Perforated Dielectric Resonator Antenna Reflectarray

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Abstract **─** A wideband perforated rectangular dielectric resonator antenna (RDRA) reflectarray is presented. The arrays of RDRA are formed from one piece of materials. Air-filled holes are drilled into the material around the RDRA. This technique of fabricating RDRA reflectarray using perforations eliminates the need to position and bond individual elements in the reflectarray and makes the fabrication of the RDRA reflectarray feasible. The ground plane below the reflectarray elements is folded as a rectangular concave surface so that an air-gap is formed between the RDRA elements and the ground plane in order to increase the bandwidth. Full-wave analysis using the finite integration technique is applied. Three cases are studied. In the first one, the horn antenna is placed at the focal point to illuminate the reflectarray and the main beam in the broadside direction. In the second one, the horn antenna is placed at the focal point and the main beam at ±30 degrees off broadside direction. In the third one, an offset feed RDRA reflectarray is considered. A variable length RDRA provides the required phase shift at each cell on the reflectarray surface. The normalized gain patterns, the frequency bandwidth, and the aperture efficiency for the above cases are calculated.

Index Terms **─** Dielectric resonator, reflectarray, wideband array.

I. INTRODUCTION

High gain antennas are desired in various applications, such as satellite communications, radar systems, and radio astronomy observations. Traditionally, large parabolic reflector antennas are selected for the systems mentioned above. However, these antennas are bulky, heavy, and their geometrical shape tends to be distorted during the implementation. Microstrip reflectarrays are good alternatives to reflectors for space applications because of their low profile, simple manufacturing process, added functionalities, and low cost especially for beam shaping applications. The microstrip reflectarray is made up of a reflective array of printed patches with a certain tuning on the phase of the reflected wave to produce a focused or shaped beam when illuminated by a primary feed. By varying the resonant properties of the elements making up the array, it is possible to introduce a graded progressive phase variation upon reflection across the surface of the reflectarray. Methods to control the phase of the re-radiated wave include using elements with variable sizes [1], patches with different stub lengths [2], slots with variable lengths at the ground plane or loaded on the patch [3,4], and the variable rotation angle technique [5]. One of the primary disadvantages of microstrip reflectarrays is their relatively narrow gain bandwidth for a single layer design [6]. The

Submitted On: March 10, 2011
Accepted On: October 15, 2011

bandwidth of the microstrip reflectarray is mainly restricted by the microstrip elements, the differential phase delay, the array element spacing, and the feed antenna bandwidth [7]. Bandwidth can be somewhat improved by using a more complex structure consisting of multiple layers of substrates and stack patches [8].

Rectangular dielectric resonator antenna (RDRA) was proposed by Long et al. [9] in 1983. RDRAs offer many advantages, such as low-profile, low-cost, ease of excitation, and high radiation efficiency. RDRAs offer high radiation efficiency even if they are used in high frequency applications. This is because of the low ohmic losses and there are no surface waves when using this kind of antennas. Since the surface waves are not supported by RDRAs, the scan blindness problems with large microstrip arrays can be solved. The scan blindness is the signal loss due to the mutual coupling and it occurs when the main beam is steered to the low elevation angles used in microstrip array. Moreover, when the RDRA is made of a high permittivity material with slight dissipation losses, it can handle high power. The high power capability is considered as an advantage when used in radar applications [10]. RDRAs may be used at a wide range of frequencies starting from 55MHz up to 94 GHz. RDRAs can be formed in different shapes offering more design flexibility, they can be rectangular, cylindrical, hemispherical, or other regular shapes. Many investigations have been reported about the RDRAs with different shapes and their characteristics have been examined [11]. Reflectarray antennas realized by rectangular and crossed dielectric resonator for linear and circular polarizations are investigated in [12-14]

One current disadvantage of RDRAs in large arrays is related to fabrication: each individual RDRA element must be located and bonded at the appropriate position in the array. For high frequency applications where the size of the elements becomes small, their exact location becomes more critical, and this approach may not be practical. The perforated technique was used in the DRA array in order to make an array from one dielectric sheet by perforating materials between the elements [15, 16]. The effective permittivity of the dielectric resonator was altered with the perforated air-filled holes drilled into its substrate material. Perforated structure was first proposed for gain enhancement in the dielectric Fresnel lens design [17]. The concept of perforated RDRA was tested experimentally in [18].

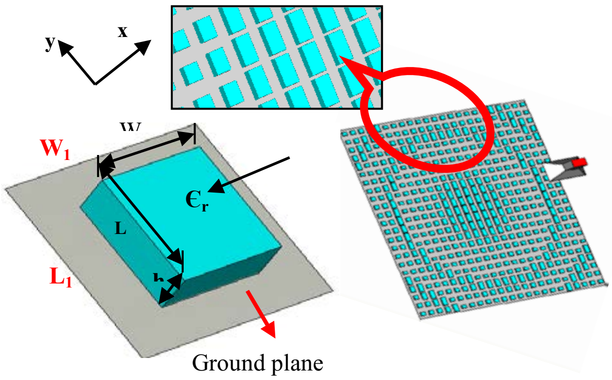
In recent years, one major aspect of the research with RDRAs has focused on the bandwidth enhancement, and many techniques have been proposed to broaden the operating bandwidth of the RDRAs [19-21]. However, these techniques of impedance-bandwidth enhancement are all on the expense of the complex DR structures. In [22], a novel wideband rectangular RDRA is proposed, where an air gap is introduced between the rectangular RDRA and the ground by adopting a rectangular concave dip in the ground plane. It shows that using a concave dip in the ground plane instead of a planar ground plane has broadened the impedance bandwidth to 1.4 times.

This paper reports a new type of reflectarray using rectangular RDRA elements for linear polarization. Perforated substrate and rectangular concave dipped ground plane are used to improve the gain bandwidth of the reflectarray. This paper extends the investigation of perforated RDRAs by examining the performance of perforated RDRAs in the reflectarray structure.

II. THE ARRAY STRUCTURE

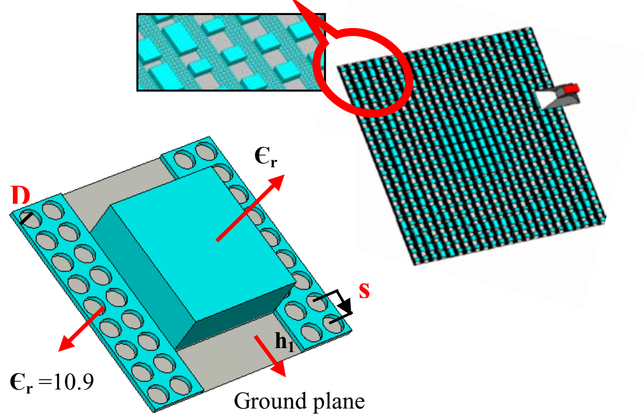
Figure 1 gives the coordinate system of the reflectarray geometry with solid ground plane. The reflectarray is composed of 23x23 elements and is covering an area of 31.05 x 31.05 cm^2. The unit cell in reflectarray antenna consists of rectangular RDRA supported on ground plane. Each RDRA element has a width W=7 mm, a height h=3.2 mm, a relative dielectric constant, ε_r =10.9, and a variable length L. This RDRA is designed to operate at 12 GHz. The cell size L_1= W_1=13.5 mm. The feeder is a pyramidal horn with dimensions of 59.9 x 29.9 x 49.5 mm^3. The horn antenna is placed at the focal point, 320 mm away from the reflecting surface.

A possible geometry of RDRA reflectarray fabricated by perforating a single dielectric sheet is shown in Fig. 2. The unit cell in the reflectarray antenna consists of rectangular RDRA supported on a perforated ground plane. The RDRAs are formed from a single dielectric sheet by perforating selected areas of the material.



(a) RDRA cell with solid GP (b) Broadside RDRA reflectarray with solid GP

Fig. 1. The geometry of the RDRA reflectarray with solid ground plane.



(a) RDRA cell with perforated ground plane (b) Broadside RDRA reflectarray with perforated ground plane

Fig. 2. The geometry of the RDRA reflectarray with perforated ground plane.

The diameter and spacing of the holes determines the effective dielectric constant of the material surrounding the RDRAs. This technique of fabricating RDRAs using perforations is intended for reflectarray applications, eliminating the need to position and bond individual elements and making the fabrication of RDRA reflectarray feasible. For perforated ground plane, S=1.5 mm, D=1.2 mm and h_1=0.35 mm. The relationship between the RDRA element length and reflecting phase shift at 12 GHz for the unit cell in Fig. 1 and Fig. 2 was determined using CST simulator [23] that depends on the finite integration technique [24, 25]. The software is used to model an infinite array of RDRA elements. This procedure assumes that the reflection from an element RDRA surrounded by RDRAs of different sizes can be approximated by the reflection of an element in an infinite array of identical RDRAs. A normal incident plane wave on a periodic infinite array was assumed to calculate the reflection phase change of one element. A typical plot of the reflection phase shift as a function of RDRA element length is shown in Fig. 3. The radius of the hole of the perforated ground plane, the distance between two holes and numbers of holes are optimized to give the results in Fig. 3. The tuning range of the reflection phase shift is 360 degrees. Excellent agreement is obtained between the results of RDRA on solid ground plane and that for perforated ground plane. Results of this study indicate that this perforation technique is a promising alternative for one using individual RDRAs elements.

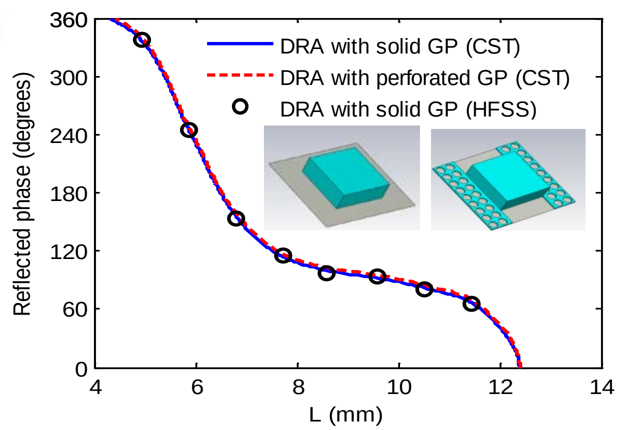


Fig. 3 Reflected phase of RDRA cell versus its length at 12 GHz, h= 3.2mm, W= 7mm, S = 1.5mm, h_1=0.35mm , D = 1.2mm, and L_1= W_1= 13.5mm.

III. NUMMERICAL RESULTS

Numerical calculations were performed by using the CST simulator, the horn, and reflectarray elements are included in the calculation. The required phase shifts of reflectarray elements in the broadside RDRA reflectarray is shown in Fig. 4. The normalized gain patterns for the broadside feed reflectarray at 12 GHz in E-plane and H-plane are shown in Fig. 5. The half-power beamwidth (HPBW) of the main beam is 5 degrees. A peak gain of 29.9 dB is predicted at $\theta=0^o$. Figure 6 shows peak gain variation with frequency. A 9.1% bandwidth is achieved with 1 dB gain variation (11.4 GHz–12.5 GHz). The aperture efficiency is 50.1%.

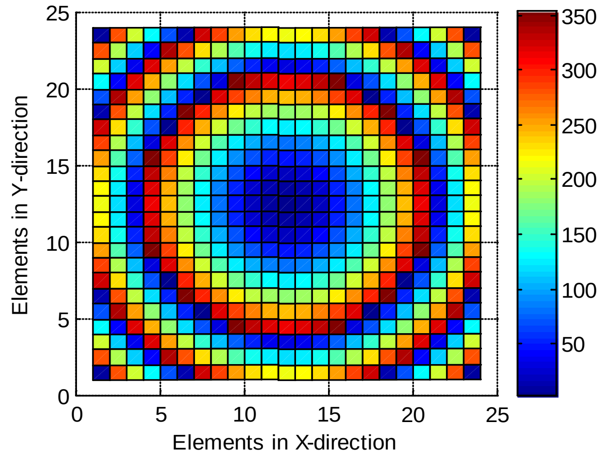
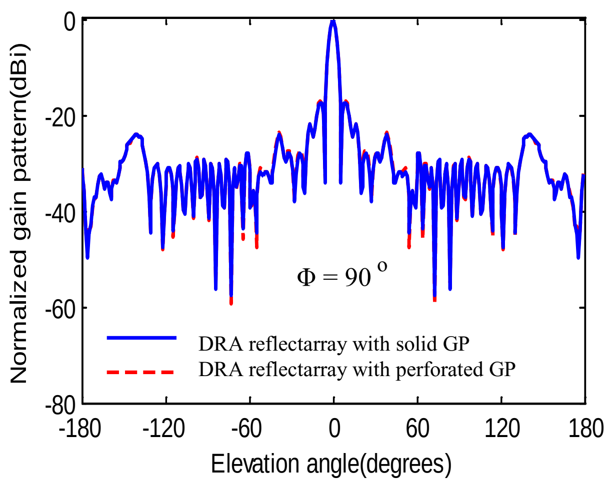
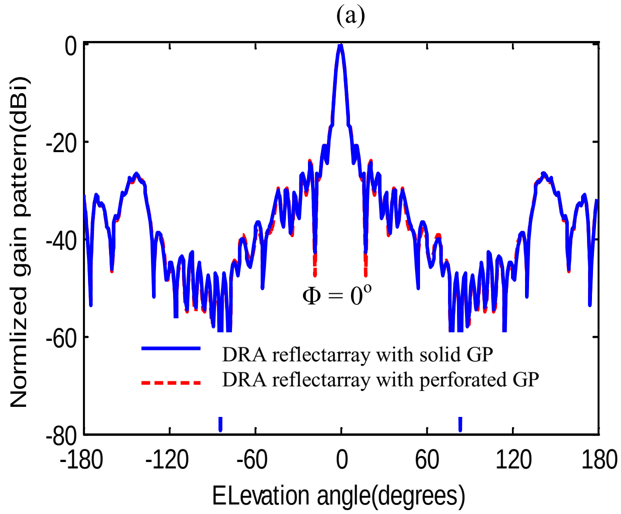


Fig. 4. The required phase shifts of the reflectarray elements.



(a)



(b)

Fig. 5. Normalized gain patterns at 12GHz for 23×23 broadside reflectarray. (a) E-plane. (b) H-plane.

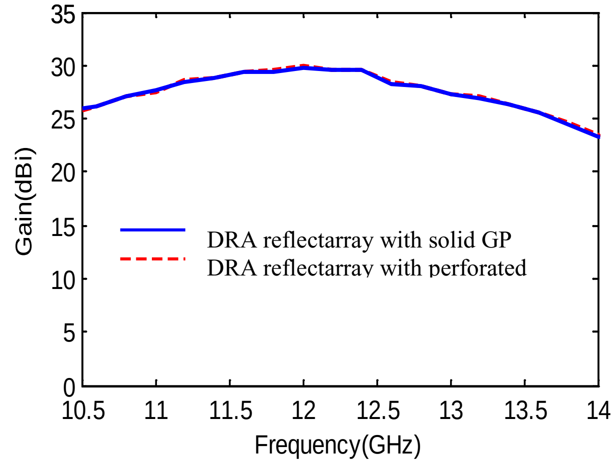


Fig. 6. The required phase shifts of the reflectarray elements.

The schematic drawing and the close up picture of the reflectarray elements with perforated ground plane and rectangular concave dip are shown in Fig. 7. An air gap is introduced between the RDRA and the ground by adopting a concave ground plane in each cell. The rectangular concave surface has dimensions L_c=4.5 mm and h_c=2 mm.

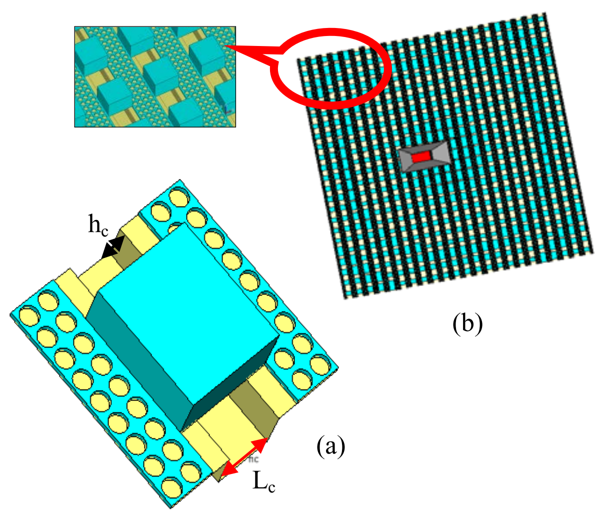
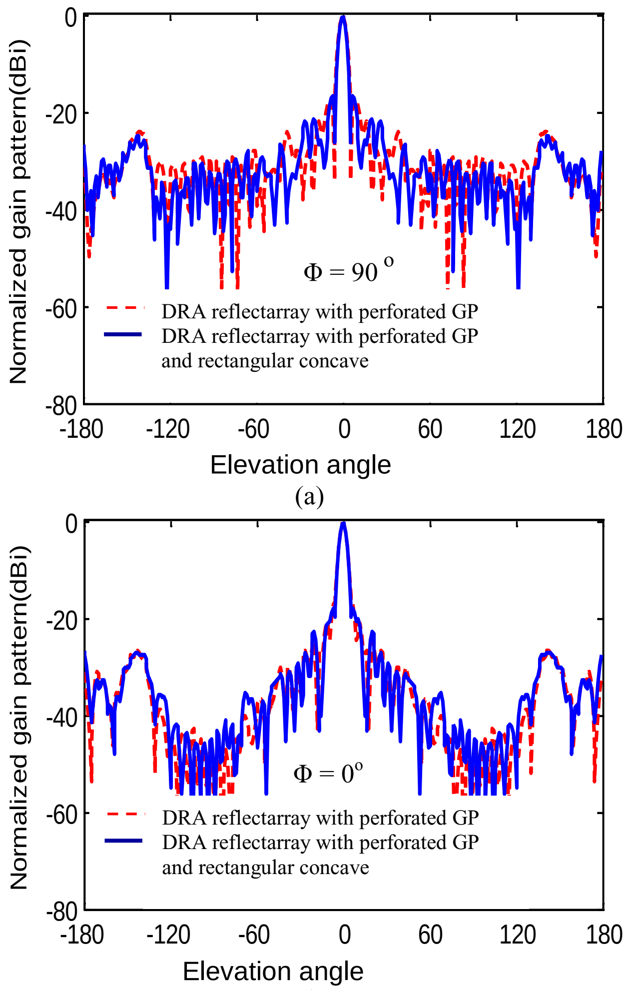


Fig. 7. (a) DRA cell with perforated GP and rectangular concave. (b) Broadside RDRA reflectarray with perforated GP and rectangular concave.

The normalized gain patterns in the E-plane and H-plane at 12 GHz frequency are illustrated in Fig. 8. The 3-dB beamwidth is 4 degrees. A peak gain of 30.6 dB is predicted at θ=0°. Simulated gain patterns at different frequencies to check the bandwidth of the array are shown in Fig. 9.

At the extreme frequencies, the gain patterns are similar with some increase in sidelobe levels and little gain variations. Figure 10 shows peak gain variation with frequency. Note the gain bandwidth is substantially improved to about 13.33%, the reflectarray can cover from 11.4 GHz to 13 GHz with 1 dB gain variation. The aperture efficiency is 57.88%.

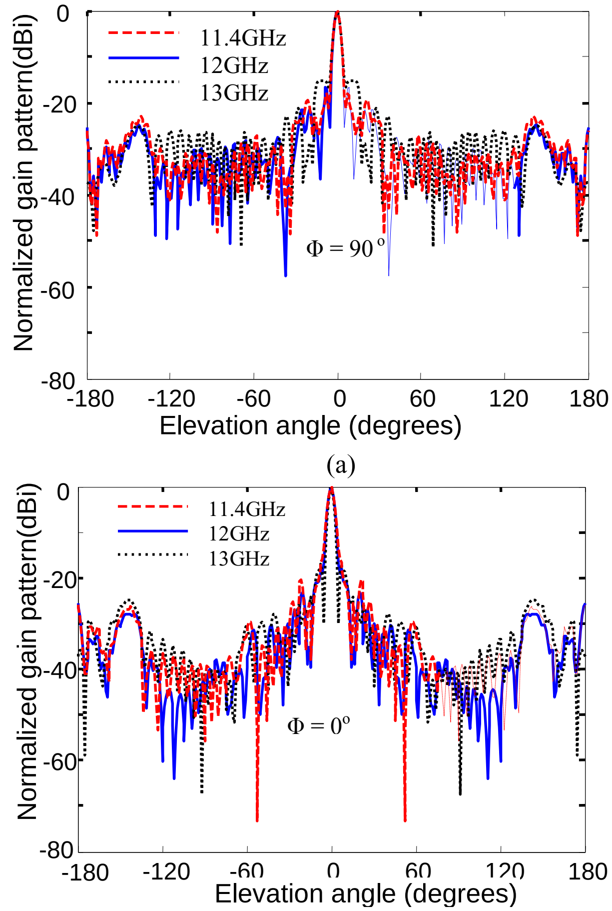


(a)

(b)

Fig. 8. Normalized gain patterns at 12GHz for 23×23 broadside RDRA reflectarray: (a)E-plane. (b) H-plane.

To minimize the feed blockage of a center-fed configuration, the reflected beam must be directed out of broadside direction. Another RDRA reflectarray with a concave ground plane with 30 degrees off broadside beam direction was designed. Figure 11 shows the construction of the 30 degrees off broadside RDRA reflectarray with perforated ground plane and rectangular concave dip.



(a)

(b)

Fig. 9. Normalized gain patterns at different plane for 23×23Broadside RDRA reflectarray. (a) E-plane. (b) H-plane.

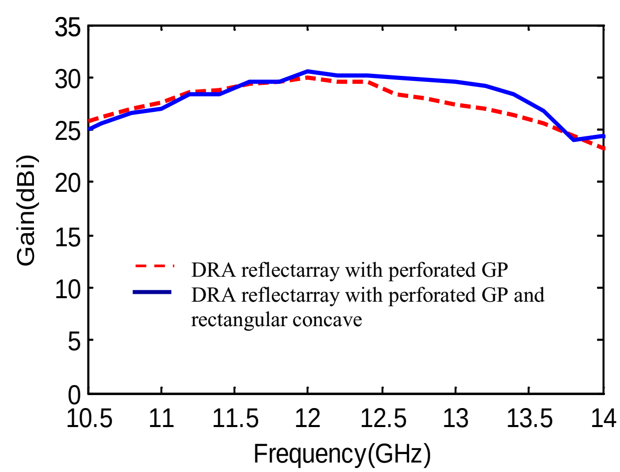


Fig. 10. Peak gain versus frequency for 23×23broadside RDRA reflectarray.

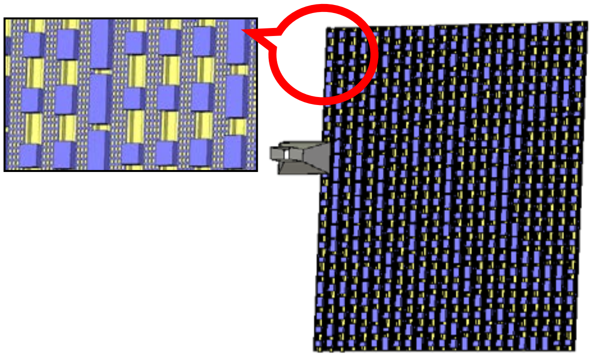


Fig. 11. 30 degrees off broadside RDRA reflectarray with perforated GP and rectangular concave.

Figure 12 shows the gain pattern on the H-plane (x-z plane). It achieves a peak gain of 29 dB. The 3 dB beamwidth is 5.5 degrees. Figure 13 shows peak gain variation with frequency. For the frequency band between 11.4 to 12.4 GHz, the gain is varying by 1 dB only. An 8.3% bandwidth is achieved. Again, the reflectarray is designed to produce main beam with tilt angle of -30 degrees from the broadside direction. The gain pattern at 12 GHz frequency for -30 degrees off broadside direction RDRA reflectarray is shown in Fig. 14. Figure 15 shows peak gain variation with frequency. The aperture efficiency is 40.6%.

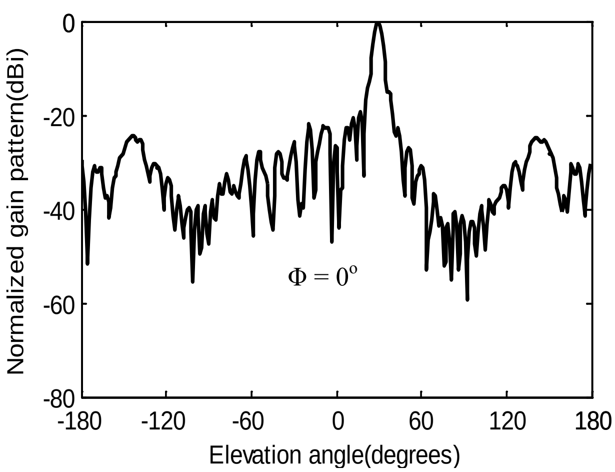


Fig. 12. H-plane patterns at 12GHz for 30 degrees off broadside RDRA reflectarray.

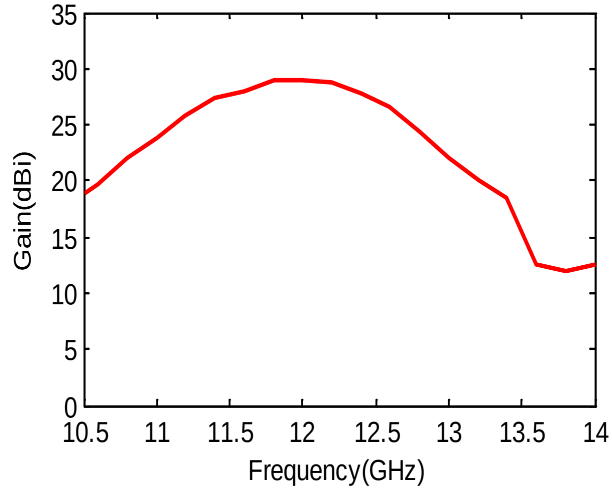


Fig. 13. Peak gain versus frequency for 30 degrees off broadside RDRA reflectarray.

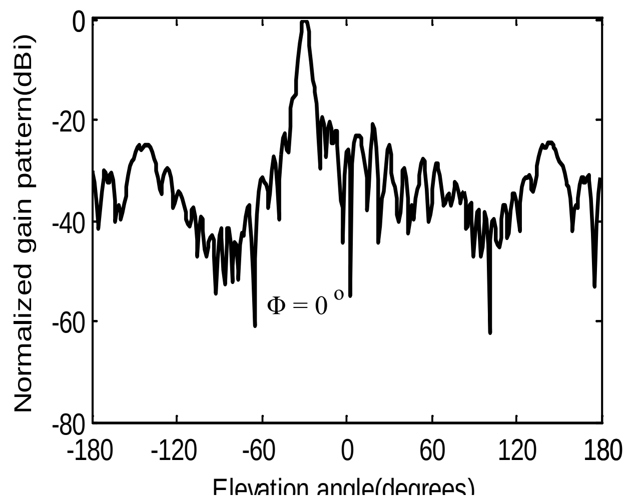


Fig. 14. H-plane patterns at 12GHz for -30 degrees off broadside RDRA reflectarray.

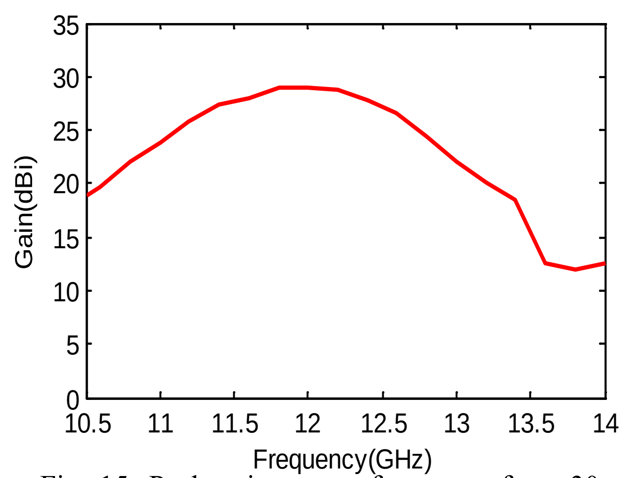


Fig. 15. Peak gain versus frequency for -30 degrees off broadside RDRA reflectarray.

Figure 16 shows the offset feed RDRA reflectarray with perforated ground plane and rectangular concave dip. The reflectarray is fed by linearly polarized pyramidal horn antenna at a tilt angle of 17^{o} as to minimize the feeder blockage. The gain patterns in the E-plane and H-plane at 12 GHz frequency are illustrated in Fig. 17. The 3-dB beamwidth is 5.5 degrees. The computed peak gain is 30 dB. Figure 18 shows the peak gain variation with frequency. For the frequency band between 11.4 to 12.7 GHz, the gain is varying by 1 dB only. The gain bandwidth is approximately 10.9% and the aperture efficiency is 47%.

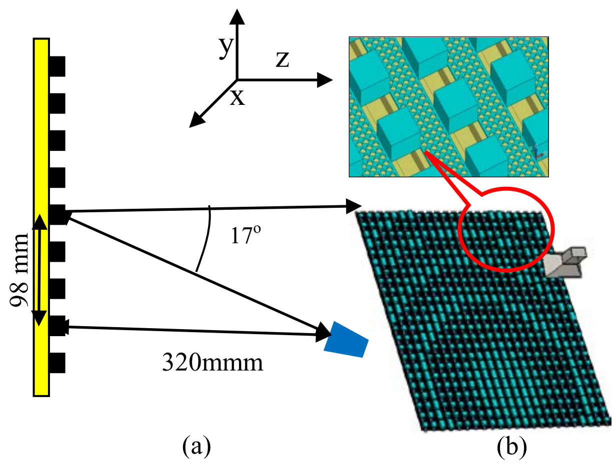


Fig. 16. (a) Offset feed broadside reflectarray with solid GP. (b) Offset feed broadside reflectarray with perforated Gp and rectangular.

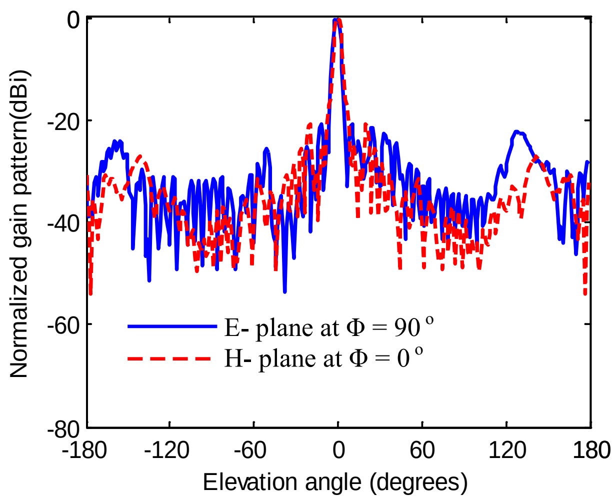


Fig. 17. Normalized gain patterns at 12GHz for 23×23 broadside RDRA reflectarray.

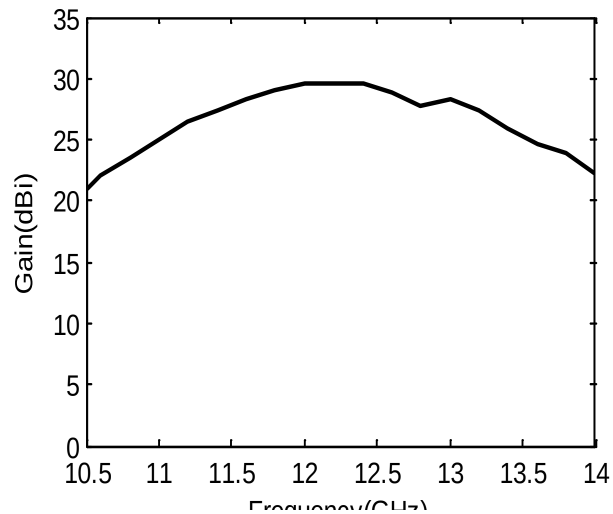


Fig.18. Peak gain versus frequency for 17 degrees offset feed broadside RDRA reflectarray.

VI. CONCLUSION

Perforated dielectric resonator antenna reflectarray was designed for linear polarization at 12 GHz. The RDRA elements are formed from one piece of material. Air-filled holes are drilled into the material around the RDRA. The performance of the array is similar to that achieved by one using individual RDRA. A novel wideband RDRA is proposed, where an air gap is introduced between the RDRA and ground by introducing a concave ground plane dip. A 23x23 reflectarray is used. The reflectarray is illuminated by a linearly polarized pyramidal horn. In this paper, a variable length RDRA was used to achieve the required phase shift at each cell on the reflectarray surface. To avoid the feed blockage of a center-fed configuration, the reflectarray was center fed and the beam peak location was designed to be ± 30 degrees off boresight. Also, the antenna was offset fed by a linear polarized pyramidal horn. The gain bandwidth is approximately 10.9% and the aperture efficiency is 47%.

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