

REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

REFLECTARRAY ANTENNA DESIGN USING ARTIFICIAL
INTELLIGENCE

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DOCTOR OF PHILOSOPHY THESIS
Department of Electronic and Communication Engineering
Program of Communication Engineering

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A thesis submitted by Alper ÇALIŞKAN in partial fulfillment of the requirements for the degree of **DOCTOR OF PHILOSOPHY** is approved by the committee on 21.08.2019 in Department of Electronic and Communication Engineering, Program of Communication Engineering .

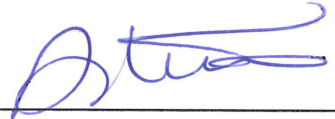
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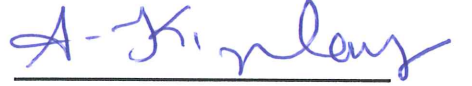
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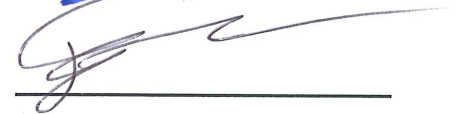
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Alper ÇALIŞKAN

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Dedicated to my family



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TABLE OF CONTENTS

LIST OF SYMBOLS	viii
LIST OF ABBREVIATIONS	ix
LIST OF FIGURES	xi
LIST OF TABLES	xiv
ABSTRACT	xv
ÖZET	xvii
1 Introduction	1
1.1 Literature Review	1
1.2 Objective of the Thesis	2
1.3 Hypothesis	2
2 Feed Antenna Designs for Reflectarray Antennas	3
2.1 Horn Antenna Design	4
2.2 Double Ridged Horn Antenna Design	9
2.3 Corrugated Horn Antenna	14
2.3.1 Circularly Polarized Corrugated Horn Antenna	17
3 Non-Uniform Reflectarray Antenna Design	19
3.1 Advantage and Disadvantage of Reflectarray	19
3.1.1 Advantages of Reflectarray	20
3.1.2 Disadvantages of Reflectarray	20
3.2 Reflectarray Phase Distribution	21
3.3 Non-Uniform Reflectarray Antenna Design	24
3.3.1 Symbolic Regression	24
3.4 Circular Polarized Corrugated Horn Fed NURA	34
4 Elliptical Ring Reflectarray Antenna Design	39
4.1 Reflectarray Antenna Performance Characteristics	39
4.1.1 Illumination Efficiency	39

4.1.2	Spillover Efficiency	40
4.1.3	Blockage Efficiency	41
4.1.4	Aperture Efficiency	42
4.2	Elliptical Ring Unit Cell Design	43
4.3	Circular Shaped Elliptic Reflectarray Antenna Design	50
4.3.1	Multi Layer Perceptron (MLP)	50
4.3.2	Experimental Results of Circular Shaped Elliptic Ring Reflectarray Antenna	55
4.4	Elliptic Ring Reflectarray Antenna Design	58
5	Results And Discussion	63
	References	65
	Publications From the Thesis	68

LIST OF SYMBOLS

η_a	Aperture Efficiency
η_i	Illumination Efficiency
η_s	Spillover Efficiency
f	Frequency
f_c	Cut-off Frequency
f/D	Focal Length to Diameter Ratio
k_0	Free Space Propagation Constant
λ	Wavelength
λ_0	Wavelength of Free Space
ε_r	Permittivity
ϕ_0	Propagation Direction Angle
ϕ_R	Required Phase Distribution for Elements
θ_0	Propagation Direction Angle
y	Distance from waveguide
z	Distance from symmetry axis

LIST OF ABBREVIATIONS

ANN	Artificial Neural Network
AP	Analytic Programming
CHA	Corrugated Horn Antenna
CST	Computer Simulation Technology
DRHA	Double Ridged Horn Antenna
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ERA	Elliptic Reflectarray Antenna
FSS	Frequency Selective Surface
GA	Genetic Algorithm
GE	Grammatical Evolution
GEP	Gene Expression Programming
GP	Genetic Programming
HPBW	Half Power Beam Width
LHCP	Left Hand Circular Polarization
MAE	Mean Absolute Error
MLP	Multi Layer Perceptron
MRA	Microstrip Reflectarray Antenna
MXE	Maximum Error
NM	Nelder-Mead
NURA	Non-Uniform Reflectarray Antenna
RA	Reflectarray Antenna

RF	Radio Frequency
RHCP	Right Hand Circular Polarization
RME	Relative Mean Error
RP	Reflection Phase
SHF	Super High Frequency
SR	Symbolic Regression
TE	Transverse Electric
TM	Transverse Magnetic
VSWR	Voltage Standing Wave Ratio
WGS	Waveguide Simulation

LIST OF FIGURES

Figure 2.1	Illustration of the reflectarray principle	4
Figure 2.2	X-band horn antenna design	5
Figure 2.3	X-band compact horn antenna design	5
Figure 2.4	The horn antenna reflection coefficient	6
Figure 2.5	Gain over frequency of the horn antennas	6
Figure 2.6	Radiation pattern of the horn antenna at a) 10 GHz b) 11 GHz . .	7
Figure 2.7	Radiation pattern of the compact horn antenna at a) 10 GHz b) 11 GHz	8
Figure 2.8	Half Power Beam Width of a) Horn antenna b) Compact horn antenna	8
Figure 2.9	3D printed compact horn antenna	9
Figure 2.10	Measured gain of compact horn antenna	9
Figure 2.11	Measured H-plane radiation pattern of the compact horn antenna at a) 10 GHz b) 11 GHz	10
Figure 2.12	Measured E-plane radiation pattern of the compact horn antenna at a) 10 GHz b) 11 GHz	10
Figure 2.13	Double ridged horn antenna	11
Figure 2.14	Feed point placement	12
Figure 2.15	Radiation pattern of DRHA a) E-plane b) H-plane	12
Figure 2.16	Double ridged horn antenna gain	13
Figure 2.17	Double ridged horn antenna frequency variations of VSWR	13
Figure 2.18	Double ridged horn antenna pattern measurement	14
Figure 2.19	Corrugated horn antenna	14
Figure 2.20	Radiation pattern of CHA at a) 11 GHz b) 12 GHz	16
Figure 2.21	Side view of PD-CHA	16
Figure 2.22	Maximum gain of CHA	17
Figure 2.23	Radiation pattern of circularly polarized CHA at a) 10 GHz b) 11 GHz c) 12 GHz	18
Figure 3.1	Spatial phase delay of the reflectarray [3]	22
Figure 3.2	Typical geometry of a printed reflectarray antenna	22
Figure 3.3	An example of syntactic tree	25
Figure 3.4	An example of crossover operation	26

Figure 3.5	An example of mutation operation	26
Figure 3.6	Centre fed non-uniform reflectarray	26
Figure 3.7	Unit cell of the NURA with its simulation setup	27
Figure 3.8	Reflection phase characteristics for variable dielectric permittivity for a) 8 GHz b) 10 GHz C) 12 GHz	29
Figure 3.9	Reflection phase characteristics for a) RO4003 (h=0.305 mm, ϵ_r =3.55) b) RO4350 (h=0.76 mm, ϵ_r =3.66) C) RO5870 (h=1.575 mm, ϵ_r =2.33)	30
Figure 3.10	CEL Robox Micro manufacturing platform	31
Figure 3.11	Parametric values of quadratic NURA	32
Figure 3.12	Reflection phase calibration characteristic of material with dielectric permittivity of 2.4 at 10 GHz	32
Figure 3.13	Prototyped 3D printed NURA	33
Figure 3.14	Parts of the prototyped 3D printed NURA	33
Figure 3.15	Measured NURA characteristics Gain-VSWR along frequency band	34
Figure 3.16	Measured radiation pattern of NURA at a) 9 GHz b) 10 GHz c) 11 GHz	35
Figure 3.17	Corrugated horn antenna fed NURA	36
Figure 3.18	Reflection coefficient of corrugated horn antenna fed NURA	36
Figure 3.19	Gain of corrugated horn antenna fed NURA	36
Figure 3.20	Radiation pattern of CHA fed NURA at a) 10 GHz, b) 11 GHz, c) 12 GHz	37
Figure 3.21	Axial ratio of CHA fed NURA at 10 GHz	38
Figure 3.22	Axial ratio of CHA fed NURA	38
Figure 4.1	Aperture efficiency versus subtended angle for different q values .	41
Figure 4.2	Side views of a center fed parabolic reflector and its equivalent reflectarray	42
Figure 4.3	An example of efficiency versus q	43
Figure 4.4	Geometric parameters of elliptic unit cell	44
Figure 4.5	TEM mode waveguide simulator for an elliptical unit cell	45
Figure 4.6	Illustration of Floquet port analysis of the unit cell	45
Figure 4.7	Reflection phase variation with the gap parameter(R1=4 mm, R2=7 mm, w=2.5 mm)	46
Figure 4.8	Reflection phase variation with the width parameter (R1=3 mm, R2=7 mm, g=0.5 mm)	47
Figure 4.9	Reflection phase variation with incident angle theta and constant phi=0 degree (R1=4 mm, R2= 7 mm g= 0.25 mm, constant) . . .	47
Figure 4.10	Reflection phase variation with incident angle theta and constant phi=90 degree (R1=4 mm, R2= 7 mm g= 0.25 mm, constant) . .	48

Figure 4.11 Reflection phase of the unit cell along frequency for WGS and Floquet port	49
Figure 4.12 Elliptic ring element reflection phase variation with the radius R2 (g=0.5 mm, w=2.5 mm and R1=4 mm)	49
Figure 4.13 Circular shaped elliptic reflectarray antenna	50
Figure 4.14 Black-Box representation of the proposed MLP based Elliptic RA .	51
Figure 4.15 MLP Black-box model result comparison with CST at a) 10 GHz b) 11 GHz c) 12 GHz	53
Figure 4.16 The design procedure for reflectarray antenna	54
Figure 4.17 Realized gain of the CERA for optimized parameters	56
Figure 4.18 Photograph of the fabricated CERA	56
Figure 4.19 Measured radiation pattern of CERA at a) 10 GHz b) 11 GHz c) 12 GHz	57
Figure 4.20 Elliptic ring reflectarray antenna	58
Figure 4.21 S_{11} - Frequency variation of ERA	59
Figure 4.22 Required phase distribution of ERA	59
Figure 4.23 Realized gain and aperture efficiency of ERA	60
Figure 4.24 E-plane and H-plane radiation pattern of the ERA	61

LIST OF TABLES

Table 2.1	X-Band horn antenna parameters	5
Table 2.2	Double ridged horn antenna parameters	11
Table 2.3	X-Band corrugated horn antenna parameters	15
Table 3.1	Training data set for reflection phase expression	27
Table 3.2	Test data set for reflection phase expression	27
Table 3.3	Performance of analytical expression	28
Table 3.4	Training data set for limited reflection phase expression	31
Table 4.1	Elliptic unit cell parameters	44
Table 4.2	Different MLP structures and their design parameters	51
Table 4.3	Performance comparison of the MLP models	52
Table 4.4	Optimization results of R1,R2 parameters (mm)	55
Table 4.5	Comparison of the antenna performance with previous works on reflectarray antenna	62

Reflectarray Antenna Design Using Artificial Intelligence

Alper ÇALIŞKAN

Department of Electronic and Communication Engineering

Doctor of Philosophy Thesis

Advisor: Prof. Dr. Filiz GÜNEŞ

In this thesis, it is aimed at designing high performance reflectarray antennas using artificial intelligence based algorithms for fast, accurate and low cost design optimization process. For this purpose firstly, different designs of high performance feed antennas such as traditionally horn, double ridged horn, corrugated horn antennas were studied. Then, two different unit cells, Non-Uniform and elliptical ring shaped cell for reflectarray antenna are taken into consideration for creating an artificial intelligence based model. The geometrical design parameters of both models are taken as the input of the artificial intelligence models where a variation in the geometrical design parameters would also cause a change in the reflection phase of the incoming electromagnetic waves. Herein, Multi-Layer Perceptron (MLP) and Symbolic Regression methods were taken as novel regression methods for modelling reflection phase characteristic of the unit cell design of the reflectarray antennas with respect to the geometrical design parameters. Finally the obtained models had been realized via the use of either traditionally prototyping methods or 3D printing technology. From the experimental results it can be concluded that the proposed methodology is a computationally efficient, fast and low cost for design optimization of large scale reflectarray antennas.

Keywords: Reflectarray antenna, artificial intelligence, symbolic regression, neural networks

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Yapay Zeka Kullanılarak Yansıtıcı Dizi Anten Tasarımı

Alper ÇALIŞKAN

Elektronik ve Haberleşme Mühendisliği

Doktora Tezi

Danışman: Prof. Dr. Filiz GÜNEŞ

Bu tezde, hızlı, doğru ve düşük maliyetli tasarım ve optimizasyon işlemi için yapay zeka bazlı algoritmalar kullanarak yüksek performanslı yansıtıcı dizi antenlerin tasarlanması amaçlanmıştır. Bunun için öncelikle, geleneksel olarak huni, çift eğimli huni, oluklu huni antenler gibi yüksek performanslı besleme antenlerinin farklı tasarımları incelenmiştir. Bundan sonra, yansıtıcı dizi anteni için tekdüze olmayan ve elips halka şeklindeki iki farklı birim hücre, yapay zeka bazlı bir model oluşturmak için göz önünde bulundurulmuştur. Her iki modelin geometrik tasarım parametreleri yapay zeka modellerinin girişi olarak alındı, burada geometrik tasarım parametrelerindeki bir değişiklik, gelen elektromanyetik dalgaların yansıma fazında bir değişikliğe neden olmaktadır. Burada, Çok Katmanlı Algılayıcı (MLP) ve Sembolik Regresyon yöntemleri, yansıtıcı dizi antenlerin birim hücre tasarımının yansıma faz karakteristiğini geometrik tasarım parametrelerine göre modellemek için yeni regresyon yöntemleri olarak alınmıştır. Son olarak, elde edilen modeller standart prototipleme yöntemleri veya 3 boyutlu baskı teknolojisi kullanılarak gerçekleştirilmiştir. Deneysel sonuçlardan, önerilen yöntemin, büyük ölçekli yansıtıcı dizi antenlerin tasarım optimizasyonu için hesap olarak verimli, hızlı ve düşük maliyetli olduğu sonucuna varılabilir.

Anahtar Kelimeler: Yansıtıcı dizi anten, yapay zeka, sembolik regresyon, nöron ağları

YILDIZ TEKNİK ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ



1.1 Literature Review

The idea of the reflectarray antenna was presented in 1963 just using waveguide components, however the genuine attention for reflectarrays just came to fruition in the late 1980s with the advancement of low profile printed antennas [1]. Consequently, the printed reflectarray can be considered as a quite new type of antenna. In a same way of a parabolic antenna, radiating element array as a reflector is illuminated by a feed and also preset phasing to create a focused beam. Printed reflectarrays consolidate certain superiorities of reflector antennas and phased arrays. They are produced on a planar substrate utilizing printed circuit innovation and offer chance of beam steering as phased arrays; then again, the feeding system utilized in planar arrays, in this way giving a higher efficiency. Reflectarrays have exhibited their ability to deliver contoured beams, which are customarily produced by utilizing formed reflectors or phased arrays.

A Microstrip Reflectarray Antenna (MRA) is a design that being a hybrid of a reflector antenna and a planar phased array antenna which uses a suitable phasing scheme for its elements to reflect the incoming electromagnetic wave form a pencil beam in a specified direction (θ_0, ϕ_0) [2–5]. One of the very popular phasing schemes involves varying dimensions of the elements such as printed dipoles or patches around their resonant size. In the recent works of [4, 5], novel multi-objective evolutionary design optimization procedures are put forward to obtain the quasi-linear phasing characteristic for the Minkowski RA's using 3D CST Microwave Studio based Multi Layer Perceptron (MLP) neural network models with Particle Swarm and hybrid Genetic Algorithm (GA) and Nelder-Mead (NM) algorithms, respectively. In fact, MRAs are advantageous antennas having the simple structures with low profiles, light weights and no need of any complicated feeding networks. However, MRAs are inherently narrow-band radiating elements and the mutual couplings between microstrip elements printed on standard substrates are significant, in addition, the conductor and surface wave loss are severe. To reduce these shortcomings solely

grounded dielectric layer with variable thickness is proposed to be use as a reflecting surface in [6]. In this Non-Uniform dielectric layer, the required phase shift is provided by determining thickness at each cell on the RA plane to produce a pencil reflected beam in a specific direction (θ_0, ϕ_0) . Thus, a RA design with the possible simpler and more advantageous structure can be obtained than MRAs.

1.2 Objective of the Thesis

In this thesis, it is aimed at designing high performance reflectarray antennas using artificial intelligence based algorithms for fast, accurate and low cost design process. Two different unit cells, Non-Uniform and Elliptical shaped unit cell for reflectarray antenna are taken into consideration. The geometrical design parameters of both models are taken as the input of the artificial intelligence algorithms where a variation in the geometrical design parameters would also cause a change in the reflection phase of the incoming electromagnetic waves. The optimally selected unit cells for a reflectarray antenna are simulated in 3D electromagnetic simulation tool CST. Then the simulated and measured results of the antenna were compared and found to be agreeable. Thus, it can be concluded that the proposed methodology is a computationally efficient, fast and low cost for design optimization of reflectarray antennas.

1.3 Hypothesis

In this thesis, firstly different designs of high performance feed antennas such as traditionally horn, double ridged horn, corrugated horn antennas had been studied. After that, two different unit cell, non-uniform and elliptical shaped reflectarray cell for reflectarray antenna are taken into consideration for creating an artificial intelligence based model. The geometrical design parameters of both models are taken as the input of the artificial intelligence models for prediction of reflection phase of the incoming electromagnetic waves. Multi-Layer Perceptron (MLP) one of the most commonly used Artificial Neural Network (ANN) and Symbolic Regression Methods had been taken as novel regression methods for modelling reflection phase characteristic of the unit cell design of the reflect array antennas with respect to the geometrical design parameters. Finally the obtained models had been realized via the use of either traditionally prototyping methods or 3D printing technology. From the experimental results it can be concluded that the proposed methodology is a computationally efficient, fast, and low cost for design optimization of large scale reflectarray antennas.

Feed Antenna Designs for Reflectarray Antennas

A reflector antenna must consist of a feed antenna that provides sufficient illumination over the reflector. Like all reflector antennas, Reflectarray antenna (RA) also works as same principle as shown in Fig. 2.1. While the feed is placed at the focal length of the reflector, the reflectarray reflects the incoming waves with RA elements which adjust the reflection phase to direct the main beam to the desired direction.

A feed is the main contact point between the reflectarray and the coaxial cable or a waveguide. Briefly, the feed is a means of communication for reflector antennas, the waves are transmitted and received thanks to the reflector. The horn is an impedance transformer that gradually provide transition from the impedance of a waveguide to the free-space impedance. A horn antenna is a handy and simple radiator stimulated by the waveguide. If the waveguide size is slowly widened or tapered, more gain can be achieved that prevents unwanted modes from reaching the waveguide. The horn antenna is used as a focal point feeder in many reflector antennas. Losses on the horn are not important. The horn function is to produce a uniform phase front with a larger aperture than the guide and therefore with more directivity.

Horn antenna, which is high gain wide-band directional aperture antenna, is usually used for communication and military systems. Horn antennas could be utilized either alone, parabolic reflector or reflectarray feeder. There are various types of horn antennas with different polarization or wider bandwidth [7]. One of the horn antenna types is ridged horn antenna which has ultra-wide operation band with 20:1 bandwidth ratio. Ridged horns are generally employed as test antenna for EMC/EMI measurements, because of its bandwidth and high gain [8].

Ridged horn antennas have wider bandwidth compared to horn antennas, because of their ridges which exponentially tapered strips extend from waveguide feeder to flare aperture. Ridges arrange cutoff frequencies of modes with changing wave impedance in the waveguide and flare. Thus, operation bandwidth reaches to

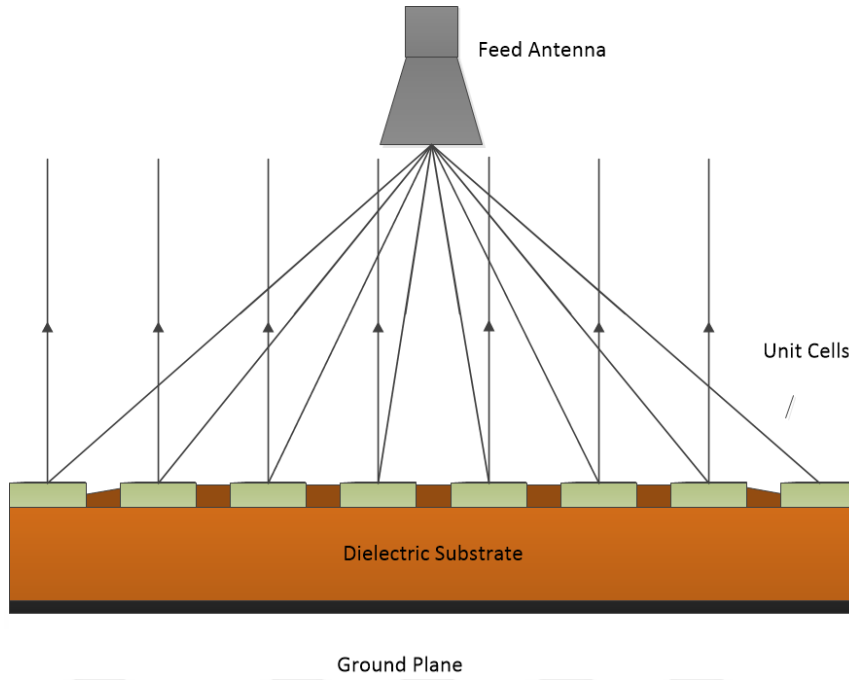


Figure 2.1 Illustration of the reflectarray principle

maximum possible bandwidth [8]. Quantities of ridges could be two or four for single or dual linear polarization. Moreover, antenna has high gain performance like other horns. However, even if DRHA have enough high gain, there are some pattern distortions at higher frequencies [8]. In order to solve these problem and to get higher gain, many studies have been conducted in literature like adding circular parts to end of ridges [9], back cavity shaping [10], dielectric lens loading [11] etc.

The CHA's have extensive applications in communication, radar, astronomy, satellite communication and remote-sensing. CHA's are usually being used as advanced feeding element for reflector antennas [12–14] as well as broadband measurements [15]. Corrugated horns radiation patterns have some specific features such as axial symmetry, high efficiency, low cross-polarization, low side and back lobe levels and good return loss characteristics [12–17].

In this chapter, various feed antennas are designed and performance results are compared.

2.1 Horn Antenna Design

Reflectarray antenna design start with a primary feed antenna. Specially, side lobes of the feed antenna should be minimized for improve the aperture efficiency of the antenna. The feed antenna radiation should be compatible with reflectarray surface to reduce spillover losses. Also, E-plane and H-plane of the feed radiation design

to obtain a symmetrical pattern. Usually these type of radiation can be achieved with conical corrugated horn. The phase center of the antenna is another critical parameter to consider and we aim to minimize the dispersion of the phase center versus the wavelength. The objective of this work is the accurate synthesis of the parameters of the RA cells. Firstly, a classical pyramidal horn in X-band has been designed and some of other feed antenna types has been investigated.

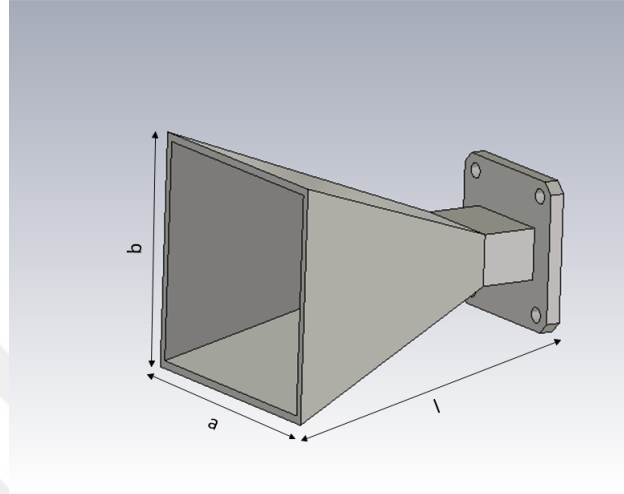


Figure 2.2 X-band horn antenna design

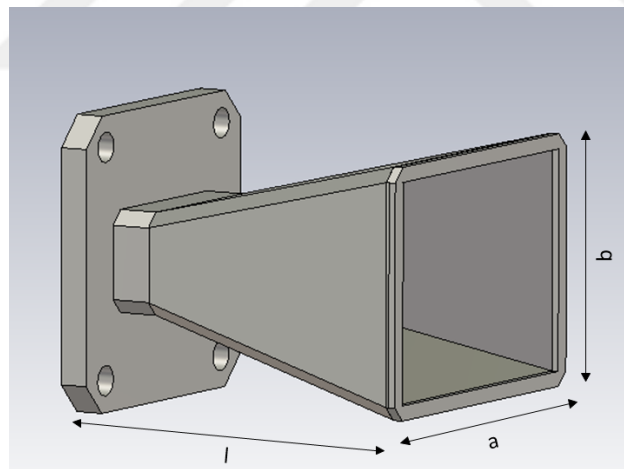


Figure 2.3 X-band compact horn antenna design

Table 2.1 X-Band horn antenna parameters

Fig	Model	Physical Descriptions (cm)
2.2	Horn	Width (a)=6.8, Height (b)=6.4, Depth (l)=9
2.3	Compact Horn	Width (a)=4.6, Height (b)=3.5, Depth (l)=5.5

Horn antenna is well known in the literature. It can be described as the simplest and one of the most used of microwave antennas. Between the many possible horn shapes (pyramidal, conical), as a starter i have chosen the standard gain pyramidal horn. It

consists of an open waveguide connected to a flared aperture in both the E-plane and H-plane, which results in narrow beam widths in both principal planes. The overall geometry of the antennas is shown in Fig.2.2 and 2.3 and the standard dimensions of the WR-90 waveguide is 22.86x10.16 mm. Geometrical parameters are given in Table. 2.1 for these horn antennas for X-band.

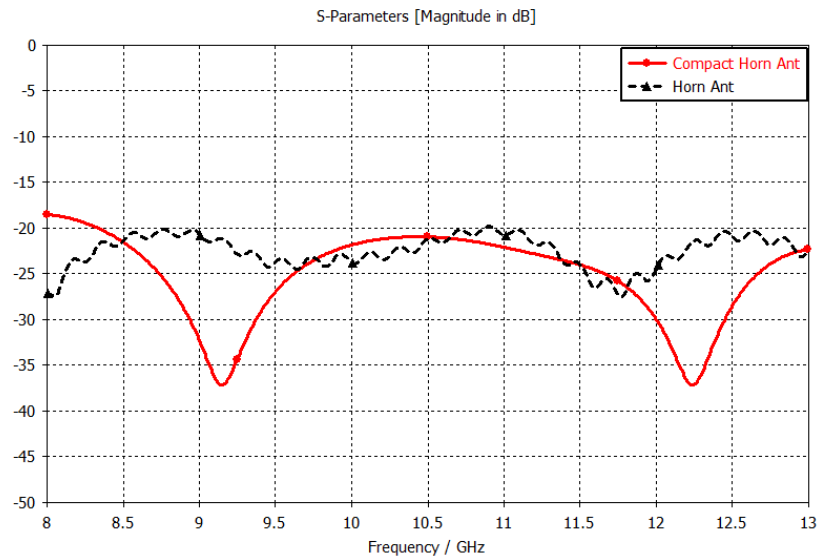


Figure 2.4 The horn antenna reflection coefficient

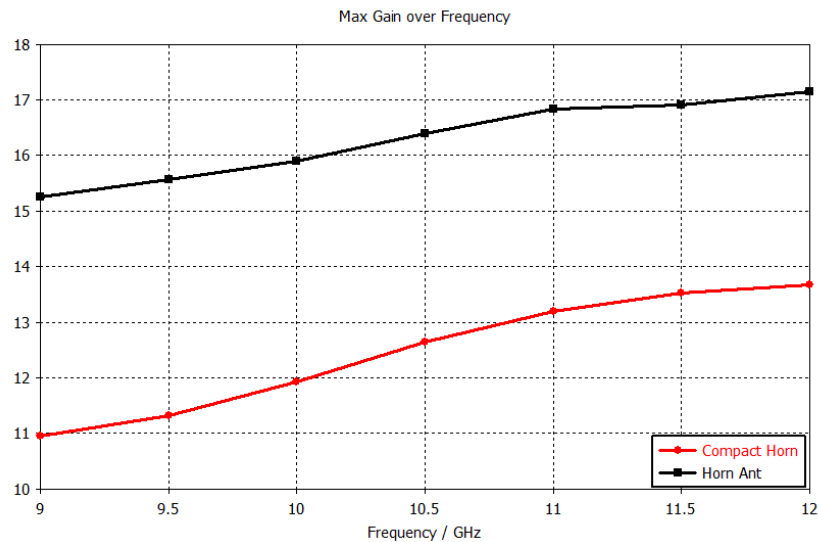


Figure 2.5 Gain over frequency of the horn antennas

Waveguide horn antennas have some specifications and those should be considered at the design stage. Waveguide horn antennas act as a point sources during illumination of large reflectarrays. Thus only a small portion of radiation pattern is used in illumination. Therefore f/D ratio should be large enough for an uniform illumination at the same time minimum spillover effect to obtain larger total efficiency. A part of energy radiated by the feed and not reach to the reflector, so that leads to loss. This

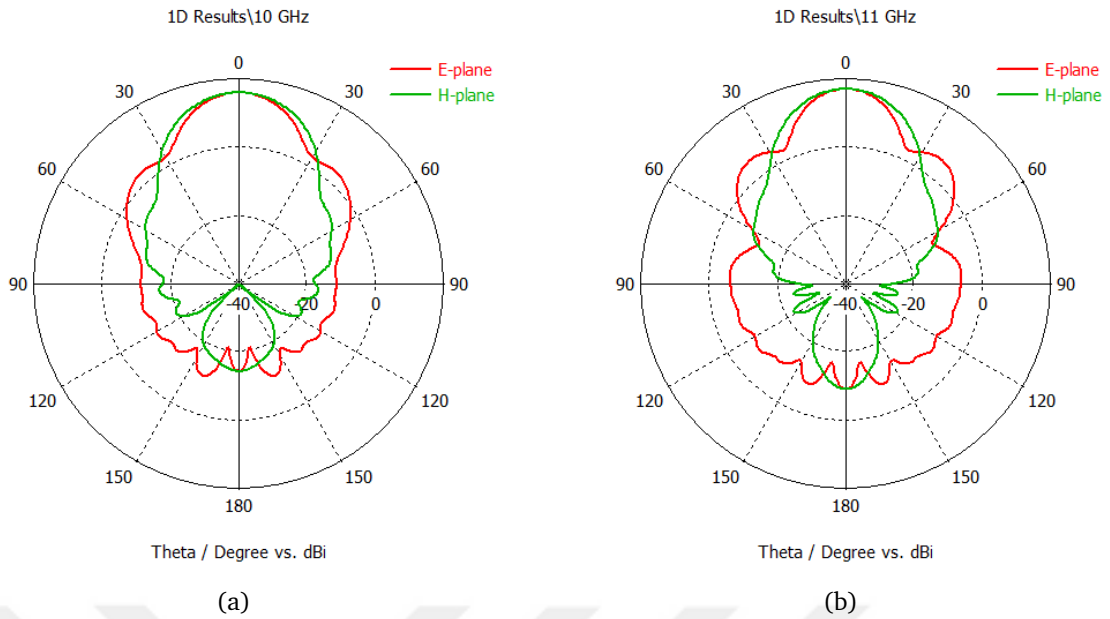
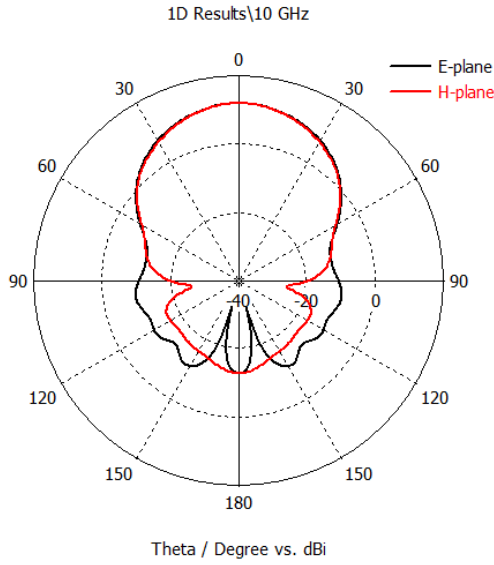


Figure 2.6 Radiation pattern of the horn antenna at a) 10 GHz b) 11 GHz

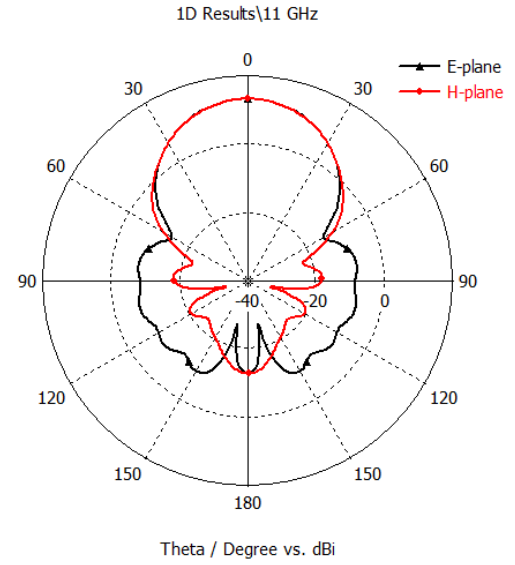
loss or spillover causes in bringing down the total efficiency and nullifies the purpose of uniform illumination. In the event that the ratio of f/D is raised further, spill over become less, captured energy and consequently efficiency increases. However, since illumination is progressively decreased, the aperture efficiency diminishes.

Two different size horn antenna designed for X-band and their reflection coefficients are given in Fig. 2.4 and also gains of the antennas are shown in Fig. 2.5. Both antennas have adequate reflection characteristic which is below -10 dB over the operational frequency band. As a gain comparison, the compact antenna's gain is 4 dB lower than the first design. Compact version of the horn antenna has smaller aperture area, thus blockage effect of the feeder could be reduced. Also, vertical and horizontal pattern HPBW are almost symmetrical and in case of need can be used for symmetrical reflector antennas. HPBW of the antennas are shown in Fig. 2.8. The early design of horn antenna does not have the same HPBW for each axis. Fig.2.8 shows that difference between beam widths and the compact version of the horn design's main beam widths for both axis are similar to each other. This specification of the compact horn antenna is provide advantages to the designer during the reflectarray design which are better illumination over the symmetrical reflectarrays such as square or circular structures and high aperture efficiency. Radiation pattern results at 10 and 11 GHz are given at Fig. 2.6 and 2.7. Also measured gain result of compact horn is given in Fig. 2.10.

A prototype of compact horn antenna is manufactured via 3D printer. Antenna geometry is modelled with PLA material and then coated with aluminum foil as

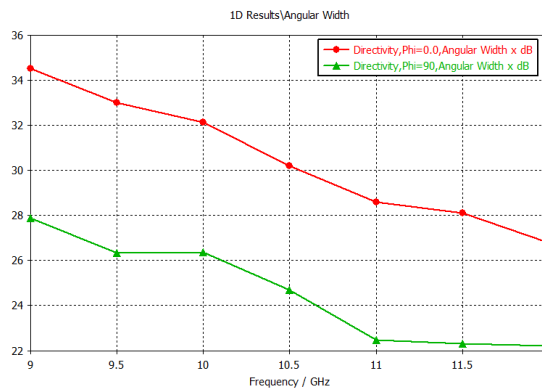


(a)

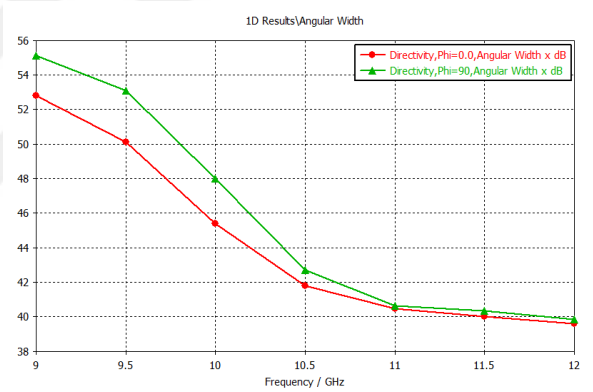


(b)

Figure 2.7 Radiation pattern of the compact horn antenna at a) 10 GHz b) 11 GHz



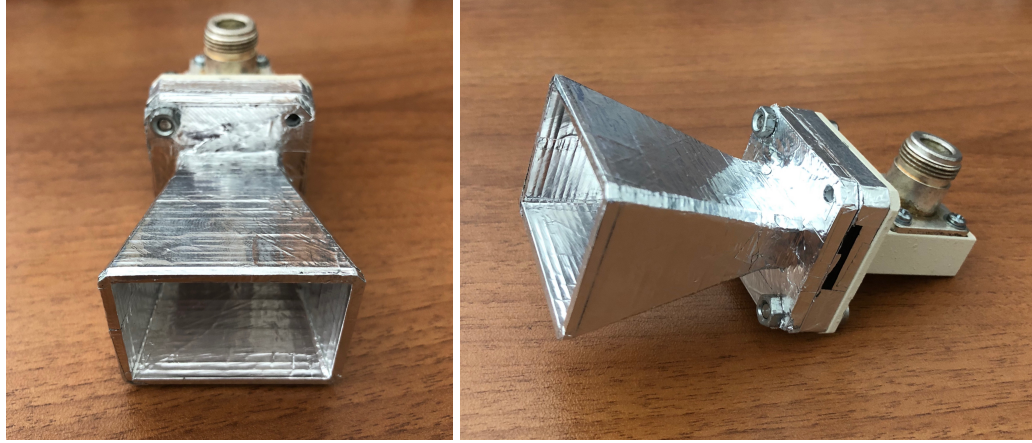
(a)



(b)

Figure 2.8 Half Power Beam Width of a) Horn antenna b) Compact horn antenna

shown in Fig. 2.9. At the input of the antenna a WR90 waveguide adaptor with N-connector is placed. Radiation pattern of the compact horn antenna is measured and E-plane and H-plane results at 10 and 11 GHz are given in Fig. 2.11 and 2.12. Horizontal pattern has some distortion because of the error while measuring angle of rotation. Due to lacking of smooth measurement environment, radiation patterns shows some fluctuation. Pattern of the compact horn antenna is measured for 180 degree on the broadside region. Because of the lacking of the complete anechoic chamber, pattern has some distortion. So, main lobe radiation pattern is investigated in measurement. Beside that, compact antenna has sufficient gain and pattern performance thus measurement results show that E-plane and H-plane pattern almost have same beamwidth so that compact horn antenna has high potential for symmetrical reflectarray antennas feed.



(a)

(b)

Figure 2.9 3D printed compact horn antenna

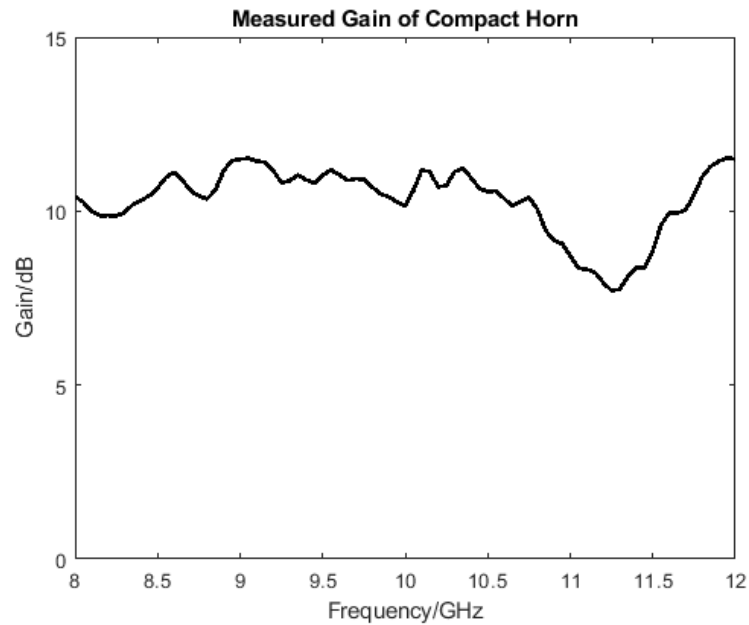


Figure 2.10 Measured gain of compact horn antenna

2.2 Double Ridged Horn Antenna Design

In this section, a Double Ridged Horn Antenna (DRHA) is designed for the operation bandwidth of 2-26 GHz, as seen in Fig. 2.13. After that, a partial dielectric is loaded as functioning a lens is loaded in antenna to improve gain performance of antenna (PD-DRHA-13). Antenna radiation is focused to main lobe direction, because dielectric load is used like optical lenses. Therefore, gain of antenna influenced positively. Dimension of the DRHA and partial dielectric load are given in Table 2.2. Besides, Teflon which has 2.1 permittivity (ϵ_r), is utilized as dielectric material. Taper function of ridges can be described as follows subject to distance from symmetry axis (z) and distance from waveguide (y);

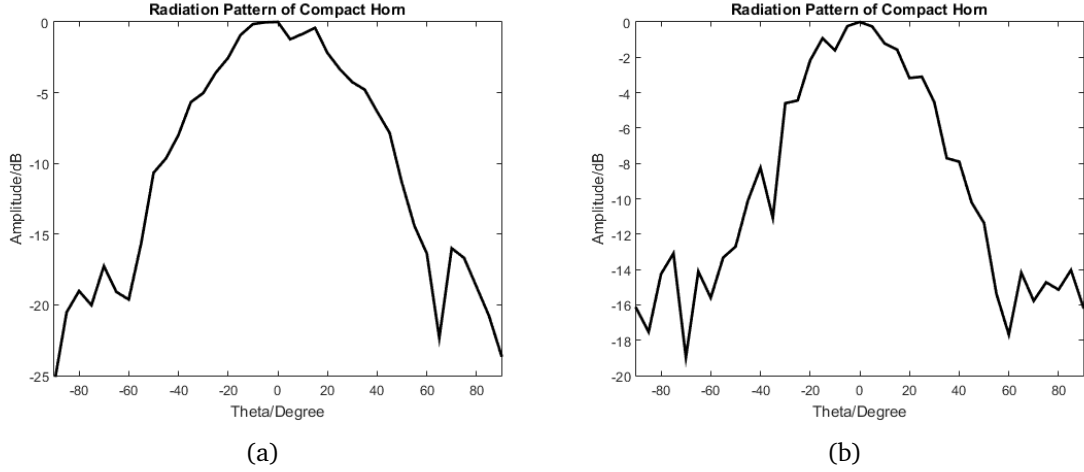


Figure 2.11 Measured H-plane radiation pattern of the compact horn antenna at a) 10 GHz b) 11 GHz

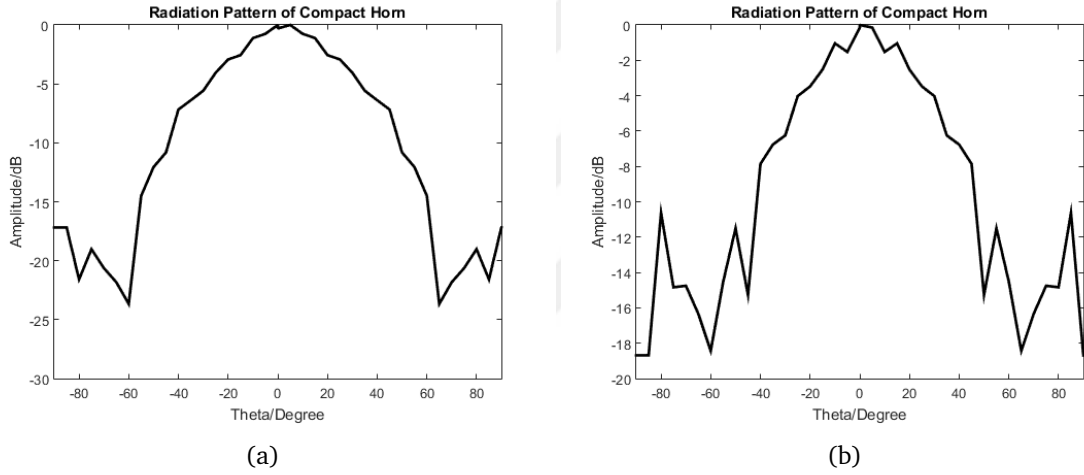


Figure 2.12 Measured E-plane radiation pattern of the compact horn antenna at a) 10 GHz b) 11 GHz

$$z(y) = z(0)e^{ky} \quad (2.1)$$

$$k = \frac{1}{L} \ln\left(\frac{Z(L)}{Z(0)}\right) \quad (2.2)$$

where L is flare length, $z(0)$ and $z(L)$ is minimum and maximum distance from symmetry axis, respectively. Width of ridges is taken as 5 mm. The designed DRHA is simulated, optimized, fabricated and then measured. Antenna illustration and picture is showed in Fig. 2.13.

In this section, designed PD-DRHA-13 simulation and measurement performance

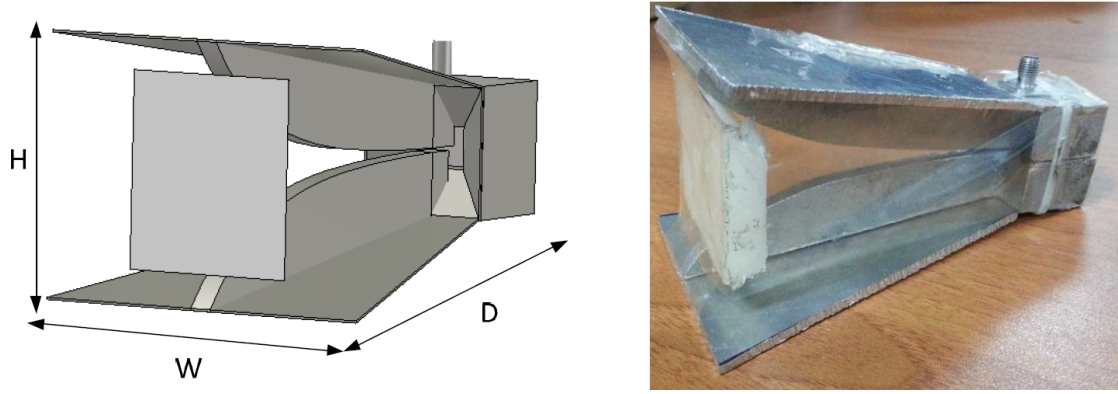


Figure 2.13 Double ridged horn antenna

Table 2.2 Double ridged horn antenna parameters

Fig	Section	Physical Descriptions (cm)
2.13	DRHA-13	Width (W)=8, Height (H)=6, Depth (D)=13
2.13	PD Load	4 x 4 x 1 cm, $\epsilon_r=2.1$ (Teflon)

results are presented. CST Studio Suite has been utilized for antenna simulations. According to results, teflon partial dielectric load enhances antenna gain after 3 GHz with approximately 5 dB, as seen in Fig. 2.16. Physical dimensions of partial dielectric load (PD Load) are given in Table 2.2. Furthermore, there are antenna pattern distortions, which main lobe splits two, after 21 GHz for DRHA-13, look Fig. 2.15. As a result of this, antenna gain does not radiate maximum performance at main direction. Fig. 2.15b is showed that pattern distortions above 20 GHz are fixed for PD-DRHA-13, because dielectric load focuses energy to main direction. Thus, splitting of patterns is shifted to higher frequencies at PD-DRHA-13, which starts from 25 GHz. Furthermore, measurement gain results justify simulations in Fig. 2.16 and measured pattern results are also given in Fig. 2.18. Measurements have been made until 15 GHz due to measurement possibilities. Additionally, there are some measurement errors at below than -15 dB side lobe levels, because of lack of fully compliant anechoic chamber.

VSWR of PD-DRHA-13 is demonstrated in Fig. 2.17. According to simulation result, VSWR is fewer than 2.5 at whole operation band. However, measurement result of VSWR is maximum 4 especially around 22 and 24 GHz due to production precisions. Simulation of antenna shows that lower ridge starting position has significant role to get better return loss of the antenna. Fig. 2.14 shows two cases of lower ridge starting profile. If lower ridge starts before than coaxial output, VSWR would be worse for higher frequencies. Optimum starting point for lower ridge is found out as center of the positive pin. Fig. 2.17 shows VSWR outcomes for different lower ridged start points.

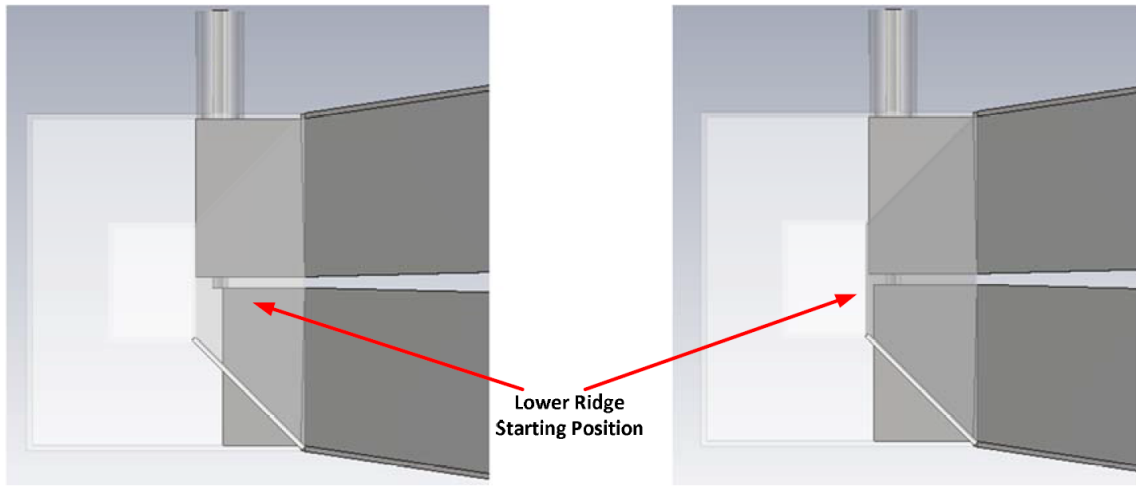


Figure 2.14 Feed point placement

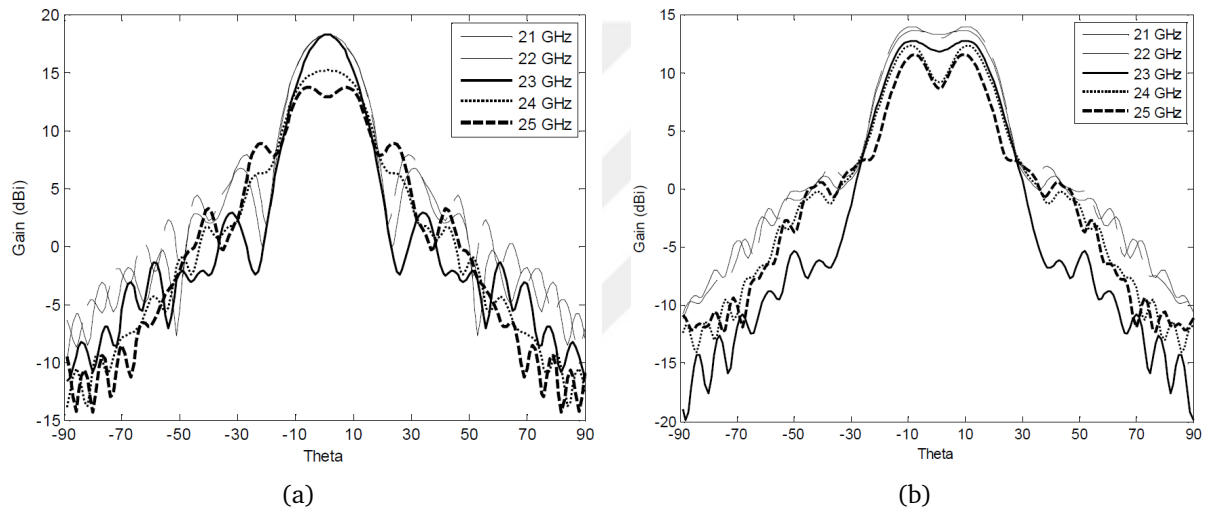


Figure 2.15 Radiation pattern of DRHA a) E-plane b) H-plane

Compact size DRHA-13 is composed with load inward from its aperture. Antenna is simulated and optimized to get better VSWR and gain performance. Besides, designed antenna is fabricated and measured. According to results, gain performance of antenna is improved due to partial dielectric load and pattern distortions are postponed to higher frequencies. Antenna has also good return loss performance for using as reflectarray feed antenna. Antenna performance shows that DRHA could be use as a feeder over a large bandwidth. For example, its frequency band cover from C-band up to K-band applications, almost all super high frequency (SHF) band. DRHA is a strong feeder antenna candidate for multi-band or wide band applications due to its UWB characteristic.

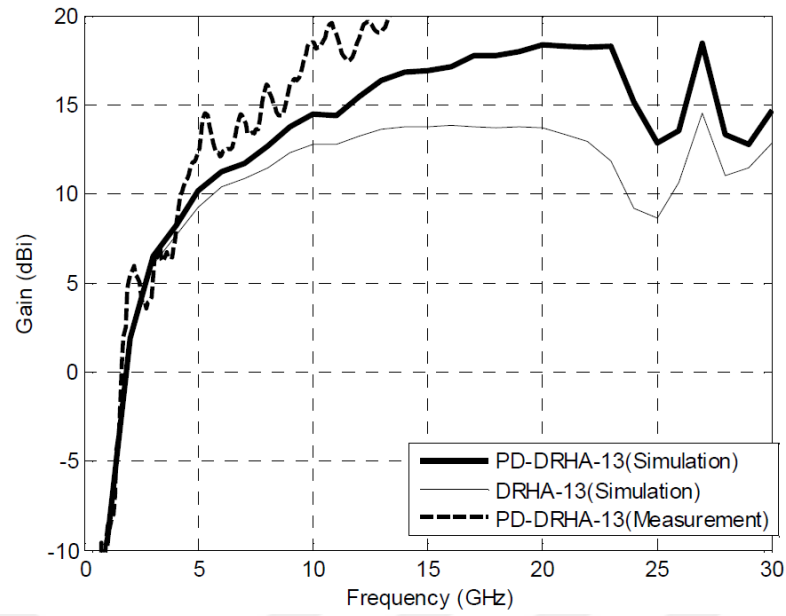


Figure 2.16 Double ridged horn antenna gain

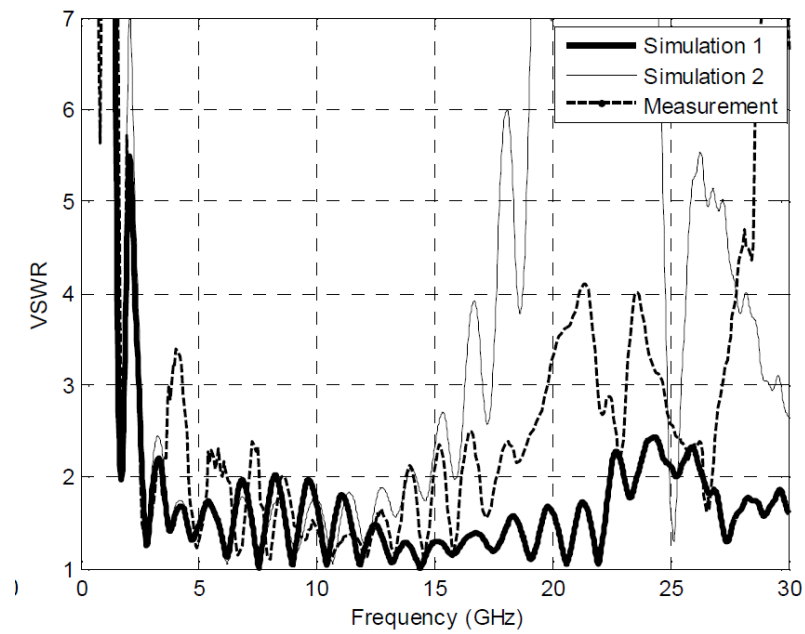


Figure 2.17 Double ridged horn antenna frequency variations of VSWR

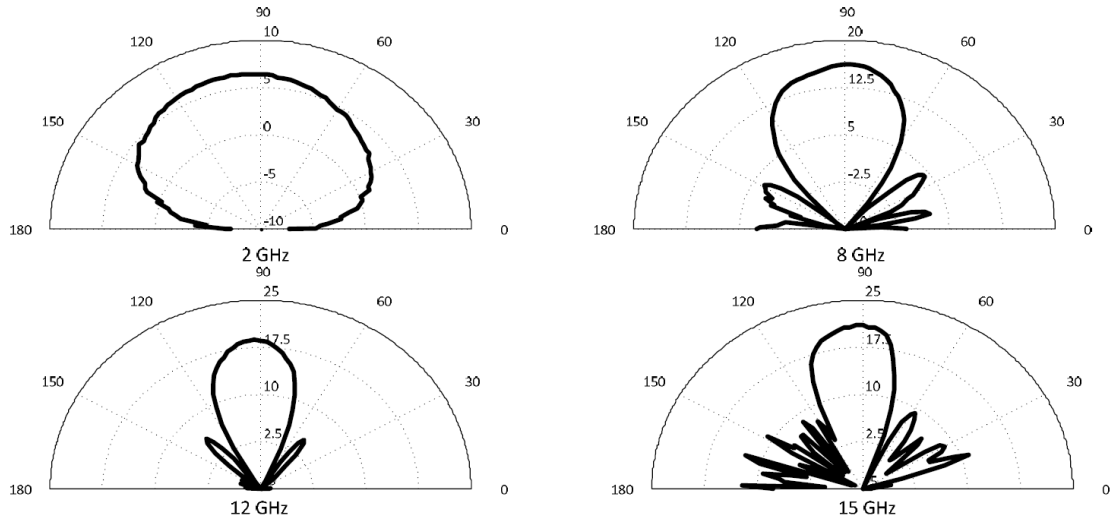


Figure 2.18 Double ridged horn antenna pattern measurement

2.3 Corrugated Horn Antenna

The design procedure has been proposed for the design corrugated horn antennas (CHA) with broadband constant beam widths with minimal design and construction complexity. Based on the proposed procedure, the beam width of corrugated horn antenna with a small change in frequencies of 10 to 12 GHz was designed and simulated using CST software. CHA geometry is depicted in Fig. 2.19. CHA geometry is described as 3 sections. First one is waveguide section, secondly flare part and corrugation parameters and lastly coaxial feed section. Design parameters of CHA is given in Table 2.3.

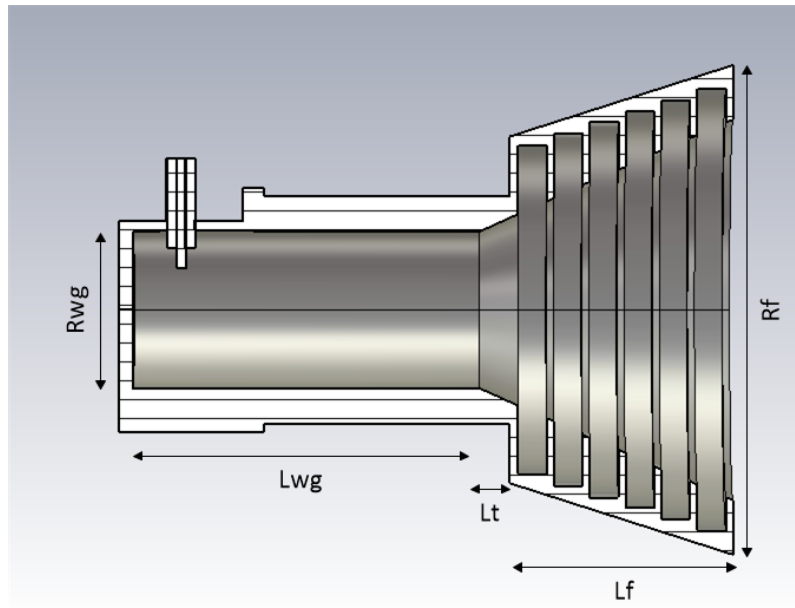


Figure 2.19 Corrugated horn antenna

Table 2.3 X-Band corrugated horn antenna parameters

Section	Physical Descriptions (mm)
Waveguide	Diameter (Rwg)=23, Length (Lwg)=31.2, Transition Length (Lt)=6.2
Flare	Length (Lf)=34, Aperture diameter (Rf)=71, Corrugation ridge width=1.1, Corrugation slot width= 4.1
Coaxial	Outer diameter=4.1, Inner diameter = 1.27, Pin length= 16

Corrugated-horn antennas usually consist of four main parts as shown in Fig. 2.19. These parts are the waveguide, mode converter, the corrugation section and the aperture. The aperture diameter and the flare angle have a important role in defining the directivity and beam width of the antenna for broadband use. The specifications of corrugations have effects on the fulfillment of the balanced hybrid-mode condition. Between the body of the corrugated horn and the circular smooth-walled waveguide input, mode converter is includes and TE_{11} mode is the dominant mode. For a smooth transition from the TE_{11} to the HE_{11} mode supported by the corrugated horn, the design should be done suitable, thus getting better impedance matching at the antenna's input.

To obtain good performance from the corrugations, the following tips should be considered [12, 13, 16, 17]: There should be enough corrugations per wavelength to have zero tangential transverse electric field at the surface of the corrugations. The corrugations ought to be narrow and $\lambda/4$ deep. The corrugations of the antenna behaves as transmission lines. The goal of this part that transform a short circuit at the end of the slots into an open circuit at the corrugation's boundary and causing a relatively zero tangential transverse magnetic field at this boundary. Slot depths less than $\lambda/4$ generate inductive reactance and result in the propagation of the EH_{11} mode, which is a surface-wave mode. This mode has a concentration of power around the radius of the corrugations and causes high levels of cross polarization.

At the design stage a center frequency must define to scales the associated wavelength dimensions of the antenna. The central frequency, f_c , should be closer to the lower end of the frequency band, because the stable hybrid mode fails faster at lower frequencies [18]. A proper value of f_c is calculated in terms of f_{min} as follows:

$$f_c = 1.2f_{min} \quad (2.3)$$

Directivity, gain, side lobe and cross polarization levels are mandatory configuration parameters for many applications. The extra outline parameters are the aperture and weight that must be minimized for the horn antenna. There are three main goals

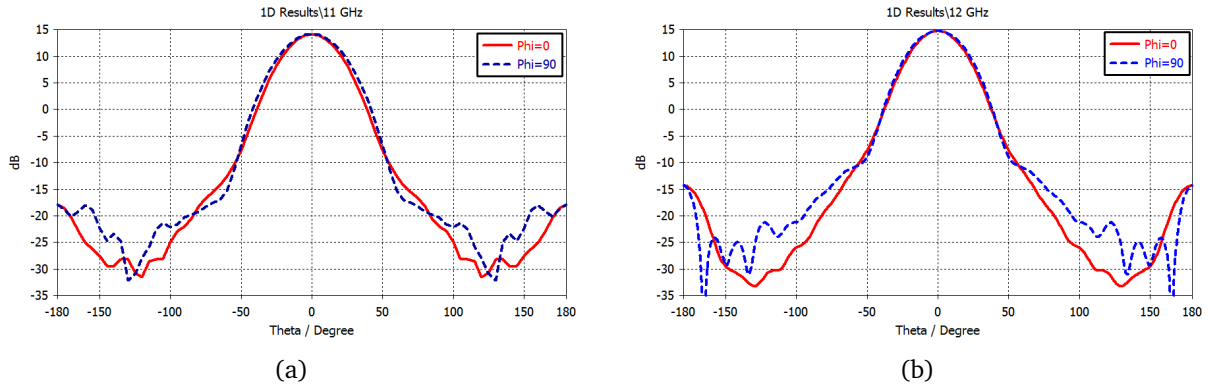


Figure 2.20 Radiation pattern of CHA at a) 11 GHz b) 12 GHz

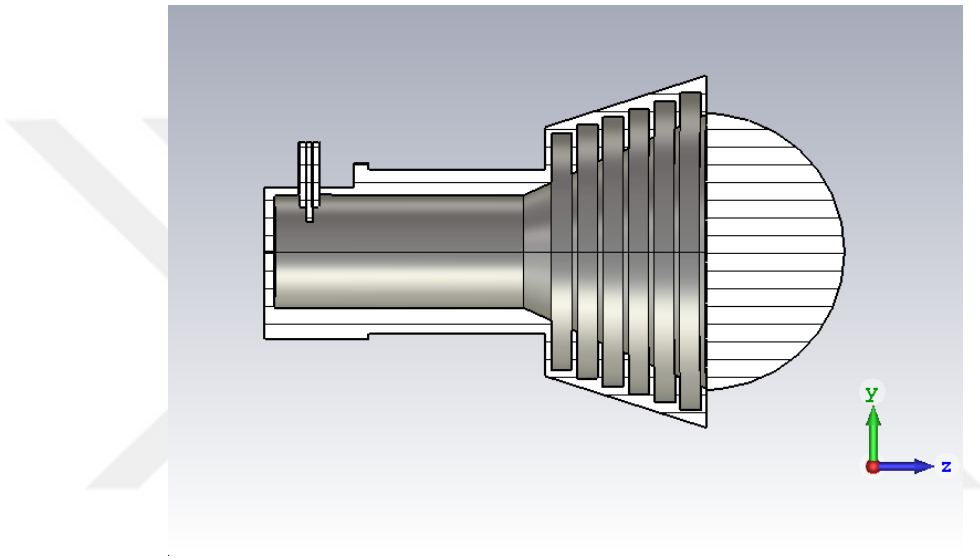


Figure 2.21 Side view of PD-CHA

behind the existence of corrugated horn antennas. One of these can be used as a potential for low-spill over and high-gain reflector antennas because they exhibit radiation pattern symmetry. Furthermore, they transmit by low cross polarization, which is important in dual polarization, and finally their bandwidth is wide. As seen from Fig. 2.20 main lobes of the CHA have almost same HPBW for both vertical and horizontal plane. The simulation results of radiation pattern at 11 and 12 GHz is given in Fig. 2.20 and HPBW for both frequency are 40 and 41 degrees, respectively.

Partially Dielectric loaded Corrugated Horn Antenna (PD-CHA) is designed and side view of antenna is shown in Fig. 2.21. Simulated result of gain comparison of with and without dielectric load on the aperture were given in Fig. 2.22. CHA gain is increased about 1-2 dB over frequency band by attaching teflon dielectric on the aperture of CHA.

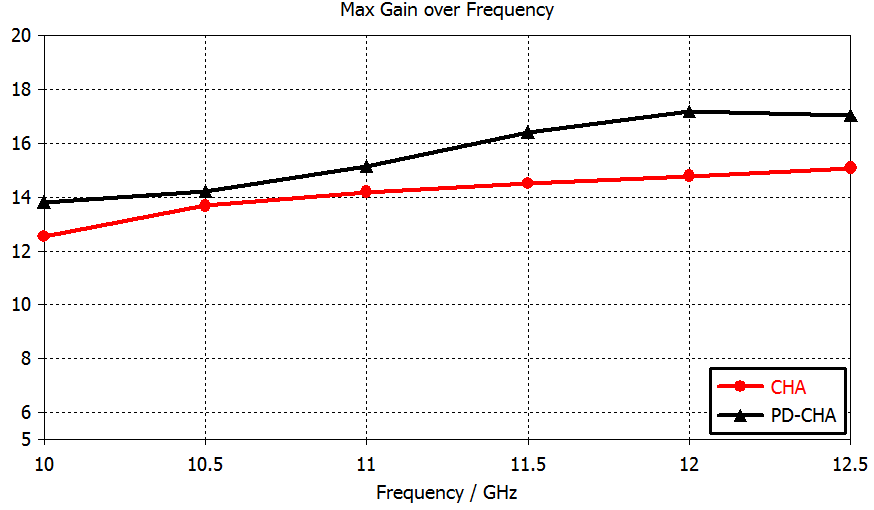
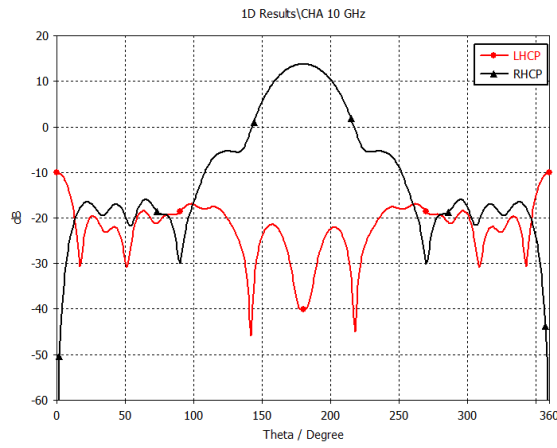


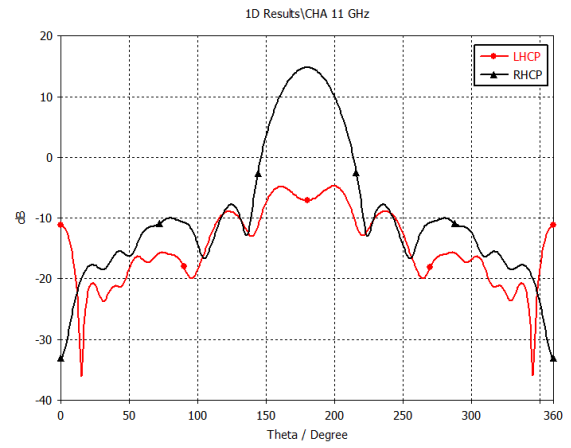
Figure 2.22 Maximum gain of CHA

2.3.1 Circularly Polarized Corrugated Horn Antenna

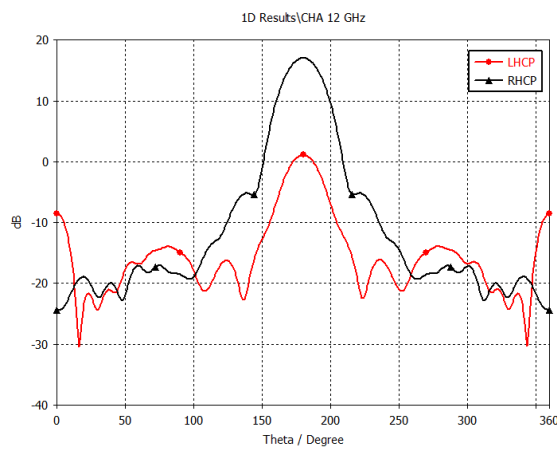
Circular and symmetrical geometry of the corrugated horn antenna geometry is appropriate to obtain circular polarization. For this purpose, feed type of the antenna changed from coaxial to waveguide port without changing any geometrical parameter. Waveguide port is excited with 2 modes to get circular polarization results. Two modes have 90 degree phase shift between each other and final simulation is performed simultaneously of these modes. RHCP and LHCP radiation pattern results are given in Fig. 2.23. As seen from the Fig. 2.23, cross-polarization level is more than -20 dB at 11 GHz and it has some rising at 12 GHz which is about -15 dB.



(a)



(b)



(c)

Figure 2.23 Radiation pattern of circularly polarized CHA at a) 10 GHz b) 11 GHz c) 12 GHz

The design procedure of a Reflectarray Antenna (RA) is consist of two main aspects of unit element design and phase distribution design, where during the element design, the candidate geometrical design of unit element should have an acceptable phase range, bandwidth, polarization etc. Geometrical parameters of each unit element in RA should selected optimally for creating the required phase distribution. The geometric properties of each element in the reflectarray surface must be adjusted appropriately to fulfill the desired phase distribution. During this phase matching step, it is indicated that the effects of the inclined incidence angle for the edge elements should also be taken into account in low profile reflectors or offset configurations based on the overlap of TM and TE wave incidences. However, in this work incident angle effect excluded from the design so this may cause a gain reduction. Finally, because there is no special software dedicated to reflectarray analysis, the reflectarray antennas can be analyzed with full-wave electromagnetic software such as CST and HFSS to get correct radiation properties. In this thesis CST is applied to obtain results.

3.1 Advantage and Disadvantage of Reflectarray

The Reflectarray Antennae (RA) is a fairly low cost innovation, which is now used in several applications, due to a large number of features, such as low cost and weight and re-configurable capabilities. On the other hand, they also have some internal limits and disadvantages, in contrast to different embodiments and in particular a relatively narrow bandwidth.

Bandwidth can be expanded, but often with a massive increase in structure complexity such as multi-layer structures. Therefore, the purpose of this section is to design a single-layer passive reflector with reflective elements having an eccentric shape and having sufficient degrees of possibility to compensate for both spatial and frequency phase change of the reflective field.

3.1.1 Advantages of Reflectarray

Most important advantage of the printed reflectarray is that, when an application such as spacecraft requires a large antenna, the flat structure of the reflectarray provide a much simpler and trustworthy folding system compared to that parabolic reflector which has curvy surface.

Reflectarray's flat reflective surface also lends itself to embedding in an existing flat structure without adding any significant amounts of mass and volume to the overall system structure. A reflectarray with many elements can be manufactured by a easy and low cost etching process in form of a microstrip patch antenna. It also has advantage when produced in large quantities.

Another important feature of this antenna is that it can obtain a very accurate contour beam shape using a phase synthesis technique with a number of elements in a reflector capable of elementary phase adjustment [19, 20]. Reflectarray antenna can be used for multi-beam applications by adding two or more feed antenna in the focus of the RA. Each antenna can be radiate different direction without intersecting. RA can be applied to the satellite and microwave application as well as to millimeter wave frequencies for many applications.

The reflector in the form of a printed microstrip antenna can be produced by a simple and low cost etching process, especially when produced in large quantities. The antenna can also be cost effective due to its flat structure. For example, the particular molding process required to produce a generally curved paraboloid is not required for a flat structure. The low profile compact form of a microstrip makes the microstrip patch reflector suitable for satellite communication due to its compactness, simple packaging requirements, compatibility capabilities and low production costs.

Another important advantage is the fact that a very large span reflector is more simple and cheaper than the reflector antennas in the space arts since the flat reflectarray does not take up much space and can be folded and opened with a simple mechanism. In order to gain even more volume in the spacecraft, two configurations for reflection can be selected; inflatable and folded reflector antennas. So, flat shape of the reflectarray is mostly preferable such applications.

3.1.2 Disadvantages of Reflectarray

Despite the above mentioned advantages, there is a disadvantage associated with the reflectarray antenna. Bandwidth of the reflectarray generally does not surpass about more than ten percent depending on its element design, aperture size, focal length,

etc. Theoretically, reflectarray antennas cannot compete with the reflector antennas which have infinite bandwidth [21, 22]. Bandwidth is mainly constrained by two factors for a microstrip reflectarray, one of these is the narrow bandwidth behavior of the microstrip unit elements on the reflectarray surface and the other is the differential spatial phase delay.

1-dB gain bandwidth is usually used as the standard antenna bandwidth. When the antenna gain falls from the maximum gain level to lowest level to -1 dB, it shows the frequency bandwidth. Antennas with a bandwidth of 20% or more are often referred to as broadband antennas. Some common types of broadband antennas are conical, bow-tie and blade dipole antennas. Bandwidth greater than 50% are known as ultra-wide band antennas such as standard horn and spiral antennas which have a bandwidth greater than 100%. The microstrip antennas are in a known manner narrow-banded which has typically 3% bandwidth. [21].

3.2 Reflectarray Phase Distribution

The gain bandwidth of a microstrip reflectarray depends on the compensation mechanism for the unequal path delay between elements in the flat reflector used to convert the feeder and the spherical wave into a planar wave. The path lengths from feed to all radiating elements are different from each other so that they all have different phase delays. These elements' phases should be compensated for phase delays in a unique calibrated phase design curve and the different types of elements will have the different curve characteristic. However, they usually have an S-shaped curve. The differential spatial phase delay, S is shown graphically in Figure 3.1.

The differential spatial phase delay can best be described, wherein the differential spatial phase delay ΔS is the difference between the electrical paths S_1 and S_2 . This can be a multiple of the wavelength at the centre frequency such as $\Delta S = N \cdot d \lambda_0$; where N is an integer and d represents the fractional number of a free-space wavelength. In order to achieve a constant phase line for reflection, each patch position d is compensated by the length of the phase delay line connected to the elements. Each element in reflectarray can have $N \cdot d$ different numbers. However, $N \cdot d$ will change depend on the frequency.

As the phase delay lines are fixed, a frequency deviation error will occur in the corrected phase front. The former $N \cdot d \lambda_0$ is now become $N \cdot d (\lambda_0 + \Delta \lambda_0)$, where $\Delta \lambda_0$ is directly proportional to the frequency change. Therefore, the amount of phase change is $N \cdot d \lambda_0$, which can be an important part of the wavelength (360 degrees). In order to reduce the amount of frequency deviation error, the number of integers N must be

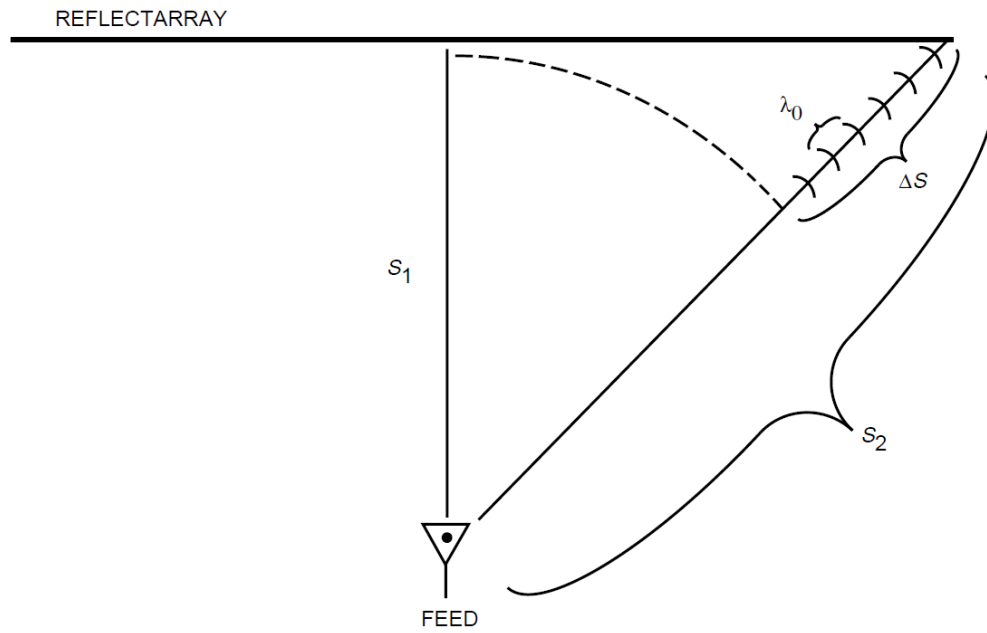


Figure 3.1 Spatial phase delay of the reflectarray [3]

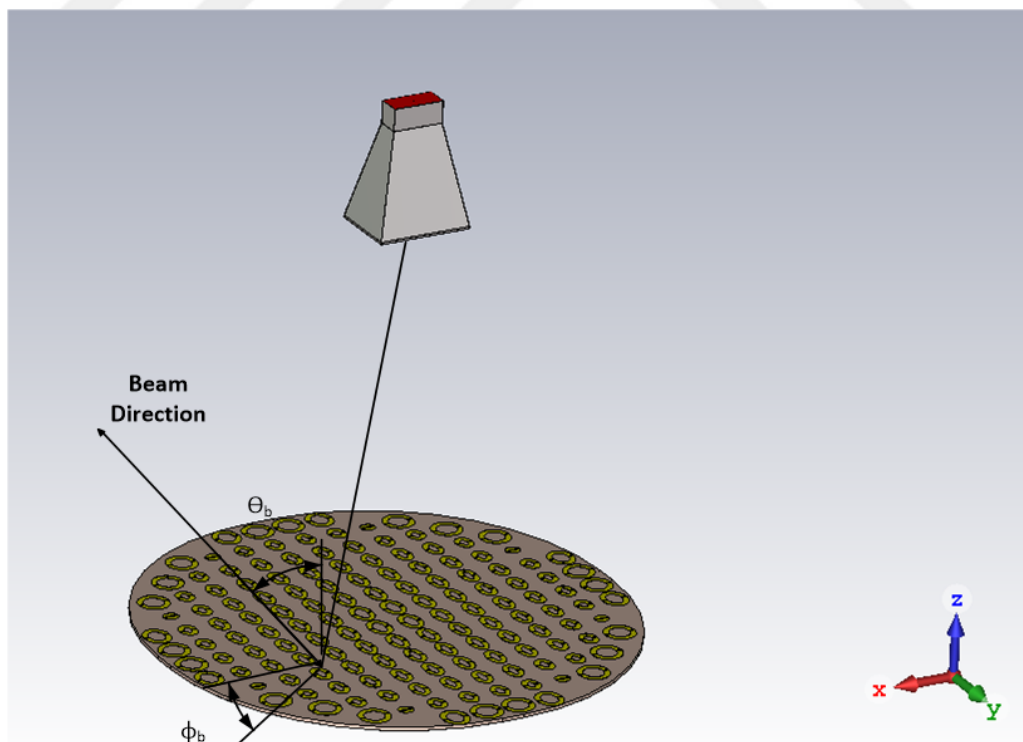


Figure 3.2 Typical geometry of a printed reflectarray antenna

reduced. There are two ways to reduce N; the first is to design the reflectarray for a larger f/D ratio, and the other one is to use only a small electrical diameter reflectarray. With a constant f/D ratio, the larger the electrical diameter, the higher the N value [3].

The reflectarray phase elements fed by a horn antenna will reflect the electromagnetic waves backwards. In Figure 2.1, the reflection mechanism of the reflectarray antenna is presented schematically. As seen from the drawing, the EM wave will reach different phases due to the cell position in the reflectarray to each unit cell.

The phase shift that must be included in each element to produce a collimated beam in a given direction is determined in this section. Considering the detailed coordinate system in Fig. 3.2, the progressive phase distribution on the reflectarray surface that produces a beam in the direction (ϕ_b, θ_b) , as known from array theory, is expressed as

$$\Phi(x_i, y_i) = -k_0 \sin \theta_b \cos \phi_b x_i - k_0 \sin \theta_b \sin \phi_b y_i \quad (3.1)$$

where k_0 is the propagation constant in vacuum, and (x_i, y_i) the coordinates of element i^{th} . On the other hand, the phase of the reflected field at each reflectarray element is equal to the phase of the incident field, as a result of propagation from the feed, plus the phase shift introduced by each cell, as

$$\Phi(x_i, y_i) = -k_0 d_i + \Phi_R(x_i, y_i) \quad (3.2)$$

In order to direct this reflected wave in a particular direction, the phase delay must be compensated by the unit cells. For this purpose, the required phase distribution of each unit cell can be achieved by applying the following formula [3]:

$$\Phi_R = k_0(d_i - (x_i \cos \phi_b + y_i \sin \phi_b) \sin \theta_b) \quad (3.3)$$

where (x_i, y_i) are the coordinates of the i^{th} , and d is the distance from the center of i^{th} element to the central point of the feed aperture. The desired beam direction is defined by ϕ_b and θ_b , which are the spherical coordinates with origin at the center of the array. Typical geometry of a reflectarray has shown in Fig. 3.2. In our designs, we are interested in the surface phase distribution for broadside radiation, for this reason $\phi_b = 0^\circ$ and $\theta_b = 0^\circ$.

3.3 Non-Uniform Reflectarray Antenna Design

In this work, a novel approach for design and fabrication of Non-uniform Reflectarray Antenna (NURA) had been proposed [23]. Firstly in the design stage, SR [24] is applied to express the reflection phase characteristics of a grounded dielectric layer in the form of an analytical expression within the domain of $1 \leq \epsilon_r \leq 6$ with variable thickness $0.3 \leq h \leq 3$ mm using the 3-D EM based data sets for X-band (8-12 GHz) applications. Then, for the design purpose, a special fine calibration characteristic is built up by SR with the sufficient reflection phase range for the 3D Printer's material PLA with $\epsilon_r=2.4$ at the operation frequency 10 GHz. SR Eureqa is a novel regression method that performs genetic programming within the mathematical expression domain to create a model consisting of summation of expressions that fits to a given dataset with a great accuracy [25, 26]. This regression method nowadays has been used to obtain solutions for various science and engineering problems [27, 28]. In the recent work [28], SR has been employed to uncover intrinsic relationships hidden within the Big Data that is derivation of a full-wave simulation based analytical expression for the characteristic impedance Z_0 of microstrip lines. In [28], Big Data is obtained from the CST Microwave Studio, in terms of the substrate dielectric constant ϵ , height h and strip width w within 1-10 GHz band.

3.3.1 Symbolic Regression

Symbolic Regression (SR) is used to discover mathematical expressions of functions that can fit the given data based on the rules of accuracy, simplicity, and generalization. This method builds a model consisting of solely an accurate analytical expression formed recombining the ready base functions using some evolutionary algorithms such as Genetic Programming (GP) [24], Gene Expression Programming (GEP) [29], Grammatical Evolution (GE) [30], Analytic Programming (AP) [31], and some optimization problems [32, 33]. The main advantage of SR is that it does not require any specific structure or parameter, instead reveals intrinsic relationships within the dataset letting its patterns. Thus this analytical model enables a designer a rapid optimization and analysis of the complicated electromagnetic devices instead using computationally inefficient commercial full wave simulators. In this work, SR in the design stage that is based on GP. Main principle of GP based SR is such that expressions (3.4),(3.5),(3.6),(3.7),(3.8) are represented in chromosomes like syntactic trees. The syntactic tree form of (3.4) is given in Fig. 3.3 for a better understanding. Based on GA principles, new individuals (children) whose representations are in fact new expressions which are evaluated by fitness, are created either by random generators, or by exchanging parent's parts by crossover or mutation operators. As an example for SR regression process, the expression given in (3.4), (3.5) are taken as Parents and

(3.6), (3.7), (3.8) are the children of these parents through cross over or mutation operations.

$$P_1 = f(a, b, c, d, e) = \sin\left(\frac{ab}{c}\right) + \sqrt{d-e} + a^2 \quad (3.4)$$

$$P_2 = \cos(ab) - e^c + \frac{d}{e} \quad (3.5)$$

$$C_1 = \sin\left(\frac{ab}{c}\right) - e^c + a^2 \quad (3.6)$$

$$C_2 = \cos(ab) + \sqrt{d-e} + \frac{d}{e} \quad (3.7)$$

$$C_3 = \sin\left(\frac{ab}{c}\right) + (d-e)^2 + a^2 \quad (3.8)$$

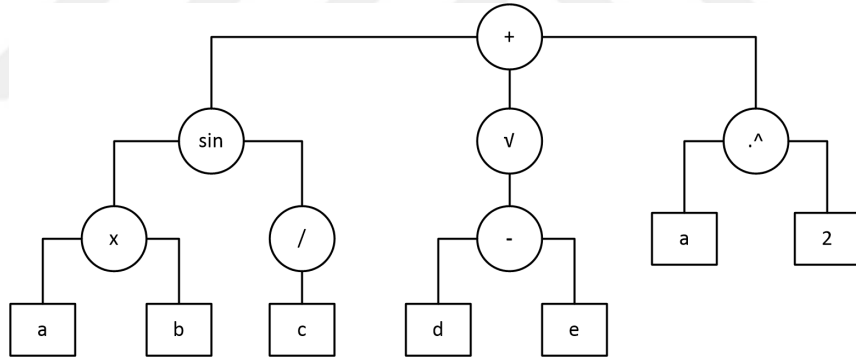


Figure 3.3 An example of syntactic tree

In Fig. 3.6, a typical NURA design is given in which with the variation of the height in the unit elements the reflection phase is changed and is focus on a desired direction.

The reflection phase characteristics of a grounded dielectric layer $1 \leq \epsilon_r \leq 6$ with variable thickness $0.3 \leq h \leq 3$ mm are obtained using the H-wall simulator [3] in order to form an analytical expression for X- band (8-12 GHz) applications. For this purpose, the required training and validation data sets of reflection phase of unit cell given in Fig. 3.7 are generated by the 3-D EM simulation tool CST.

A series of simulations are carried out to gather training and test data samples Table 3.1 and 3.2 for SR search of Reflection Phase by using CST 3D EM simulation tool, respectively.

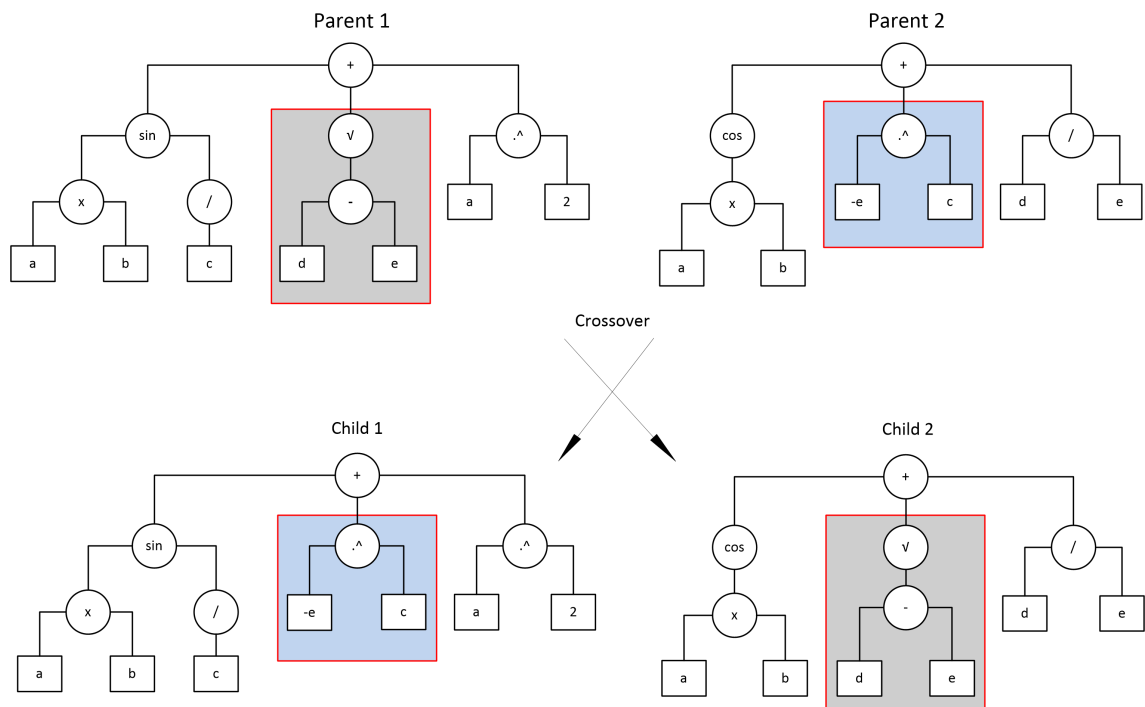


Figure 3.4 An example of crossover operation

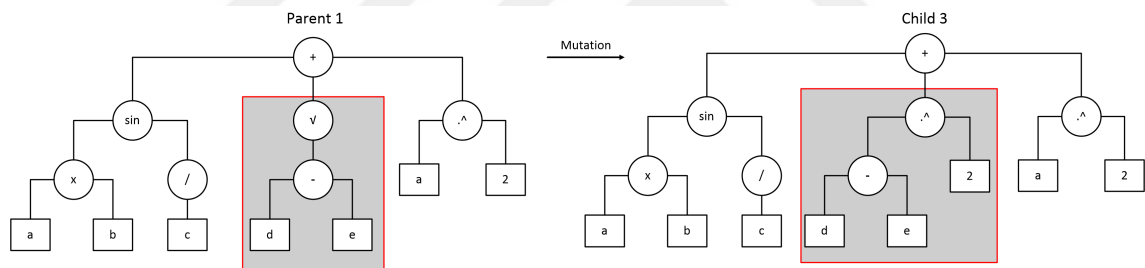


Figure 3.5 An example of mutation operation

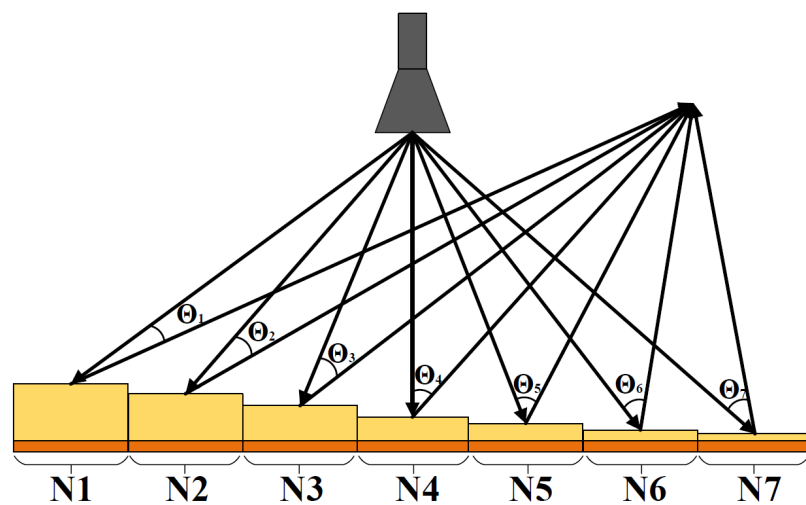


Figure 3.6 Centre fed non-uniform reflectarray

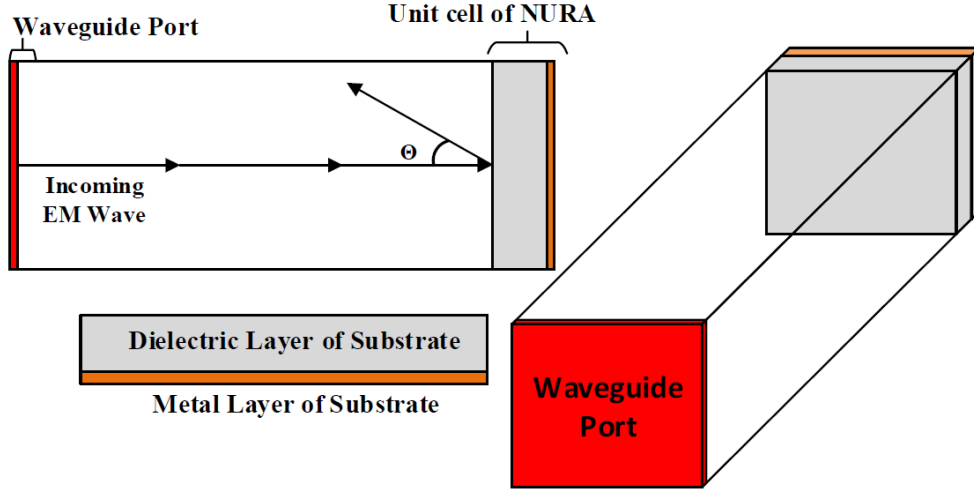


Figure 3.7 Unit cell of the NURA with its simulation setup

Table 3.1 Training data set for reflection phase expression

Parameter	Sample Ranges	Sample Step
Dielectric Permittivity	1-6	0.25
Substrate Height	0.3-3	0.1
Frequency (GHz)	8-12	0.5
Total	5292	

Table 3.2 Test data set for reflection phase expression

Roger	ϵ_r	Height (mm)	Frequency (GHz)	Total
4003	3.55	0.305, 0.406, 0.508, 0.813, 1.524	8-12	12012
4350	3.66	0.338, 0.76, 1.52	8-12	
5870	2.33	0.381, 0.508, 0.787, 1.575	8-12	

The 5292 data in Table 3.1 are used as the training data in Eureka environment [6] to perform SR search. The following commands are used to start the SR search:

Use data points equally for training and validation purposes;

Use all basic formula blocks;

Use all exponential blocks;

Use Mean Absolute Error as error-metric (Default);

Thus, the targeted analytical expression for Reflection Phase (RP) is obtained as a function of dielectric constant ϵ_r , height h , frequency f as follows:

$$RP = 541.73 - \frac{3.1\epsilon_r^2(hf)^4}{10^6} - \frac{0.5}{h} + \frac{0.62 + 0.019(hf)^2}{0.97 + \epsilon_r} - (45.59 + 2.68h)f \quad (3.9)$$

The performance of the obtained expression is validated by Eureka itself, however we also validated accuracy of the model using approximately 12.000 additionally test data

belonging to the typical X-band substrates as given in Table 3.2, even we also tested extrapolation performance. In this analysis, the common error-metrics measures are employed which are Mean Absolute Error (MAE), Relative Mean Error (RME) and Maximum Error (MXE) as given in Eqs. (3.10), (3.11), (3.12) for both training and test data:

$$MAE = \frac{1}{N} \sum_{n=i}^N |T_i - P_i| \quad (3.10)$$

$$RME = \frac{1}{N} \sum_{n=i}^N \frac{|T_i - P_i|}{|T_i|} \quad (3.11)$$

$$MXE = \frac{1}{N} \max(|T_i - P_i|) \quad (3.12)$$

Table 3.3 Performance of analytical expression

Error Metric (Degree)	Training Data	Test Data
MAE	0.27	0.1027
RME	0.0006	0.003
MXE	13.96	0.3586

Results of the performance measures of Eq. 3.9 are presented at Table 3.3 alongside of Figs. 3.8 and 3.9 of reflection phase versus variable substrate height for typical ϵ_r , f values as compared with CST values.

Fast and accurate prototyping process of microwave devices and antennas have an extreme importance for design process. In today's RF and microwave technology, there is an ever-increasing demand for higher level of fast, low cost and accurate prototyping. One of the most recent innovation for fast and accurate prototyping is 3D printing technology [32]. 3D printing is a method of manufacturing in which materials, such as plastic or metal, are deposited onto one another in the form of layers to produce a three dimensional object, such as a pair of eye glasses or other 3D objects. To date, 3D printing has primarily been used in engineering to create engineering prototypes. In this work, firstly the 3D model is exported in ".STL" file format, so that the CEL Robox Micro in Fig. 3.10 can create its code for printing of the prototype. Also, in case of large structure models, the model can be sliced into smaller parts such as given in Fig. 3.14 where the antenna model is sliced into smaller size parts (1/12). The material used for 3D printer is PLA "Black as Night" [33] with a dielectric constant of 2.4 and the printing accuracy (printed layer height) is chosen as 0.1 mm for the best quality printing results.

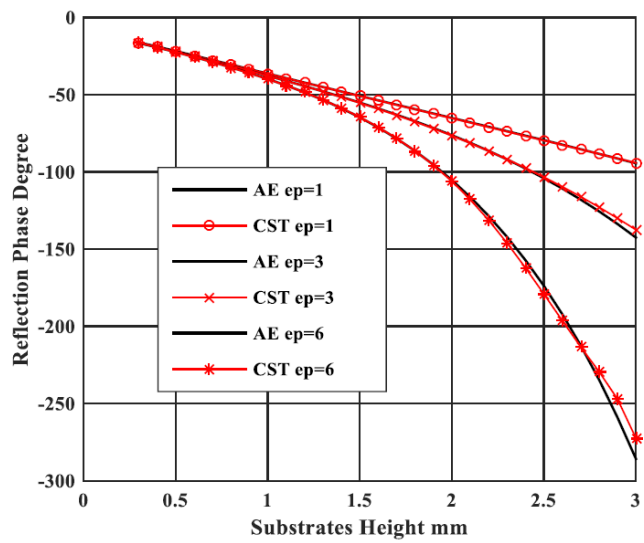
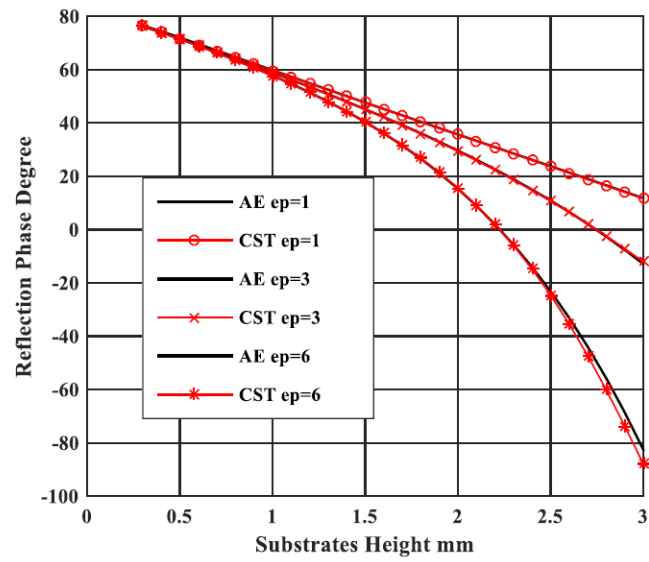
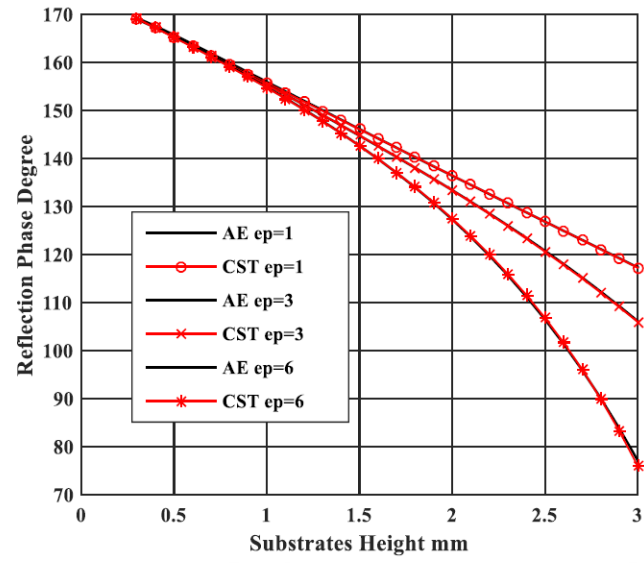


Figure 3.8 Reflection phase characteristics for variable dielectric permittivity for a) 8 GHz b) 10 GHz C) 12 GHz

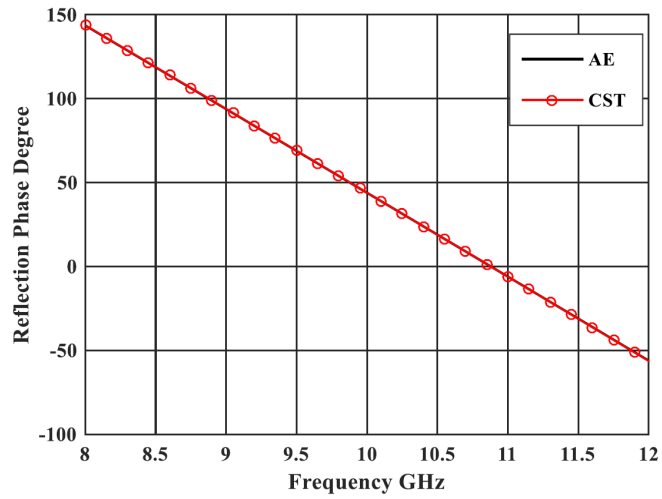
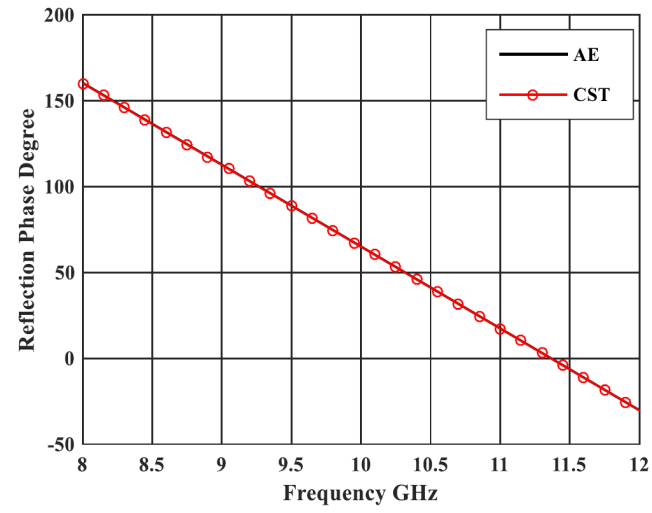
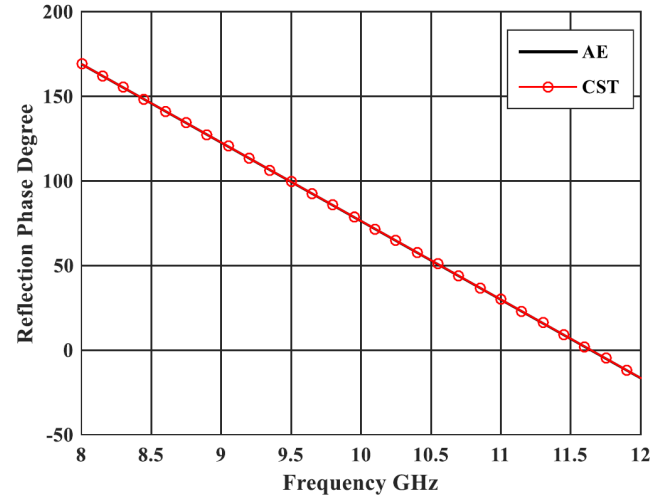


Figure 3.9 Reflection phase characteristics for a) RO4003 ($h=0.305$ mm, $\epsilon_r=3.55$)
b) RO4350 ($h=0.76$ mm, $\epsilon_r=3.66$) C) RO5870 ($h=1.575$ mm, $\epsilon_r=2.33$)

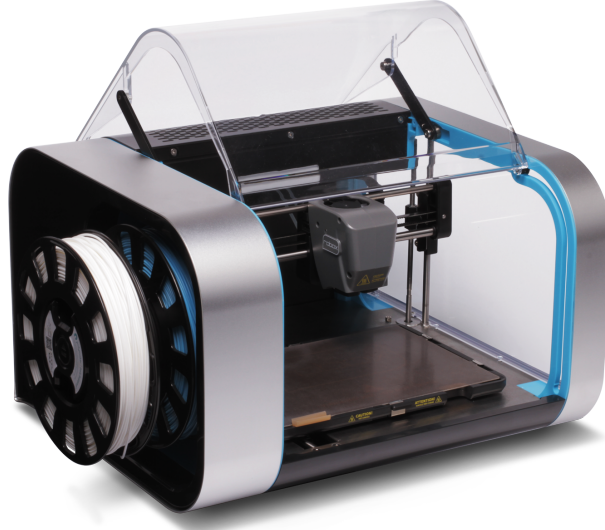


Figure 3.10 CEL Robox Micro manufacturing platform

Herein, by using CEL Robox Micro manufacturing platform the prototyping of the NURA (Fig. 3.13) made from “Black as Night”, with $\epsilon_r=2.4$ at 10 GHz is carried out as the experimental work. Firstly, applying the same process given in section II, a new and simpler Reflection Calibration Characteristic having almost 360 degree phase range is obtained using SR Eureka with the 270 CST MWS data in Table 3.4 where for the substrate height variation is taken between 0.5-10 mm which is considered as 0.1 mm sample steps.

Table 3.4 Training data set for limited reflection phase expression

Parameter	Sample Ranges	Sample Step
Substrate Height (mm)	0.5-10	0.1
Dielectric Permittivity	2.4	
Frequency (GHz)	10	
Total	96	

$$Phase = 1.88 + \frac{21.2}{h} - (0.022 * h^2 - 0.51 * h + 3.19) * h^3 \quad (3.13)$$

Since the NURA is symmetric with respect to the center, thus Fig. 3.11 gives heights of the quadratic NURA being divided 10 segments and starting from the corner point. The values given in Fig. 3.11, are necessary compensation values at each element using the equation (3.13) to convert spherical wave to the plane wave [2]. Thus, a pencil beam in the normal direction of the RA plane, is achieved by designing the height of each RA cell using the reflection phase calibration characteristic in Fig. 3.12, to reflect the incident wave independently with a phase compensation proportional to

the distance from the phase centre of the feed horn as well-known from the classical array theory [2].

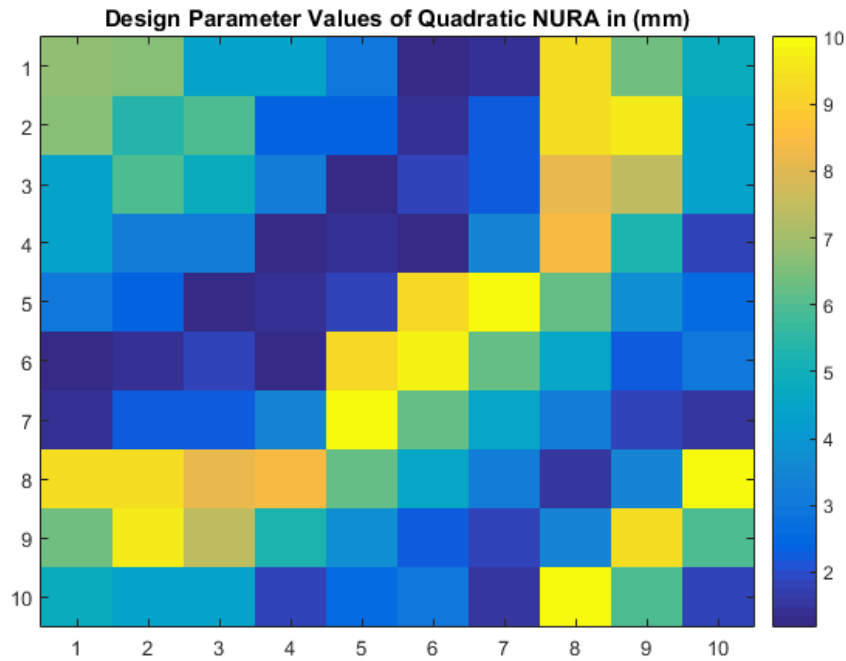


Figure 3.11 Parametric values of quadratic NURA

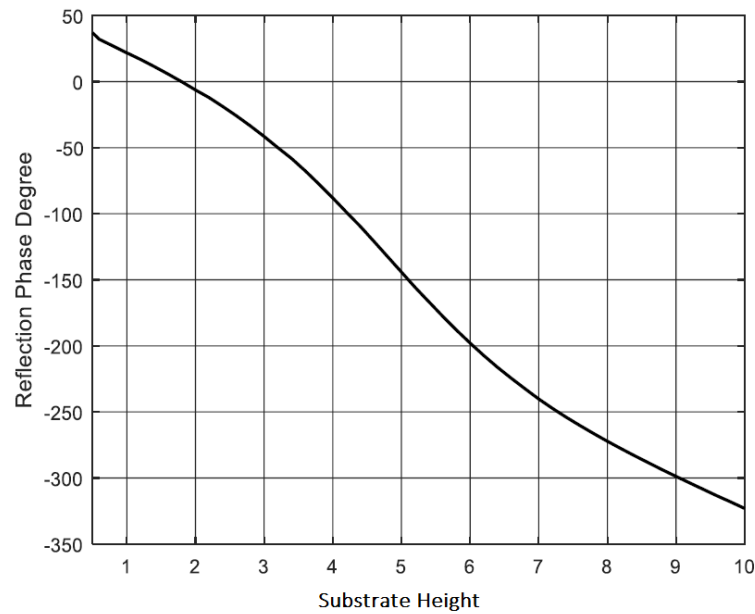


Figure 3.12 Reflection phase calibration characteristic of material with dielectric permittivity of 2.4 at 10 GHz

In Fig. 3.15, the measurement results of the prototyped NURA design are presented. Also, normalized radiation patterns at operating frequencies are shown in Fig. 3.16 As it can be observed from the measurement results, the VSWR characteristics of

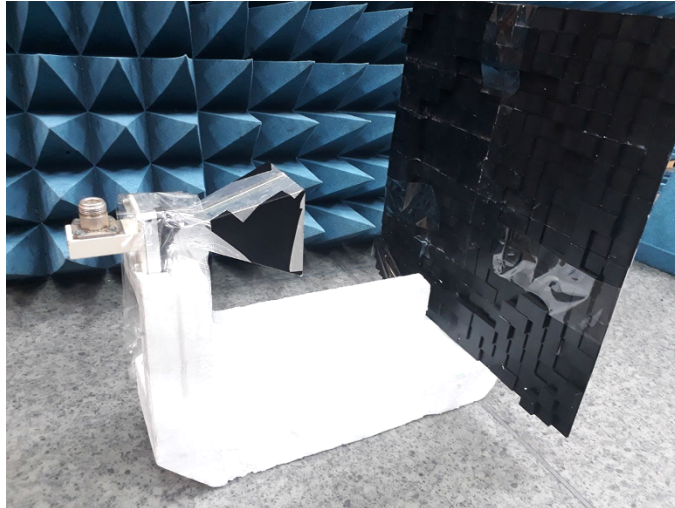


Figure 3.13 Prototyped 3D printed NURA

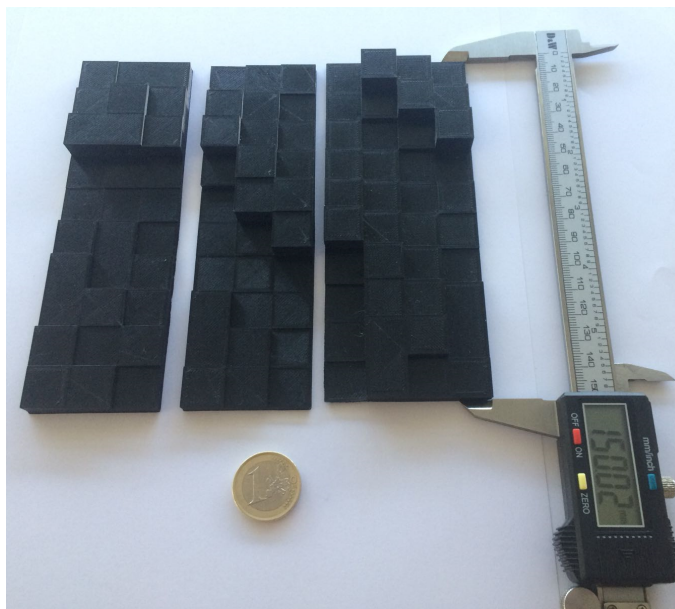


Figure 3.14 Parts of the prototyped 3D printed NURA

the NURA is below 2 in all X-band. Also, the design has a gain of 22 dB (gain enhancement of 8-9 dB) at 10 GHz. The gain measurement results of NURA, show a 1-dB gain bandwidth of almost the 21% and confirm the promising characteristics of such radiating element. The feed is prime focus, positioned with an $f/D = 0.66$.

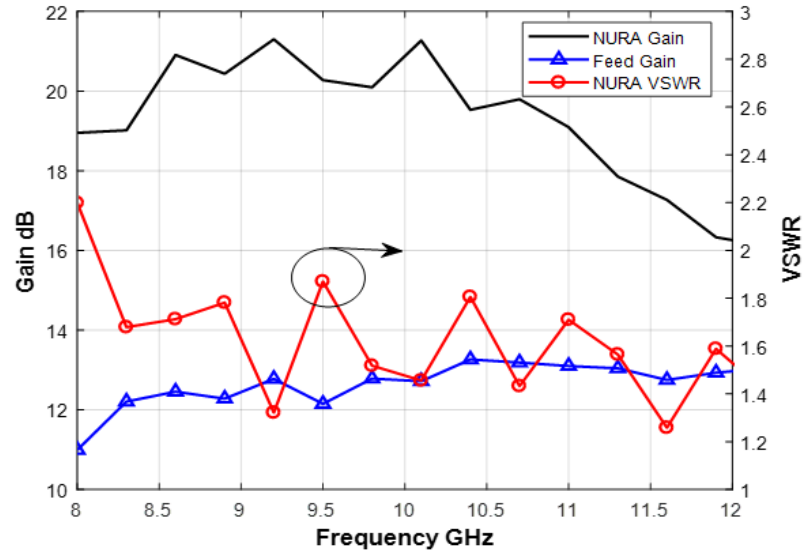


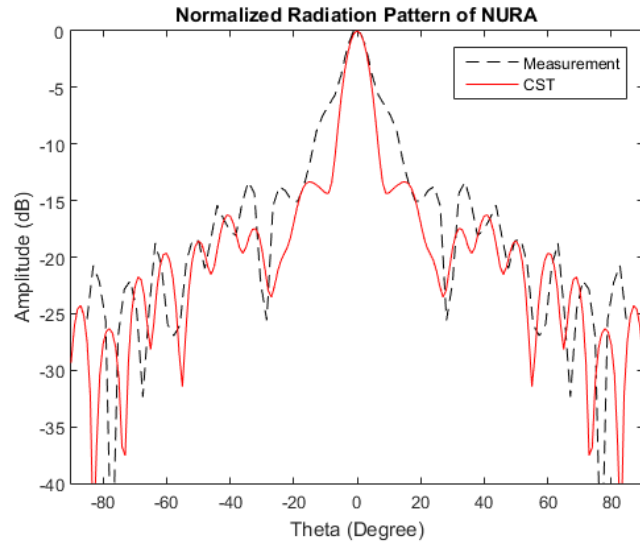
Figure 3.15 Measured NURA characteristics Gain-VSWR along frequency band

3.4 Circular Polarized Corrugated Horn Fed NURA

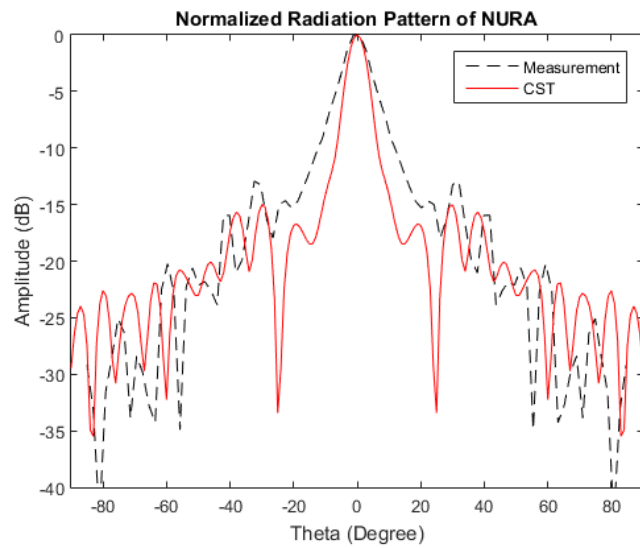
Circularly polarized Corrugated Horn Antenna (CHA) is used as a feeder for proposed NURA antenna Fig. 3.17 and firstly reflection coefficient result is given in Fig. 3.18. The phase center of the CHA is placed at a certain focal distance which makes the f/D ratio 0.76 and illuminates the elements. Changing the feed antenna also effect the overall array antenna performance, however it is still below -6 dB in acceptable level for radiation.

The circular polarized NURA performance depends on the cell characteristics. As a result, the cells are proved to satisfy circular polarization requirements such as axial ratio and gain etc. The NURA is illuminated by a circular polarized corrugated horn antenna. The LHCP is considered as the co-polarized wave and the RHCP is cross-polarized one. Circular polarized NURA analysis and verification are performed using CST software.

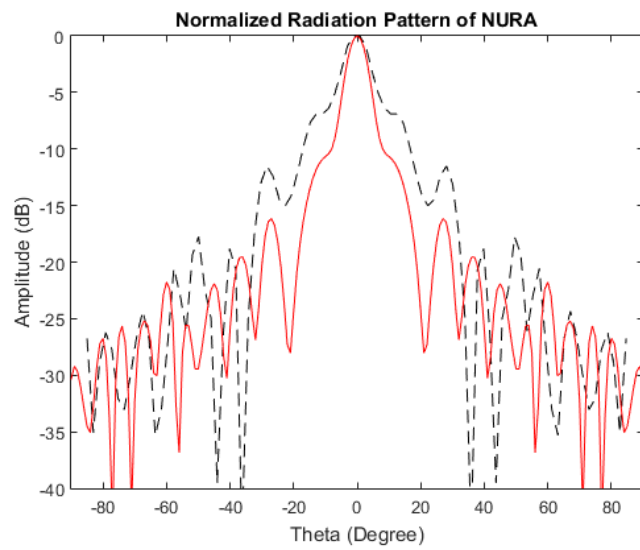
The gain level is varied from 24.91 dB at 10 GHz to 24 dB at 12 GHz. The gain plot is illustrated in Fig. 3.19. If the 1.5 dB gain level considered, bandwidth is about 30.4%. The radiation patterns for each frequency are shown in Fig. 3.20. As seen from that figure, maximum realized gain is reached at 10 GHz and its value is 24.91 dB.



(a)



(b)



(c)

Figure 3.16 Measured radiation pattern of NURA at a) 9 GHz b) 10 GHz c) 11 GHz

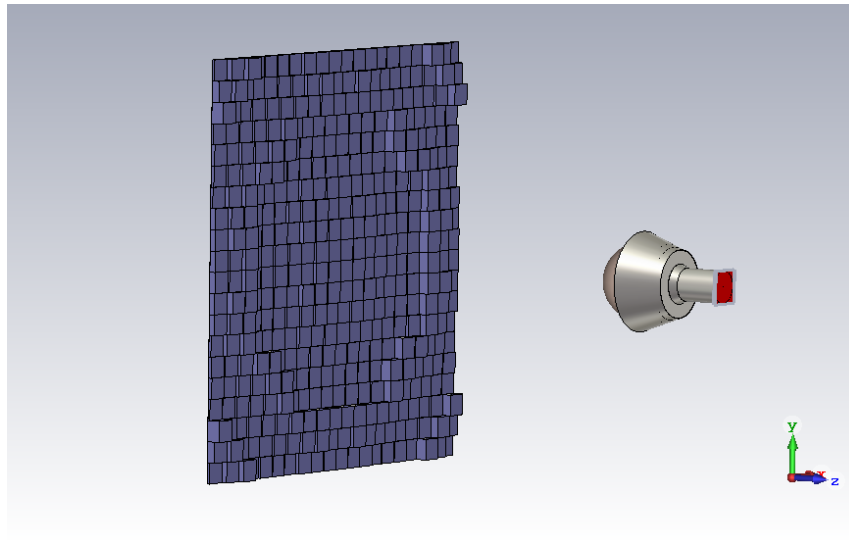


Figure 3.17 Corrugated horn antenna fed NURA

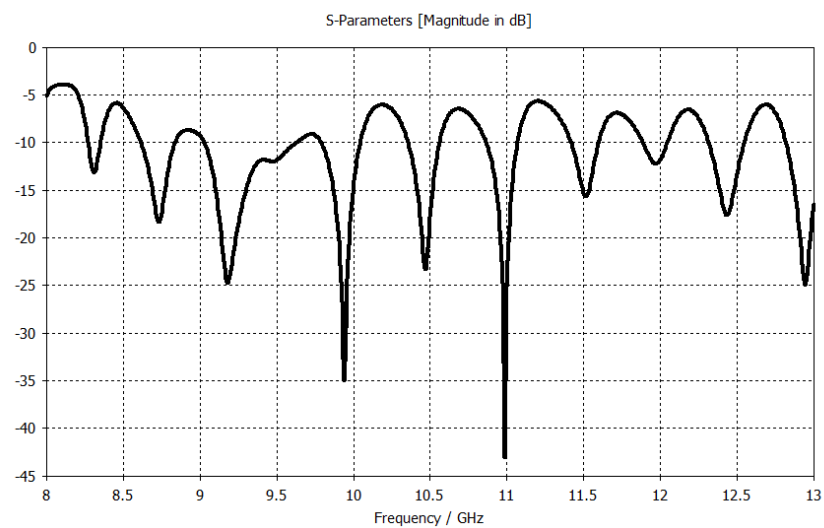


Figure 3.18 Reflection coefficient of corrugated horn antenna fed NURA

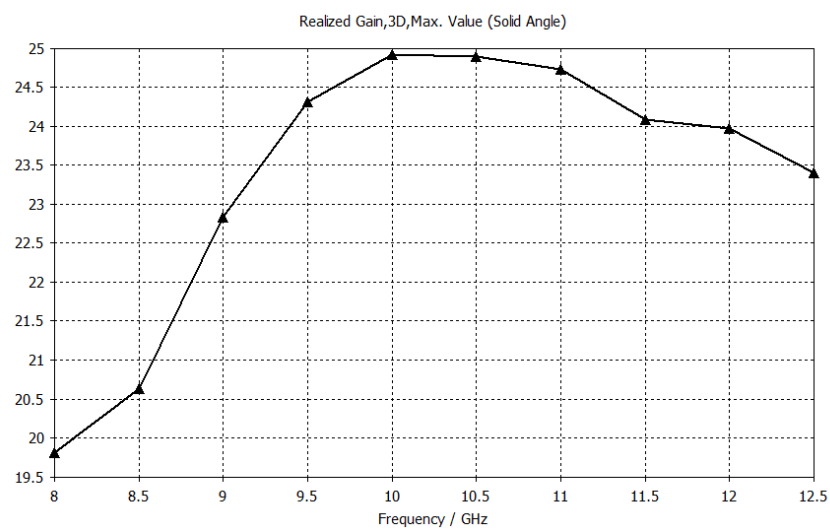


Figure 3.19 Gain of corrugated horn antenna fed NURA

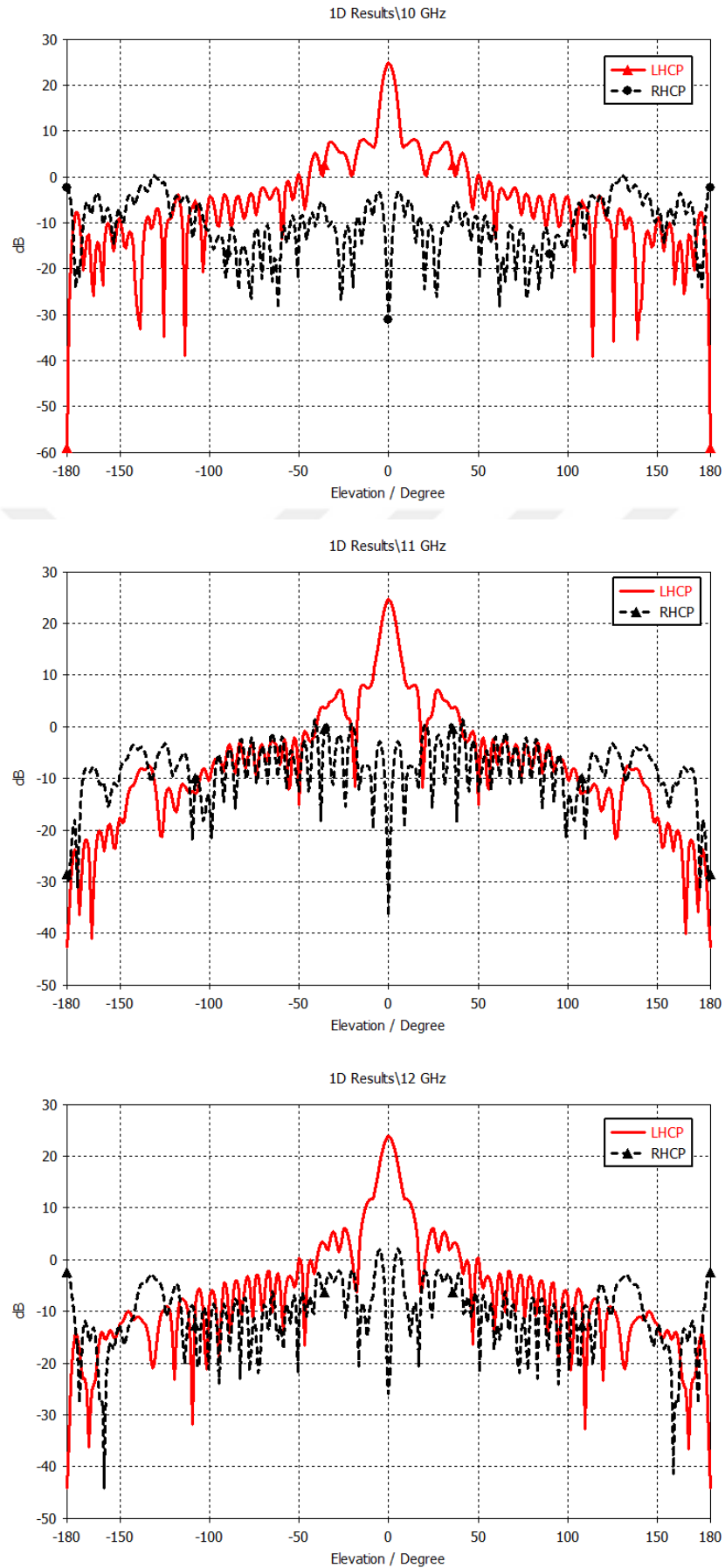


Figure 3.20 Radiation pattern of CHA fed NURA at a) 10 GHz, b) 11 GHz, c) 12 GHz

The axial ratio of circularly polarized antenna is the ratio of right-hand circular polarization (RHCP) to left-hand circular polarization (LHCP) or vice versa. For considerable circularly polarized antennas, it defines the level of axial ratio to be below 3 dB. The axial ratio of reflect is simulated and result at 10 GHz is given in Fig. 3.21. The axial ratio along the main beam reached the maximum value of 4. However, axial ratio values over the frequency band are given in Fig.3.22 at main beam direction are quite close to zero which is desired.

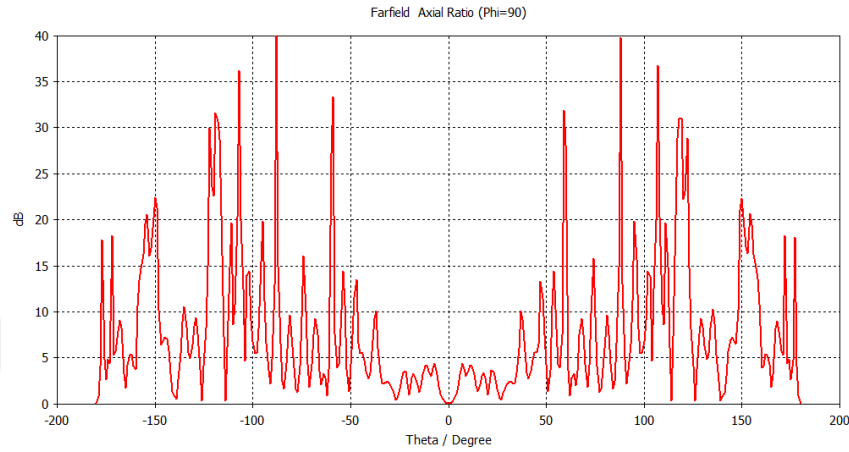


Figure 3.21 Axial ratio of CHA fed NURA at 10 GHz

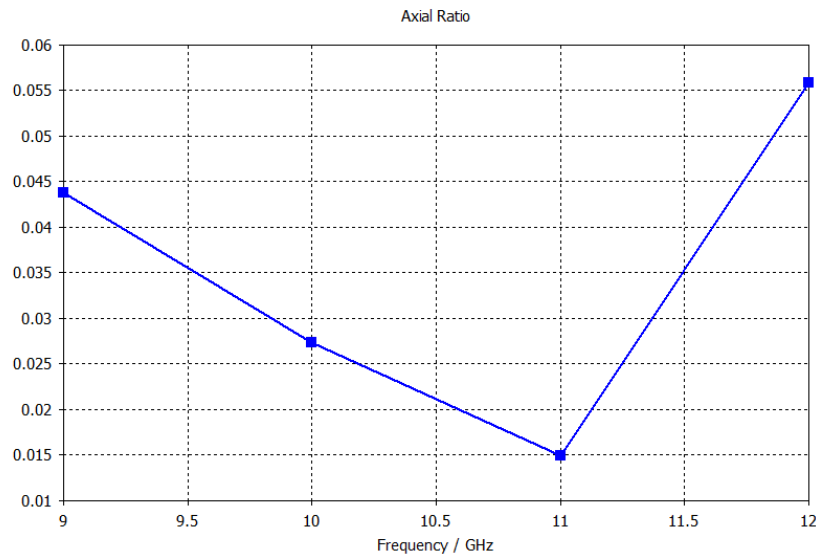


Figure 3.22 Axial ratio of CHA fed NURA

Elliptical Ring Reflectarray Antenna Design

The reflectarray unit element is designed by using a microstrip split elliptic ring patch. The elliptical patch inherently has not large bandwidth and phase range is also limited. Some geometric parameters are investigated to achieve optimal reflectarray design such as gap between elliptic pair and width of metallic patch and as a result of simulations parameters are determined. Commonly, single layer elements with large linear phase range are desirable. However, if the required phase values for each element fulfill the designed range, sufficient phase values can be used for an efficient reflectarray. The reflectarray is designed by periodic arrangement of the reflecting unit elements along with the ground plane on the backside of substrate.

4.1 Reflectarray Antenna Performance Characteristics

The aperture efficiency of a conventional reflector is divided into a number of efficiency figures to isolate factors that cause deviation from ideal performance [34]. The most common factors that deteriorate performance are: feed illumination taper, feed illumination spillover, aperture phase error, cross-polarization effects, feed blockage, dielectric and conductor loss, and feed mismatch.

The definitions used in [34] are applied to presents a mathematical expression for each of these factors and to provide a specific comparison of the reflectarray performances with the traditional parabolic reflector in terms of each of these factors.

4.1.1 Illumination Efficiency

Illumination efficiency is a measure of the uniformity of the feed illumination on the reflectarray. It is known that the level of sidelobe tends to fall and the main beam is broaden as the illumination tapers toward the edge of the reflectarray. The illumination efficiency expression as follow:

$$\eta_i = \frac{1}{\pi a^2} \frac{\left[\int_0^{2\pi} \int_0^a |E_y(\rho, \phi)| \rho d\rho d\phi \right]^2}{\int_0^{2\pi} \int_0^a |E_y(\rho, \phi)|^2 \rho d\rho d\phi} \quad (4.1)$$

where is assumed that the desired aperture area is y-polarized and that the aperture is circular with a radius a . In the case of the conventional reflector, the feeding illumination taper is determined only by the feed pattern, but in the case of reflectarray, the illumination also depends on the radiation pattern of the forming elements of the reflectarray. The broadside radiation pattern of the cell element causes the power captured by the element to be reduced by the beams from the feed far away from the broadside direction of a particular element. Therefore, element pattern is affected by the illumination taper of feed. In case of $f/D < 0.5$, element pattern has an effect when the angle of illumination of the feed increases for the edge elements of the reflectarray. This relatively larger taper requires slightly lower illumination efficiency of the reflectarray and also lower side lobe levels.

4.1.2 Spillover Efficiency

This efficiency term represents the amount of power that is not captured by the reflector and the mathematical expression for spillover efficiency:

$$\eta_s = \frac{\int_0^{2\pi} \int_0^{\psi/2} g(\theta, \phi) d\theta d\phi}{\int_0^{2\pi} \int_0^{\pi} g(\theta, \phi) d\theta d\phi} \quad (4.2)$$

where ψ is the subtended angle of reflectarray or reflector aperture defined in Fig. 4.2 and $g(\theta, \phi)$ is the feed radiation pattern. It can be seen that for the same D and f/D ratio, the subtended angle of the parabolic reflector is slightly larger than that of the reflectarray. The difference between the subtended angles of parabolic reflector and its equivalent reflectarray increases as f/D shrinks and puts parabolic reflector at an advantage in terms of spillover efficiency as compared to its reflectarray equivalent.

Assuming that the feed pattern is of $\cos^q(\theta)$ form, one can derive the following

expression for spillover efficiency [35]:

$$\eta_s = 1 - \cos^{q+1}(\psi_{RA}/2) \quad (4.3)$$

where ψ_{RA} is the subtended angle of the reflectarray that is shown in Fig. 4.2. A similar expression has been derived for illumination efficiency of the reflectarray illuminated by $\cos^q(\theta)$ feed structure [35]:

$$\eta_i = \frac{2\eta}{\tan^2(\psi_A/2)} \frac{(1 - \cos^{\frac{q}{2}-1}(\psi_{RA}/2))^2}{\left(\frac{q}{2} - 1\right)^2 (1 - \cos^q(\psi_{RA}/2))} \quad (4.4)$$

The illumination efficiency is the product of spillover and taper efficiencies. The reflectarray aperture efficiency is plotted in Fig. 4.1 for different values of q for the feed pattern of $\cos^q(\theta)$. As it is the case for conventional reflector, it can be seen for a given feed pattern, there is an optimum subtended angle for which the illumination efficiency is maximized.

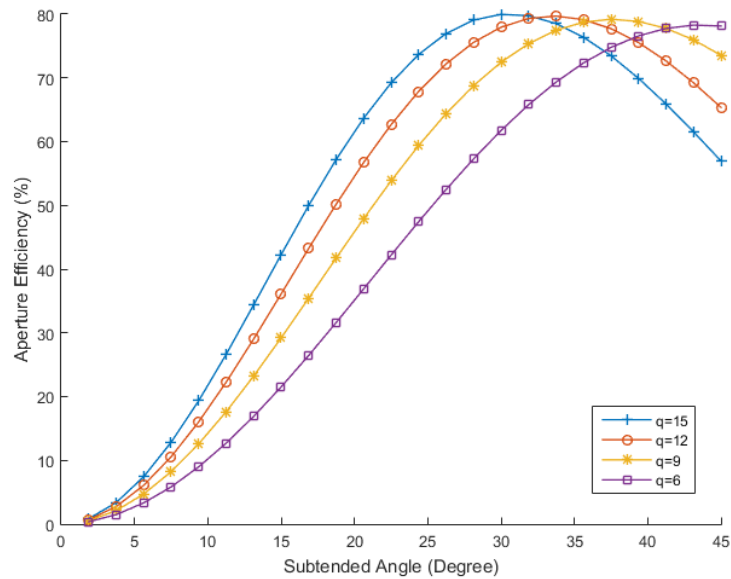


Figure 4.1 Aperture efficiency versus subtended angle for different q values

4.1.3 Blockage Efficiency

The feed antenna blocks the radiation from the reflector, thereby increasing cross-polarization and reducing the gain performance. In the center-fed reflectors, it is inevitable to prevent feed blockage. As the feed antenna larger, the blockage

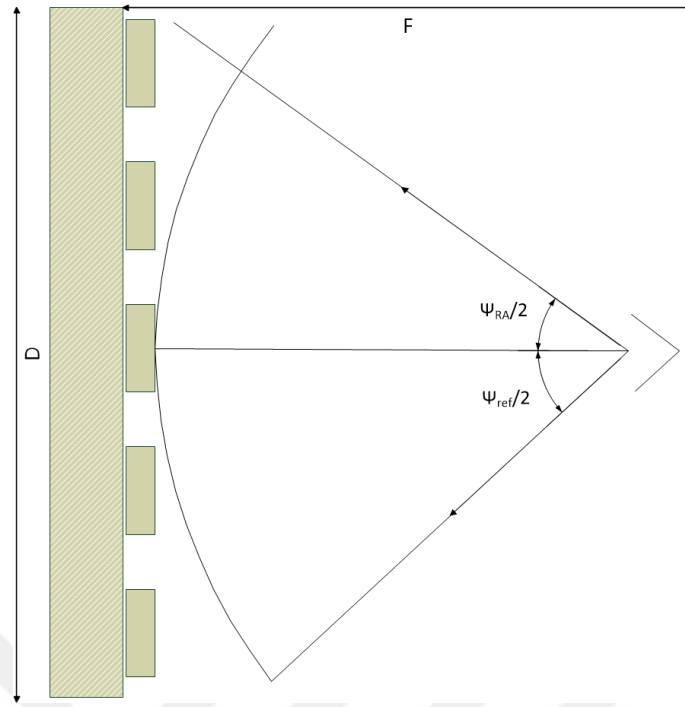


Figure 4.2 Side views of a center fed parabolic reflector and its equivalent reflectarray

efficiency is reduced. However, a center-fed reflector can be designed to completely prevent obstruction by adjusting the direction of the outgoing beam properly. In order to implement this precaution, the higher blocking efficiency in the case of center fed reflectarrays is quite practical. In addition, in the case of a center-fed reflector, the feed beam can be significantly improved by adjusting the outgoing beam in an off-boresight direction to avoid the feed assembly region.

4.1.4 Aperture Efficiency

Theoretically aperture types antennas such as reflectarrays have a maximum available directivity depends on the aperture area of the antenna A ;

$$D_{max} = 4\pi \frac{A}{\lambda^2} \quad (4.5)$$

where λ is the wavelength of the design. The directivity multiplied by the aperture efficiency and gain can be calculated as:

$$G = 4\pi \frac{A}{\lambda^2} \eta_a \quad (4.6)$$

Similar to reflector antennas, many efficiency factors influence the overall aperture

efficiency of reflectarray antennas, and the dominant terms are typically spillover (η_s) and illumination (η_i) efficiencies. In our designs, we mostly consider the aperture efficiency as the product of these two terms,

$$\eta_a = \eta_s \eta_i \quad (4.7)$$

It is important to mention that these two efficiency factors in Eq. (4.7) are directly dependent to the antenna configuration parameters, hence they also serve as key factors for the reflectarray design. Other efficiency factors are typically associated with the choice of reflectarray phasing elements such as material losses, losses due to phase error, mismatch, and polarization losses [36].

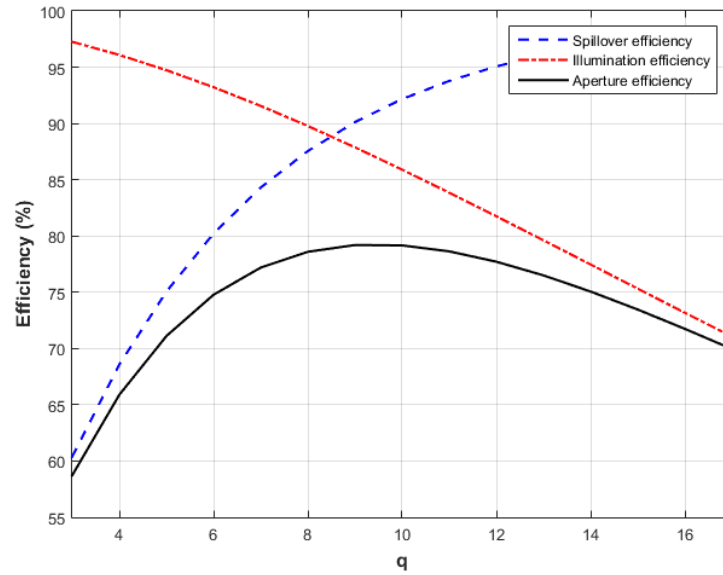


Figure 4.3 An example of efficiency versus q

4.2 Elliptical Ring Unit Cell Design

The unit-cell size is designed to be $L = 15\text{mm}$ (0.5λ for 10 GHz, λ is the wavelength in free space). Firstly, R1 which is first radius value is started from 3 mm and lengthened to the 7 mm while R2 value is constant 4 mm. Unit cell's reflection coefficient is zero level that means it reflects the incident energy. Phase variation of reflection coefficient at 10 GHz and 11 GHz is nearly 306 and 315 degree, respectively.

An elliptic split ring shaped unit cell designed at X-band frequency band. Elliptic element has two radius parameters which are R1 and R2, first and second radius respectively. As a substrate, RO4350B which has 3.5 permittivity and 1.52 mm height

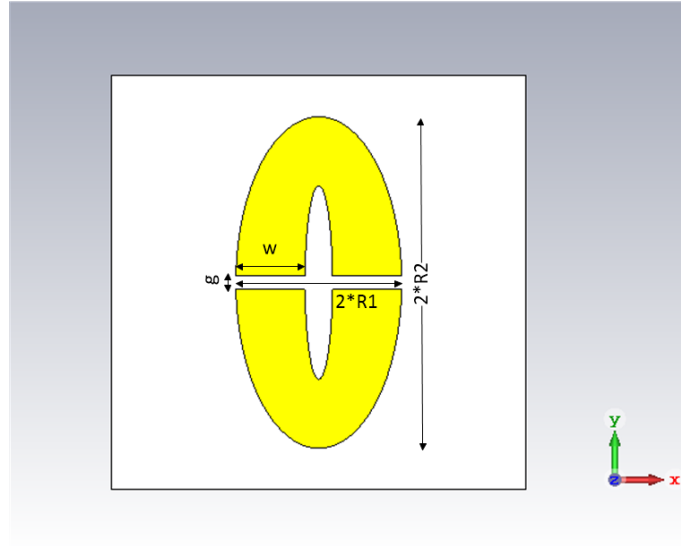


Figure 4.4 Geometric parameters of elliptic unit cell

Table 4.1 Elliptic unit cell parameters

Physical Descriptions	Value (mm)
First radius	$R1=3:0.5:7$
Second radius	$R2=3:0.5:7$
Gap	$g=0:0.25:1$
Width	$w=2.5$

is used. Dimension of the unit-cell and also spacing between elements is chosen as $\lambda/2$. After the parametric design of the unit cell, 20x20 elements reflectarray antenna modelled via CST.

Here, as shown in Fig. 4.4, a single element is obtained by adding gap to elliptic patch which is horizontally notched on the center to enhance the phase variation performance. The proposed design is etched on 1.52 mm thick, RO4350B substrate ($\epsilon_r = 3.5$, $\tan\delta = 0.02$). The lattice periodicity of elements is kept at 0.5λ at 10 GHz frequency. There is two variable radius of the structure $R1$ and $R2$ which are changes between 3 to 7 mm, respectively. The width of the elliptic patch and gap of the elliptic patch have chosen as $w= 2.5$ mm and $g=0.5$ mm, respectively. In Fig. 4.7, reflection phase change with gap parameter is given. Gap parameter changed from 0 to 1 mm step by 0.25 mm and other parameters were left fixed values $R1=4$, $R2=7$, $w=2.5$ mm. The width parameter is taken a constant value in design process. Variation of that parameter is shown in Fig. 4.8. If it is become thinner get better the phase range. However, phase change rate become faster and it can cause highly sensitive to the geometric parameters. In addition to have a more than 360 degree phase range, the slope must be sufficiently low to ensure low sensitivity to design errors. For this reason, width value has chosen as 2.5 mm at the design process. Fig. 4.4 shows the detail of

the split elliptic ring element structure and the bottom of the element is ground plane. Parameter and dimensions of the unit cell is summarized in Table 4.1. The unit cell was analyzed using the commercial electromagnetic software CST Microwave Studio.

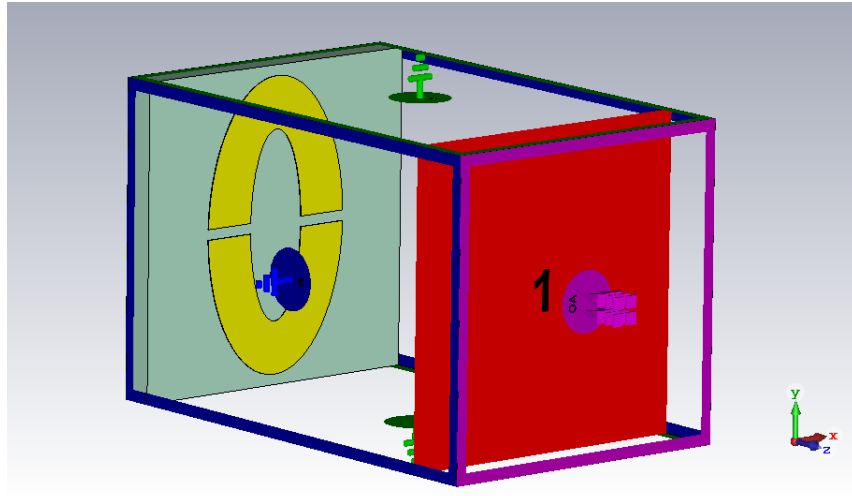


Figure 4.5 TEM mode waveguide simulator for an elliptical unit cell

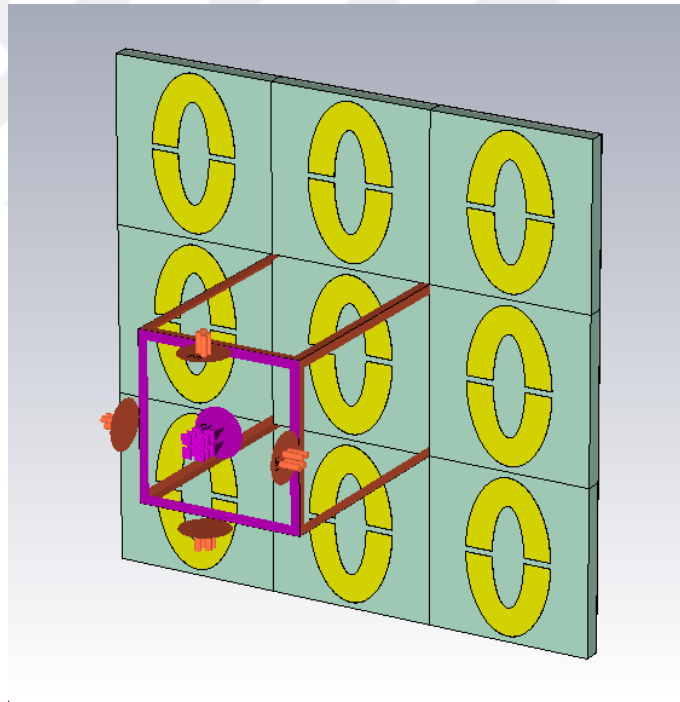


Figure 4.6 Illustration of Floquet port analysis of the unit cell

The reflection phase of the unit cell of the infinite periodic array model can be obtained by performing waveguide simulation (WGS). The WGS method is detailed in [37]. Fig. 4.5 shows the waveguide one-port that has been used to design and analysis a reflectarray element and the boundary conditions in the simulation set up for TEM mode propagation subject to the infinite array approach. When applying the WGS approach, the sidewalls of the waveguide are formed by a perfect magnetic conductor

while its bottom and top walls are consist of a perfect electric conductor. The vertically polarized incident waves will see the element at the end of the waveguide at the broadside direction and then scattered back at the broadside direction with a certain amplitude and phase information [38]. Therefore, the amplitude and phase of the reflected wave in each element is determined as the amplitude and phase of the scattering parameter S_{11} for the single port of the waveguide containing that element. The structure was analyzed and simulated using CST Microwave Studio.

In the design presented by the WGS approach, the reflection phase of the elements is estimated by considering the normal wave incidence, whereby it is estimated that an additional assumption is applied that the phase response is independent of the angle of incident wave. This assumption applies to the central elements of a onset fed reflection, where the angles of the incidence are not far from the normal axis. In reference [39], it has been shown that the phase variation is small for an incident angle less than 40 degree and could be neglected for small size reflector antennas. If the incidence angle is greater than 40, the phase change can be up to 50 for an incidence angle of 60 degree, where approximate reflection phases of the normal wave incidence can not be applicable [39].

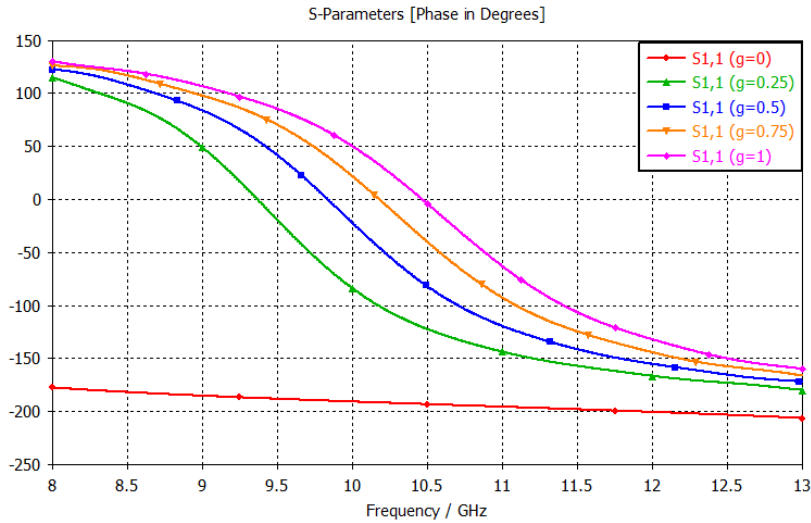


Figure 4.7 Reflection phase variation with the gap parameter($R_1=4$ mm, $R_2=7$ mm, $w=2.5$ mm)

The mutual coupling effect can be potent between the unit cell elements because of the distance can be small. In this case, the reflection phase can be calculated by taking into account an infinite periodic array model in which the mutual matching between the elements can be taken into account automatically [40]. The infinite periodic sequence model is a unit cell and an array structure with repeated geometry defined in uniform periodic intervals. This method is commonly used in applications such as reflectarray, frequency selective surfaces (FSS) and meta-materials. In this

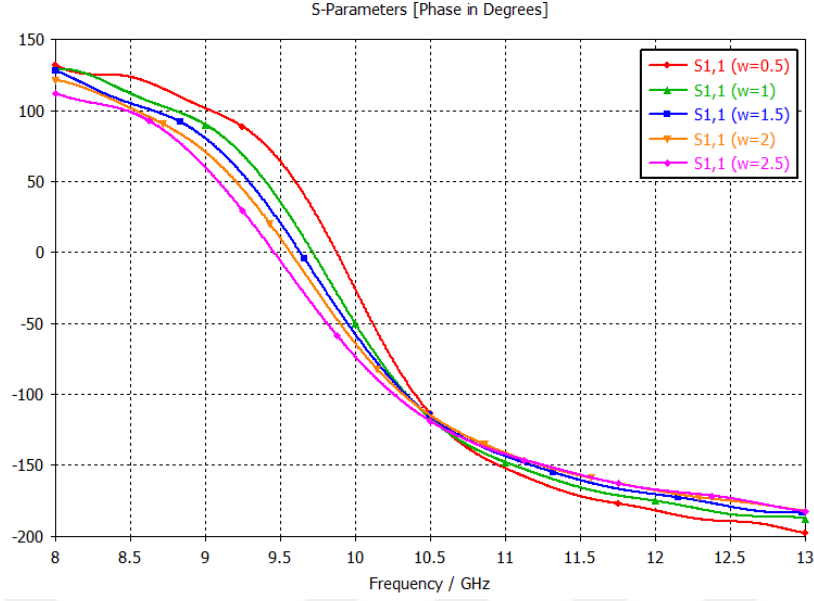


Figure 4.8 Reflection phase variation with the width parameter ($R_1=3$ mm, $R_2=7$ mm, $g=0.5$ mm)

way, the infinite periodic array model can be reduced to only one unit cell with a Floquet incident wave [41, 42] thanks to the application of the Floquet theorem, which makes it so efficient, as well as making the characterization very accurate [43]. Reflection phase variation of elliptic unit cell due to incident angle was analyzed by using floquet port model which is consider the mutual coupling effect as seen from Fig. 4.6. Reflection phase of elliptic unit cell was simulated with floquet port model and results are given in Fig. 4.11.

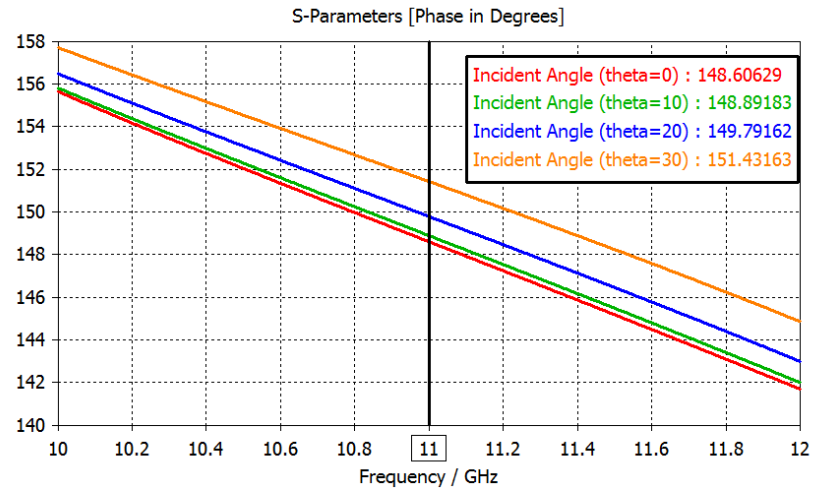


Figure 4.9 Reflection phase variation with incident angle θ and constant $\phi=0$ degree ($R_1=4$ mm, $R_2=7$ mm $g=0.25$ mm, constant)

Simulations performed with frequency domain solver and incident angle θ is changed from 0 to 30 degree while ϕ is 0 and 90 degree. ϕ is defined as horizontal

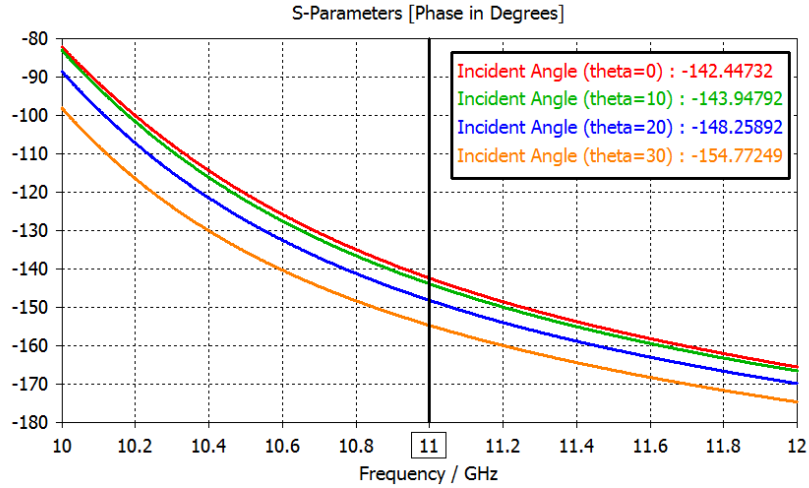


Figure 4.10 Reflection phase variation with incident angle theta and constant phi=90 degree (R1=4 mm, R2= 7 mm g= 0.25 mm, constant)

angle over the unit cell. As seen from the Figs. 4.9, 4.10, phase changes with small values. Horizontal changes of theta does not effect the reflection phase, vertical one shifts maximum 12.3 degree when theta is 30 degree. During the design process that difference is neglected because main beam is not affected much from the phase shift. The behavior of the phase as a function of length or size could be smoother by increasing the thickness of the substrate, but this solution is not applicable for standard commercial substrate and also cause to reduce of total phase range and 360 degree phase range cannot be achieved. This problem and linear behavior of the phase variation can also be solved by stacking two or more layers, but this method causes design complexity and production difficulties. The phase variation is not strongly linear due to the behavior that shows very rapid changes near the resonance due to the narrow band behavior of the microstrip patches and is very slow at extreme values as seen from Fig. 4.12.

The rapid phase variation makes the phase distribution very sensitive to fabrication tolerance errors. Because of the non-linear behavior, the phase is very sensitive to changes in frequency and significantly reduces the operating band of the reflectarray.

In Fig. 4.12, the phase variations with respect to the variation of R2 at 10, 11 and 12 GHz are shown, for a fixed values of the g=0.5 mm, w=2.5 mm and R1=4 mm. Reflection phase of the unit cell changes with similar S shaped curve and variation lines are parallel to each other at operating frequencies. This phase change characteristic is a necessary condition for broadband operation.

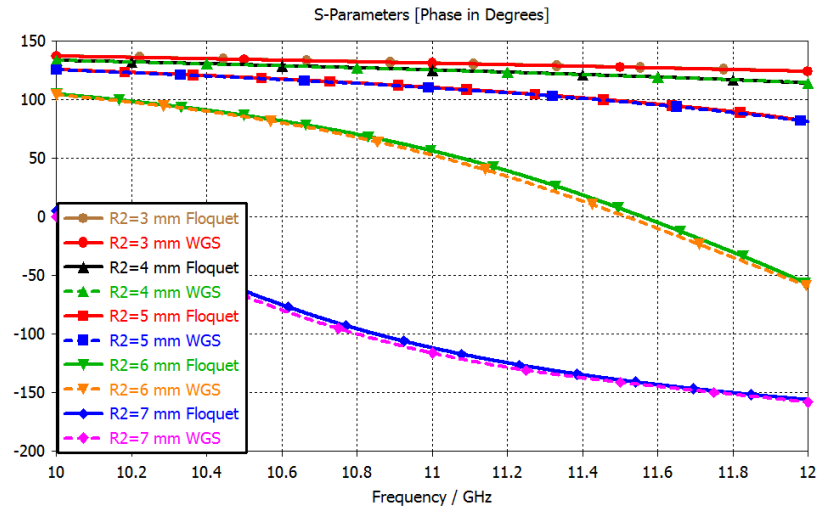


Figure 4.11 Reflection phase of the unit cell along frequency for WGS and Floquet port

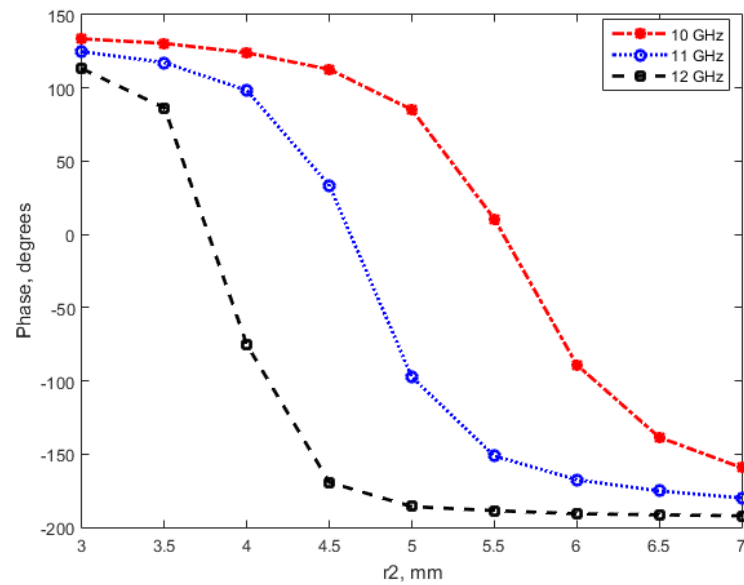


Figure 4.12 Elliptic ring element reflection phase variation with the radius R_2 ($g=0.5$ mm, $w=2.5$ mm and $R_1=4$ mm)

4.3 Circular Shaped Elliptic Reflectarray Antenna Design

As a first design model, Circular shaped Elliptic Reflectarray Antenna (CERA) is modelled via MLP and parameters were optimized to obtain required reflection phase. Geometry of the CERA is given in Fig. 4.13. The highest gain is about 23.7 dB at 11.5 GHz and 1.5-dB gain bandwidth is 9.75-12 GHz. It can be seen that CERA has a 20.6% bandwidth in the 1.5-dB gain variation and almost constant gain in the 10 GHz to 12 GHz frequency range. The aperture efficiency of CERA is 36.6% at 11.5 GHz, mainly due to the small size of the reflector. Overall results show that the reflector has excellent broadband performance. Gain results of the optimization and simulation are shown in Fig. 4.17.

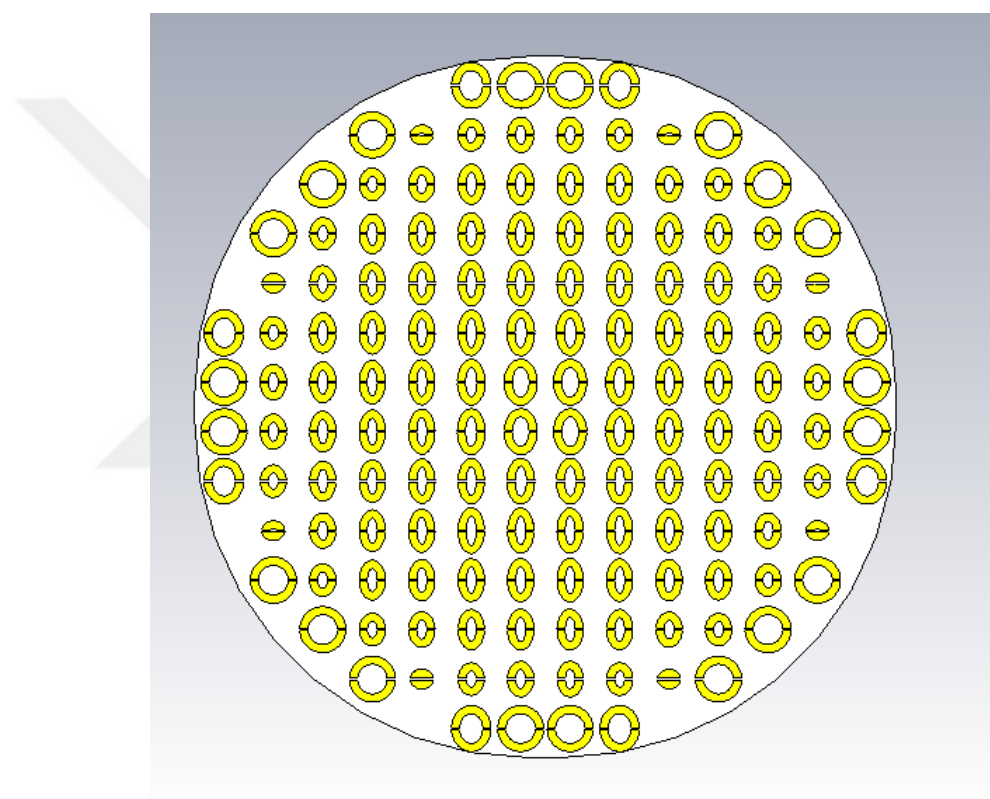


Figure 4.13 Circular shaped elliptic reflectarray antenna

4.3.1 Multi Layer Perceptron (MLP)

In this study case, one of the most commonly used Artificial Neural Network models, Multi-layer Perceptron (MLP) has taken into consideration for modelling the reflection phase characterization of the elliptic RA element with respect to its geometrical design parameters given in Fig. 4.4 and Table 4.1. The Black-Box representation of the proposed MLP based RA element is given in Fig. 4.14.

Here the important design procedure of the MLP based model is the determination of

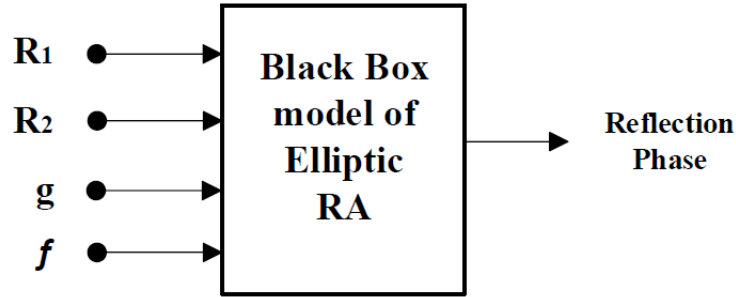


Figure 4.14 Black-Box representation of the proposed MLP based Elliptic RA

the optimal MLP architecture design parameters such as number of hidden neurons, number of hidden layers, training algorithm. In order to have an accurate prediction between the input variables and the requested output these values should be chosen optimally. For this mean different MLP structures (Table 4.2) were trained and tested with the data given in Table 4.1 via a K-fold validation process of K=2. Totally 1216 data sample is used. The performance results of the MLP models are given in Table 4.3.

Table 4.2 Different MLP structures and their design parameters

Model ID	Hidden Layer Number	Hidden Neuron Number
1	1	5
2		10
3		15
4	2	15-10
5		20-15
6		30-10
7	3	15-10-5
8		20-10-20
9		15-30-15

As it can be seen from Table 4.3, with the increase in the number of both layers and hidden neurons, the overall performance of the MLP model has improved. However it should be noted that the overall performance is starts to saturated after a certain values and it also might start to loss performance with the extreme increase in the total number of layers and neurons due to the challenging optimization problem of neurons weighting coefficients. All the results in Table 4.3 are obtained after 10 different runs and the values are the mean values. Here the MLP model 9 found to be the optimal design for the modelling of reflection phase characteristic of the elliptical RA element.

The comparison of MLP results with target value based on CST data is given in Fig. 4.15. Results are shown for constant g and frequency while different values of R_1 and R_2 parameters. The estimated values from MLP black-box model are quite similar to

the values that should be. Results of MLP modelling can be said to be successful in predicting reflection phase of unit element.

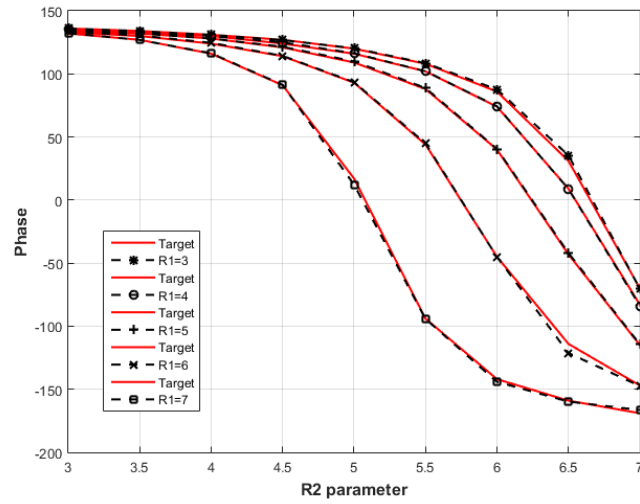
The values given in Table 4.4 are obtained using the MLP based model with respect to the requested phase compensation required for forming an elliptical shaped RA design. Here a similar optimization technique in [4, 5] has been performed. The global optimization technique called Honey-Bee Mating Optimization is used for obtaining the optimal R1 and R2 values. The MLP black-box model is created with 4 input parameters which are three geometric parameters R1, R2, g and frequency (f). During the optimization process, the gap parameter is excluded from the optimization to simplify geometric complexity and is taken as a fixed value of 0.25 mm. Two radius parameters are optimized to find the optimum R1 and R2 parameters for the reflectarray antenna to operate at the desired frequency.

The design procedure of circular shaped elliptic reflectarray antenna is depicted in Fig. 4.16. Firstly, unit element parameter size variation characteristic is obtained from CST. Unit element reflection characteristic is modeled via MLP. Data validation results are shown for different frequencies in Fig. 4.15. At the optimization stage, MLP black model is used for determining to optimum R1 and R2 values. All the optimal values for the RA design are given in Table 4.4.

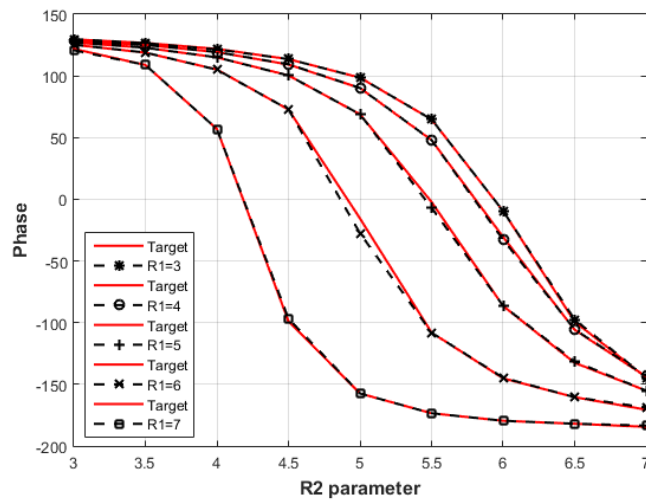
Table 4.3 Performance comparison of the MLP models

Model ID	MAE (Eq. (3.8))	RME (Eq. (3.9))	MXE (Eq. (3.10))
1	36.08	0.2975	340.72
2	8.99	0.07419	369.16
3	8.30	0.0685	336.41
4	6.95	0.05735	285.09
5	7.82	0.06452	280.64
6	7.91	0.06528	351.85
7	3.63	0.030	186.61
8	6.66	0.0549	330.48
9	2.12	0.0175	246.91

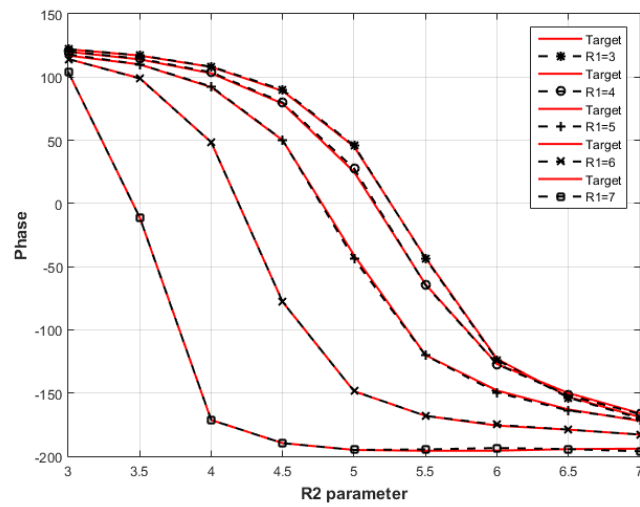
The method of the look-up table is computationally expensive because it requires performing full wave analysis of the periodic sequence several times for different frequencies and incident angles, as well as geometric parameters. In addition, large amounts of dynamic memory are required to store the data used by these simulations. The whole reflectarray can be designed, either by controlling the phase of each element to form the desired beam such as phase-only synthesis or indirectly by optimization like synthesizing using optimization algorithms. The advantage of using global optimization is that it can handle multiple degrees of freedom and offer a configuration that provides predefined constraints.



(a)



(b)



(c)

Figure 4.15 MLP Black-box model result comparison with CST at a) 10 GHz b) 11 GHz c) 12 GHz

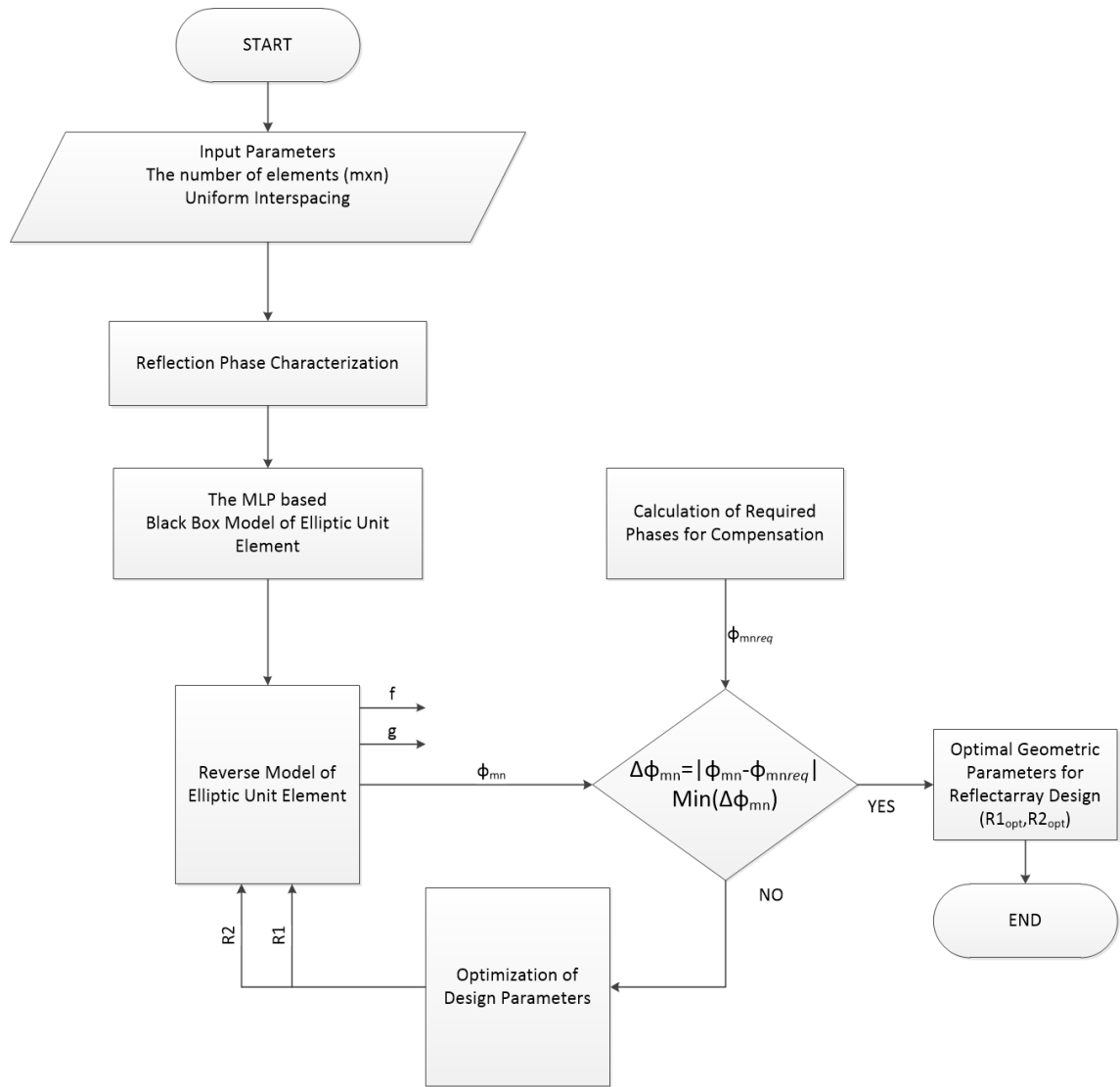


Figure 4.16 The design procedure for reflectarray antenna

Table 4.4 Optimization results of R1,R2 parameters (mm)

Element number	1	2	3	4	5	6	7
1	4.12	4.87	5.75	4.3	6.14	5.46	6.93
	6.9	6.44	5.55	5.98	4.73	4.43	5.77
2	4.87	4.95	3.55	6.02	6.85	4.66	5.56
	6.44	6.22	6.3	4.98	4.18	4.29	6.9
3	5.75	3.55	4.09	4.9	3.13	3	3.1
	5.55	6.3	6.04	5.48	5.47	3.05	6.83
4	4.3	6.02	4.9	6.17	4.66	6.93	5.75
	5.98	4.98	5.48	4.56	4.29	5.77	5.55
5	6.14	6.85	3.13	4.66	6.98	6.77	5.82
	4.73	4.18	5.47	4.29	6.8	4.84	5.14
6	5.46	4.66	3	6.93	6.77	3.39	5.06
	4.43	4.29	3.05	5.77	4.84	6.16	5.26
7	6.93	5.56	3.1	5.75	5.82	5.06	3.39
	5.77	6.9	6.83	5.55	5.14	5.26	4.47

The proposed unit cell offers several degrees of freedom for RA design and allows the dual parameter design method to be applied to passive RA design. The implementation of the double parameter design allows the reflector to perform within a defined frequency range. 1-dB gain bandwidth is obtained as 12.3% but 1.5-dB gain bandwidth of the CERA applied by this unit cell achieved as 20.6% over the entire desired frequency band. It can be seen from Fig. 4.17, by changing the desired frequency, the gain of the antenna is changed accordingly. The global optimization was performed for all 3 frequencies for a flat gain change across the entire frequency band. The values obtained as a result of optimization do not give the highest possible gain value. It provides phase compensation for the targeted bandwidth with some margin of error. The differences between the required phase distribution and the predicted phase values are tried to be minimized using the reverse MLP model.

4.3.2 Experimental Results of Circular Shaped Elliptic Ring Reflectarray Antenna

Circular shaped elliptic ring reflectarray antenna is printed on a low cost FR4 substrate with 148 elements. Even though modelling and simulation of the unit cell and antenna are performed with Roger substrate, prototype of the antenna is used FR4 substrate for fast and low cost production. It is known that FR4 has some tangent loss at higher frequencies such as X-band application. Therefore, realized gain of the manufactured reflectarray antenna with FR4 is lower than the simulation of the reflectarray with RO4350B substrate so total gain is reduced due to substrate change. Photograph of

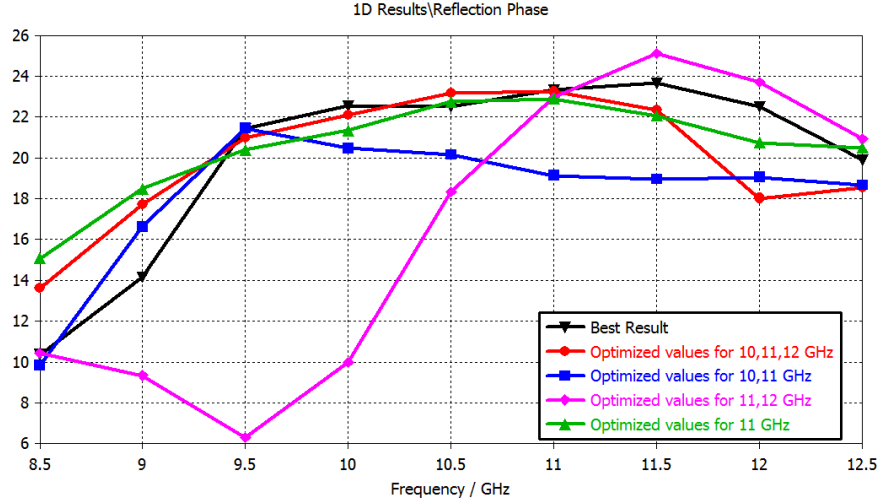


Figure 4.17 Realized gain of the CERA for optimized parameters

the prototype is shown in Fig. 4.18. Radiation pattern is measured for both E-plane and H-plane and results are given in Fig. 4.19. Measured gain of the circular shaped elliptic reflectarray antenna is about 20-21 dB at operating frequency band.

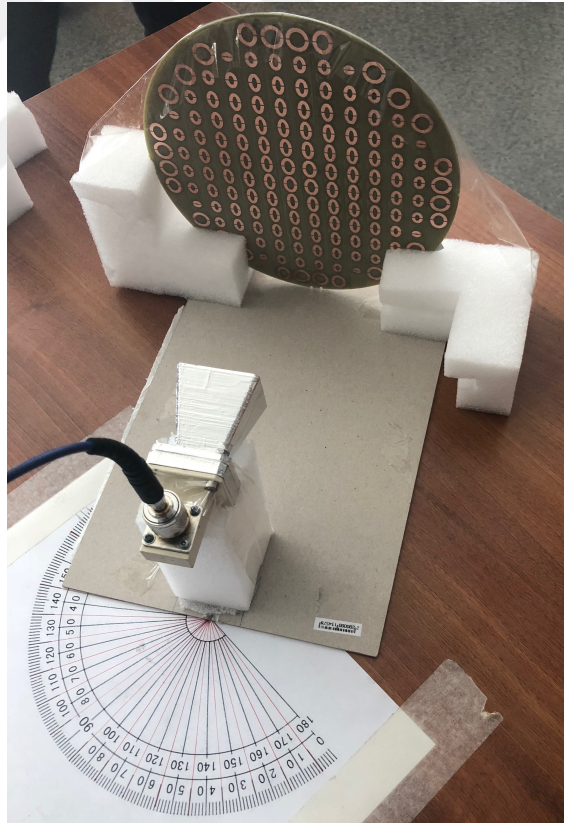
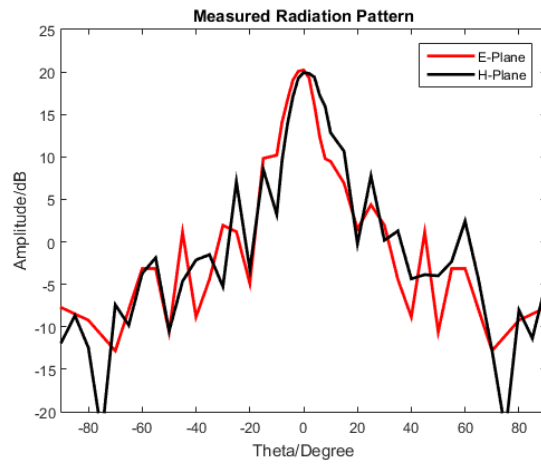
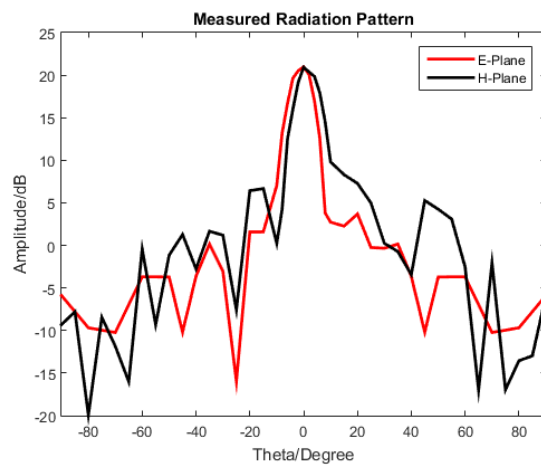


Figure 4.18 Photograph of the fabricated CERA

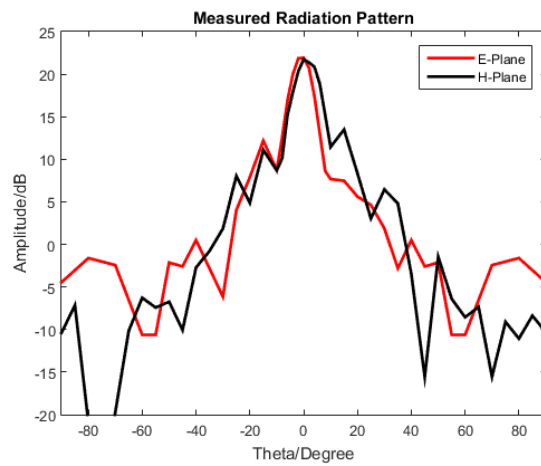
A single layer onset fed X-band microstrip reflectarray constituted by elliptic ring elements for broadband has been proposed. The reflectarray of this antenna has been designed with ANN and geometric parameters are obtained with optimization. Finally,



(a)



(b)



(c)

Figure 4.19 Measured radiation pattern of CERA at a) 10 GHz b) 11 GHz c) 12 GHz

full wave simulation is performed with CST microwave studio. The measured results of the reflectarray show good agreements with the simulation on main beam width and gain. The center feed blockage is reduced thanks to the compact horn antenna so side-lobe level of the reflectarray has good performance.

4.4 Elliptic Ring Reflectarray Antenna Design

The simulation results of the proposed single layer reflectarray antenna are examined in this section. The goal of this section is to design a single layer high efficiency reflectarray at X-band for potential applications. A square 0.3x0.3m Elliptic Reflectarray Antenna (ERA) is designed on the top layer of the substrate using 400 split elliptic ring elements. The substrate is a 1.52 mm thick RO4350B with low tangent loss. The proposed design of reflectarray are presented in Fig. 4.20. The compact horn antenna is used as the feed antenna because of its radiation symmetry. The compact feed horn is placed at 20 cm ($f/D = 0.66$) considering both aperture efficiency and antenna size. Focus to diameter ratio is quite small which gives an advantage of compact size as a volume. In this design feed antenna is physically placed in the center of the reflectarray and reflectarray antenna full wave simulation is performed with CST Microwave Studio's time domain solver. Alternatively, feed antenna could be solely simulated and then far field results can be exported. These results would be feed source for the reflectarray. However, this solution technique will neglect the blockage effect of the feed antenna. So, the feed horn antenna is added to main reflector to get results as in realization model. The symmetry planes are defined to reduce computational time. Then, gain and far-field radiation patterns are obtained to verify the reflectarray antenna performance.

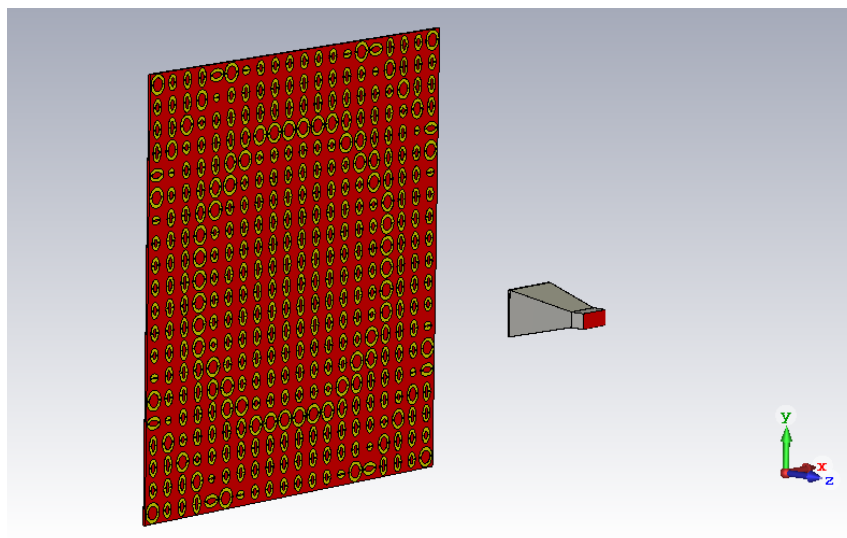


Figure 4.20 Elliptic ring reflectarray antenna

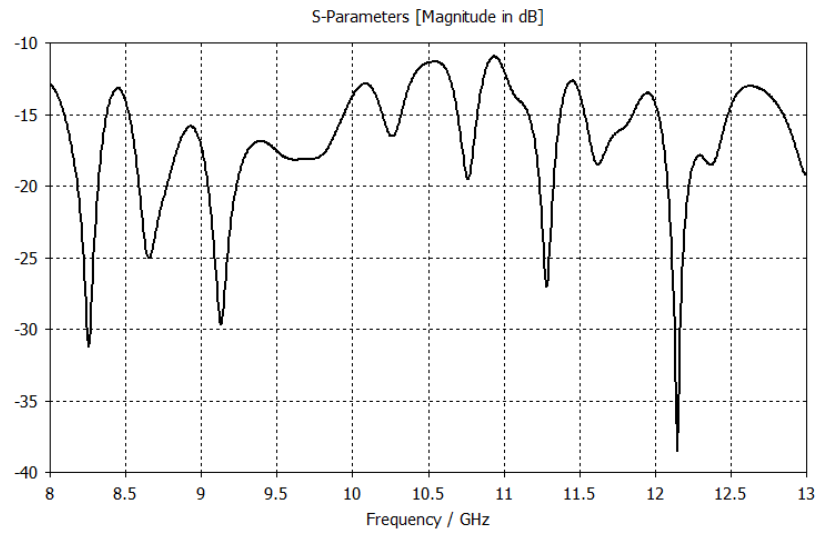


Figure 4.21 S_{11} - Frequency variation of ERA

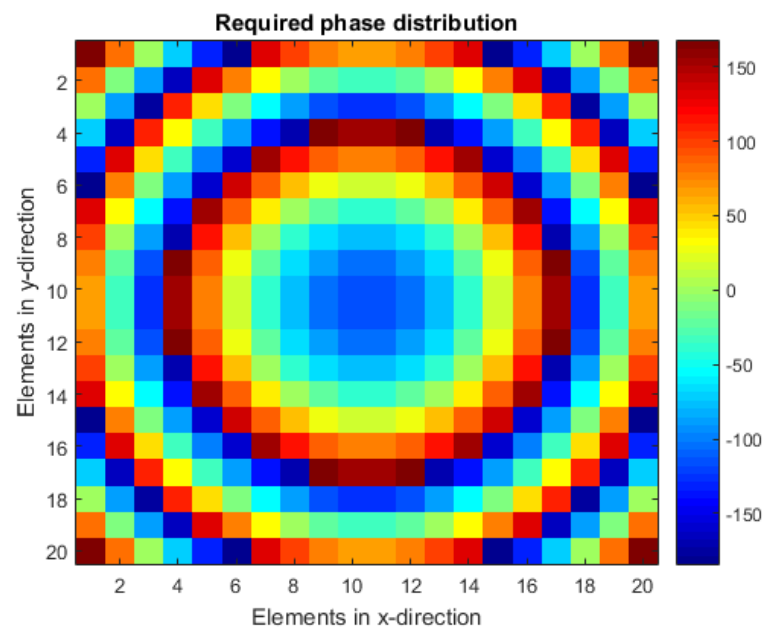


Figure 4.22 Required phase distribution of ERA

The required phase values are calculated with (3.3) and phase distribution is depicted in Fig. 4.22. The angle of the feed horn antenna pattern was chosen as 10 dB below from peak value of the gain at center frequency so that reflectarray is illuminated more power to the surface. However, side lobe level could be rise because of the distortion of the uniformity on reflectarray surface. As seen from Fig. 4.24, proposed design of ERA has acceptable side lobe levels.

The simulated results of E-plane and H-plane radiation patterns are shown in Fig. 4.24. Similar radiation pattern characteristic are observed at 10 GHz and 11 GHz, HPBW is average 5.5 degree and side lobe levels are -20 dB overall, at 12 GHz gain start to decrease and a slight increase in side lobe levels as frequency increases. Aperture efficiency of the ERA is 60% at 10.5 GHz where realized gain reaches maximum value 29.2 dB. Considering the aperture efficiency, ERA is a very successful design, however its bandwidth seems narrow because of the single layer model design. 3-dB gain bandwidth of the ERA is 23.4% as seen from Fig. 4.23. Due to single layered unit element narrow band characteristics maximum antenna efficiency match only single frequency and decreasing for both lower and upper frequency. Performance comparison of elliptic reflectarray antenna with the similar works in the literature is given in Table 4.5.

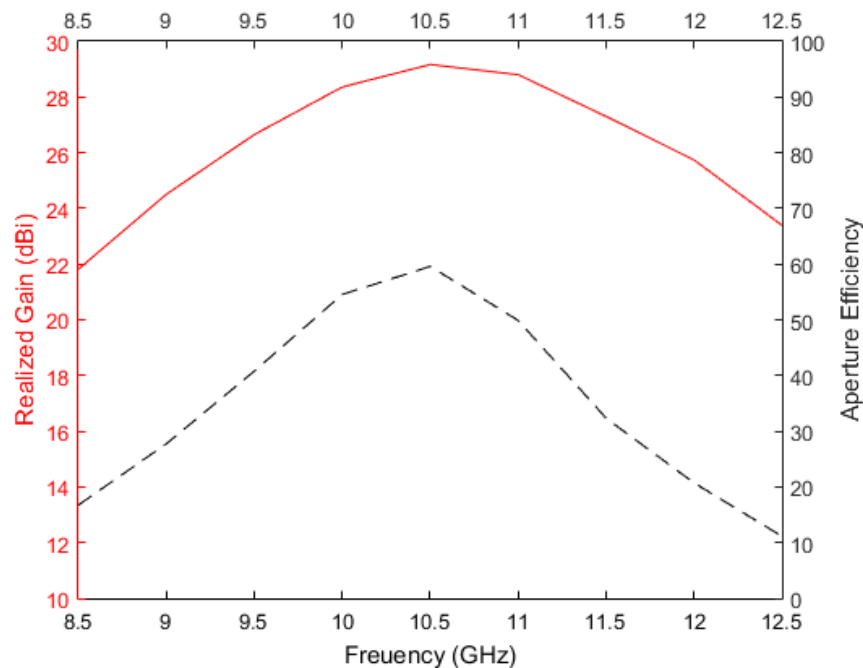


Figure 4.23 Realized gain and aperture efficiency of ERA

The elliptic ring element has been proposed as a unit cell for passive phase compensation. This element is classified as a single layer elliptical ring patch structure with gap. The unit cell offers a good phase range and convenient for reflectarray antenna design. Firstly a circular shaped reflectarray antenna is designed. ANN black

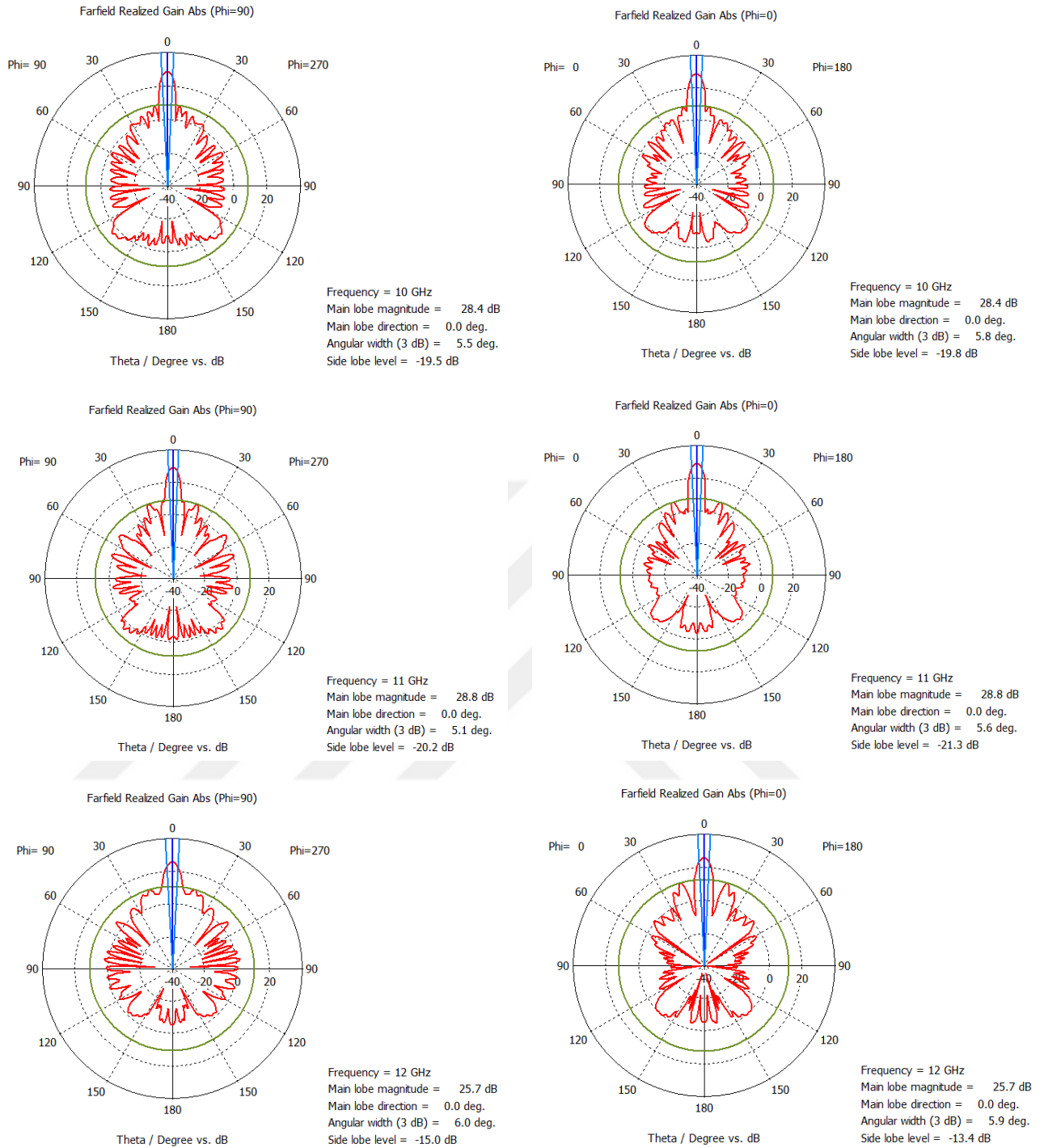


Figure 4.24 E-plane and H-plane radiation pattern of the ERA

Table 4.5 Comparison of the antenna performance with previous works on reflectarray antenna

Reference	ERA	CERA	[44]	[45]	[46]	[47]	[48]
Center Frequency (GHz)	10.5	10.9	10.2	10.2	10	13.5	11
Bandwidth 3-dB (%)	23.4	26.2	-	12	-	-	-
Bandwidth 1-dB (%)	12.33	12.28	25	-	18	20	2-dB 36.4
Number of Layers	1	1	2	2	1	1	2
Aperture Efficiency (%)	60	36.6	39.8	35	40.3	39	30
Gain (dB)	29.2	23.7	19.3	19	26.1	25	20
Side-lobe Level	-20	-15.1	-	-14	-16	-	-13
f/D	0.66	0.9	1	0.9	1	0.97	-

box model of unit cell is used to get a fast description of reflection characteristics. Optimal geometric parameters are obtained for a specific operating frequency band. Lastly, a larger and square version of elliptic ring reflectarray is designed according to simulation results from CST. The results of realized gain and efficiency are very promising.

5

Results And Discussion

In this thesis, a novel regression SR and prototyping method which is 3D printing is applied to the realization of the Non-Uniform Reflect Array (NURA). Results shows that SR is used as a successful tool for building an accurate analytical expression for the reflection phase calibration characteristic of NURA that is used in a fast design optimization and performance analysis. The required amount of training data is comparable with the counterpart regression methods [28], in spite of this, a model consisting of a solely single analytical expression is resulted revealing the intrinsic relationships of the data set using the existing data patterns. Therefore, this method can be efficiently employed in the accurate, fast modelling and design optimization of electromagnetic devices in the form of analytical expressions. In the realization step, the designed NURA is then manufactured by using 3D printer technology where the PLA material can be easily shaped and create unit cell at printing accuracy of 0.1 mm per layer. Thus, by this mean the prototyping cost of NURA design can be reduced drastically both in means of time and ease of manufacturing. Measurements of the mismatching and radiation properties of the realized NURA are resulted to be agreed with the novel theoretical performances.

Finally, a single layer split elliptic ring element is modeled via MLP and by using the optimization, the required parameters are obtained. Full wave simulation results of two elliptic reflectarray antenna with different sizes have been analyzed and compared in Chapter 4. First design is 148 element circular reflectarray antenna shows good broadband performance from 9.5 GHz to 11.8 GHz. The design of the unit element has been modeled using novel artificial intelligence (AI) algorithms for prediction of their reflection phase characteristics with respect to their geometrical design parameters and then the AI based models used for design of reflectarray antenna. As a second design, 20x20 element square reflectarray antenna with high efficiency and low volume is purposed. Due to its focus to diameter ratio is quite small which gives an advantage of compact size.

Herein, two different RA unit element design has taken into the consideration (i)

Non-uniform RA element, (ii) elliptical shaped microstrip patch RA element. Both of the design has been modeled using novel artificial intelligence (AI) algorithms for prediction of their reflection phase characteristics with respect to their geometrical design parameters and then the AI based models used for design of reflectarray antennas.



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Publications From the Thesis

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Papers

1. P. Mahouti, F. Gunes, M. A. Belen and A. Caliskan, "A Novel Design of Non-Uniform Reflectarrays with Symbolic Regression and its Realization using 3-D Printer" *Applied Computational Electromagnetics Society Journal*, vol. 34 no. 2, 2019.