Single Layer Reflectarray Antenna with Pie-Shaped Elements for X-band Applications

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Abstract ─ In this paper, a single-layer reflectarray design is presented for X-band applications. The reflectarray comprises of pie-shaped reflective elements. The unit element has compact dimensions of $0.28\lambda_o \times 0.28\lambda_o$. The major segment angle of pie-shaped element controls the reflection phase range and offers a total of 650º phase variation. A reflectarray prototype comprising 23×23 elements is realized to demonstrate the necessary reflection characteristics. Different parameters are analyzed for performance evaluation of the reflectarray. The proposed reflectarray offers measured gain of 24 dBi with 1-dB and 3-dB gain bandwidth of 18% and 28% respectively. Moreover, side-lobe-levels and cross-polarizations are less than 22 dB and 35 dB respectively.

Index Terms ─ Radiation patterns, reflectarray antenna (RA), reflection magnitude, reflection phase range.

I. INTRODUCTION

Among various modules of high-speed transceivers, the RF front-end has gained considerable attention over the last two decades. High gain antennas, being the crucial part of front-end, play an important role in long distance communication and other applications like remote sensing. Conventionally, parabolic reflectors and phased-arrays are used for high gain applications. Parabolic reflectors are difficult to realize owing to their curved geometry and phase arrays on the other hand have complicated and lossy feed networks. The phased-arrays and parabolic reflectors can be effectively substituted by reflectarrays. The reflectarrays offer certain advantages over parabolic reflectors as well as phase arrays by combining the features of these two high gain antenna classes. Reflectarrays are low cost, light weight and easy to fabricate and deploy. Reflectarrays have multiple reflective elements printed on a substrate, backed by a ground plane and illuminated by a feed horn antenna. The operating principle of reflectarray is illustrated in Fig. 1. Overall, one of the common limitations of reflectarrays is their narrow operating bandwidth. However, their bandwidth can be improved by employing elements with a broad linear phase range [1 - 3].

Recently, different techniques are proposed to control the reflection phase of reflectarrays. These techniques include but are not limited to variation in geometrical parameters, variable size patches, identical elements with different rotation angles etc. In [4], a modified cross loop reflectarray is presented. A wide phase range of 550º is achieved by varying the length of cross shape. A fractal reflectarray of first and second order with phase range of 354º is presented in [5]. A slotted hollow ring with stacked ground plane is presented recently where the desired gain is achieved by rotating the slotted ring [6]. In [7], a square shaped reflectarray attached with lattice stubs is reported. The stub length is optimized to achieve a broad phase variation of 600º. Parallel dipoles based reflectarray for high gain and broad phase range of 413º is presented in [8]. A single layer qausi-spiral reflectarray with small dispersion in transmission modes is presented in [9]. It is envisioned that the phase range can be further enhanced to improve the design bandwidth with simple geometry and single layer realization as compared to the existing literature.

In this article a single layer pie-shaped reflectarray for X-band applications is proposed. The reflectarray is designed and optimized using a commercially available 3D full-wave electromagnetic solver based on Finite Element Method (FEM) algorithm (Ansys HFSS). The outline of the paper is as follows: unit element design is

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presented in Section II. The reflectarray configuration and measurement setup is elaborated in Section III. Finally, Section IV concludes the paper.

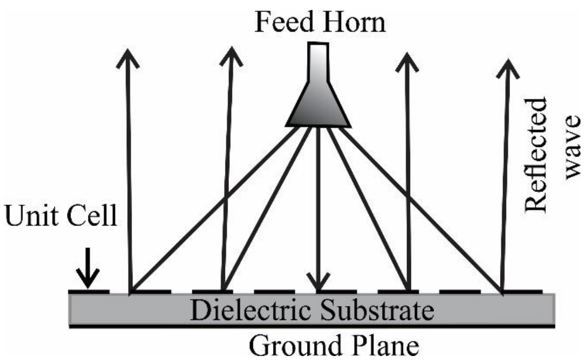
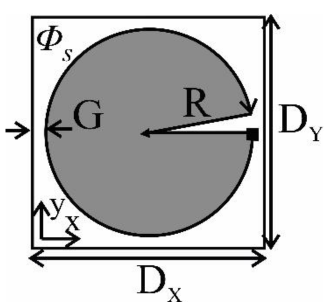


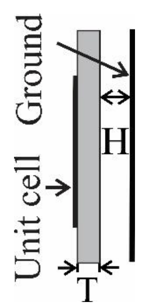
Fig. 1. Reflectarray operational principle.

II. UNIT ELEMENT DESIGN AND ANALYSIS

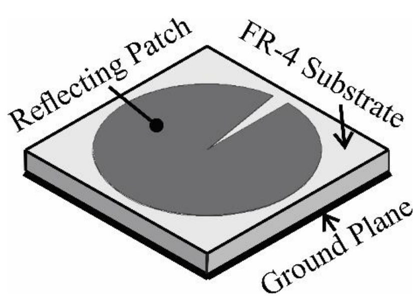
Unit element is designed and optimized for X-band applications with centre frequency of 10 GHz. The reflectarray unit element geometry is shown in Fig. 2. The design has compact dimensions of $0.28\,\lambda_o \times 0.28\,\lambda_o$, where λ_o is free space wavelength at 10 GHz. The reflectarray is designed on FR-4 substrate with dielectric constant of 4.4 and a loss tangent of 0.02. The top-layer comprises of pie-shaped unit element and the ground plane is placed on the flip side of substrate. The unit element optimized parameters for 10 GHz are shown in Table 1.



(a) Unit element geometry



(b) Side view



(c) 3D view

Fig. 2. Reflectarray unit element configuration.

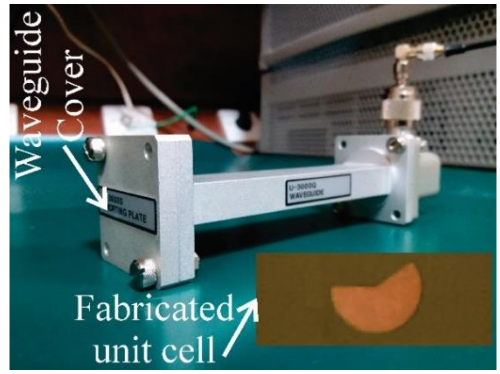


Fig. 3. Unit element measurement through waveguide simulator method.

Table 1 : Unit cell optimized parameters at 10 GHz

Parameter	D_Y	D_X	R	G	T
Value (mm)	8.5	8.5	4	0.25	1.6

A. Unit cell performance parameters

The parametric analysis for simulated reflection magnitude against frequency is shown in Fig. 4. The reflection curve moves towards lower frequencies when the major segment angle of pie-shaped element, ϕ_s, is increased and vice versa. Moreover, reflectarray unit cell prototype for 10 GHz frequency is fabricated, as shown in Fig. 3 and reflection magnitude is measured through waveguide simulator method.

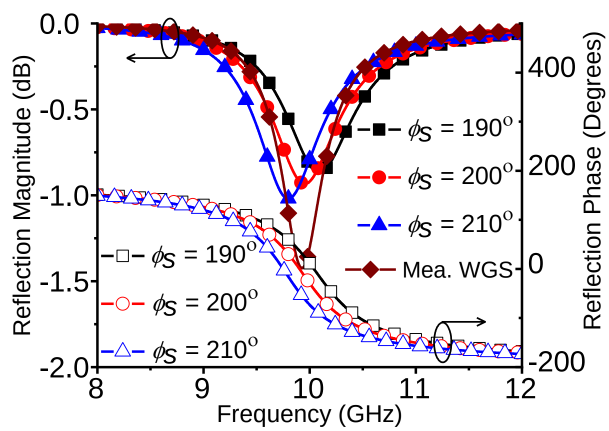


Fig. 4. Reflection magnitude at different segment angles.

The phase range is examined over different parameters, i.e., oblique incident angles in transmission modes and different frequencies. The phase range at 9, 10 and 11 GHz is shown in Fig. 5. By varying the major segment angle, ϕ_s, from 0º to 350º, the design achieves a phase range of 650º. The simulated phase range for TE and TM modes at different oblique incident angles is shown in Figs. 6 (a) and 6 (b). A stable phase response with little shift is obtained at 30º and 45º oblique incident angles, which is within acceptable limits [10]. Conventionally, the value of real part of impedance should be higher to avoid losses in the reflectarray. The real and imaginary parts of impedance are shown in Fig. 7. The real part of impedance (resistance) is more than 2000 Ω at 10 GHz frequency [11].

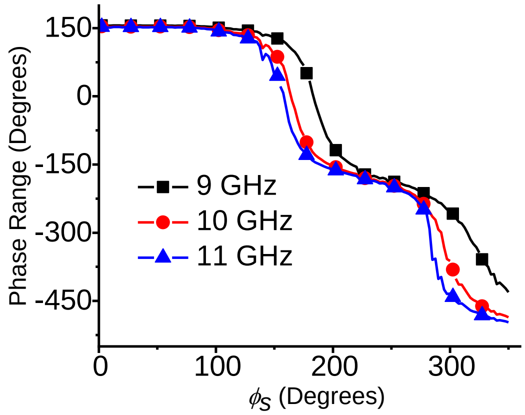
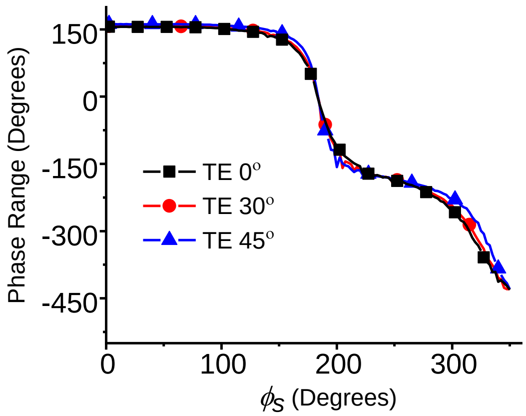
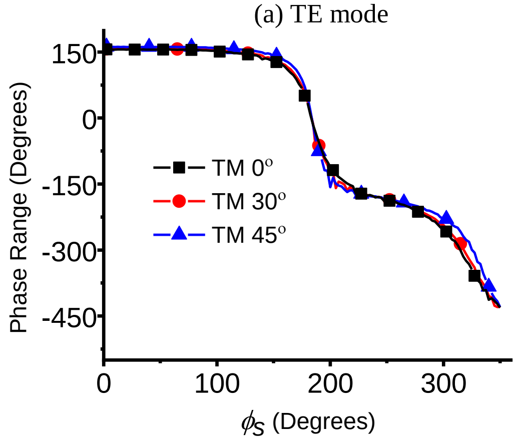


Fig. 5. Reflection phase range at 9, 10 and 11 GHz.



(a) TE mode



(b) TM mode

Fig. 6. Performance parameters effect on phase range.

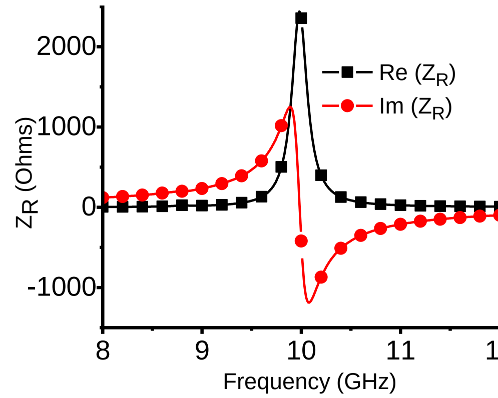


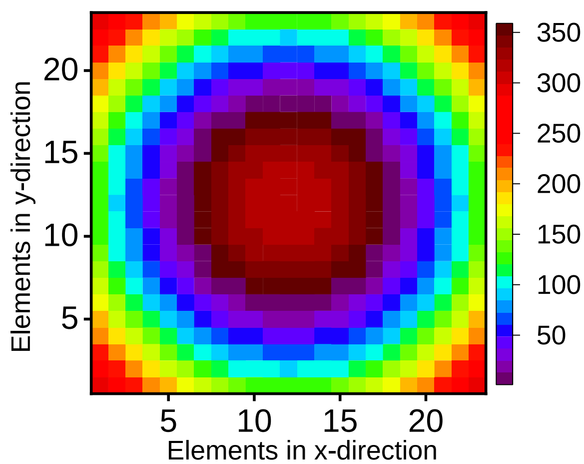
Fig. 7. Input impedance at 10 GHz.

III. REFLECTARRAY REALIZATION AND MEASUREMENT SETUP

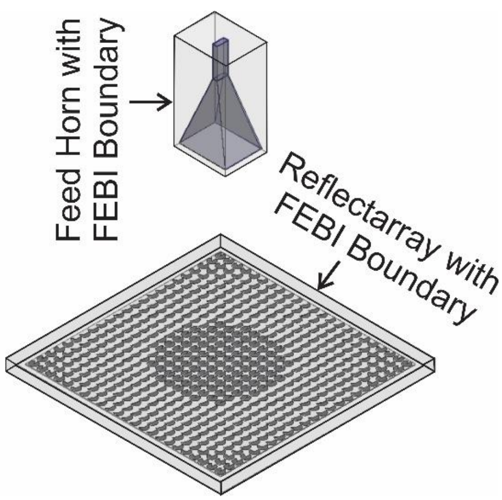
A *23×23* element reflectarray is designed on FR-4 substrate. The reflectarray panel has dimensions of 6.5λ_o × 6.5λ_o, where λ_o is the free space wavelength at 10 GHz. The array elements are equally spaced with inter-element spacing of 0.28λ_o. The spacing between elements is commonly kept less than 0.5λ_o, to reduce the presence of grating lobes [1]. Generally, in array configuration, a minor change in the size of unit element produces a large phase shift in the reflected wave. The required phase distribution on each element in reflectarray is attained by using Equation 1:

$$\phi_R = K_o(d_i - (x_i cos\phi_o + y_i sin\phi_o) \times sin\,\theta_o). \quad (1)$$

The parameters used in array Equation (1) are elaborated in [1, 12]. The phase distribution plot is used to calculate the opening angle of each array element. The phase distribution on center-fed pie-shaped reflectarray is depicted in Fig. 8 (a). A stronger phase shift is observed at the center than at the corners/sides. The ratio of focal length to diameter of reflectarray is defined as *F/D* ratio. The fabricated pie-shaped reflectarray has an *F/D* ratio of 1. Reflectarrays have electrically large aperture size and require high computational resources and time. Therefore, a hybrid Finite Element Boundary Integral (FEBI) algorithm is used for reflectarray system simulations. This algorithm combines the Finite Element Method (FEM) with Integral Equation (IE) method [12]. This method efficiently handles the complex and electrically large sized structures. The reflectarray far-field radiation characteristics are obtained by using hybrid FEBI method. Full reflectarray simulations with feed horn and 23×23 reflectarray elements were performed on a ten-core HP Z840 workstation with workable memory of 64 GB. The CPU took about 23 hours to fully simulate the reflectarray. The reflectarray antenna FEBI system model as shown in Fig. 8 (b) is used to obtain far field characteristics.



(a) Phase distribution on *23×23* element reflectarray

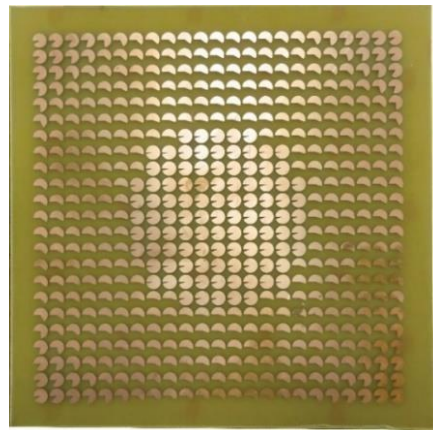


(b) Reflectarray system modeling with FEBI algorithm

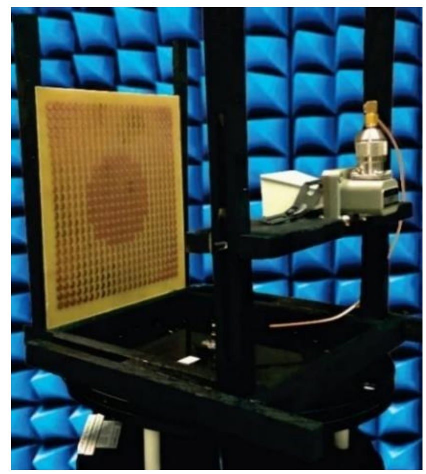
Fig. 8. Reflectarray system model along with phase distribution.

The fabricated reflectarray antenna and the measurement setup is shown in Fig. 9. The fabricated 23 × 23 elements reflectarray on FR-4 laminate is placed inside a wooden stand and illuminated by an X-band WR-90 feed horn antenna. The feed horn is placed 194 mm away from the center of array panel. The reflectarray antenna measurements are carried out in an anechoic chamber.

The simulated and measured E and H-plane radiation patterns at 10 GHz are shown in Fig. 10. The side-lobe-levels and cross polarizations are less than 22 dB and 35 dB for the reflectarray. The gain against frequency is shown in Fig. 11. A gain of 24 dBi with aperture efficiency of 48% is achieved at 10 GHz. Moreover, 1-dB and 3-dB gain bandwidths are 18% and 28% respectively. The proposed reflectarray comparison with previously reported reflectarrays is listed in Table 2.



(a) Fabricated 23 × 23 element reflectarray

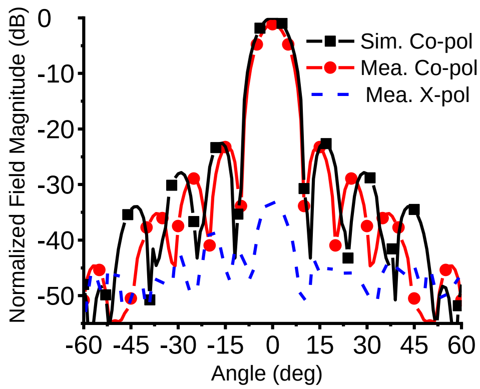


(b) Reflectarray under testing

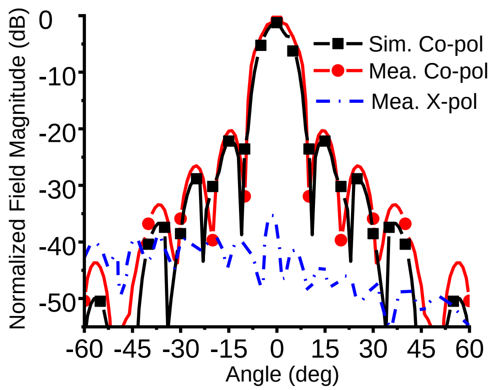
Fig. 9. Fabricated reflectarray and measurement setup.

Table 2: Comparison with previously reported reflectarrays

References	**This Work**	**[15]**	**[14]**	**[13]**	**[12]**
Middle frequency (GHz)	10	12.5	10	13.5	10
Gain (dBi)	24	26.6	26.1	25	24.5
Aperture efficiency (%)	48	52.5	40.3	39	49.5
1-dB bandwidth (%)	18	8.1	18	20	12.5
3-dB bandwidth (%)	28	19.8	30	—	34
Side-lobe-levels (dB)	-22	—	-16	-25	-35
X-pol (dB)	-35	-21	-23	-30	-40



(a) E-plane pattern



(b) H-plane pattern

Fig. 10. E and H-plane gain patterns at 10 GHz.

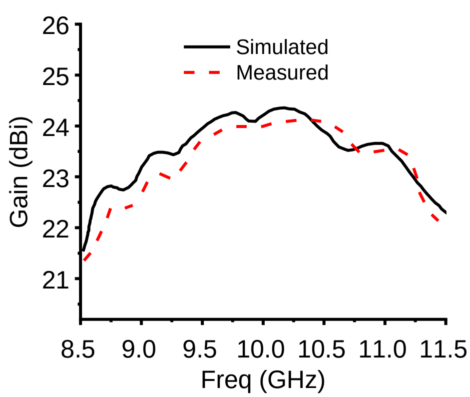


Fig. 11. Gain vs. frequency.

VI. CONCLUSION

Pie-shaped reflectarray for X-band is presented in this paper. Reflectarray prototype of size $6.5\lambda_o \times 6.5\lambda_o$ is fabricated with an *F/D* ratio of 1. The reflectarray performance is analyzed in terms of reflection magnitude, phase range, TE and TM modes. The reflectarray has a measured gain of 24 dBi at 10 GHz frequency. The simulated results are in good agreement with the measured results. The results strongly suggest that the reflectarray is a suitable candidate for high gain X-band applications.

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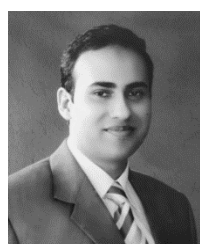

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