Design and Development of Reflectarray Antenna with Bandwidth Enhancement for Ku Band applications

Ph.D. Synopsis

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1. Abstract

High gain and bandwidth are important in space applications. Reflectors and arrays can be used to do this. Reflectors have the disadvantage of being bulky. The size of the reflector array structure grows exceedingly huge. As a result, reflectarrays were created, which combine the benefits of arrays and reflectors. Reflectarrays receive a linearly polarized wave, phase-shift and amplify the directed waves through transmission lines, and then re-radiate it. Many attractive characteristics of these antennas include conformability, decreased insertion loss, and ease of design, analysis, and fabrication. Reflectarray antennas can be constructed using dipole arrays, FSS (Frequency Selective Surface) structures, or patches. Reflectarray's only restriction is its low bandwidth.

To increase the bandwidth, several techniques such as patches of variable sizes and aperture coupling are used. The research work carried out in the thesis focuses on the development of microstrip patch antennas with increased bandwidth for Ku band applications. A comparison of several dielectric materials, feeding techniques, height of the substrates and patch shapes is performed. Based on the comparison, a unit cell with a unique structure is designed and constructed for frequencies ranging for Ku band applications. This study employs a single layer variable size patch for bandwidth enhancement. To investigate the unit cell in an array environment, an infinite array analysis is performed. To investigate the properties of resonant elements, the reflection phase curve is obtained.

The reflection phase, also known as the 'S' curve, displays the phase shift as a result of parameter changes. The width variation is regarded as a parameter variation for the proposed design. A comparison of various S curves is displayed in relation to the obtained reflection phase and frequencies. The reflection phase for the entire geometry in accordance with the 'S' curve is acquired, which aids in determining the dimensions of the elements in accordance with the S curve obtained for the unit cell design. A feed is designed to excite all of the elements on the reflectarray surface. The feed also yields a promising result of 5 dB gain. To acquire adequate gain results, the entire antenna shape is constructed in HFSS tool and a proper f/D ratio is maintained.

The unit cell has been fabricated and tested, yielding a bandwidth of 1.88 GHz, or about 31% of the band. The 'S' curve is obtained for frequencies ranging from 12 GHz to 13 GHz, representing 50% of the lower part of the Ku band. When constructed properly, the final geometry provides promising improvements at frequencies ranging from 12.5 GHz to 13 GHz.

2. A brief description of the State of the Art of the research topic

Motivation:

Space communication has become an inevitable part of human life. Whether it is telecasting or deep space study, an efficient system with appropriate transmission and reception of signals is always a prime requirement. Many antennas in the history have proved to be in the working class for space communication. With the advancement in technology, the need for compact, conformal, low cost and compatible antenna has increased. Reflectarrays are one of the class of antennas which are proving to be immensely useful because of its compactness and conformability. These antennas can be designed at X, Ku and many other higher frequency bands that are widely used for satellite communication.

Amidst all the advantages proving capable for satellite communication, Reflectarrays have a disadvantage of very narrow bandwidth which restricts it to use the available frequency spectrum efficiently. The problem is due to two reasons, one being the spatial phase delay and other being the narrow bandwidth of the unit cell element. So, a wide research has been carried out to enhance the bandwidth of reflectarrays using various techniques. Among various methods of enhancing bandwidth, variable size patch and FSS structures prove to be cost effective because of its ease of fabrication.

Literature Survey

High gain antennas are primarily need for most of the long distance communications and radar applications. Traditionally, reflectors and arrays are used for high gain applications. When it comes to reflectors, the main factor which comes across is the bulky structure. The array antennas are considered to be most versatile in antenna systems as they can easily replace the high gain bulky reflectors. The array antennas are widely used in space systems. The arrays, scans the main lobe with the relative excitation between the elements and it also synthesize any desired amplitude pattern. But the problem with arrays is that they are becoming costly to implement. The cost increases when phase shifters are added to achieve wide angle beam scanning. The cost gets added because of use of complicated beam former and also high cost amplifier modules. The amplifier modules must be used to alleviate the problem associated with the power inefficiency that occurs in the high loss beam former and phase shifters. When reflectors and arrays are having their own designing challenges, a new generation of antenna which has high gain, low mass, low profile as well as low cost have gained much attention [1]. This hybrid antenna has the advantages of both the reflectors and the arrays as shown in Figure 1. This antenna can be used for achieving contoured beam, for electronic scanning and for multiple frequencies applications.

Figure 1: Geometry of offset fed reflectarray antenna

Because of its flat surface, the reflectarray is cutting out the cost in comparison to the parabolic reflectors which need costly moulds for its fabrication. The reflectarray concept was demonstrated in 1960s [2]. Reflectarrays have evolved from having waveguides as unit cell to spirals and finally microstrip patches. Reflectarrays can be designed using various shapes of resonators as shown in Figure 2. For dual band as well as for multi band scanning, FSS structures prove to be promising. There are various techniques used for enhancing bandwidth like using patches of variable sizes, aperture coupled patches, multilayer structures. In addition to this, the substrate material used also plays a very important role. Cost and ease of fabrication is one of the most important parameters when it comes to antenna designing

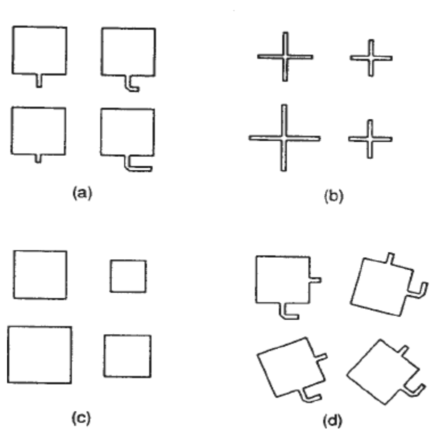


Figure 2: Various printed reflectarray elements, (a) identical patches with variable length phase delay lines (b) variable size dipoles (c) variable-size patches (d) variable angular rotations

The design presented in [3] produced bandwidth of 30% but was very difficult to fabricate because of use of Radome. One other design proposed in [4] used two resonating elements with high cost dielectric material and gave bandwidth of 29.3%. In the design presented in [5], multilayer structure was used to enhance bandwidth. Hence it became difficult to fabricate and is pricy. In addition to the above parameters, there should be a good performance in bandwidth which is adequate for reflectarray to function appropriately. The designs shown [6], [7], [8] were very easy to fabricate with lesser cost but produced poor bandwidth of just 19%.

In addition to this, adequate gain and bandwidth both should be obtained. The design in [9] gave a bandwidth of 15%, added a difficulty of orientation of delay line as aperture coupling was used. However, the design in [10] gives good performance with the single layer but again with not much novelty in printed element design. The design challenges are also faced when multiple elements are used [11]. For enhanced bandwidth, the ‘S’ curve obtained should be parallel for most of the frequencies of operation. If that is not mentioned, there is an automatic reduction in bandwidth [12]. Further, the dielectric material used also gives a vital designing challenge [13] and it also directly affects the overall cost of the antenna [14]. Reflectarrays have vast diversity on the basis of the application for which it is used. In addition to this, the feed which is used also contribute in the overall cost of the reflectarray antenna geometry, hence that should also be chosen wisely [15].

3. Definition of the Problem

The microstrip reflectarray has an inherent disadvantage of narrow bandwidth. Bandwidth is less due to two reasons. One is the spatial delay which is occurring due to the flat geometry as shown in Figure 3. The other reason for less bandwidth is due to microstrip elements which are used. The microstrip antenna has a limitation of low bandwidth around 10-19%.

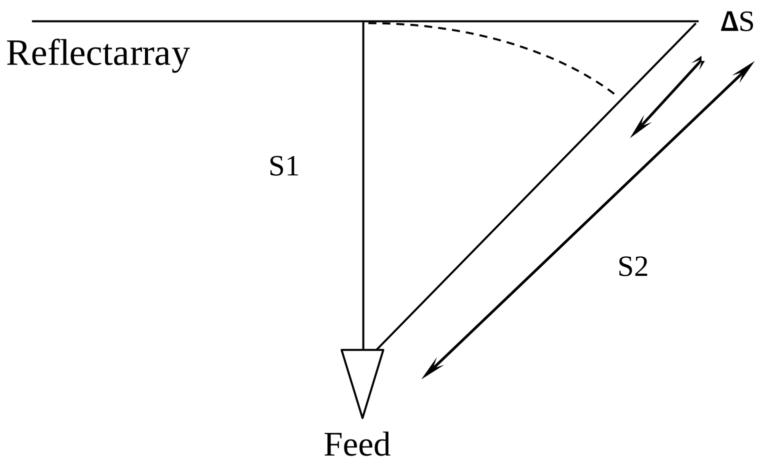


Figure 3: Spatial Delay

The research aims at designing a microstrip reflectarray antenna with enhanced bandwidth for Ku band.

4. Objective and Scope of work:

- To design radiating element for microstrip reflectarray antenna with enhanced bandwidth at low cost.
- To fabricate and test the best radiating element design.
- To do Infinite array analysis of the radiating element when considered as a unit cell.
- To develop the mechanism for obtaining the phase for each element of the reflectarray.
- To design appropriate feed to illuminate the elements.
- To design the entire antenna geometry.

5. Original contributions by the thesis

The goal of this thesis is to design a reflectarray antenna with increased bandwidth. The thesis's original contribution can be summed up as follows:

- Different microstrip patch antenna designing parameters affecting the bandwidth have been examined. RT Duroid, Teflon, and FR4 are the materials that have been employed in design. All of the materials mentioned above have been used to conduct a thorough comparison. Additionally, a comparison of various feeding strategies and substrate heights has been conducted.
- Several element designs have been created and simulated in order to get increased bandwidth after the material was finalized. Numerous designs have been produced and simulated using shapes including rectangles, patches with two or four slots, Swastik with extended lines, rings, and patches with stubs. All of the designs have been compared in terms of bandwidth.
- The best performing radiating element design have been fabricated and put through performance tests.
- The reflection phase vs. the element variation graph, also known as the 'S' curve, has been analyzed for all of the designs while maintaining them in an infinite array setting. Different 'S' curves of diverse designs are compared. Additionally, the electromagnetic band gap (EBG) effect has been researched, and comparisons between the 'S' curve with and without the EBG effect have been made. Sub wavelength technology has also been researched and modeled.
- Phase-only synthesis is created in accordance with the reflectarray's radiation process. Depending on the 'S' curve that is chosen, the dimensions of each unit cell element are determined.
- A feed that works well for frequencies between 12 GHz and 14 GHz has been created with a gain of roughly 5 dB. The cost-effectiveness factor has also been considered when selecting the feed.
- At last, the entire reflectarray geometry for 4x4 components has been created, and a gain of about 25 dB for frequencies of 12.5 GHz, 12.7 GHz, and 13 GHz.

6. Methodology of research and results

This section presents the designing of reflectarray antenna for Ku band applications. The methodology of research is as follows:

- Study of various parameters affecting the bandwidth and cost of Microstrip Patch Antenna using various feeding techniques, shapes of patches, various dielectric material and various heights of substrates.
- Novel unit cell simulation, testing and measurement
- Infinite array analysis of unit cell and comparison of 'S' curve using EBG effect and sub wavelength analysis
- Phase only synthesis to obtain appropriate phase of all elements and array tapering.
- Designing of feed antenna.
- Designing of reflectarray geometry in HFSS

6.1. Study of various parameters affecting the bandwidth and cost of Microstrip Patch Antenna using various feeding techniques, shapes of patches, various dielectric material

A comparison was done on the basis of various parameters for Ku band frequencies they are as follows:

a) Feeding techniques
b) Dielectric materials**.**
c) Height of the substrate
d) Shapes and sizes of patches

a) Feeding technique

Microstrip patch antenna has various feeding techniques like the inset feed, microstrip line feed, proximity feed and aperture coupled feed. Here two types of feeding techniques; the microstrip line feed and the aperture coupled feed are studied and compared. In addition to this, various parameters which are controlling the bandwidth are also studied. The table below shows the comparison and the various parameter variations for both the types of feeding techniques.

Table 1: Parameters controlling the design

Feeding Technique	**Feed line**	**Port**	**Slot**	**Patch**	**Height**
Microstrip feed	Gain	Bandwidth	-	Centre Frequency	Working Band
Aperture Coupled	Gain and bandwidth	-	Gain and bandwidth	Centre Frequency	Working Band

Table 1 gives the information about the various parameters which are controlled by various parts of the antenna. From Table 2, it is seen that aperture coupled technique gives better bandwidth but it has fabrication cost more compared to microstrip feed technique.

Table 2: Results for feeding technique comparison

Feeding Technique	**Return Loss (dB)**	**Bandwidth (GHz)**	**Cost and ease of fabrication**
Microstrip feed	-21.1	0.2	Cost less, Easy to fabricate
Aperture Coupled	-27.07	1.2	Cost high, Difficult to fabricate

b) Dielectric materials

The main component of microstrip patch antenna is the dielectric material. As the loss tangent decreases, the performance of the dielectric material as a substrate increases. So in Table 4, a comparison is presented between three dielectric materials, RT Duroid, Teflon and FR4.

Table 3: Comparison of various dielectric materials

Material	**Bandwidth (GHz)**	**Return Loss (dB)**	**Dimensions of patch (W x L in mm)**	**Cost**
FR4	1.1	-26.5	5.8x6	Less
RT Duroid	3	-52.8	7.8 x7.8	More
Teflon	3	-63.75	7.5 x7.8	More

The comparison of Table 3 shows that RT Duroid and Teflon gives better results in terms of bandwidth and return loss. But, when it comes to cost and availability, both the substrate materials are very much high in cost and rarely available. In addition to this, when the dimensions are compared, FR4 gives lesser dimensions of patch than the other two materials, i.e. RT Duroid and Teflon.

c) Height of the substrate

As the height of antenna increases, the bandwidth also increases. So a study has been carried out using various heights of substrates available for FR4.

Table 4: Comparison of various heights of substrates

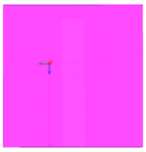
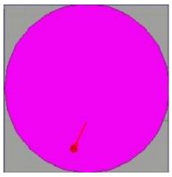
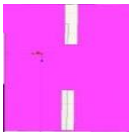
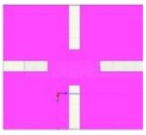
Height (mm)	**Return Loss (dB)**	**Bandwidth (GHz)**
1.012	-16.39	0.93
1.670	-27.07	1.2

Table 4 shows that as the height of substrate increases, there is increment in bandwidth.

d) Shapes and sizes of patches

For designing a novel structure for enhancing bandwidth of microstrip patch antenna, various shapes and sizes of patches have been designed and studied. A comparison has been done between various designs to meet the key requirements of bandwidth for the unit cell design. The Table 5 below shows comparison between various shapes and sizes of patches.

Table 5: Different shapes and sizes of patches

Shape	**Design**	**Bandwidth (GHz)**	**Return Loss (dB)**
Rectangular		1.22	-27.07
Circular		1.22	-26.90
Two slots		1.23	-17.68
Four slots		1.50	-22.56
Swastik with extended lines		1.67	-26.69, -33.86

From all the above designs, the Swastik with extended lines gives good results in terms of return loss and bandwidth both. The structure is also simple in shape and single layered with an ease for fabrication.

6.2. Novel unit cell simulation, testing and measurement

The unit cell is simulated in HFSS and tested. The results of simulation and testing are as shown in Figures 7 and 8 respectively.

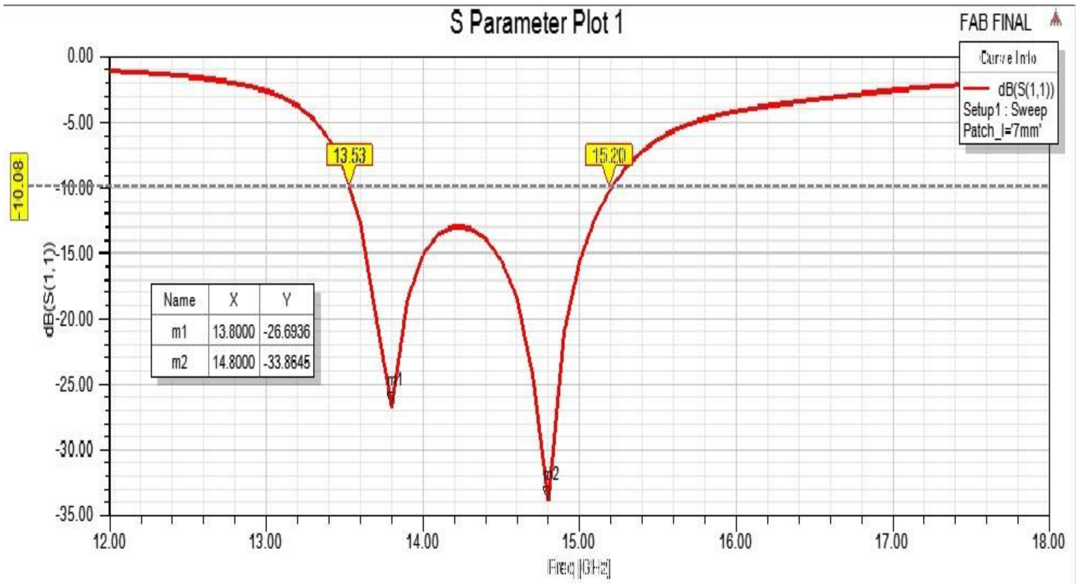


Figure 7: Simulated Return loss of Swastik with stubs (FSS structure)

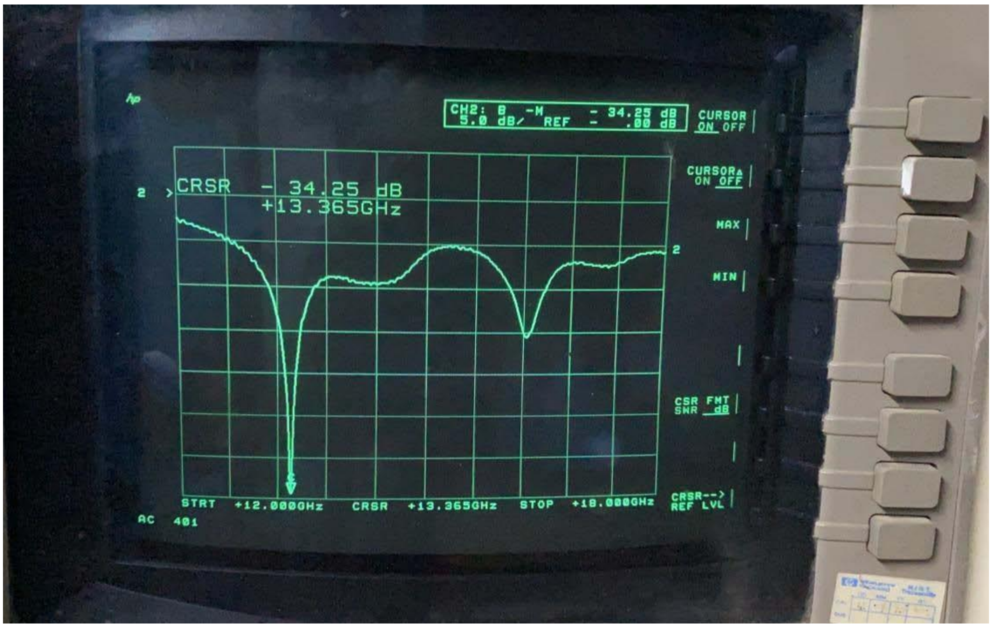


Figure 8: Measured Return Loss of Swastik with extended lines

The measured results give 1.88 GHz of bandwidth and the simulated result gives 1.67 GHz of bandwidth. Figure 9 shows the fabricated antenna and the antenna under test.

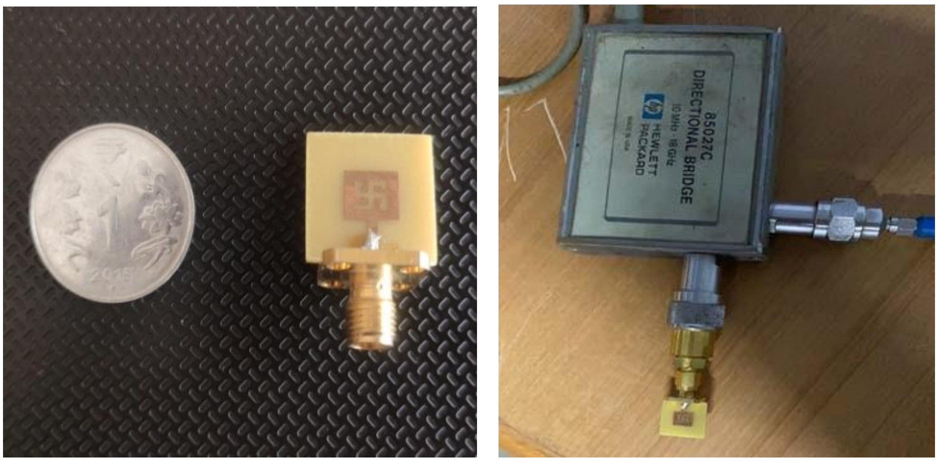


Figure 9: a) Fabricated antenna b) Antenna under test

A comparison table is given here comparing the simulated and measured results of the unit cell.

Table 6: Comparison of simulated and measured unit cell design

Parameters	**Simulated**	**Measured**
Frequency (Band – I)	13.8 GHz	13.4 GHz
Return Loss	-26.69 dB	-34.25 dB
Frequency (Band – II)	14.8 GHz	16.2 GHz
Return Loss	-33.86 dB	-16.4dB
Overall Bandwidth	1.67 GHz (13.53GHz – 15.20GHz)	1.88 GHz (13.1 GHz – 13.92 GHz; 16.35 GHz – 17.41 GHz)

From Table 6, it is clear that the measured results give higher bandwidth than the simulated results. Thus, the design is taken forward for infinite array analysis.

6.3. Infinite array analysis of unit cell and comparison of S curve

Infinite array analysis is carried out to see the behavior of the unit cell in array environment. The Figure 10 below shows the master slave boundary condition and Floquet port excitation for array analysis.

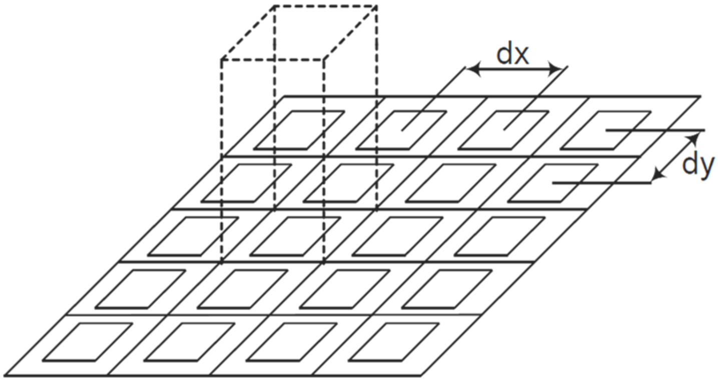
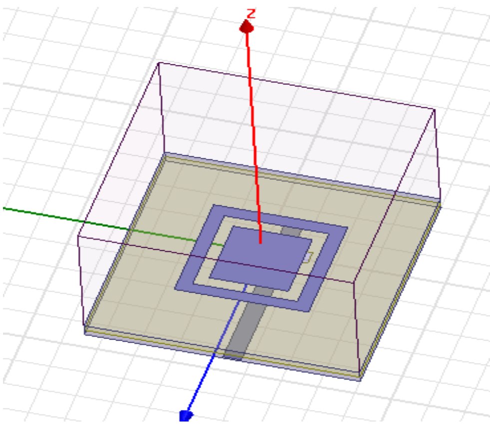
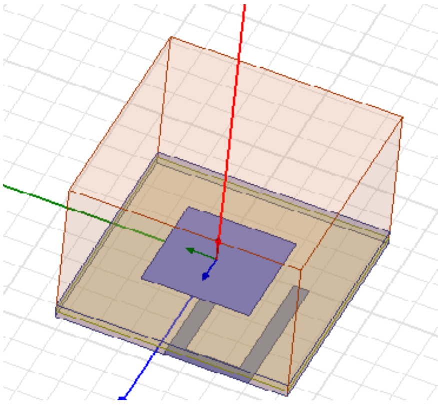
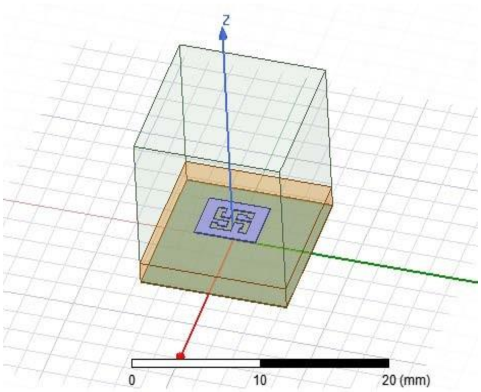


Figure 10: Unit cell treated as an infinite array

Once the infinite array analysis is done, 'S' curve is obtained which tells the reflection phase needed for each element in order to overcome the spatial delay and the comparison of S curve is based on: a) The degrees of phase variation b) The frequencies till which the variation is obtained. S curve was compared for various designs which is shown in Table 7 below.

Table 7: Comparison of various designs to obtain reflection phase

Design	Start Phase	End Phase
Ring Structure 	-30°	-49°

Delay line 	-41°	-47°
Swastik with stubs (FSS structure) 	161.3°	-117.2°

The other parameter which is controlling the bandwidth is the frequencies for which the S curves are obtained in parallel manner. For that, again a comparison has been done for different designs of Swastik with extended lines, which is presented in the Table 8.

Table 8: Comparison with dimension change in Swastik FSS structure

Designs	**Start Phase**	**End Phase**	**Bandwidth**
1	161.8°	-135.5°	0.7GHz
2	129.1°	-179.76	1 GHz
3	161.3°	-117.2°	1 GHz

The Swastik FSS structure has slots in the design which can contribute to the EBG effect. So a comparison was also carried out to study the S curve with and without

EBG effect which is shown in Figure 11.

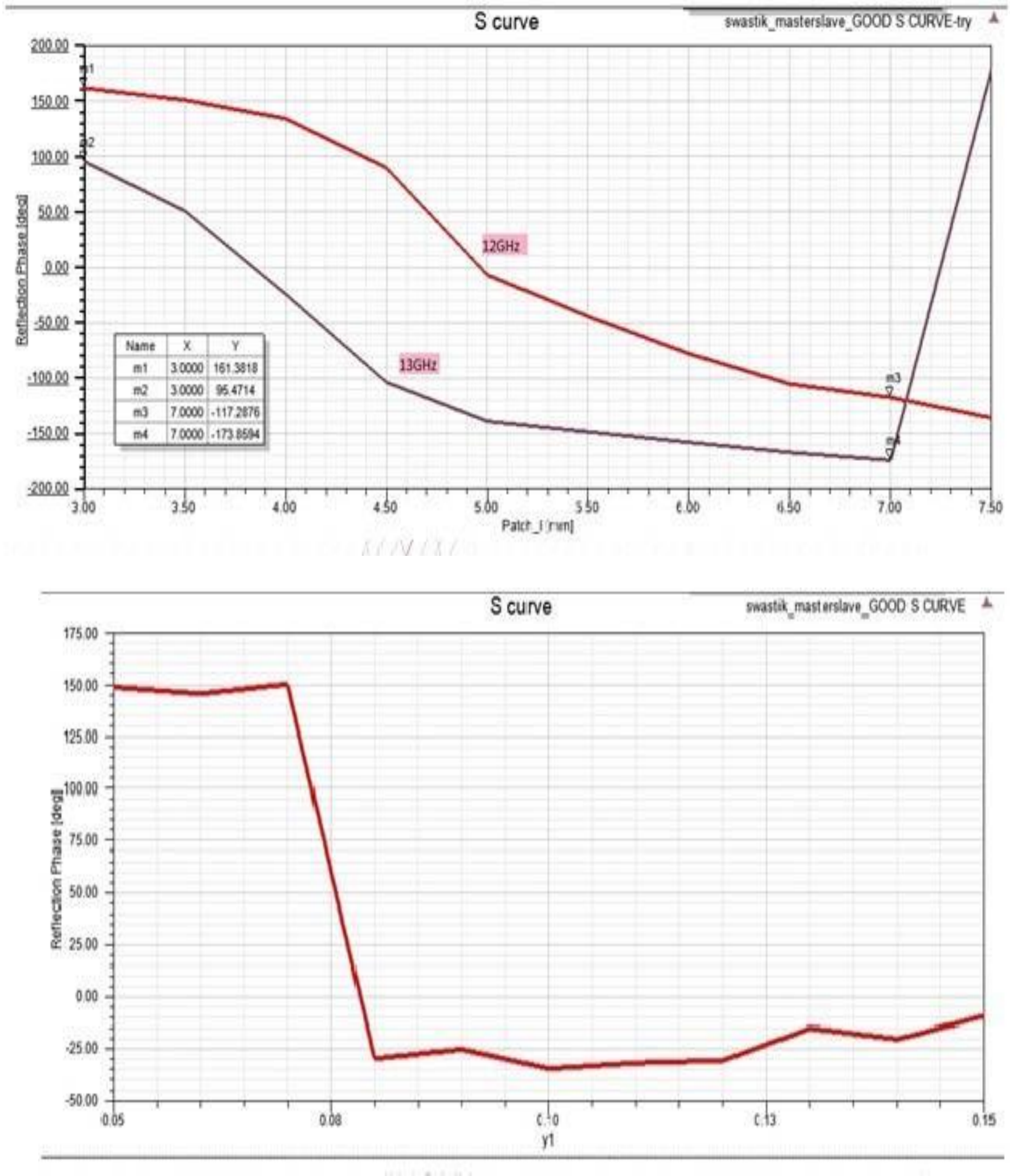


Figure 11: a) Without EBG effect b) With EBG Effect

The main aim, while designing the unit cell antenna, is to get ‘S’ curve in the range of 180° to -180°. So, while designing reflectarray antenna, more number of patches can be incorporated to obtain higher gain. The variation obtained for EBG effect is from 0.05mm to 0.15 mm. In the comparison, it is found that, without EBG effect, it gives more variation in ‘S’ curve and hence that parameter is chosen for reflectarray geometry design.

Instead of using a half-wavelength design that is generic, elements in sub wavelength techniques are created for sub wavelength. Three sub wavelength elements are created in this design. Compared to the previously illustrated design, the dimensions are smaller. The sub wavelength approach is used to test the bandwidth efficiency.

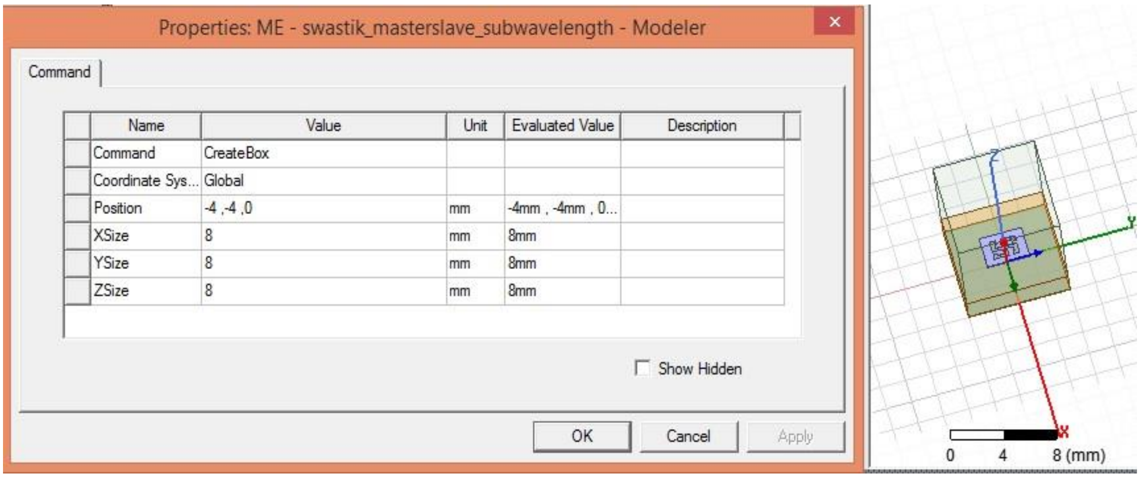


Figure 12: Sub wavelength element dimensions

The dimensions of the unit cell are taken with respect to λ/3, as shown in Figure 12. The performance of the S curve is tested while simulating the unit cell in an infinite array environment.

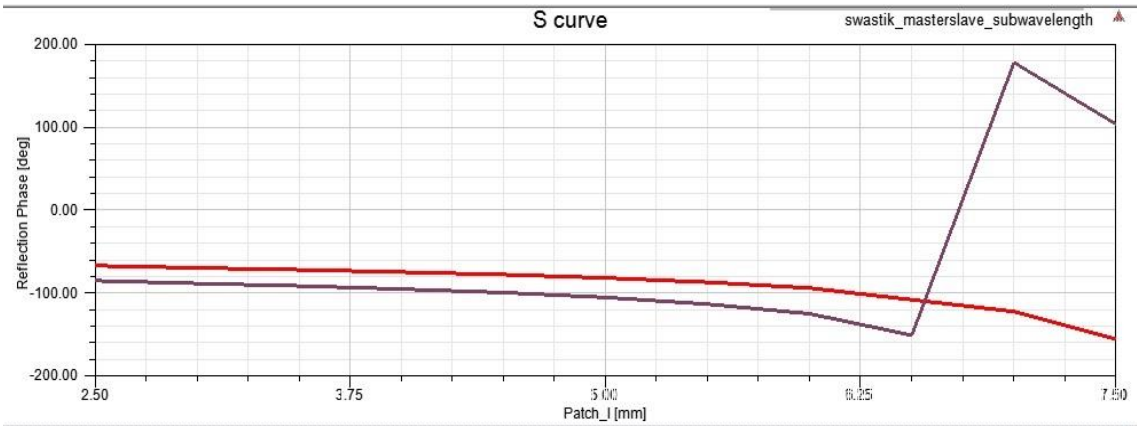


Figure 13: S curve for the frequencies 12 GHz and 13 GHz

Figure 13 shows that the S curve for the intended frequency range, 12 GHz to 14 GHz, is virtually flat, which is not what is desired. The bandwidth cannot be taken into account because the suitable S curve was not obtained in this instance.

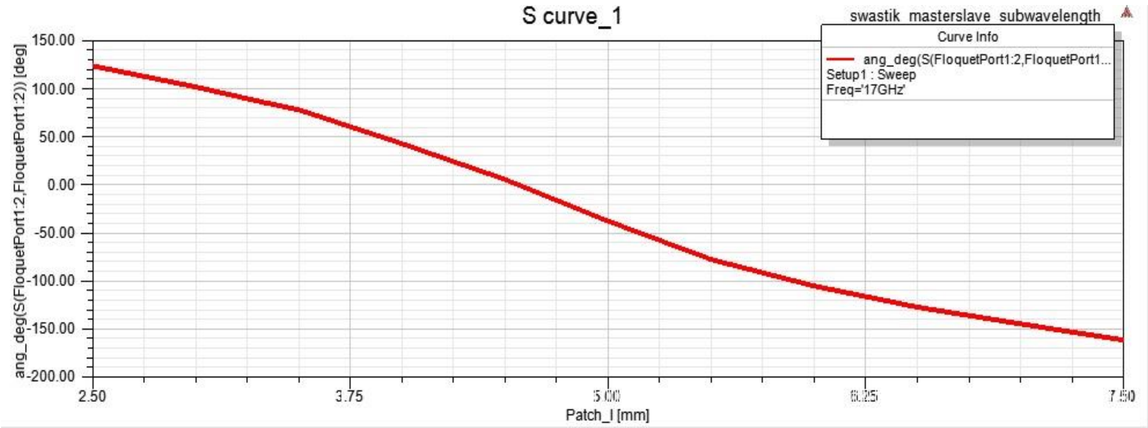


Figure 14: S curve for 17 GHz frequency

When the 'S' curve was observed at various frequencies, it was found that the higher Ku band frequencies, between 16 and 18 GHz, had a preferable S curve. From 17 GHz to 17.8 GHz, the acceptable phase variation was attained. In this instance, the bandwidth equals 0.8 GHz. The 'S' curve for 17 GHz frequency is shown in Figure 14.

The λ/2 variation design rather than the λ/3 variation design is chosen since the thesis focuses on the lower Ku band. Additionally, the λ/2 variation design provided 1 GHz of bandwidth, and the λ/3 variation design provided 0.8 GHz of bandwidth.

6.4. Phase only synthesis

MATLAB GUI code produces the phase required for each unit cell in accordance with the 'S' curve. Here, the array tapering is used because the cells at the edges are inactive and may contribute in the generation of the grating lobes. So, after tapering, the geometry becomes circular. Once the input parameters like frequency of operation, diameter of the antenna and location of the feed are given, the MATLAB GUI code simulates the reflection phase needed for each element in graphical and numerical formats. Figure 15 shows the reflection phase for all elements when the diameter of geometry is chosen to be 100mm.

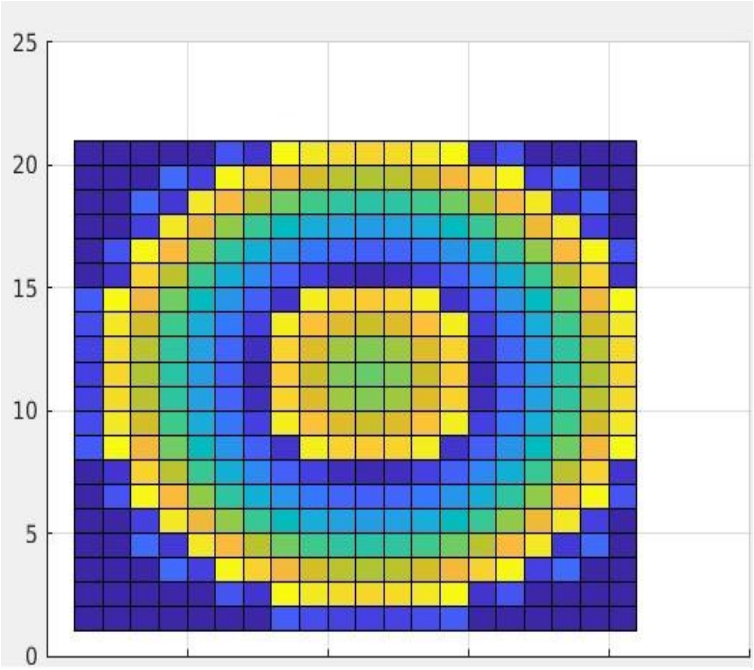


Figure 15: Reflection phase for diameter of 100 mm

In the similar manner, the reflection phase is obtained for 4x4 arrays after entering the input parameters in the window shown in Figure 16.

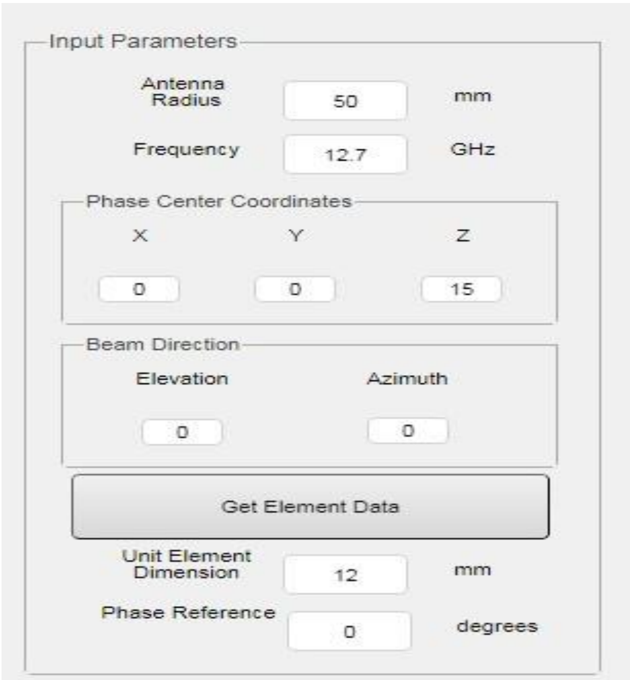


Figure 16: Phase calculation

6.5. Feed Design

A feed is designed which works for illuminating the patches on the reflectarray surface. The feed works well with the defined frequencies. The simulation results are shown in Figure 17 and 18.

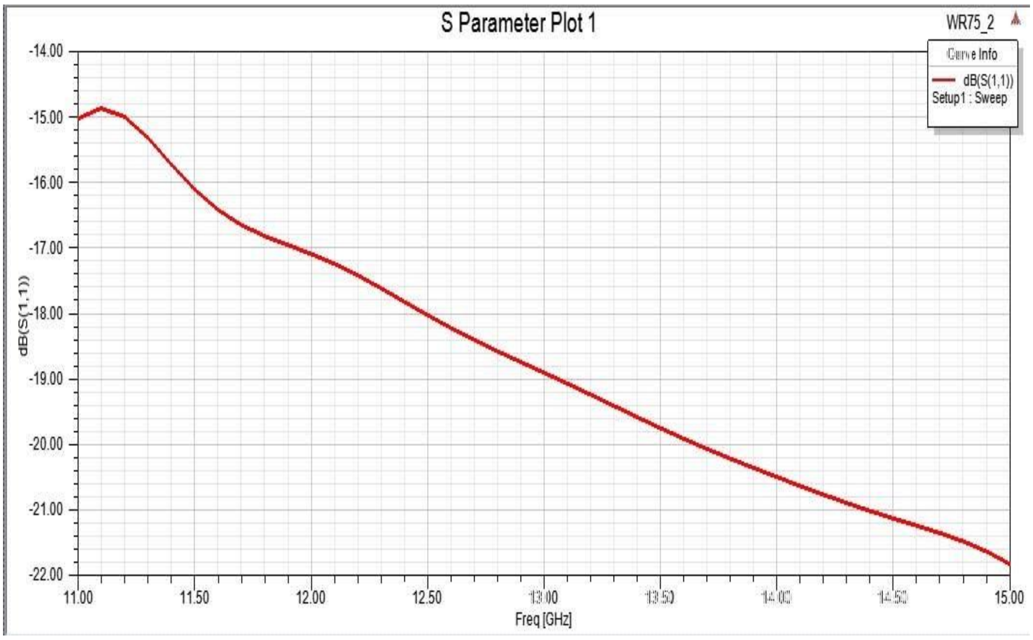


Figure 17: Return loss graph for the feed

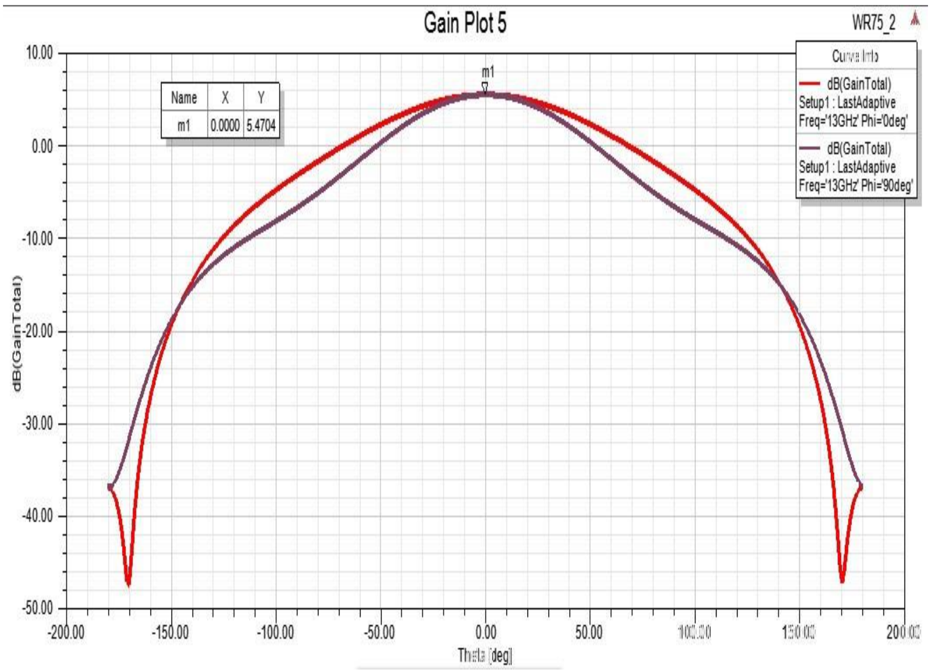


Figure 18: Gain plot for the feed

The feed gives gain of around 5.47 dB for the frequencies of operation

6.6. Designing of reflectarray geometry in HFSS

Once the unit cell is completely designed, its infinite array analysis is done. The feed is designed, the MATLAB GUI code simulates the reflection phase and after that the complete geometry of reflectarray antenna can be done. Here, the geometry is designed in HFSS taking 4*4 elements. AS array tapering is used, the cells at the edges are removed and the geometry turns out to be circular. The geometry is tested for three frequencies 12.5 GHz, 12.7GHz and 13 GHz. The whole antenna geometry is shown in Figure 19.

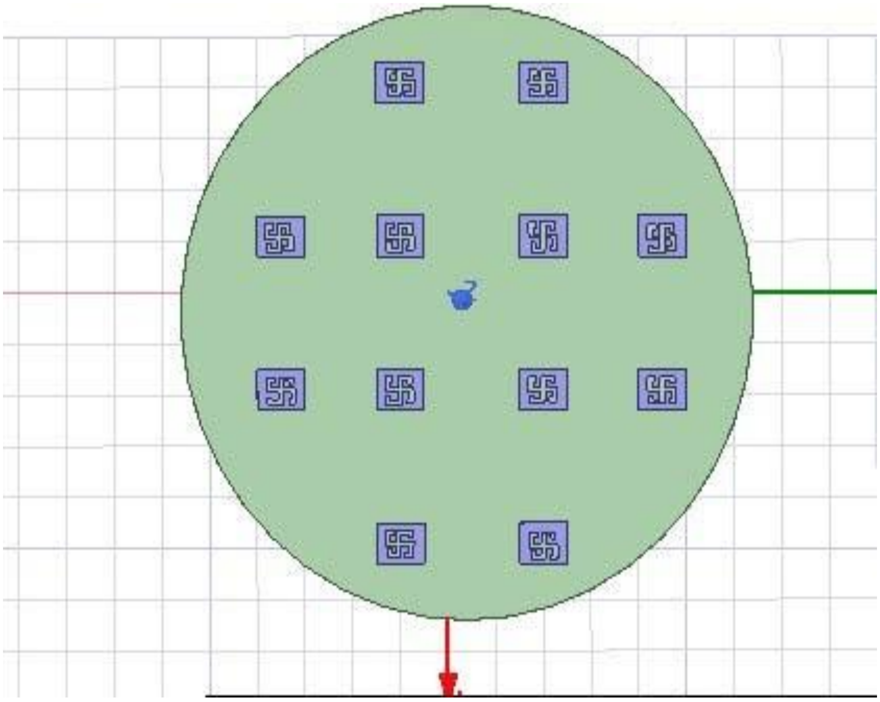


Figure 19: Reflectarray geometry for 4*4 array elements

The reflectarray gives a gain of about 25 dB for all the frequencies for which it is tested. The gain graphs for all the three frequencies are shown in Figure 20. As the two peaks are obtained in two directions, this antenna can be used as for multibeam application.

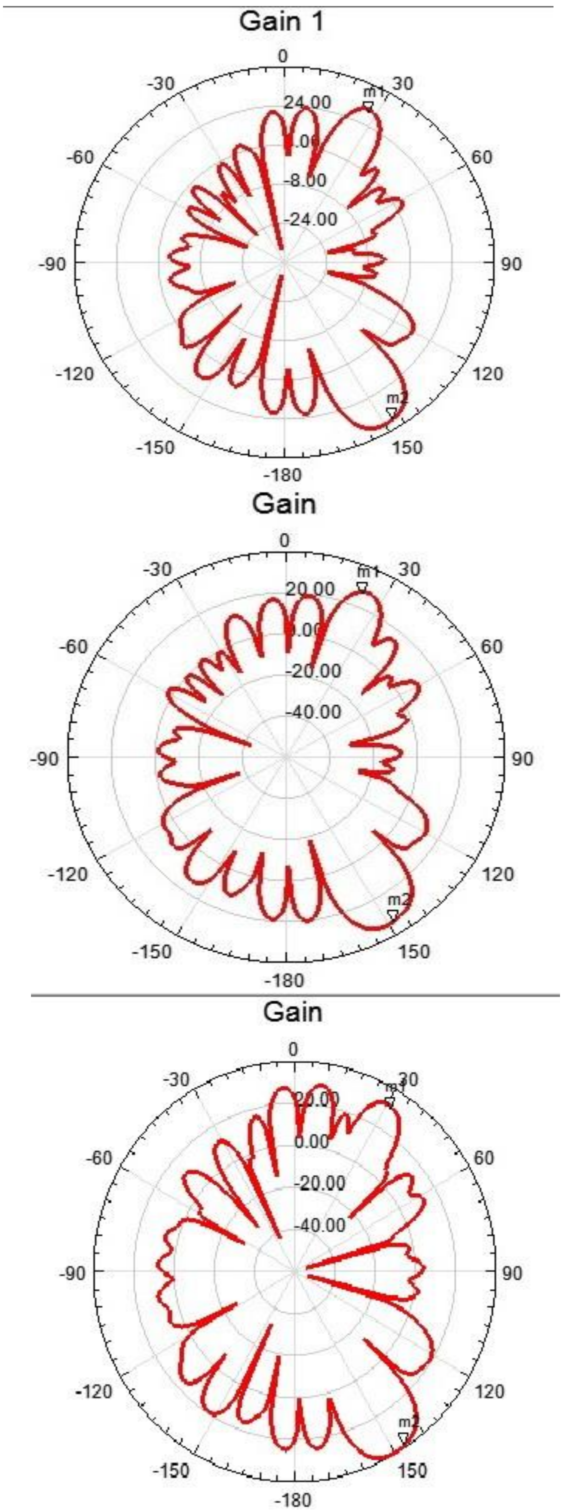


Figure 20: Gain plots a) 12.7 GHz b) 12.5 GHz c) 13 GHz

7. Achievements with respect to Objectives

The aim was to design a reflectarray antenna with enhanced bandwidth for Ku band.

- The bandwidth obtained for unit cell is around 1.87 GHz in the measured results which is higher than simulated results as well as many existing designs.

- The bandwidth obtained in the ‘S’ curve is almost 1 GHz which is 50% of the Ku band (12GHz to 14GHz)
- When the unit cell is kept in reflectarray environment, promising gain of around 35 dB is obtained for centre frequency and around 25 dB for 12.5GHz and 13 GHz frequencies.
- In addition to this, various publications have been done in Springer book chapter, Scopus indexed, UGC care and UGC approved journals as well as in International conference.

8. Conclusion

In this research work, full procedure for designing of Reflectarray antenna has been proposed for Ku band applications.

- Various dielectric materials are taken and the results are compared to obtain increment in bandwidth along with lesser cost.
- In addition to this, various feeding techniques and various heights of substrate are also studied and simulated accordingly.
- Various shapes of radiating structures are developed using the most suitable feeding technique and the dielectric material and a comparison is done between them.
- The best radiating element has been fabricated and tested to compare the practical and simulated working. The measured results gave better performance than the simulated results.
- Once the radiating structure is finalized, infinite array analysis is done on the unit cell. In addition to this, many other designs of unit cells are also made and compared.
- ‘S’ curve which gives the reflection phase along with the element variation has been presented for various designs and a comparison of bandwidth for all designs has been presented.
- A comparison is also presented between the patch width variation and the EBG effect variation and ‘S’ curve for both are obtained and compared.
- A comparison is also presented for sub wavelength analysis.
- Reflection phase for each element is obtained in accordance with the S curve.
- Finally, a 4x4 reflectarray has been developed and simulated in reflectarray environment and gain plots are obtained for different frequencies.

9. Future Scope

The work can be further extended for designing the microstrip reflectarray antenna for enhanced bandwidth with dual frequency bands. It can also be designed and tested for other high frequency bands by varying various parameters like height, width, feed pattern, material etc. in feasible and acceptable range.

10. Publications

[1] Prapti R. Pandya, Dr. M. Sarda Devi, “ A Compendium Of Development in Analysis and Design of Microstrip Reflectarray Antenna” in International Journal for Research in Engineering Applications and Management (IJREAM) 2019, vol 4, issue 11, Feb 2019, pg no. 357-361, ISSN no. 2454-9150. **(UGC approved)**

[2] Prapti R. Pandya, Dr. M. Sarda Devi, Namrata Langhnoja, “ Analytical Methods for Bandwidth Enhancement of Microstrip Patch Antenna,” published in ICTACT journal on Microelectronics, vol 7, issue 01, April 2021, pg no. 1095-1100, ISSN no. 2395-1680 **(UGC care approved)**

[3] Presented a Paper entitled “Relative analysis of distinct microstrip patch antenna for different substrate materials using aperture coupling” at 13th International Conference (**ATMS – 2021** Virtual Platform), 18-20 Feb, 2021.

[4] Prapti R. Pandya, Dr. M. Sarda Devi, Namrata Langhnoja, “Empirical Analysis of Microstrip Patch Antenna for different Substrate Materials and Shapes using Aperture Coupled Technique”, published in Radioelectronics and Computer systems, vol 101, issue 1, Feb 2022, pg no 170-177, ISSN no. 2663 -2012, doi:10.32620/reks.2022.1.13. **(Scopus indexed journal and UGC care group 2)**

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