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Research Article

Broadband Reflectarray Antenna with High Gain for X Band (8 to 12GHz) Applications

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Abstract: In this paper high gain reflectarray antenna for broadband applications is proposed. The proposed design, based on a novel hexagonal unit cell shows a large reflection phase range of 1000° with smooth linear phase slope. A center horn fed 11 x 11 reflectarray antenna with the proposed unit cell is designed for X Band (8 to 12 GHz) applications. It is simulated for different f/D (focus point to largest dimension of antenna) ratios to evaluate its effect. For optimum results, only two f/D ratios 1.0 and 1.96 are chosen. The simulated results show that a wide operational bandwidth of 39.6% for 3dB gain dropping is obtained over the frequency band of 8 to 12 GHz which is much improved than the previously reported results. Simulations for the f/D ratio of 1.96 shows improvement in the aperture efficiency with 3 dB gain bandwidth of 29%. This single layer, low profile reflectarray antenna can be a useful candidate for high gain broadband applications.

Keywords: Broadband reflectarray, High Gain, X-Band, Compact antennas.

1. INTRODUCTION

In the age of radio communication, antennas play an active role in making the overall mobile communications systems viable. For this purpose continued advancement and investigation in the domain of antennas is done to further improve the performance and effectiveness of antenna specification while keeping in view the issue of antenna miniaturization. Usually high-gain parabolic reflectors are employed in navigational devices and long range communications. But they are massive, rigid, spacious and hard to be fixed also having inefficiency in beam scanning. These weaknesses of parabolic radiators were covered by a highly directive group of antennas called as phased-array antennas. They are driven with steerable phase shifters, to electronically achieve large beam scanning angle, having slim and portable design. Regardless of these benefits, it is having certain drawbacks such as its intricate design, use of expensive phase shifters and amplifier units to obtain required phase response and beam angle. To overwhelm the inadequacies of the former antennas, an innovative antenna design was presented in 1960's known as "reflect array antenna" [1, 2].

Reflect array antenna is a planar structure consisting of smart radiative units. These units (or antennas) are devised in such a manner that it reradiates the incoming wave in the aimed path with the precise phase adjustment. It is a simple structure with horn antenna acting as a source for the whole setup rather than having individual sources for each and every unit of the structure as in phased array antennas thus minimizing the system intricacy. It has gained popularity and replaced the parabolic reflectors because it combines the intelligent attributes of high directivity and desired pattern configuration from parabolic reflectors and phased array antennas respectively along with its own adaptability in beam shaping. Despite of these favors, main drawback of reflectarray antennas is limited bandwidth [3]. To overcome this deficiency, different approaches are presented by researchers. These techniques include multi-layer approach in which multiple layers are stacked together thus making it heavy and inflexible and only 10% to

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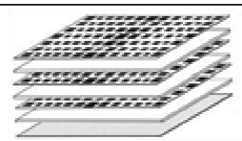
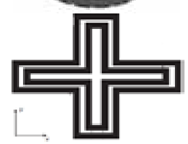
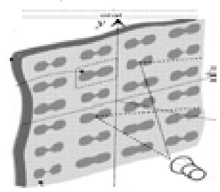
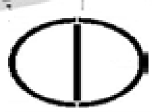
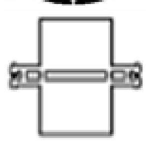
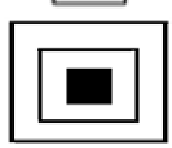
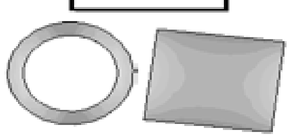
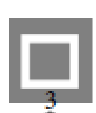
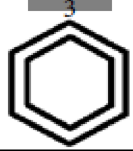
20% bandwidth was achieved [4, 5]. Similarly nested conductive loops with thick substrates [6], double crossed loops structures with changeable lengths showed radiation efficiency of 55% and 10% bandwidth [7]. Resonating module's structure and shape has notable impact on the performance of the antenna. So in this context new shape elements such as ridge, dog bone were introduced with 13% gain-bandwidth [8]. In [9] a circularly polarized RA antenna was represented with loop elements having variable rotations resulting in improved gain but narrow band.

In the same manner varactor diodes are used in the array modules for the purpose of phase adjustment. Required phase shifts and phase correction is done by changing the electrical length of the patches. High gain and wide beam contouring

Table 1. Performance characteristics of different Reflectarray Antennas

Methodology	unit cell geometry	Phase range (degrees)	Centre frequency (GHz)	Bandwidth (%)
Multi layer structure [4,5]		360	12	10-20
Double loop structure with thick substrate [6]		330	10	10
Dual cross loop structure with adjustable dimensions [7]		500	22	10
Comparison of Dogbone shaped resonating element with existing shapes [8]		>360	12	13
Circularly polarized with loop elements [9]		------	7.1	4
Electronically tunable antenna [12]		≈360	5.8	-----
Single layer [15]		360	5	30.8
Analysis of S-Shaped phasing curves [16]		150 -- 177	10	1-10
Optimization of reflection curve [22]		≈420	5.8	7
Double hexagonal ring structured cell [26]		>360	10.5	28.5

ability is examined from the results [10-13].

Factors such as intermediate gap between the radiating elements and the mutual coupling also play an active role in the improvement of bandwidth as in [14] and [15]. 3-dB bandwidth of 30.8 % is attained by varying these factors. Some papers [16-18] focused on s-shaped reflection phase curves to achieve phase range greater than 360° for widening the bandwidth. In [19, 20] Genetic algorithm (GA) based controller is represented to have more command over the phase adjustment to achieve desired radiation pattern in relation with the varying path lengths of the source from the reflecting surface. Other papers [21, 22] showed optimization methods to enhance the performance of reflectarray antennas. Based on available published results, maximum 30.8% bandwidth is achieved up till now at the cost of system complexity or size. Table 1 compares the performance characteristics achieved so far for reflectarray antennas.

In this paper, a novel element having hexagonal structure with open ended triangular loops on the inner side is proposed. A wide reflection phase sweep of 1000°and phase gradient of 303°/mm is achieved as a function of varying element size, thus adding freedom for further enhancement in bandwidth. An 11 x 11 elements symmetrical single layer reflectarray is designed for X-band and illuminated by a horn antenna. Simulations are carried out in CST microwave studio and 3 dB gain bandwidth of designed reflectarray reached 39.6% for this band. Thus a very good bandwidth is achieved with smaller size having approximately 9% enhancement of bandwidth as compared to other single layer reflectarray antennas.

2. METHODOLOGY

The theoretical analysis for the design of reflectarray antenna is executed using full-wave simulation tool i.e. Computer Simulated Technology (CST MWS). Fig. 1 shows the complete methodology having two main steps i.e. element design and system design. Basically three approaches are utilized in the analysis and design procedure of reflect array antennas. These three approaches include homogenous array, non-homogeneous array and resonating elements with variable angular rotations. In this paper non homogenous array approach is used because of its simplicity as other approaches require stubs, delay lines or phase shifters for the phase compensation.

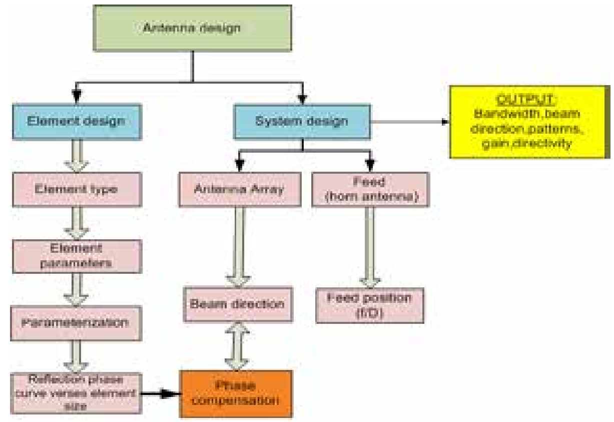


Fig. 1. Flowchart of Methodology for Reflectarray Antenna design

Unit cell design is the initial stage in which parameterization is done to obtain S-shape curves of reflection phase versus variable parameters of the resonating element. This method is known as unit cell analysis. In unit cell analysis, Floquet modes are applied to analyze the behavior of unit cell. Floquet modes compute the performance of unit cell in an infinite array environment.

Second step is the analysis of Phase distribution on the entire reflectarray using the proposed elements. Using this step phase compensation is done to achieve a sharp beam normal to the plane of reflect array antenna. After this step, whole system consisting of an array and horn antenna is designed and simulated to determine the radiation properties of that antenna.

2.1 Element Design

The proposed element of reflectarray antenna is shown in Fig.2. It is designed to function in X-band

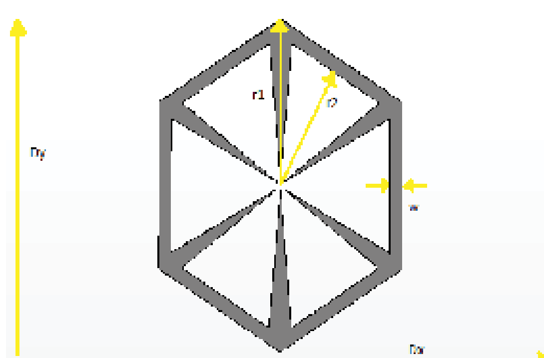


Fig. 2. Resonating Element

(i.e. from 8 to 12 GHz) with a center frequency of 10 GHz. The resonating unit is a hexagon ring structure with triangle shaped loops inside. As seen in the Fig. 2, r1 represent the radius of the hexagon ring and r2 is the height of the inner triangular loop. Whereas hexagonal ring width “w “is given a constant value of 0.1mm.

These resonating elements are arranged in a square prototype having length Dx and width Dy of 15mm respectively. Thus obtaining periodicity of 15mm (i.e. the space (S) between the adjacent cell centers).This value of periodicity helps in the reduction of the grating lobes according to the criterion given below,

$$S \leq \lambda/(1+\sin\theta) \quad (1)$$

Where θ is the reflected rays angle and wavelength (λ) is 30mm according to the center frequency of antenna.

Parameters r1 and r2 are related in accordance with the following equation i.e. r2 = r1-(0.1*r1). To attain optimization goals, distribution of phases is controlled for the whole operating range of frequencies through the process of parameterization. By alternating the variables r1 and hence r2, the resonating frequency is varied and the phase adjustment is achieved at different positions of the reflectarray antenna.

Structure of the unit cell consists of a sheet of dielectric material having relative permittivity of 2.08 and tangent loss factor of 0.0004. An air gap is inserted between the dielectric material and ground. The purpose of the accommodation of the air gap is to achieve wide range of reflection phases. Specifications of the single unit cell are summarized in Table 2.

Table 2. Summary of the Unit Cell Dimension

SPECIFICATIONS	VALUE
Width of hexagonal ring, w	0.1mm
Height of triangular loop	r 2
Radius of hexagonal ring	r 1
Dielectric constant , ε_r	2.08
Substrate loss tangent , tan δ	0.0004
Dielectric material thickness , t	2mm
Air gap thickness, h	5.5mm
Relationship between r_1 & r_2	$r_2 = r_1 - (0.1*r_1)$
Periodicity, p	15mm
Resonance frequency, f	10 GHz

Table 3. Parametric Sweep

Parameters	VALUE
r1 (mm)	1.0 - 4.4
r2 (mm)	r1-(w*r1)
w (mm)	0.1

2.2 Geometry Optimization

Variables such as hexagonal ring radius r1, hexagonal ring thickness w, triangular loop altitude r2 , and the relationship between these variables i.e. r2=r1-(0.1*r1) are introduced in the geometry of the phasing element to achieve optimization goals. These variables help in controlling the reflection phase responses over the whole working range of frequencies.

The purpose of parameterization is to get an even phase response of the phasing element. Settings for the parameter’s sweep are given in Table 3. In order to compute the analysis of the phasing element for X-band, frequency domain solver (FD) is applied. Floquet modes with unit cell boundaries are used in the unit cell analysis; thus analyzing the performance of resonating element in an infinite array environment [23].

2.3 Phasing Characteristics Of Unit Cell Element

In antenna arrays design procedure, phasing properties of the resonating element play a vital role in revealing the overall response of the antenna. Whenever a wave is incident upon the reflecting surface (antenna array), it is scattered in the medium with some arbitrary angle. In order to achieve a sharp directive beam, the resonating elements must have the capability to adjust and correct the phase of the incoming wave and reradiate it as collimated beam in the particular direction. Hence the range of reflected phases versus variable dimensions of the resonating patch must be larger than 360° to offer appropriate phase adjustment.

Therefore, variation of the following two factors determines the phase characteristics of the unit cell i.e. Shape of Resonating Patch Element and Thickness of Substrate. Reflected phase responses as a function of the variation of these two elements are plotted which are also known as S-shape curves. These S-shaped plots are helpful in giving an insight of the antenna specification [24].

2.4 Shape of Resonating Patch Element

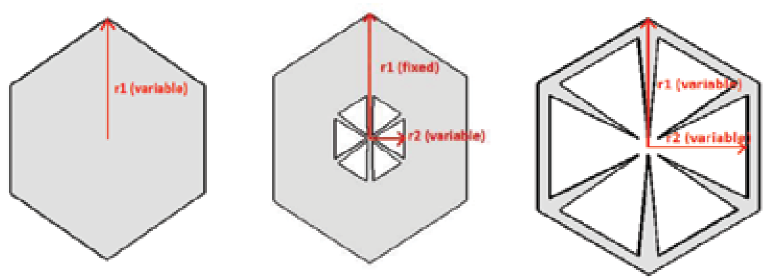
Patch element's profile plays a very important role in passive reflectarrays to control the deviation of phases. Through variation in one of the parameter of the resonating element, one can get control on the phase changes in the arrays antenna. It acts like weights in phase array antennas which multiply to the actual phase of the incident wave to get the desired phased beam.

Fig. 3 shows three different shapes of the patch which are examined. Simple hexagonal patch is shown in Fig. 3 (a) in which radius r1 is kept variable for obtaining different phase responses. Similarly, in Fig. 3 (b), r1 is kept fixed, where height of the triangular area in hexagon r2, is varied to determine the reflection phase curve for this variation. In Fig. 3 (c) both r1 and r2 are varied, as to consider the impact of two variable parameters to get an optimum phase response.

Fig. 4 shows the reflection phases for different shaped resonating elements. It shows the combined results of all three patches. The variation of the parameter r1 from 1 to 4.4 mm of simple hexagonal shape shows variation in the reflection phase from 10° to -50°. Thus total range of 60 degrees is obtained with slope of 18.1°/mm with simple hexagon.

The Fig. 4 also shows the plot of fixed hexagon with variable triangular loops. The parameter r was varied to achieve different phases. With variation of parameter r from 1 to 4.4 mm, phase variation is from -61° to -65°. Thus total phase range of 4° is obtained with slope of 1.21°/mm.

The variation of the parameter r1 from 1 to 4.4 mm for variable hexagon having variable triangular loops is also shown. Total phase range of 1000° is achieved with a slope of 303°/mm. The result shows a drastic variation in the phase range and phase slope. The third curve which is for



(a) (b) (c)

Fig. 3. Different Shapes of the Phasing Element (a) Simple Hexagonal Patch Element (b) Fix Hexagonal Patch with Variable Triangular Gaps (c) Variable Hexagonal Shape with Variable Triangular Gap

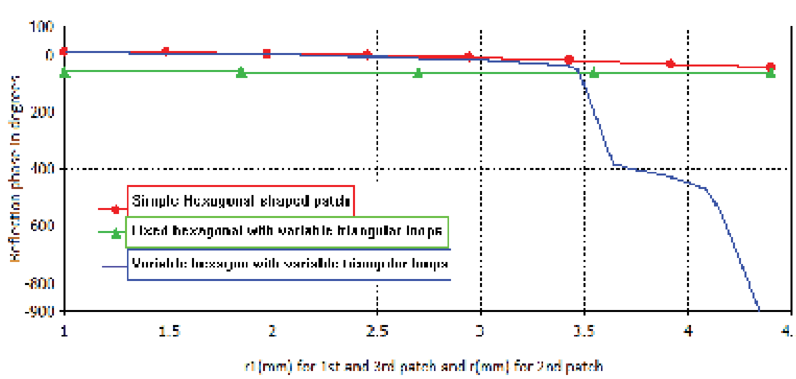


Fig. 4. Plot of Reflection Phases versus Variable Parameter of Resonating Elements

the proposed resonating element having variable hexagon with triangular loops shows very good reflection phase curve, as having wide range of 1000° for compensation of phase changes. In addition to this, the slope is also smooth, so it can tolerate fabrication errors.

2.5 Thickness of Substrate

Varying the thickness of substrate i.e. air gap has a visible effect on the phasing property of the resonating element. Suppression of surface waves becomes possible through the introduction of air gap [25, 26]. It also extends the range of reflection phase to have larger functional bandwith band of antenna. Thus to widen the bandwidth, an air-filled space is introduced.

Fig. 5 represents the plots of the reflected phase responses for variable heights of the air-filled gap. The curve with circles shows air gap height of 3.0 mm. This height gives deviation of phase from 76° to -670°, when r1 is varied from 1.50 to 4.40 mm.

The second curve for air gap height of, 4.0 mm shows a total phase range of 650°. Similarly, third curve for height of 5.0 mm shows deviation in phase response from 15° to -608°, attaining the phase range of 623°.

Second to last curve is for air gap height of 6.0 mm exhibiting the change in the reflected phase from 0° to 1072°. This curve shows leveled and an even response with extended range of 1072 degrees. But in order to get improved gain bandwidth product, an air gap height of 5.50 mm is chosen. This height of substrate gives reflected phase deflection from 0° to 1000°.Summary of the results are presented in the Table 4.

2.6 Reflection Phase Response

By investigating various shaped phasing elements, variable thickness and size of the substrate material, the most favorable response in terms of reflection phase angles is achieved with variable hexagon having variable height of the triangular area. Final plot of the reflection phase response versus the variable dimension r1 of resonating patch element is shown in Fig. 6. The finalized phasing element

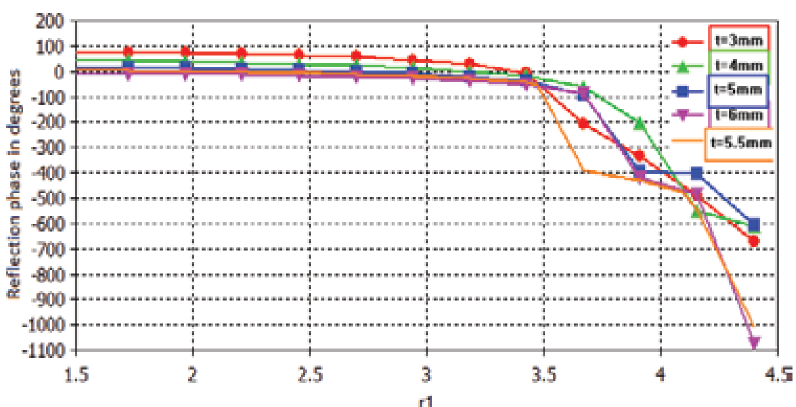


Fig. 5. Reflection Phase Curves for Variable Thickness/height of Air-filled Gap

Table 4. Summarized Results for Different Resonating Elements and Variable Air Gap Height/Thickness

Resonating Element's Patch Structure	Phase Slope	Phase Range
Plain hexagonal patch	18.1°/mm	60°
Variable radius of hexagon with variable height of triangular area	303°/mm	1000°
Fixed hexagon with variable height of triangular gap	1.21°/mm	4°
Air gap ,t=6.0 mm	369°/mm	1072°
Air gap , t=5.50 mm	303°/mm	1000°
Air gap, t=5.0 mm	214°/mm	623°
t=4.0 mm	224°/mm	650°
t=3.0 mm	257°/mm	746°

aids in attaining even and extended phase range of 1000°. Hence these characteristics support wide bandwidth and a good figure of merit.

2.7 Array Analysis

In array designing, phase tuning is an essential aspect of the whole array setup. Usually horn is used as a feed. The incident wave from the horn antenna on the patch element of the reflectarray antenna is reflected back in the medium with the necessary phase angle making a progressive phase shift distribution on the reflecting surface. This pattern of gradually increasing phases on the plane of the reflectarray is presented by;

$$\phi(x_i,y_i) = -k\sin\theta_b(\cos\varphi_b x_i + \sin\varphi_b y_i) \quad (2)$$

(x_i,y_i) are the coordinates of ith element,

k is the free space propagation constant,

$(\theta b,\varphi b)$ gives the direction of beam.

The resultant phase of the wave originating from every element of the reflectarray is equivalent to the phase of incoming wave from feed plus the induced phase shift by each element.

$$\phi(x_i,y_i) = -kd_i + \phi_{element\ phase}(x_i,y_i) \quad (3)$$

Where d_i is the distance of the i[th] array element from the center of the source, therefore the necessary phase for each element is obtained by,

$$\phi_{element\ phase}(x_i,y_i) = -kd_i\, k(x_i\cos\varphi_b + y_i\sin\varphi_b)\sin\theta_b \quad (4)$$

An array of size 11x11 having 121 radiating elements is designed using CST MW Studio at center frequency of 10 GHz for X-band as shown in Fig. 7. Proposed reflectarray antenna has square aperture with dimension of 15mm x 11mm .A

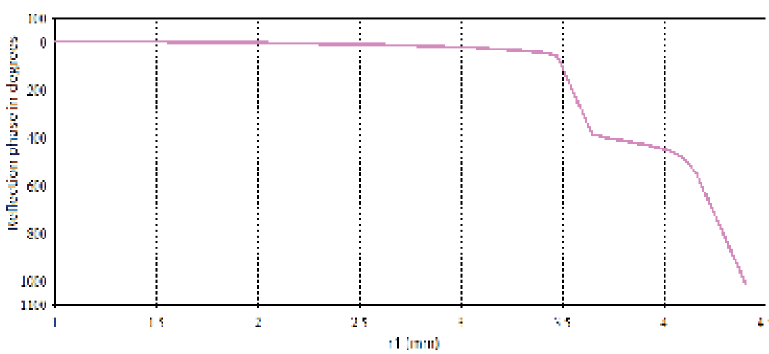


Fig. 6. Finalized Reflected Phase Response

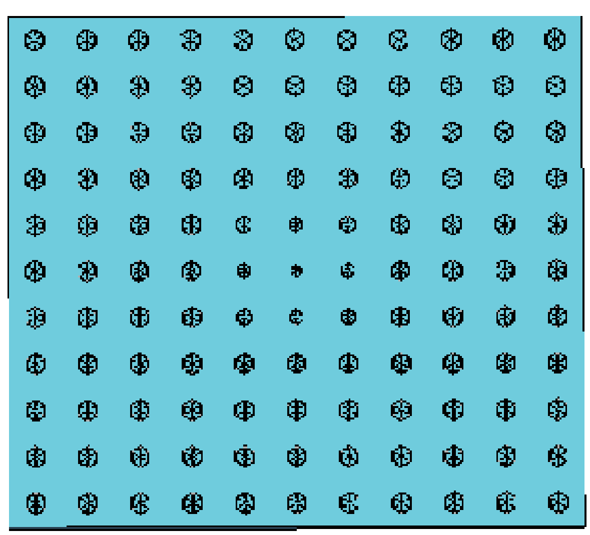
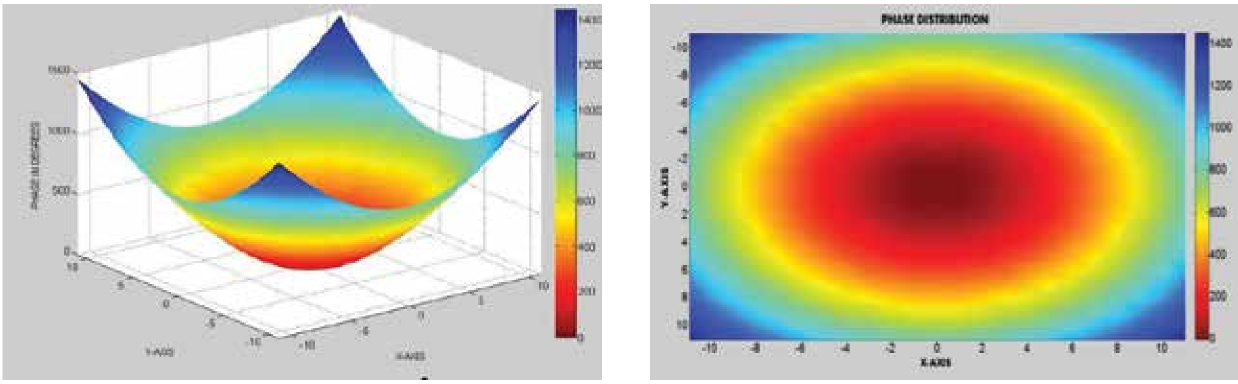


Fig. 7. 11 x 11 Reflectarray Antenna



(a) (b)

Fig. 8. (a) Distribution of Phase on a Square Reflectarray Antenna with 10 GHz Centre Frequency (b) 3-D phase distribution corresponding to parabolic reflector

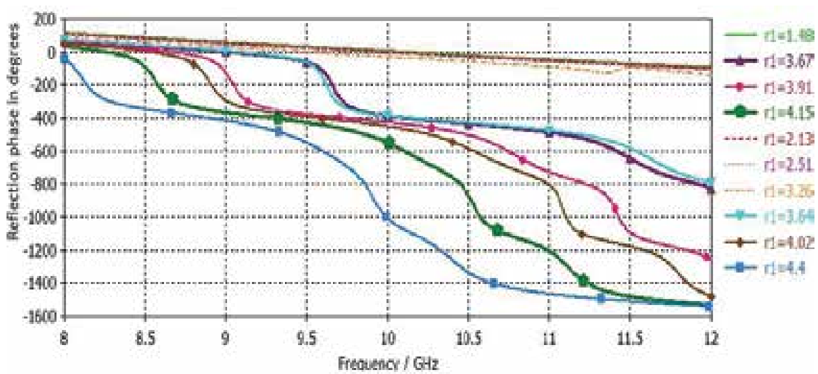


Fig. 9. Reflected Phase Response versus Frequency

normal incident center fed source is supposed for this specific antenna i.e. ϕ & $\theta = 0°$.

Using (3) and (4), one can obtain required phase distribution as depicted by Fig. 8. Hence the required weights for directive and coherent beam are achieved through this methodology.

Fig. 8 (b) shows the correspondence of the phase shifts at each element with the parabolic reflector. Thus the reflected beam from the plane reflectarray will behave in the same way as reflected from the parabolic reflector antenna.

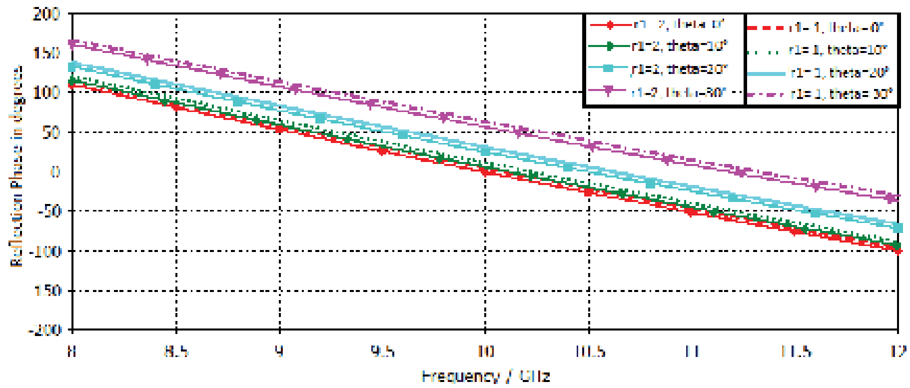
3. RESULTS & DISCUSSIONS

To evaluate the performance of proposed reflectarray antenna, simulations are carried out in CST MW Studio. Discussions will also be made in this section on the basis of simulation results.

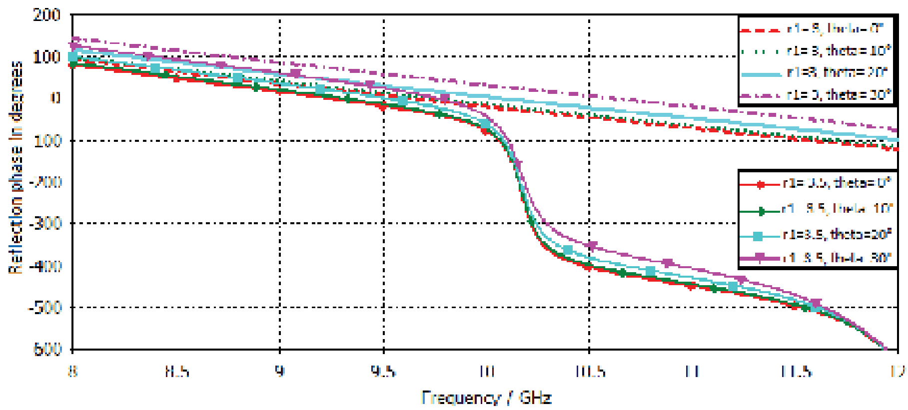
3.1 Reflect Array Unit Cell

Reflection phase response versus frequency range of the proposed unit cell from 8 to 12 GHz is plotted as shown in Fig. 9 to analyze the behavior of unit cell over the whole frequency range. By observing the frequency band from 8 to 12 GHz, the change in reflected phase by changing one of the dimensions of the phasing element; is quite visible.

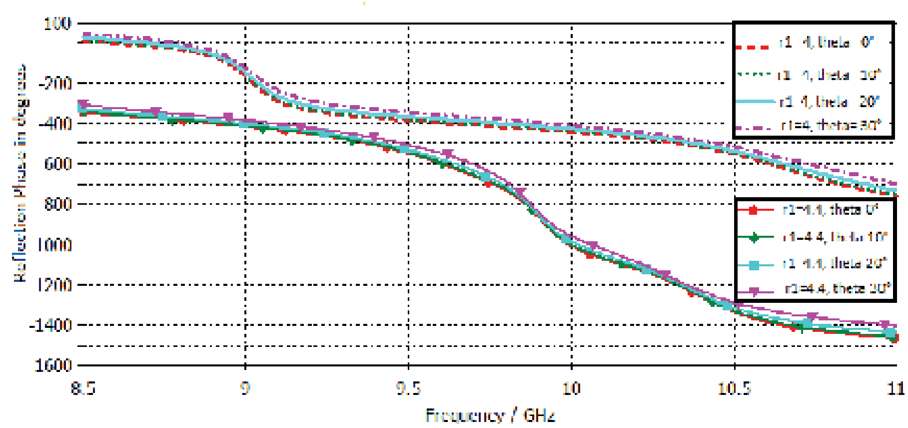
For the analysis of unit cell, floquet modes are utilized as mentioned earlier. This approach provides the facility to test the behavior of resonating element for various angles of incidence. In this paper, angle of incidence is varied from 0° to 30° for verifying the influence of angle of incidence on the results. Reflection phase characteristics obtained in Fig. 10 shows that the performance is nearly identical for angles of incidence other than the normal incidence. Thus set of curves with good parallelism corresponding to the particular value of r1 over the entire frequency range can be achieved with the devised element as shown in Fig.10(a), Fig.10(b) and Fig.10(c) . The previously proposed unit cells had this drawback of degrading performace with changing angle of incidence [4-6].



(a)



(b)



(c)

Fig. 10. Reflecd Phase Response of the Element with respect to frequency for different values of angle of incidence and r1 (mm) **(a)** r1=1 and 2 **(b)** r1=3 and 3.5 **(c)** r1=4 and 4.4

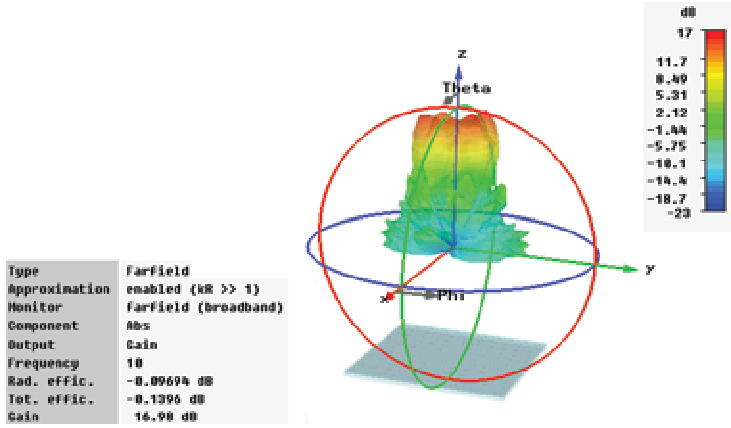


Fig. 11. Array far field Radiation Pattern at Center Frequency of 10 GHz

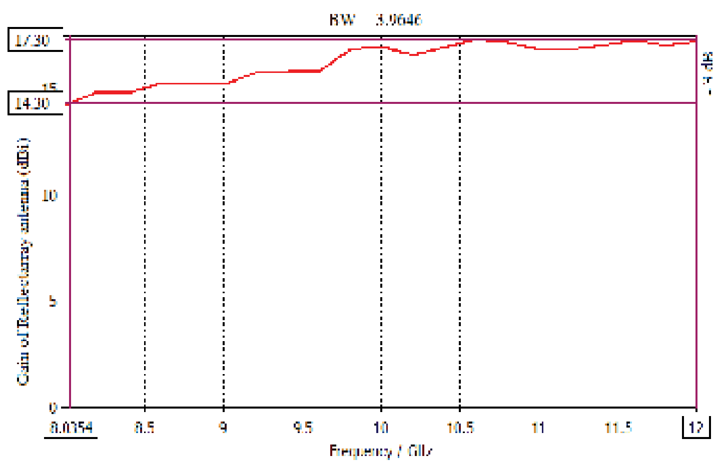


Fig. 12. 3-dB Gain-bandwidth at f/D =1

3.2 Reflectarray Antenna

Based on the proposed unit cell having optimum phase response, an array of 121 elements is designed and simulated. Array is in square pattern as shown in the Fig. 7. A center fed horn antenna operational in X-band is used as a source impinging incident wave normal to the reflecting plane. Each element's individual phase was calculated by the contour of phase distribution.

Radiation pattern in Fig. 11 proves the achievement of 97 % radiation efficiency with high gain of 16.98 dBi. The displacement between the array and horn antenna i.e. fraction of the focal length to the antenna's largest diameter (f/D) is set to a value of 1.0.

Fig. 12 shows that a simulated 3 dB Gain dropping bandwidth of 39.6% is attained, i.e. from 8.035 to 12 GHz at the mid frequency of 10 GHz. Till present, hardly any reflectarrays are able to attain 30% of the bandwidth as can be seen in Table 1. Hence the simulated results are satisfying the wide band nature of reflect array antenna.

3.3 S-Parameters for Different Position of Horn Antenna from the Array

Position of Horn antenna plays an essential role in determining the radiation and aperture efficiency of the designed array [8-9]. Fig. 13 demonstrates different curves of S-parameters which are obtained by placing the horn antenna at various lengths from the array. In this paper two lengths of d = 165mm and d = 323mm are selected for giving the most suitable results on the basis of directivity and gain. By further increasing the distance of horn

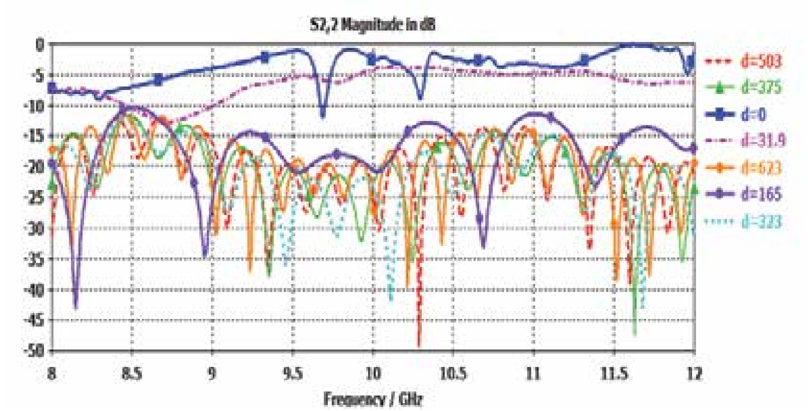


Fig. 13. S-Parameters for Different Positions ‘d’ of Horn Antenna from the Array

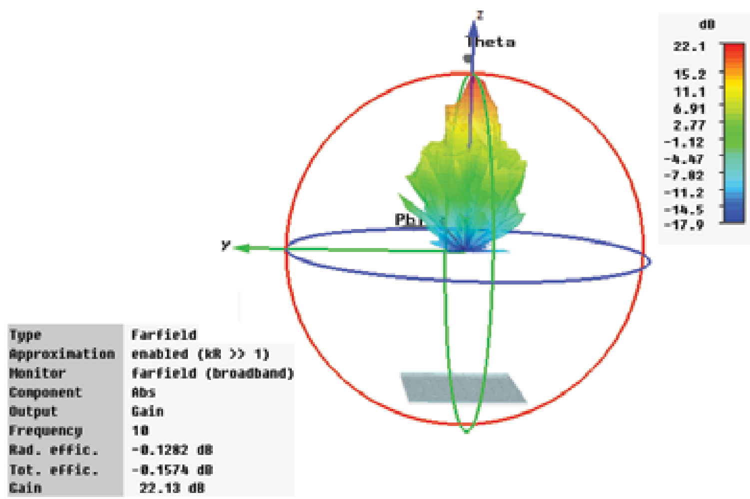


Fig. 14. Far field Radiation for F/D of 1.96 at Centre Frequency of 10 GHz

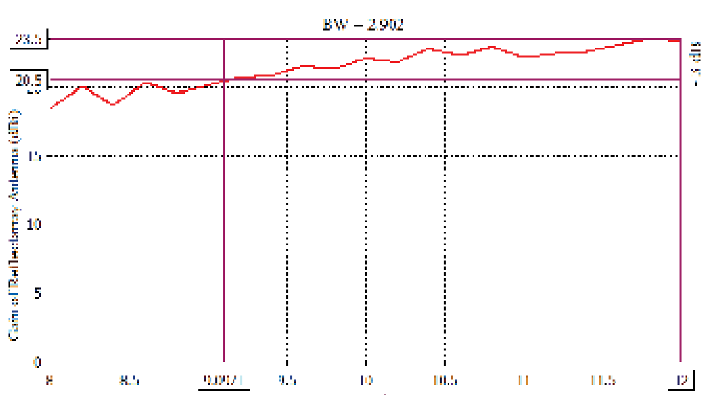


Fig. 15. 3-dB Gain Dropping Bandwidth for F/D=1.96

antenna beyond 323 mm, the effect on S-parameter becomes negligible, i.e. saturation point is reached. Hence distance of 323 mm is chosen for having less simulation time and high gain.

3.4 Simulated Results of RA Antenna at F/D =1.96

Simulated results in Fig. 14 shows that the radiation efficiency is 96% with an increased gain of 22.13 dB at center frequency of 10 GHz. Hence source positioned at 323 mm away from array antenna provides reasonable gain. At a distance larger than the saturation point, simulation time increases without any significant increase in the gain.

Fig. 15 is the gain bandwidth curve of reflectarray antenna for f/D ratio of 1.96. Satisfactory gain of 19 to 23.5 dBi is obtained in the X-band. But now, the 3-db gain-bandwidth is reduced to 29 %. Thus, by placing linearly polarized horn antenna at a distance of 323 mm from the array provides high gain but at the expense of reduced bandwidth.

Consequently, we can draw further conclusion that aperture efficiency of the reflectarray antenna increases with increasing the spacing between horn and array antenna.

4. CONCLUSION

A single layer low profile reflectarray novel element and a resultant reflectarray antenna has been designed, simulated and analyzed in this paper. This reflectarray antenna is proposed for wideband applications at X-band. Using parameterization and optimization method, desired objective of broad band reflectarray antenna design is achieved. 3-dB gain bandwidth of 39.6% is obtained. Till present hardly any reflectarrays are able to attain 30% of the bandwidth. Thus the desired goal of achieving broad band characteristic of RA antenna is validated through the simulation results.

The intended antenna has also been simulated for different f/D ratios to calculate its effect. From simulation results we can conclude that improved aperture efficiency is obtained with increasing distance of source from the reflectarray antenna plane but at the cost of reduced bandwidth and radiation efficiency.

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