Perforated Transmitarray-Enhanced Circularly Polarized Antennas for High-Gain Multi-Beam Radiation

S.H. Zainud-Deen[1], S.M. Gaber[2], H.A. Malhat[1*], and K.H. Awadalla[1]
[1]Faculty of Electronic Eng., Menoufia University, Egypt, [*]er_honida1@yahoo.com
[2]Egyptian Russian University, Egypt, shaymaa.gaber@yahoo.com

***Abstract*- The paper presents the radiation characterization of 2×2 sub-array DRA antennas combined with the transmitarray to form directive beam system. Using the transmitarray increases the size of the radiating aperture and enhances the directivity of the 2×2 sub-array DRA antenna. The advantages of using the transmitarray is observed to be 6 dBi extra gain. The antenna array design is optimized by full-wave simulation for high gain radiation up to 18.8 dB. The transmitarray designed at frequency of 10 GHz. The unit cell element in the transmitarray achieves 360 degrees of phase agility with less than 3 dB of variation in transmission magnitude in the tuning range. Single-feed dual-beam perforated transmitarray antenna designs will be investigated for covering two regions at the same time. The transmitarray introduces dual beam at ± 45 degrees. The antenna introduces maximum gain of 12.5 dB at the dual direction with circular polarization characteristics.**

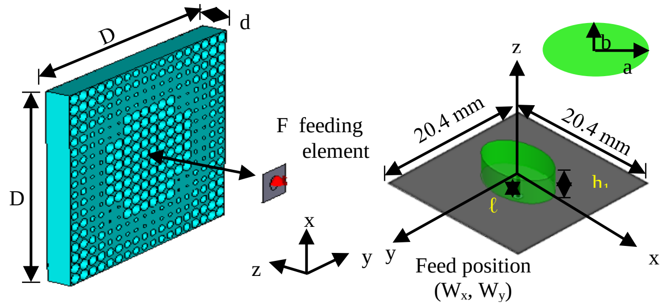
I. INTRODUCTION

High gain antennas are desired in various applications, such as satellite communications, and wireless broadcasting. Recently, the gain and radiation patterns of planar printed antenna can be improved by covering the antenna with a superstrate at a specific distance in free space [1]. Various configurations of superstrates were used to improve the radiation performance of the antenna, such as dielectric slabs [2], electromagnetic bandgap (EBG) structures [3], highly-reflective surfaces [4], and the most recently artificial magnetic superstrates [5]. In these entire configurations, the substrate-superstrate spacing and the thickness of the superstrate are optimized for antenna gain enhancement. High permeability superstrate is required to achieve very high radiation from the patch antenna. Artificial magnetic structures (AMS) can be used to provide such superstrate [5]. DRAs have attracted broad attention in many applications due to their attractive features such as high radiation efficiency, wide bandwidth, light weight, and small size [6]. One drawback with DRAs is that they have low directivity. In 1968, the idea of left-handed metamaterial (LHM) with simultaneously negative permittivity and permeability was conceived by Veselago [7]. Recently, they have started to be used as superstrates for planar antennas, working in the transmission bands of the LHM [8,9] with the goal of improving the radiation performance of antennas. A high-directivity DRA with metamaterial is presented in [10]. The metamaterial was positioned over a cylindrical DRA mounted on curved ground plane to improve its directivity. Three different types of metamaterials as superstrates, viz., S-shape, split ring resonator, and cubic high dielectric resonator are discussed. The metamaterial structure is used as a lens to improve the directivity of DRA. The distance between the metamaterial superstrate and the cylindrical DRA antenna is optimized for high directivity, small half-power beamwidth, and wide impedance bandwidth and matched input impedance. More recently, planar dielectric slab is used with an array of dielectric resonators to further enhance the array gain as well as reducing the number of the array elements by 75% in [11]. In [12], the lens-enhanced phased array configuration was proposed and studied for implementing high-directivity steerable antennas.

A transmitarray antenna combining the features of lens and phased array antenna is a paradigm for implementing high-directivity reconfigurable apertures. Like an optical lens, the elements of a transmitarray produce specific phase shift that, when properly tuned, can focus incident waves. The transmitarrays can be integrated into radomes for electronic beam scanning, or embedded into the walls or roofs of structures to create large high-directivity apertures. Various transmitarray approaches have been described in the literature [13-15]. In this paper, the gain of the circularly-polarized DRA antennas above a ground plane is enhanced by placing a transmitarray on top of the ground plane. The transmitarray is composed of a dielectric material with a lattice of holes. The separation between the holes and the number of the holes are optimized to maximize the transmission through the structure. The performance of the structure is validated by simulation using the finite element method (FEM) [16] and the finite integration technique (FIT) [17].

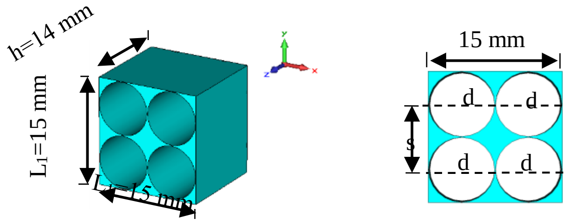
II. NUMERICAL RESULTS

Transmitarray using perforated dielectric material is shown in Fig.1a. The transmitarray is constructed from one piece of perforated dielectric material sheet. The perforations result in changing the effective dielectric constant of the dielectric material. The simplicity of the structure makes it practical in terms of cost, space, and ease of fabrication. The dielectric sheet had a thickness of 14 mm and a relative permittivity of ε_r =12. The transmitarray is composed of 9 × 9 unit cell elements and is covered an area of 13.5×13.5 cm^2 in x-y plane. Single elliptical DRA element fed the transmitarray is shown in Fig.1b. The configuration of the proposed unit cell is shown in Fig.2a. A square cell with length L =15 mm, and substrate thickness h = 14 mm with ε_r =12 is used. The 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 FIT method was used to simulate the unit cell element of this transmitarray antenna. The unit cell is simulated in an infinite periodic array. A circularly polarized normal incident plane wave is illuminated the two-dimensional infinite array of similar unit cells. The variations of the transmission magnitude and phase versus the hole radius are illustrated in Fig.3. The results are compared with that calculated using the FEM method at 10 GHz to validate them. Good agreement between the two approaches is obtained. Simulation results are showing from 0° to 345° of phase variation with less than -4 dB of variation in transmission magnitude throughout the tuning range.



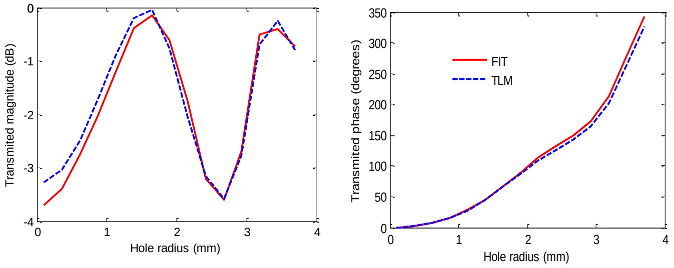
a. 3-D geometry b. Feeding element

Fig.1. Geometry of the 9×9 perforated transmitarray fed by single elliptic dielectric resonator antenna excited by a single probe.



a. 3-D view b. Front-view

Fig.2. The detailed dimensions of the unit-cell and the waveguide simulator arrangement.



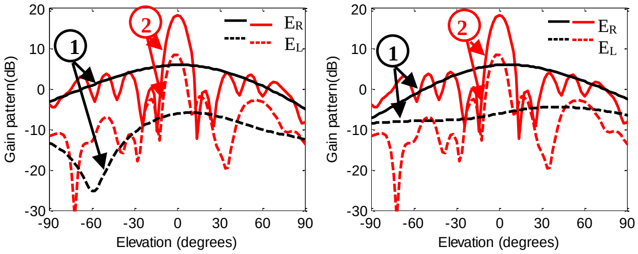
a. b.

Fig. 3. Transmission magnitude (a) and phase (b) versus hole radius.

In this paper, two numerical examples are given. In the first one, single elliptical DRA element fed the transmitarray is considered. Figure 1b shows the geometry of the structure. The semi-major axis a=5.25 mm, the semi-minor axis b=3.5 mm, h_1= 3.25 mm, ε_r= 12, ℓ= 2.78 mm and the feed probe radius of 0.25 mm. The probe is located (1.85 mm, 1.85 mm). The focal length–to-diameter ratio, F/D, is optimized for lower side lobe levels and highest transmitarray gain. Five transmitarrays are simulated using FIT for F/D = 0.5, 0.6, 0.7, 0.9, and 1. The results are summarized in Table I. As the total structures of antennas are very large, simulation with FEM method requires a huge amount of memory which makes it difficult. Consequently, the antennas were modeled and simulated by FIT method. The transmitarray is illuminated by the fields radiated from elliptical DRA antenna. The E-plane and H–plane patterns for the transmitarray are shown in Fig. 4 for F/D=0.6 and f=10 GHz. The output beam in this case points to the boresight direction, and directivity is 18.7 dBi that is 13.1 dBi higher than the value found for antenna alone (5.6 dBi). The transmitarray gain and axial ratio variations versus frequency are shown in Fig.5. The 1-dB gain variation bandwidth is 0.5 GHz. The band of circular polarization is not changed as the electromagnetic wave passes through the transmitarray.

Table I. Comparison between the radiation characteristics of 9×9 perforated transmitarray fed by single elliptic DRA at different ratios of F/D.

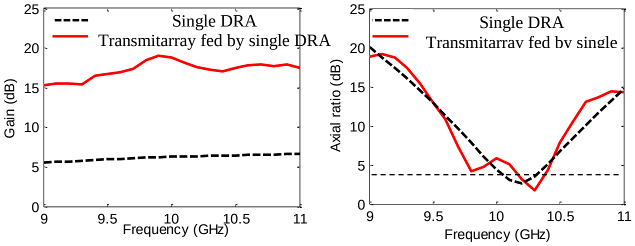
Array position F/D	Gain in dB at f= 10 GHz	1-dB gain variation BW	3-dB Axial ratio BW
1	16.2	0.5	zero
0.9	17.6	1.4	0.2
0.7	18.4	0.7	0.1
0.6	18.7	0.5	0.1
0.5	17.7	0.7	0.1



a. x-z (E-plane) b. y-z (H-plane)

Fig.4. The gain pattern and of the 9×9 perforated transmitarray fed by single elliptic DRA at F/D=0.6 at 10 GHz.

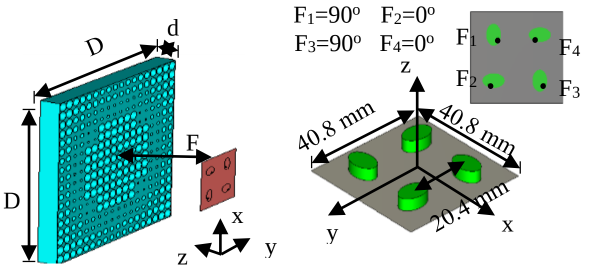
① Single DRA ② Transmitarray fed by Single DRA



a. Gain b. Axial ratio

Fig.5. The gain and axial ratio of the 9×9 perforated transmitarray at F/D=0.6.

In the last one, four elliptical DRA elements fed the transmitarray is considered. Fig.6a shows the geometry of four elliptical DRA elements in such 2×2 sub-array improve the gain of the antenna. Each element is fed uniformly in power from orthogonal feed points F_1 and F_2. The elements in one diagonal are 90° out of phase and rotated 90° in orientation relative to the elements in the other diagonal as shown in Fig.6b. The results of circular polarization components are summarized in Table II for F/D = 0.5, 0.6, 0.7, 0.9, and 1. The E-plane and H–plane patterns for the transmitarray are shown in Fig.7 for F/D=1. Narrow beamwidth with HPBW of 13 degrees is obtained in both the E-plane and H–plane. The axial ratio versus frequency is shown in Fig.8. The sub-array provides an extremely broadband axial ratio bandwidth due to the orthogonality of the array elements in phase and orientation.

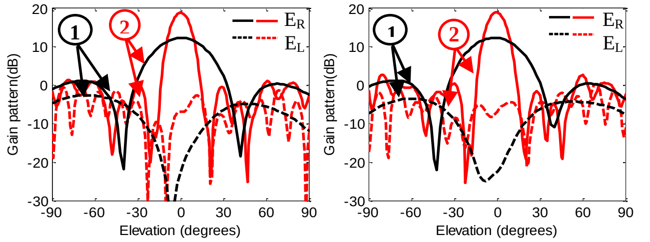


a. 3-D geometry b. Feeding element

Fig.6. Geometry of the 9×9 perforated transmitarray fed by 2×2 sequentially feed elliptic DRA sub-array.

Table II. Comparison between the radiation characteristics of 9×9 perforated transmitarray fed by 2×2 sequentially feed elliptic DRA sub-array at different ratios of F/D.

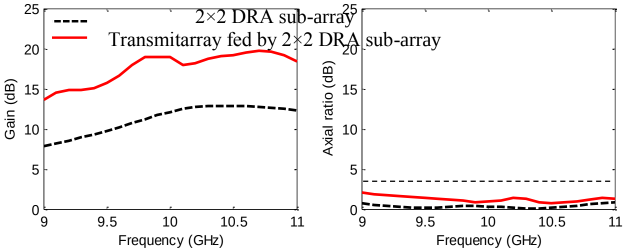
Array position at F/D	Gain in dB at f= 10 GHz	1-dB gain variation BW
1	19	0.4
0.9	18.6	1.2
0.8	18	0.8
0.7	18.7	0.8
0.6	16.8	0.5



a. x-z (E-plane) b. y-z (H-plane)

Fig.7. The gain patterns of the 9×9 perforated transmitarray fed by 2×2 sequentially feed elliptic DRA sub-array at F/D=1 and f= 10 Ghz.

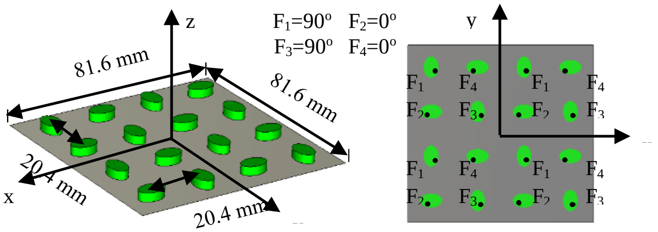
① 2×2 DRA sub-array ② Transmitarray fed by 2×2 DRA sub-array



a. Gain b. Axial ratio

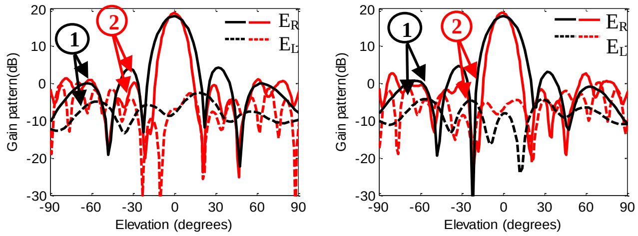
Fig.8. The gain and axial ratio of the 9×9 perforated transmitarray fed by 2×2 sequentially feed elliptic DRA sub-array at F/D=1.

To account for the number of DRA elements required for increasing the DRA gain and keeping on the circular polarization bandwidth 4×4 sequentially fed DRA phased array is investigated. Figure 9 shows a complete structure of the 4×4 sequentially fed DRA phased array in which the 2×2 DRA sub-array is employed and is repeated in sequential feeding manner. The E-plane and H–plane patterns for 4×4 sequentially fed DRA phased array compared with that of the transmitarray fed by 2×2 DRA sub-array are shown in Fig.10. The transmitarray introduces more directive beam with HPBW of 13 degree compared with 18 degrees for the 4×4 sequentially fed DRA phased array. The gain and axial-ratio variation versus frequency for 4×4 sequentially fed DRA phased array compared with that of the transmitarray fed by 2×2 DRA sub-array are shown in Fig.11. Approximately the same behaviors of the gain and axial ratio variation versus frequency are obtained with the transmitarray with reduction of the DRA elements to about 75%.



a. 3-D geometry b. Top-view

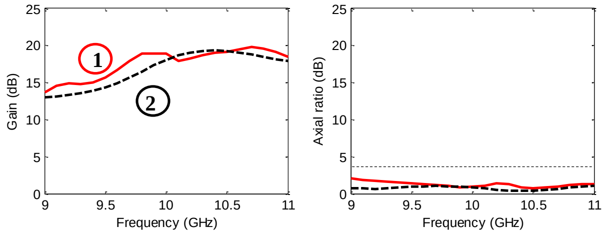
Fig.9. Geometry of the 4×4 sequentially feed elliptical DRA phased array.



a. x-z (E-plane) b. y-z (H-plane)

Fig.10. The gain patterns of the 4×4 sequentially feed elliptic DRA phased-array at f= 10 GHz.

① 4×4 DRA phased-array ② Transmitarray fed by 2×2 DRA sub-array

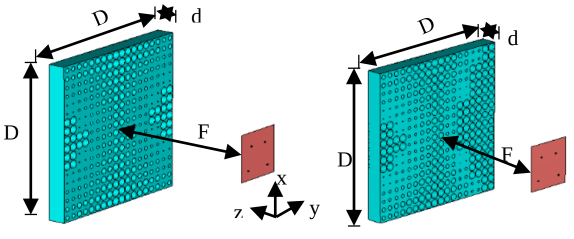


a. Gain b. Axial ratio

Fig.11. The gain and axial ratio of the 4×4 sequentially feed elliptic DRA phased-array.

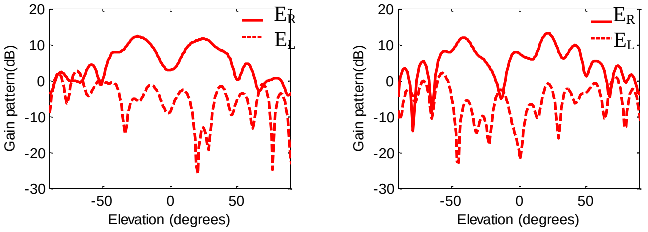
A. Dual-beam transmitarray

Many applications, as crash avoidance systems, imaging systems, base stations for wireless communication systems, etc., require antennas capable of supporting several radio links at the same time. Dielectric lens antennas with multiple feeds are used in [18]. In this section, two transmitarray structures each one with single-feed dual-beam will be investigated for covering two regions at the same time. The first designed transmitarray has main beam at θ_o = ± 25° in x-z plane (H-plane) as shown in Fig.12a and the second transmitarray has main beam at +20° and -45° in x-z plane (H-plane) as shown in Fig.12b. Each transmitarray is designed at 10 GHz and is fed by 2×2 DRA sub-array circularly polarized DRA with F/D ratio is set to 1. The cell phase compensation's is used to compensate the transmitted wave's different paths to be coherent in phase at certain plane. The gain patterns in x-z plane of the two dual beam transmitarray are shown in Fig.13. The first transmitarray introduces dual beam at ± 25° in x-z plane with maximum gain of 12.3 dB while the second transmitarray introduces dual beam at + 20° and -45° in x-z plane with maximum gain of 13.1 dB. The gain and axial ratio variations versus frequency are shown in Fig.14.



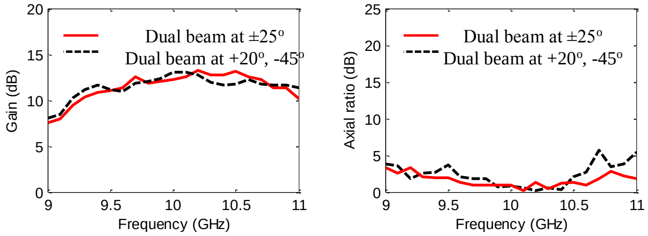
a. Dual beam at ±25° b. Dual beam at +20°, -45°

Fig.12. Geometry of the dual beam 9×9 perforated transmitarray fed by 2×2 sequentially feed elliptic DRA sub-array.



a. Dual beam at ±25° b. Dual beam at +20°, -45°

Fig.13. The gain pattern of the dual beam 9×9 perforated transmitarray fed by 2×2 sequentially feed elliptic DRA sub-array.



a. Gain b. Axial ratio

Fig.14. The gain and axial ratio variation versus frequency for the dual beam 9×9 perforated transmitarray fed by 2×2 sequentially feed elliptic DRA sub-array.

III. CONCLUSIONS

In this paper, the radiation characteristics of DRA antenna characteristics combined with the transmitarray to form high directive beam systems are investigated. The transmitarray is constructed from one piece of perforated dielectric material sheet. The transmitarray is composed of 9x9 unit cell elements and is covering an area of 13.5x13.5 cm^2. Two numerical examples are considered. Single elliptical DRA element fed the transmitarray is investigated in the first example. The directivity is 18.7 dBi that is 13 dBi higher than the value found for antenna alone (5.6 dBi). The band of circular polarization is not changed as the electromagnetic wave passes through the transmitarray. In the second example, four elliptical DRA element fed the transmitarray is considered. Narrow beamwidth with HPBW of 13 degrees is obtained in both the E-plane and H-plane. For comparison 4x4 sequentially fed DRA phased array is considered. Approximately the same behaviors of the gain and axial ratio variations versus frequency are obtained with the transmitary fed by 2x2 DRA sub-array with reduction of the DRA elements to about 75%. Also, two transmitarray structures each one with single-feed dual-beam is investigated for covering two regions at the same time. The first designed transmitarray has main beam at θ_o = ± 25° in x-z plane and in the second transmitarray has main beam at +20° and -45° in the same plane.

REFERENCES

[1] D. Jackson and N. Alexopoulos, "Gain enhancement methods for printed circuit antennas," *IEEE Trans. Antennas Propagat.*, vol. 33, no. 9, pp.976–987, Sep. 1985.

[2] H. Vettikalladi, O. Lafond, and M. Himdi, "High-efficient and high-gain superstrate antenna for 60-ghz indoor communication," *IEEE Antenna Wireless Propagat. Lett.*, vol. 8, pp. 1422–1425, 2009.

[3] Y. J. Lee, J. Yeo, R. Mittra, and W. S. Park, "Application of electromagnetic bandgap (EBG) superstrates with controllable defects for a class of patch antennas as spatial angular filters," *IEEE Trans. Antennas Propagat.*,vol. 53, no. 1, pp. 224–235, Jan. 2005.

[4] A. Foroozesh and L. Shafai, "Investigation into the effects of the patch type fss superstrate on the high-gain cavity resonance antenna design," *IEEE Trans. Antennas Propagat.*, vol. 58, no. 2, pp. 258–270, Feb. 2010.

[5] H. Attia, L. Yousefi, M.M. Bait-Suwailam, M.S. Boybay, and O.M. Ramahi, "Enhanced-gain microstrip antenna using engineered magnetic superstrates," *IEEE Antenna Wireless Propagat. Lett.*, vol. 8, pp. 1198-1201, 2009.

[6] K. M. Luk and K. W. Leung, Dielectric Resonator Antennas: Research Studies Press LTD Baldock, Hertfordshire, England, 2003.

[7] V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of e and fl," Sov. Phys. Usp., vol. 10, pp. 509-514, 1968.

[8] K. Jaewon and A. Gopinath, "Application of cubic high dielectric resonator metamaterial to antennas," in IEEE Antennas and Propagation Society International Symposium, Honolulu, HI, pp. 2349-2352, USA, 2007.

[9] B.-I. Wu, W. Wang, J. Pacheco, X. Chen, T. M. Grzegorczyk, and J. A. Kong, "A study of using metamaterials as antenna substrate to enhance gain," Progress In Electromagnetics Research B, PIER B, vol. 51, pp. 295-328, 2005.

[10] S.H. Zainud-Deen, Mourad S. Ibrahim, and A.Z. Botros, "A High-Directive Dielectric Resonator Antenna Over Curved Ground Plane Using Metamaterial," 28th National Radio Science Conference (NRSC 2011), National Telecommunication Institute, April, 2011, Egypt.

[11] Ahmed A. Kishk, "DRA-array with 75% reduction in elements number," Radio and Wireless Symposium (RWS), Austin, TX, USA, pp.70-72, January 2013.

[12] A. Abbaspour-Tamijani, L. Zhang, and H.K. Pan, "Enhancing the directivity of phased array antennas using lens-arrays," Progress In Electromagnetics Research M, PIER M, vol. 29, pp.41-64, 2013.

[13] J. Y. Lau, and S. V. Hum," Analysis and characterization of a multipole reconfigurable transmitarray element," IEEE Trans. Antennas Propag.,vol. 59, no. 1, January 2011.

[14] C. G. M. Ryan, M. R. Chaharmir, J. Shaker, J. R. Bray, Y. M. M. Antar, and A. Ittipiboon," A wideband transmitarray using dual-resonant double square rings," IEEE Trans. Antennas Propagat., vol. 58, no. 5, pp.1486-1493, May.2010.

[15] S.H. Zainud-Deen, Sh. M. Gaber, and K.H. Awadalla, "Transmitarray using perforated dielectric material for wideband applications," Progress in Electromagnetics Research M, PIER M, vol.24, pp.1-13, 2012.

[16] A.C. Polycarpou, Introduction to the Finite Element Method in Electromagnetics, Morgan and Claypool, USA, 2006.

[17] M. Clements, and T. Weiland, "Discrete electromagnetism with the finite integration technique," Progress in Electromagnetics Research, PIER, vol.32, pp.65-87, 2001.

[18] K.K. Chan, G.A. Morin and S.K. Roa, "EHF multiple beam dielectric lens antenna," in IEEE Antennas and Propagation Society International Symposium, Newport Beach, CA, vol.1, pp.674-677, USA, 1995.