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Investigations on Beam-Scanning Improvement of Reflectarrays Using Single-Layered Sub-Wavelength Elements

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Abstract—This paper investigates the use of double concentric circular ring elements arranged in a sub-wavelength grid on a single layer of substrate, in an effort to enhance the beam-scanning capability of reflectarrays. The work is done at 10 GHz on a 405 mm × 405 mm aperture. In addition to a broad gain bandwidth, the reflectarray with a sub-wavelength grid exhibits a superior beam-scanning performance compared to the one with $\lambda/2$ grid. The measured results show that the reflectarray with 0.3λ grid spacing achieves a 1-dB gain bandwidth of 22% with an aperture efficiency of 56.6%. With the reflectarray fixed, this paper studies the possibility of beam scanning by displacing the feed horn laterally. The results show that beam scanning of $\pm 15^\circ$ is possible while preserving the broadband characteristics. It is also observed that a 1-dB gain bandwidth of 28% is achieved for the 0.3λ array when the feed is displaced laterally with an angle of 30°.

1. INTRODUCTION

Reflectarrays are promising alternatives to traditional parabolic dishes due to advantages of low profile, low mass, conformal geometry and ease of fabrication [1, 2]. Considerable research efforts have been made towards the bandwidth improvement of reflectarrays, and various methods have been thus tried to design wideband reflectarrays, such as multilayer designs [3, 4], single-layer multi-resonant designs [5–8], disc/ring elements attached with variable-length phase-delay line designs [9, 10] and aperture coupled designs [11, 12]. An alternative simple and effective technique for broadband design has been introduced by using sub-wavelength elements in place of the conventional $\lambda/2$ elements [13–16], and recently our group has undertaken the research on bandwidth improvement of reflectarrays using sub-wavelength single-layered double concentric circular rings [17, 18]. The elements proposed in [17, 18] allow an additional degree-of-freedom to improve the bandwidth by adjusting the spacing between the two rings. By deploying single-layer multi-resonant elements with sub-wavelength grid spacing, both the simple structure and improved bandwidth performance can be realized. It is demonstrated in [18] that the reflectarray with $\lambda/4$ grid spacing achieves a 2-dB gain bandwidth of 33% with an aperture efficiency of 36.2%. Our recent research shows that the gain bandwidth and aperture efficiency can be further enhanced by using a 0.3λ grid spacing together with a suitably designed feed horn location. Furthermore, compared to the single band operation in [18], a single layer dual band reflectarray element which has a similar shape to [18] is also proposed [19]. The configuration is based on the integration of a Shorted Annular Patch (SAP) with an Inverted-SAP (I-SAP) antenna. The dual-band radiators can be easily printed on the same substrate without using additional layers and thus strongly simplifying the fabrication process complexity and cost. Additionally, the weak coupling between the two antennas allows a strong simplification of the design process which results in the possibility to design each element in the dual band reflectarray cell almost independently. It is noticed in [19] that although the cell element is fully characterized and analyzed, the performance of the whole array is not reported.

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In addition to the fixed beam reflectarray designs, in many applications beam-scannable reflectarrays are also highly desired. Lateral feed displacement near the focal point of parabolic reflectors has sometimes been adopted to provide limited beam scanning or for producing multiple beam antennas. A scanned beam from a displaced feed of a parabolic reflector typically suffers from a loss in gain and degradation in antenna radiation patterns mainly owing to phase errors [20]. Reflectarrays' beams can also be scanned by lateral displacement of the feed, as shown in [21]. However, it is observed in [21] that the scanning of reflectarrays is limited to a few beamwidths and degraded radiation patterns are observed. Furthermore, the bandwidth performance of scanned reflectarrays is not reported.

In addition, the concept of beam-scanning improvement of reflectarrays by reducing the cell size at millimetre waves is presented in [22]. The influence of cell size on the gain and beam-scanning performances is investigated. In contrast to lateral feed displacement method, the beam scanning of the reflectarray is realized by moving the WR-10 waveguide source on a circle path in the x-z plane. The measured results show that the $\lambda/4$ reflectarray at 94 GHz achieves a beam scanning improvement in terms of gain loss compared with the $\lambda/2$ reflectarray. However, the gain bandwidth performance at scanned angles is also not reported in the article.

In this paper, the beam-scanning improvement of reflectarrays using single-layered double concentric circular ring elements on a sub-wavelength grid is studied. In Section 2, the phasing element and its performance are briefly described. It should be noted that although one may argue that the element used in this study looks the same as the one in our previous research [18], there are two new contributions in this work. Firstly, the element grid spacing and feed horn location are different to [18] and have been optimized to obtain a much improved gain bandwidth and aperture efficiency which will be shown in the later section. Secondly, this article mainly focuses and investigates the scanned properties of single-layered reflectarrays, including gain loss and gain bandwidth performance of scanned reflectarrays. The beam-scanning in this study is achieved by displacing the feed horn laterally, as the same as in [21]. In addition to the gain loss investigation of scanned reflectarrays as shown in [21, 22], our paper also emphasizes on the gain bandwidth behaviour when the reflectarrays are scanned. To the authors' best knowledge, no research has shown the results on the gain bandwidth performance of such scanned reflectarrays. In this study, two offset-fed X-band reflectarrays with element periodicities of $\lambda/2$ (15 mm) and 0.3λ (9 mm) respectively, are designed to provide a beam pointing at $\theta = 25^\circ$ nominally. Five laterally displaced feed positions with scan angles of 0°, 10°, 20°, 30° and 35° are also designed to investigate the bandwidth and scan behaviour of reflectarrays. The reflectarray with 0.3λ grid spacing demonstrates a remarkable 15% increase in the 1-dB gain bandwidth compared to the one with $\lambda/2$ grid spacing. More importantly, its broadband characteristic is retained and the variation in peak gain is small when the beams are steered. Furthermore, it is interesting to report that the reflectarray based on 0.3λ grid can achieve a huge 1-dB gain bandwidth of 28%, ranging from 9.9 GHz to 13 GHz when the feed is displaced laterally with an angle of 30°.

2. ELEMENT DESIGN AND GAIN PERFORMANCE OF REFLECTARRAYS

In this study, the element used is reported in our previous work [18]. However, as mentioned earlier, the grid spacing of 0.3λ instead of $\lambda/3$ or $\lambda/4$ as studied in [18] is proposed here to further improve the bandwidth. Figure 1 illustrates the configuration of the element design. The double concentric circular ring elements are etched on a Rogers 4003C substrate with thickness of 0.2032 mm, dielectric constant of 3.55 and loss tangent of 0.0027, supported by a layer of 3 mm polycarbonate ($\varepsilon_r = 2.8$) and backed by a conducting ground plane. The element geometry provides an increased span of phase variation compared to the single circular ring, while the polycarbonate layer offers the necessary thickness for a smooth varying phase variation when the double ring sizes are changed. This is imperative to obtain wideband performance. The design operates at X-band centered at 10 GHz and the unit cell is characterized using the commercial full-wave electromagnetic software Ansoft HFSS. The reflectarray is assumed to be formed by identical elements arranged in square lattices. The reflected phase curves can be obtained by considering an infinite array of identical elements with a plane wave incidence upon them. It is noted that the reflection characteristics are dependent on the incident angle of the plane wave. However, it has been demonstrated that the normal incidence can present good approximations for incident angles up to about 40° [23].

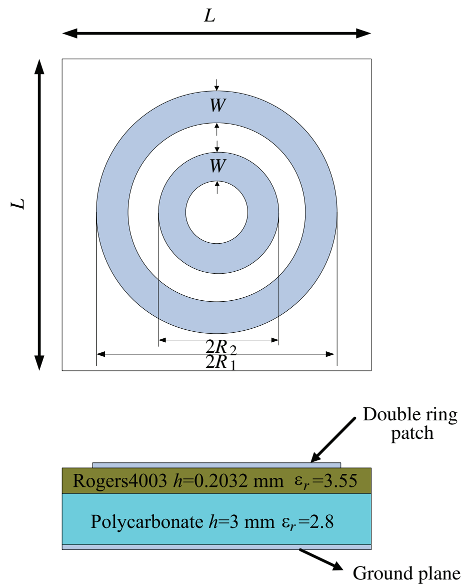


Figure 1. Geometry of the double concentric circular ring element.

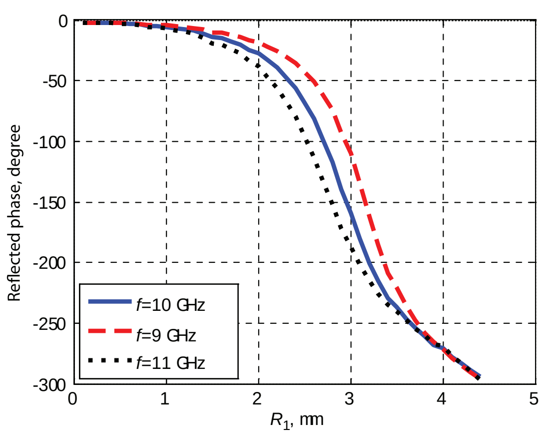


Figure 2. Reflected phase curves of the double concentric circular ring element with 0.3λ (9 mm) grid and ring spacing of $R_2 = 0.53R_1$ for different frequencies.

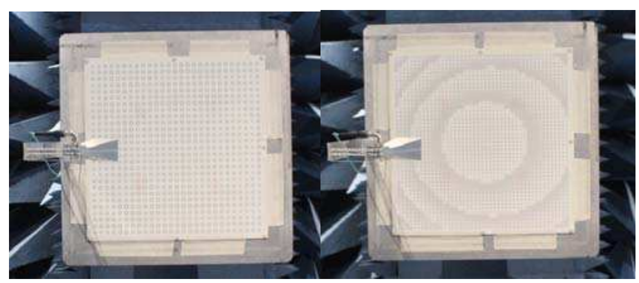


Figure 3. Prototypes of the reflectarrays, (a) $\lambda/2$ array with 729 double concentric circular rings, (b) 0.3λ array with 2025 double concentric circular rings.

It has been shown in the simulation that the linearity of the reflected phase curves is highly dependent on the double concentric circular ring spacing. Thus the double ring spacing has been optimized when applied on two grids and the ring spacings of $R_2 = 0.8R_1$ and $R_2 = 0.53R_1$ are chosen to achieve relatively good linearity and reflected phase range for the $\lambda/2$ and 0.3λ grids, respectively. Figure 2 displays the reflected phasing curves of the double concentric circular ring element with grid spacing of 0.3λ and normal incidence for different frequencies. It is observed in Figure 2 that the phase curves feature more linear behaviour and less sensitive to the frequency variation with 0.3λ grid spacing. Therefore, a broadband performance is expected to be obtained with a 0.3λ grid.

In this work, a proper pyramidal horn antenna rather than the WR-10 waveguide proposed in [22] is used to illuminate the reflectarray. It is noted that due to millimeter band operation such as at 94 GHz, a WR-10 waveguide may be employed as a relatively simple and fast approach for a feed [22]. However, it may not produce an adequate illumination on reflectarrays. On the other hand, a pyramidal horn is a much more viable and popular feed solution for reflectarrays at X-band and can be designed to suitably feed the reflectarray. The feed antenna used here is as the same as in [18] which covers a frequency range of 7.85 GHz–12.6 GHz with a peak gain of 13 dBi and a 10-dB beamwidth of 76° at 10 GHz. However, the feed horn location of this study has been optimized according to the methods in [24] to realize a much improved aperture efficiency. An offset feed method ($\theta_i = 25°$) is adopted to avoid aperture blockage and the elements' reflection phases are adjusted to produce a main beam 25° off broadside. Two X-band reflectarrays with $\lambda/2$ and 0.3λ grid spacings are designed and fabricated, both at 10 GHz. Each antenna has a square aperture of 405 mm × 405 mm hosting 729 and 2025 elements for $\lambda/2$ and 0.3λ arrays, respectively. Prototypes of the reflectarrays are shown in Figure 3.

Figure 4 depicts the measured E-plane radiation patterns of two reflectarrays at 10 GHz. Note that the main beams are designed to peak at $\theta = 25°$ off-broadside in both reflectarrays. The measured side lobe levels are better than 15 dB. The 0.3λ array has a better side lobe performance of 18 dB. The cross polarization is better than 25 dB at the main beam location for both arrays. The relatively high cross polarization level could be due to the element configuration and measurement errors. Furthermore, it is seen that the beamwidth of both arrays is about 4.5°.

The measured Gains versus Frequency of the reflectarrays are compared in Figure 5. The measured maximum gains are 30.2 dBi and 30.7 dBi for $\lambda/2$ and 0.3λ arrays. This corresponds to an aperture efficiency of 50.5% and 56.6%, respectively. Using a 1-dB gain bandwidth as a criterion, one notes that the 0.3λ array can achieve a 22% bandwidth compared to a 7% bandwidth of the $\lambda/2$ array. Table 1 compares the performance of the proposed design with various published sub-wavelength reflectarray designs. It is shown in Table 1 that the proposed reflectarray features a good performance among all designs. For example, compared with [14], both improved aperture efficiency and gain bandwidth have been achieved; compared with [15], although our proposed design exhibits a slightly lower aperture efficiency, the gain bandwidth is wider and the feed horn height 287.5 mm instead of 432 mm in [15] is observed, which makes the reflectarray profile more compact; compared with [16], apart from a wider bandwidth, our design also features a single-layered structure which is easier for fabrication. Moreover,

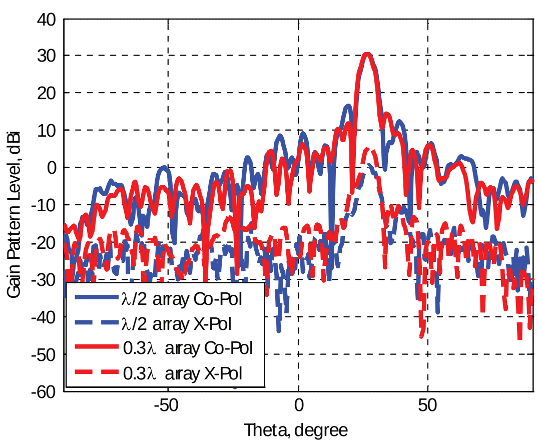


Figure 4. Measured E-plane radiation patterns at 10 GHz for two reflectarrays.

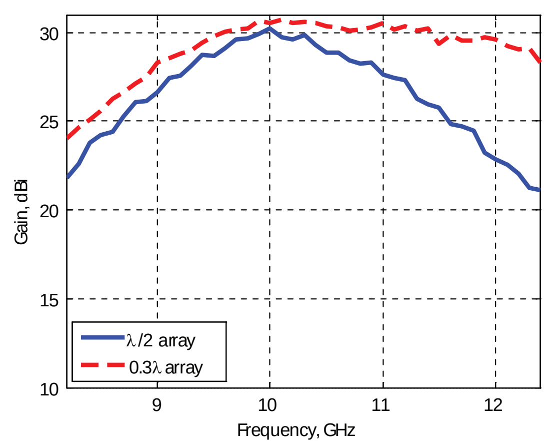


Figure 5. Measured gain of two reflectarrays.

Table 1. Performance comparison of various sub-wavelength reflectarrays.

Ref.	Layer	Freq. (GHz)	Gain (dBi)	Eff. (%)	BW (1-dB)
[14]	Single	32	30.95	43.6	10.9%
[15]	Single	12.5	32.8	60	19%
[16]	Double	32	32.55	N.A.	19.1%
[18]	Single	10	28.6	33	20%
Proposed	Single	10	30.7	56.6	22%

compared with our previous $\lambda/4$ array design in [18], the proposed 0.3λ array in this study shows notable performance improvement, especially significantly higher aperture efficiency.

3. BEAM-SCANNING PERFORMANCE OF REFLECTARRAYS

In this section, the beam-scanning capabilities of two reflectarrays are investigated. The beam-steering of the reflectarrays is realized by lateral displacement of the feed, as shown in Figure 6(a). The five other feeds are all set at the same height h (287.5 mm) as that of the nominal 25° off-set feed and rotated with incidence angles of 0°, 10°, 20°, 30° and 35° respectively to realize the beam-scanning. Five supporting struts are also designed and built to accommodate the feeds. The prototypes of 0.3λ reflectarray with five lateral displacement feeds are shown in Figure 6(b).

Figure 7 displays the measured scanned beam patterns of the reflectarray with $\lambda/2$ and 0.3λ grid spacings at 10 GHz, respectively. It is observed that for both arrays, there is no significant beam distortion although there is slight deviation of the desired scanned angle when the feed is displaced. This is similar to the effect of beam deviation factor occurred in reflector antennas. Some degradation in terms of elevated sidelobe levels are also noticed when the scan angles are at 0° and 35° for both

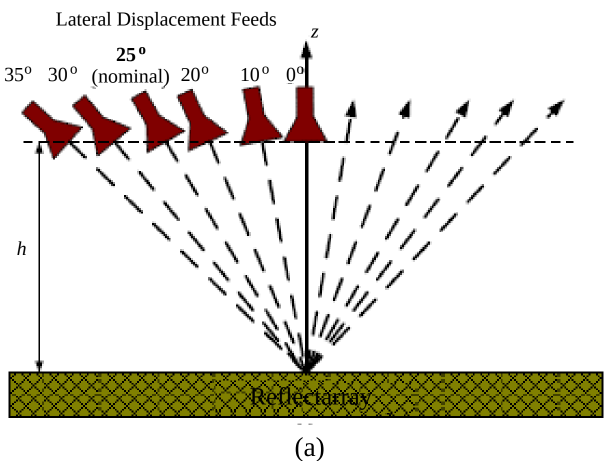


Figure 6. (a) Lateral displacement of feeds and (b) prototypes of the 0.3λ reflectarray with lateral displaced feeds.

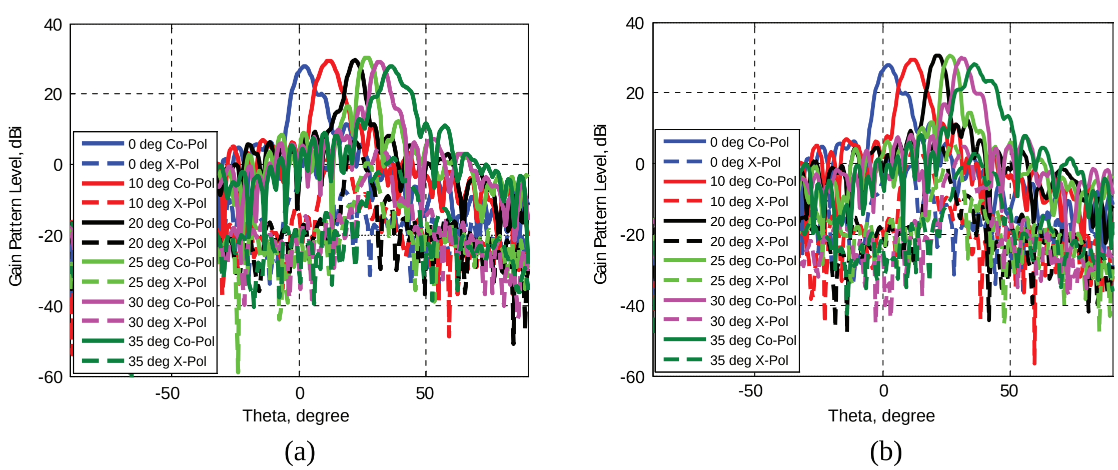


Figure 7. Measured scanned beam patterns of the reflectarray with (a) $\lambda/2$ grid spacing and (b) 0.3λ grid spacing at 10GHz.

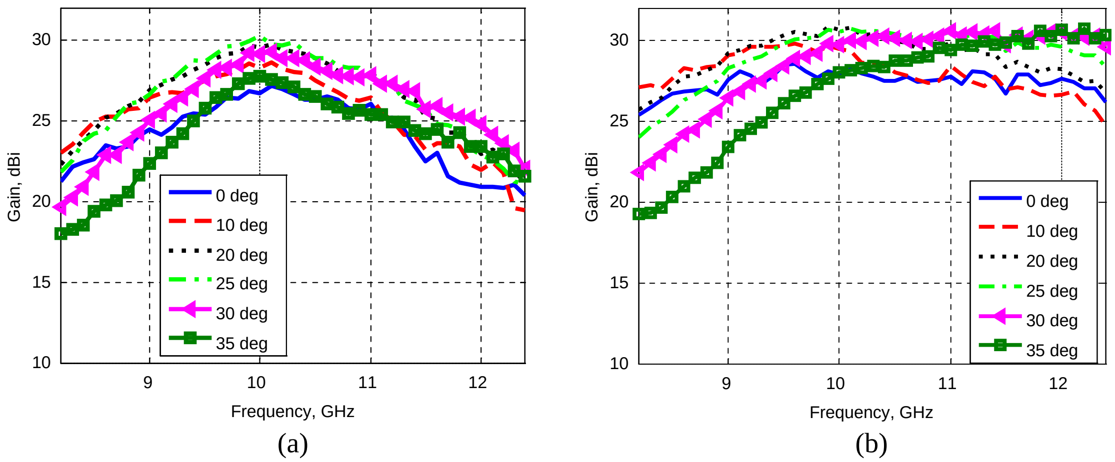


Figure 8. Measured gain of the reflectarrays when the beam is scanned (a) $\lambda/2$ grid spacing and (b) 0.3λ grid spacing.

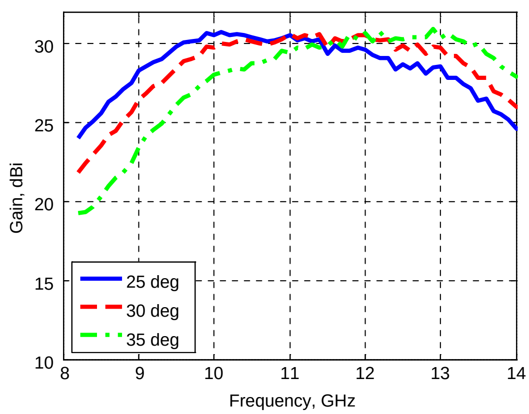
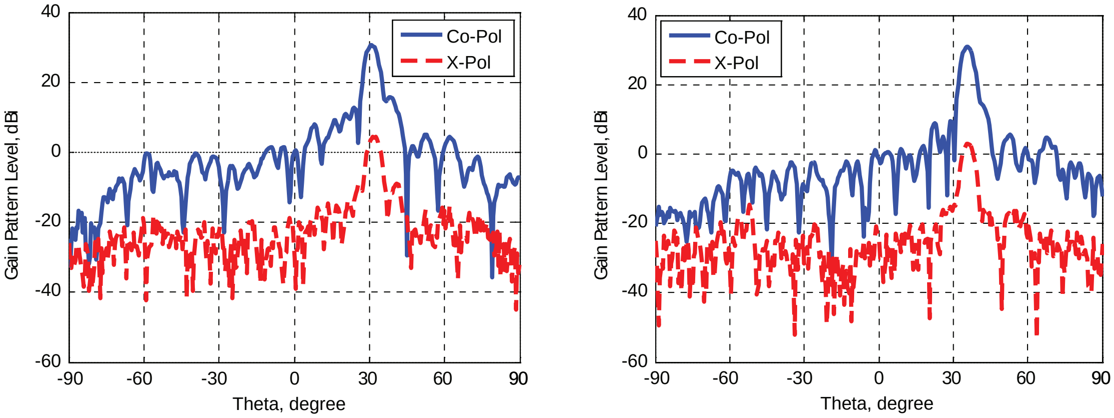


Figure 9. Measured gain of the 0.3λ reflectarray with scan angles of 25°, 30° and 35°.

arrays. It is observed that the beam-scanning range of ±15° or alternatively about ±3.5 beamwidths can be achieved in the proposed reflectarray design.

The measured gain performance of two reflectarrays with various scanned angles is shown in Figure 8. It is found in Figure 8(a) that the gain bandwidth of the $\lambda/2$ array is narrow when the beam is steered. In addition, when scanned, the gain bandwidth performance of the $\lambda/2$ array tracks that of the nominal beam angle. It is clearly seen that at the design frequency 10 GHz, the peak gain increases from 0° onwards and reach the maximum of 30.2 dBi at the nominal angle of 25°. From 25° onwards, the peak gain starts to drop and decreases to 27.8 dBi at the scan angle of 35°. More importantly, the peak gain variation at various scan angles for the $\lambda/2$ array is relatively significant. The gain decreases compared to the nominal 25° case. For scan angles of 0°, 10°, 20°, 30° and 35°, the decreases in gain are 3.5 dB, 1.9 dB, 0.7 dB, 1.1 dB and 2.4 dB, respectively. On the other hand, it is noticed in Figure 8(b) that for the 0.3λ array the bandwidths still remain reasonably wide when the beam is scanned. Furthermore, the peak gain variation at different scan angles is relatively small. The gain drops compared to the nominal 25° scenario for scan angles of 0°, 10°, 20°, 30° and 35° are 2.8 dB, 1.2 dB, 0 dB, 1 dB and 2.7 dB, respectively.

For the case of 0.3λ array, although the peak gains at design frequency 10 GHz for scan angles of 30° and 35° decrease compared with the nominal 25° case, the gain bandwidths for these two cases appear to shift to the high frequencies. This could be due to more pronounced reflected phase dependence on increased incident angles. In these two cases, most of elements of the reflectarray are illuminated with



(a) (b)

Figure 10. Measured E-plane radiation patterns of the 0.3λ reflectarray with (a) scan angle of 30° at 11 GHz and (b) scan angle of 35° at 12.9 GHz.

Table 2. Gain bandwidth and aperture efficiency comparison of two reflectarrays when scanned.

	Scan angle	1-dB gain bandwidth	Aperture efficiency
$\lambda/2$ array	0°	~10%	~22.6%
	10°	~8%	~32.2%
	20°	~9%	~44%
	25° (Nominal)	~7%	~50.8%
	30°	~8%	~42.4%
	35°	~5%	~32%
0.3λ array	0°	~25%	~33.7%
	10°	~12%	~46.2%
	20°	~16%	~57.4%
	25° (Nominal)	~22%	~56.6%
	30°	~28%	~47.9%
	35°	~17%	~39.6%

incident wave angles larger than 30° or 35°, instead of a normal incidence assumed for the reflected phase curve design. Figure 9 plots the measured gain curves for the scan angles of 25°, 30° and 35° in an extended frequency range. It is observed that the proposed 0.3λ reflectarray with scan angle of 30° can achieve a huge 1-dB gain bandwidth of 28%, ranging from 9.9 GHz to 13 GHz; while for the scan angle of 35°, the 1-dB gain bandwidth is 17%, spanning from 11.3 GHz to 13.5 GHz. However, the peak gains for scan angles of 30° and 35° are 30.6 dBi and 30.9 dBi occurring at 11 GHz and 12.9 GHz respectively and this would result in relatively lower aperture efficiencies of 47.9% and 39.6%, respectively. Figure 10 displays the measured E-plane radiation patterns of 0.3λ reflectarray with scan angles of 30° and 35° at 11 GHz and 12.9 GHz, respectively. It can be seen that good radiation properties are obtained with relatively low side lobe levels and reasonable cross polarizations.

Additionally, compared to the 0.3λ array, it is shown in Figure 8(a) that the $\lambda/2$ array with scan angle of 30° and 35° can only achieve 1-dB gain bandwidth of 8% and 5%, respectively. Table 2 compares the gain bandwidth and aperture efficiency performance of the two reflectarrays when scanned. It is clearly seen that the 0.3λ array exhibits a superior gain bandwidth performance compared with the $\lambda/2$ array when scanned.

4. CONCLUSION

The concept of using single-layer double concentric circular ring elements on a sub-wavelength grid for beam-scanning improvement has been studied. The measured results show that the 0.3λ array achieves a considerable bandwidth improvement compared to the $\lambda/2$ array, where the 1-dB gain bandwidth has been increased from 7% to 22%. More importantly, the wideband performance can be retained, and the peak gain variation is small when the beams are scanned. With the reflectarray fixed, it is demonstrated that the beam-scanning range of $\pm 15^\circ$ is possible. It is also interestingly found that the proposed 0.3λ array with a scan angle of 30° can achieve a relatively good 1-dB gain bandwidth of 28%, i.e., from 9.9 GHz to 13 GHz.

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