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TRANSMITARRAY USING PERFORATED DIELECTRIC MATERIAL FOR WIDEBAND APPLICATIONS

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Abstract—In this paper, linearly polarized transmitarray is investigated as to avoid the usage of multi-layers for improving the bandwidth of transmitarray. The transmitarray is formed from a single dielectric sheet by perforating selected areas of the material. A perforated dielectric layer is divided into square cell elements. Each cell has four holes with the same diameters. Holes with different diameters in the cell elements are used to allow continuous tuning of the transmitted signal's phase over 360° range with a maximum loss of 3.6 dB at 10 GHz. The transmission coefficient versus the diameter of the holes is calculated by using the finite integration technique. The results are compared with those calculated with transmission line method for verification. The focal-to-diameter ratio of the transmitarray is optimized for lower side lobe level and highest transmitarray gain. A comparison between the transmitarray and the reflectarray with the same aperture area is illustrated.

1. INTRODUCTION

In the last few years reflectarrays and tranmitarrays have received an interesting attention. The reflectarray is a good alternative to reflector antenna which is the most commonly used high gain and narrow beamwidth antenna in radar and communication [1–3]. The disadvantage of the reflectarray is the offset feed structure to avoid blocking loss. The offset geometry destroys the symmetry of an antenna aperture and increases the angle of incident wave. The transmitarray combines the features of the lens and phased array antennas. In transmitarray, there is no ground plane so, the incident

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electromagnetic wave transmits through the surface and converted from spherical wave into a plane wave [4, 5]. The design of a reflectarray is simpler than that of a transmitarray antenna because the radiating element must provide only the required phase compensation for the incident wave as well as the reflection coefficient compensation. In the transmitarray, the radiating element has to provide both the transmission and phase compensation at the same time. The main drawback of the transmitarray is its limited bandwidth. Transmitarray is important for satellite-based telecommunication systems, and radar systems.

Various transmitarray approaches have been described in the literature. Transmitarrays have been designed using microstrip patches connected through multiple layers by a delay line [6]. A four-layer transmitarray operating at 30 GHz is designed using a dual-resonant double square ring as the unit cell element in [7, 8]. Results of a 7.5%, −1 dB gain bandwidth and 47% radiation efficiency are reported.

In this paper a wideband transmitarray using perforated dielectric material is presented. The transmitarray is made from one piece of dielectric material sheet; with a perforated dielectric and completely eliminating all the rest of the dielectric materials. The perforations result in changing the effective dielectric constant of the dielectric material [9–12]. The simplicity of the structure makes it practical in terms of cost, space, and ease of fabrication. This structure is used to avoid the usage of multi-layers for improving the bandwidth of the transmitarray. Reflectarrays using perforated substrates are explained in [13–15]. The transmitarray is designed to operate at 10 GHz. It is composed of 21×21 cell elements and is covering an area of $31.5 \times 31.5\,\text{cm}^2$. Each cell element had four hole with area of $15 \times 15\,\text{mm}^2$. A variable hole diameter provides the required phase shift at each cell on the transmitarray surface. The gain patterns, the frequency bandwidth, and the aperture efficiency for the tansmitarray are calculated. A comparison between the transmitarray and the reflectarray with the same aperture area is explained. The structure is modeled and designed using the finite integral technique (FIT) [16] and the results are compared with those calculated by the transmission line model (TLM) [17] for verification.

The paper is organized as follows. Section 2 shows the simulation results for the perforated transmitarray. In Section 3, a comparison between the transmitarray and the reflectarray is presented. Finally, the conclusions are drawn in Section 4.

2. PERFORATED TRANSMITARRAY

The transmitarray is to transform the spherical wave emanating from the feed into a plane wave at the output. Considering the array on the x-y plane illuminated by a feed horn, the required phase distribution, $\phi(x_i, y_i)$, at each element of the array to collimate a beam in the (θ_o, φ_o) direction is determined as

$$\phi(x_i, y_i) = k_o (L_i - \sin\theta_o(x_i \cos\varphi_o + y_i \sin\varphi_o)) \tag{1}$$

$$L_i = \sqrt{(x_i - x_f)^2 + (y_i - y_f)^2 + z_f^2} \tag{2}$$

where k_o is the propagation constant in vacuum, L_i is the distance from the feed horn (x_f, y_f, z_f) to the element i of the array and (x_i, y_i) are the coordinates of the cell element i. The transmitarray should theoretically be capable of producing a transmission phase shift between 0 and 360° at each cell element location and the magnitude of the transmission coefficient, $|S_{21}|$ is approximately equal one, then no signal will be reflected from the structure [18–20]. In this paper the desired phase shift from each cell element is obtained by changing the effective permittivity of the dielectric substrate through the variation of the diameters of the holes according to the theory of perforated dielectric material which is based on [12]:

$$\varepsilon_{eff} = \varepsilon_r(1 - \alpha) + \alpha \tag{3}$$

$$\alpha = \frac{\pi}{2\sqrt{3}} \left(\frac{d}{s}\right)^2 \tag{4}$$

where s is the distance between the hole centers and d is the diameter of the hole.

The configuration of the proposed unit cell is shown in Figure 1. The cell element of the transmitarray consists of square cell, with

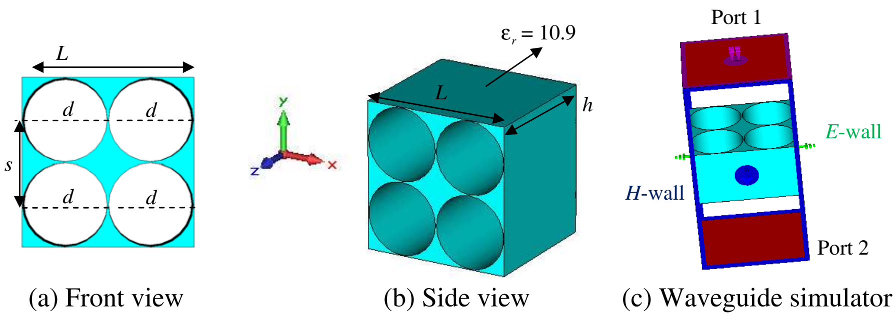
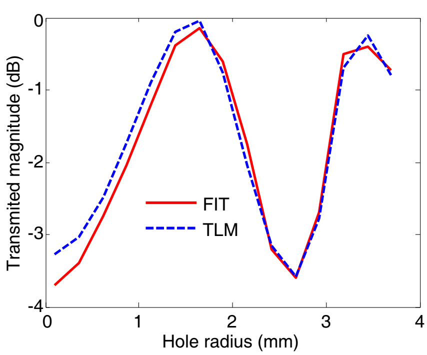
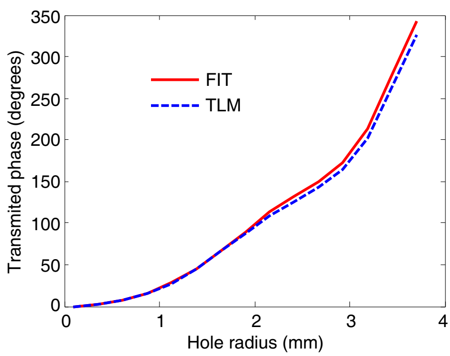


Figure 1. Unit cell structure.

length $L = 15\,\text{mm}$, and AD1000 substrate thickness $h = 9.5\,\text{mm}$ with $\varepsilon_r = 12$, (The dielectric material for the dielectric resonators is HiK500F) and each cell has four circular holes of equal diameters. The number of the holes in the cell element is optimized to maximize the transmission coefficient through the structure. The relationship between variable hole diameter and transmission coefficient at 10 GHz was then determined using the finite element method. The cell is backing in the middle of the waveguide simulator (see Figure 1(c)). The perfect electric and magnetic wall boundary conditions are applied to the sides of the surrounding waveguide, and result in image planes on all sides of the unit cell [1-chapter three]. In this manner, the cell element is repeated to infinity in the simulator. There are several limitations to the infinite array approach. First, all elements of the

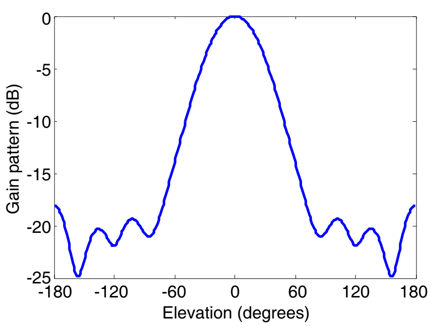


(a)

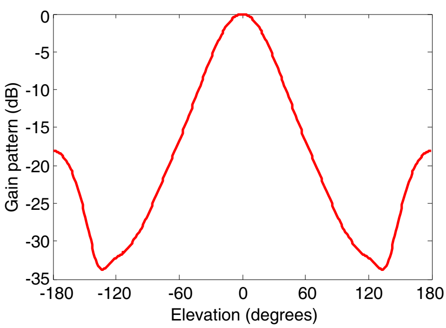


(b)

Figure 2. Transmission (a) magnitude and (b) phase versus hole radius.



(a) *E*-plane



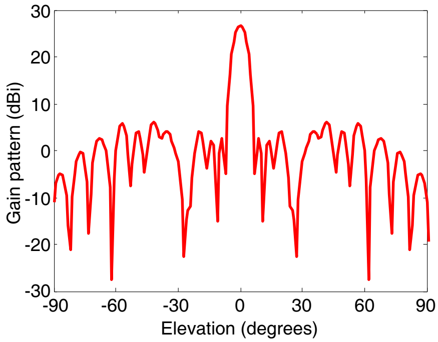
(b) *H*-plane

Figure 3. Gain patterns for the feed horn.

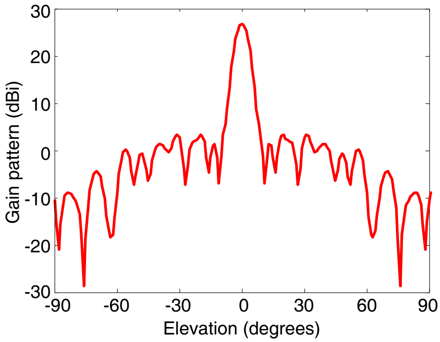
array are identical; this is clearly not the case in a real transmitarray in which the diameters of the holes in the cell element must vary according to the phase compensation required. Secondly, the transmitarray itself is not infinite in extent. Consequently, edge effects such as diffraction are not accounted for in the simulation. The variation of the transmission magnitude and phase versus the hole radius is determined using the FIT technique and are illustrated in Figure 2. The results are compared with that calculated using the TLM method to make sure of it. Good agreement between the two approaches is obtained.

Table 1. Side-Lobe level (SLL) level and gain of the transmitarray for different ratios of F/D.

F/D	The highest SLL in H-plane	The highest of SLL in E-plane	Peak gain at 10 GHz	-1 dB gain bandwidth
0.6	3.1 dB	6 dB	26.4 dB	3.6 GHz (36%)
0.7	4.4 dB	7 dB	27.3 dB	3.55 GHz (35.5%)
0.8	6.4 dB	7 dB	27.1 dB	3.05 GHz (30.5%)
0.9	7.8 dB	8.6 dB	27.14 dB	2.55 GHz (25.5%)
1	8.9 dB	9 dB	26.8 dB	1 GHz (10%)



(a) E-plane

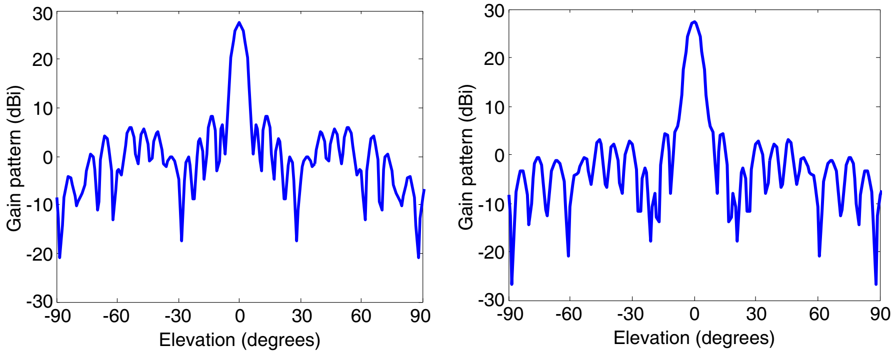


(b) H-plane

Figure 4. Patterns plot of 21×21 cell elements transmitarray with $F/D = 0.6$.

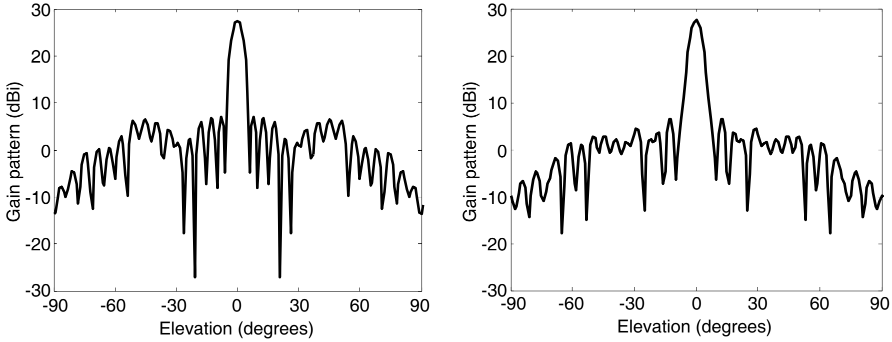
Simulation results are showing from 0° to 355° of phase variation with less than 3.6 dB of variation in transmission magnitude throughout the tuning range.

The transmitarray is composed of 21×21 cell elements and is covering an area of $315 \times 315\,\mathrm{mm}^2$ in x-y plane. A linearly polarized pyramidal horn is used as the feed. The feed horn was 59.9 mm long, with an aperture size of $49.5\,\mathrm{mm} \times 29.9\,\mathrm{mm}$. The radiation patterns for the pyramidal horn in E-plane and H-plane are shown in Figure 3 at 10 GHz. The focal length-to-diameter ratio F/D is optimized for lower side lobe levels and highest transmitarray gain. Five transmitarrays are



(a) *E*-plane (b) *H*-plane

Figure 5. Patterns plot of 21×21 cell elements transmitarray with $F/D = 0.7$.



(a) *E*-plane (b) *H*-plane

Figure 6. Patterns plot of 21×21 cell elements transmitarray with $F/D = 0.8$.

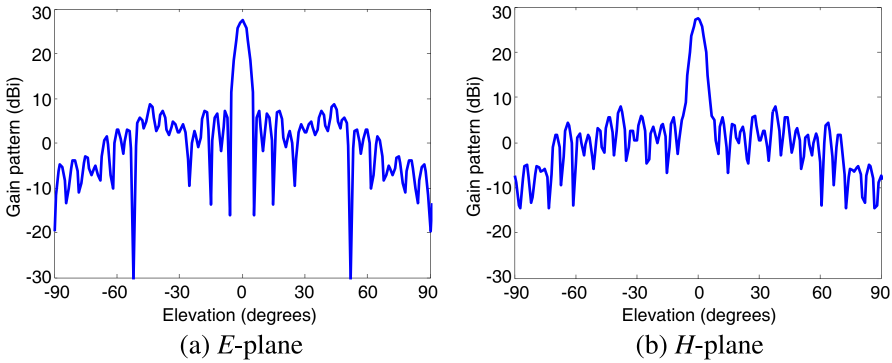


Figure 7. Patterns plot of 21 × 21 cell elements transmitarray with $F/D = 0.9$.

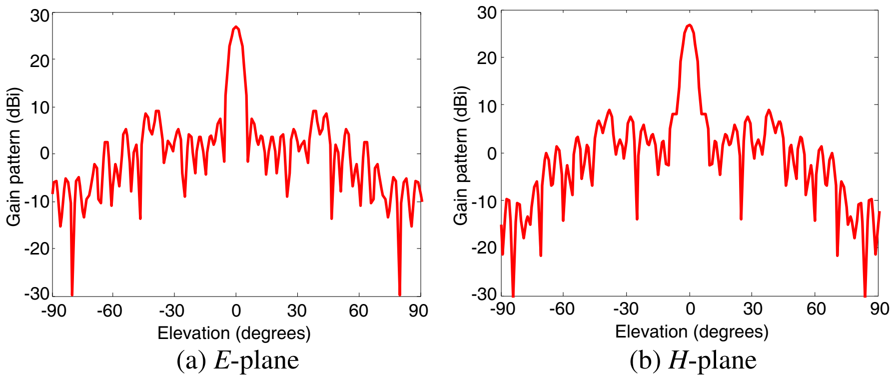


Figure 8. Patterns plot of 21 × 21 cell elements transmitarray with $F/D = 1$.

simulated using the finite integration technique, FIT, for $F/D = 0.6$, 0.7, 0.8, 0.9, and 1. The E-plane and H-plane patterns for the transmitarrays are shown in Figures 4–8. Also shown in Figure 9 are gain against frequency responses for different F/D ratios. The results are summarized in Table 1.

From Table 1, the transmitarray with $F/D = 0.7$ is chosen for maximum peak gain and reasonable bandwidth. Going beyond that for the F/D ratio reduces the bandwidth to end up as a narrow-band array. The transmitarray layout at 10 GHz with $F/D = 0.7$ is shown in Figure 10.

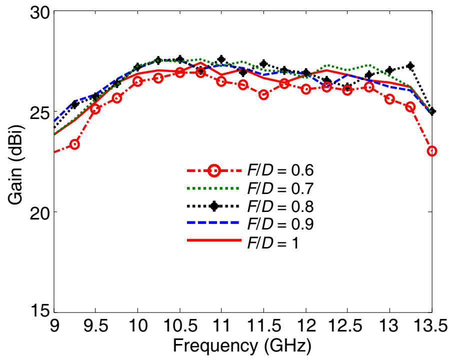
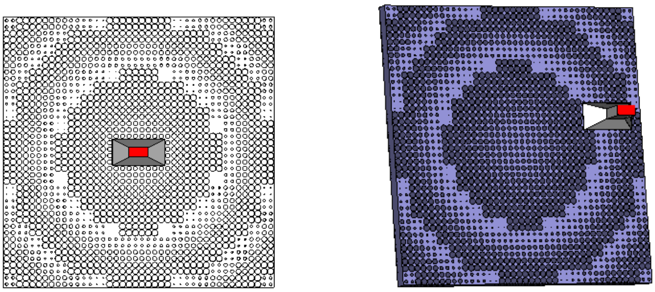


Figure 9. Gains versus frequency with different F/D for 21×21 cell elements transmitarrar.

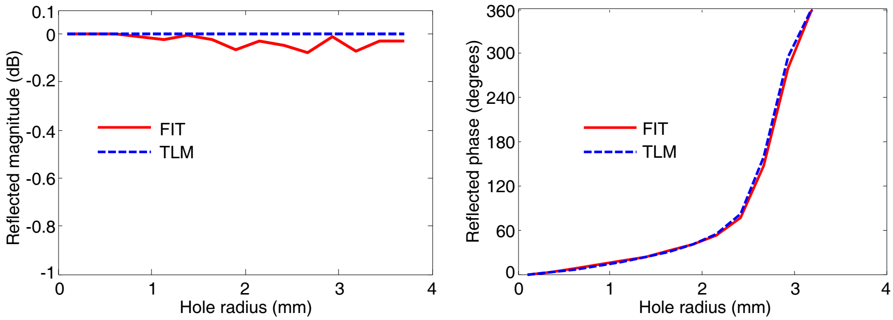


(a) Front view (b) 3D view of cell

Figure 10. Transmittarray layout with $F/D = 0.7$.

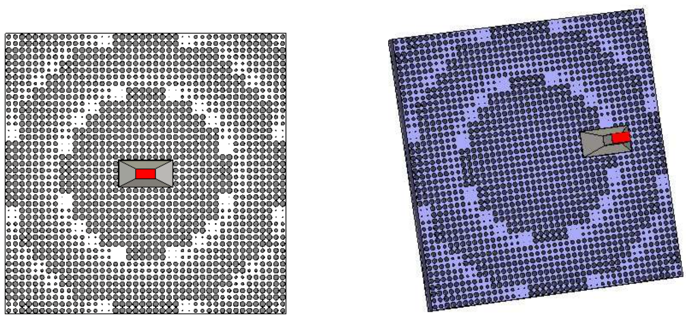
3. COMPARISON BETWEEN THE PERFORATED DIELECTRIC MATERIAL REFLECTARRAY AND TRANSMITARRAY

The reflectarray that consists of similar square dielectric cell elements is to be considered in this section. Each unit cell has four circular holes of equal diameters and is supported on perfect conducting ground plane. The single cell is covering an area of $15 \times 15\,\text{mm}^2$. The substrate thickness $h = 10\,\text{mm}$ with $\varepsilon_r = 10.9$, i.e., same material as that for the transmitarray is used. A typical plot of the reflection coefficient, S_{11}, as a function of hole radius, used in the design of a 21×21 elements, is shown in Figure 11. The reflection phase variation covers approximately a range of $0°$ to $360°$ degrees. Good concordance between the FIT results and TLM is obtained. The reflectarray has the same aperture area of the transmitarray. It is



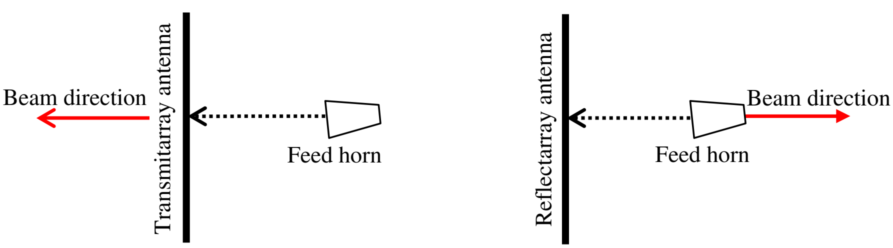
(a) (b)

Figure 11. Reflection coefficient versus the hole radius, (a) magnitude, (b) phase.



(a) Front view (b) 3D view

Figure 12. Reflecttarray layout at 10 GHz.



(a) Transmitarray (b) Reflectarray

Figure 13. Geometry of the array.

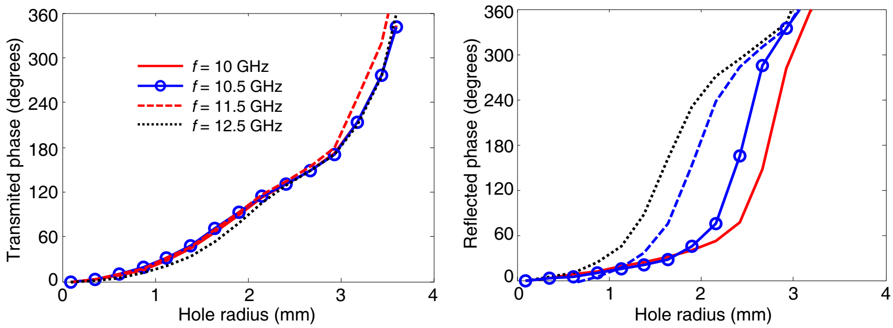


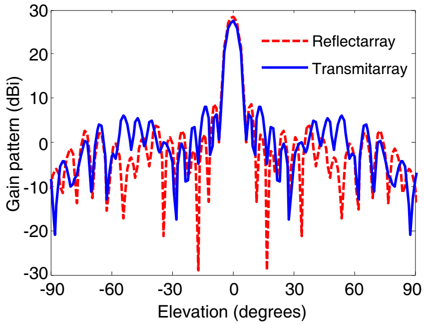
Figure 14. The variations of the the reflected phase and the transmitted phase with the hole radius at different frequencies.

Table 2. Comparison between the transmitarray and the reflectarray parameters.

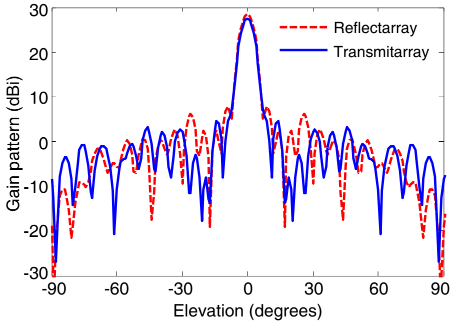
Array	Peak gain at 10 GHz	3-dB beamwidth	Aperture efficiency	−1 dB gain bandwidth
Transmitarray	27.3 dB	5.6°	38.7%	3.55 GHz (35.5%)
Reflectarray	28.4 dB	5.85°	49.9%	0.75 GHz (7.5%)

covering an area of $315 \times 315\,\text{mm}^2$ with $F/D = 0.7$ as shown in Figure 12. Geometry of the reflectarray and transmitarray is illustrated in Figure 13. The reflectarray is center fed by linearly polarized pyramidal horn antenna. The variations of the transmitted phase for the transmitarray and the reflected phase for the the reflectarray against the hole radius at different frequencies above 10 GHz are shown in Figure 14. It is noticed that the reflected phase for the reflectarray is more sensitive to the frequency variations than that for the transmitarray. Computed radiation patterns of the reflectarray compared with that of the transmitarray in E-plane and H-plane at $f = 10\,\text{GHz}$ are shown in Figure 15, respectively. Figure 16 shows the gain as function of the frequency. Broadband transmitarray was shown to achieve a maximum 1 dB gain bandwidth close to 35.5%. The computed aperture efficiency is about 38.7%. Table 2 shows the comparison between the transmitarray and the reflectarray parameters.

The peak gain for the transmitarray is less than that of the reflectarray by 1.1 dB at 10 GHz. This is due to the reflected power at the surface of the perforated dielectric in case of the transmitarray. The



(a) E-plane



(b) H-plane

Figure 15. Gain patterns plot of 21×21 cell element reflectarray with $F/D = 0.7$.

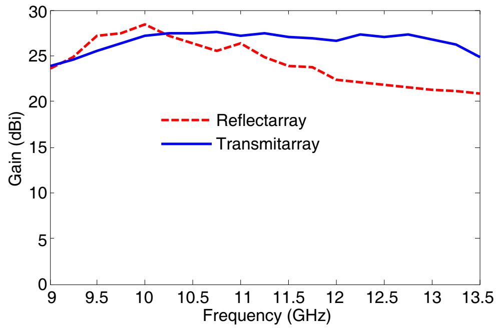


Figure 16. Gains versus frequency.

reflectarray has an inherent narrow bandwidth, because it depends on resonating dielectric blocks. This is not the case for the transmitarray, therefore it has a wider bandwidth than the reflectarray. For arrays of the same size and F/D ratio, and as has been indicated in Table 2, both the transmit and receive arrays have almost the same gain and beamwidth. The transmitarray shows a higher gain than the reflectarray from 10.5 GHz to 13.5 GHz because of the sensistivity to the frequency variations of the reflected phase as shown in Figure 14.

4. CONCLUSION

The simulated performance of the transmitarray using perforated dielectric material has been presented. The transmitarray used consists of 21×21 square cell elements. Four holes with the same diameters were introduced for each cell element. The diameters of the holes vary from a cell to the other according to the needed phase shift. In this paper some design criteria like F/D and the simulation results have been presented. The simulation was carried out using the finite integration technique and the results are compared with those calculated by the transmission line method for verification. Results of this study indicate that this perforated transmitarray is a promising alternative for the multi-layers transmitarray as well as the parabolic reflector antennas. A comparison between the perforated reflectarray and the transmitarray with the same aperture size is made. It has been shown that the transmitarray is having a wider bandwidth with almost the same gain and beamwidth for the same F/D ratio.

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