. According to Fig. 10, the measured radiation patterns for the several frequencies maintain stable and keep good radiation performance. As the increase of frequency, the radiation patterns get a little deformation, which is mainly due to the feed horn's narrow operation band. Besides, the phase center of the feed gets a deviation with frequency

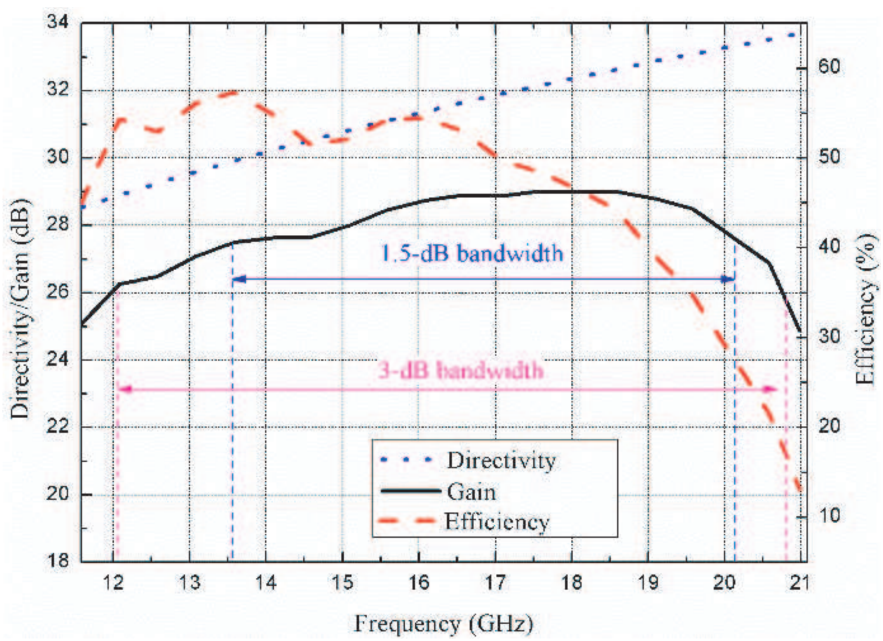


Figure 11. Directivity, measured gain and aperture efficiency of the reflectarray versus frequency.

changing, which causes notable phase errors and brings an adverse influence on the antenna.

Figure 11 presents the directivity, measured gain and aperture efficiency against frequency in a wide frequency range. From this figure, one can see that 47.8% (13.58–20.08 GHz) 1.5-dB gain bandwidth and 64% (12.08–20.78 GHz) 3-dB gain bandwidths with the center frequency at 13.58 GHz are achieved. The frequency range of measured gain larger than 26.5 dB (1 dB smaller than the gain at center frequency) is from 12.58 GHz to 20.58 GHz. The peak gain of the reflectarray is 29 dB at 17.58 GHz with aperture efficiency of 45.7%. In the frequency range from 12.08 GHz to 17.08 GHz, the aperture efficiencies are over 50%, which means a high efficiency in wide frequency range. The peak aperture efficiency of 57.3% is achieved at the center frequency of 13.58 GHz. The bandwidth of aperture efficiency over 50% is 36.8% (12.08–17.08 GHz).

Table 2 presents the proposed reflectarray performance and several recent published works on broadband reflectarrays. As one can see, the proposed reflectarray has the advantages on efficiency and bandwidth performance.

Table 2. Comparison of the proposed reflectarray performance with previous broadband works.

Reference	**This work**	**[7]**	**[8]**	**[9]**	**[11]**	**[12]**
Frequency (GHz)	13.58	32	10	11.7	8.5	10.3
Gain (dB)	27.5	32.55	28.2	24	26.4	25.4
1-dB gain BW (%)		19.1			16.5	10
1.5-dB gain BW (%)	47.8		18			
3-dB gain BW (%)	64		32	18		15.5
Efficiency (%)	57.3		56.5	35	59.2	45
Sidelobe level (dB)	< -20		< -12	< -11	< -20	< -17
Cross-pol level (dB)	< -27.5		< -30	< -13	< -25	< -23
Number of layers	1	2	1	1	1	1
Polarization	Linear	Linear	Linear	Linear	Linear	Circular
Aperture area	$78\lambda_0^2$	-	$92.1\lambda_0^2$	$78\lambda_0^2$	$58.5\lambda_0^2$	$62.4\lambda_0^2$

4. CONCLUSION

A single-layer element which is composed by a circular ring attached two sets of phase-delay lines is proposed. By optimizing the parameters of the element, parallel large range reflection phase curves with good linearity are achieved over an ultra-wide band. Employing the element, a reflectarray is designed and tested. The peak aperture efficiency of 57.3% with a measured gain of 27.5 dB is achieved at the center frequency of 13.58GHz. The 1.5-dB and 3-dB gain bandwidths are about 47.8% and 64% with the center frequency at 13.58 GHz, respectively. The bandwidth of aperture efficiency over 50% reaches 36.8%.

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