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DESIGN OF MICROSTRIP ANTENNA PHASED ARRAY WITH DUAL BEAM AT 5G FREQUENCY WITH LARGE BANDWIDTH

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Abstract

The paper deals with the design and analysis of radiation pattern for the phased array micro strip antenna by calculating the array factor of the array. The analysis starts with the calculation of the array factor for isotropic antenna elements, and further using pattern multiplication, the overall radiation pattern is plotted for the phased array microstrip antenna using MATLAB software. The final designed array has a size of 3 X 8 having an inter-element spacing of 0.8 λ in the horizontal direction and 0.4 λ in the vertical direction. The array's theoretical estimated results were compared to the results of the identical array's electromagnetic simulation using CST simulation software. The array was created using the Rogers RT Duroid substrate having 2.2 as the dielectric constant and a substrate height of 0.508 mm for a frequency of 25–29 GHz that can be used for a wide range of applications, including 5G. There is a small variation between theoretical and simulated results as the electromagnetics are also taken into account after electromagnetic simulation. The phase difference in the final phased array is created using a rat race hybrid ring which provides a 180-degree phase shift. The inclusion of phase shift from the normal array forms a dual beam and increased bandwidth but with a gain reduction.

Keywords: Array Factor, Gain, Micro strip Patch Antenna, Multi Beam, Pattern Multiplication, Phased Array.

1. INTRODUCTION

The single antennas are being used in various targeted applications[1-4], but the common problems related to single antenna are low gain and less bandwidth, so the communication industry started evolving towards linear and planar arrays, further improvement in communication technology involves movement towards phased array antennas that are used for various applications including 5G/6G systems, satellite and tracking applications [5-7].

Multiple antennas in various geometrical shapes may be positioned in space to create a high-gain antenna array [8,9]. The pattern of a linear or planar array is generated by selecting the appropriate magnetic and phase excitation coefficient values for array members.

As a result, array factor synthesis is a significant difficulty in antenna engineering. Various analytical, iterative, and algorithm-based approaches have been proposed thus far for this aim [10-12].

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The antenna elements in linear antenna arrays are arranged in a straight line [13,14]. Linear evenly spaced antenna array design technique has been extensively discussed in the literature [15,16]

In [17], it proposes a combination of static and dynamic sequential optimization algorithms. It is attempted in this study to improve the procedure's performance by introducing the shrinkage coefficient and crossover operator, to construct a huge planar array, a new approach based on Zernike polynomials is proposed[18].

The array factor is a mathematical equation that describes the total radiation pattern of all the array's constituent members. It takes into account the positions and characteristics of the elements, as well as the phase and amplitude relationships between them.

Phased array antennas are those where the elements are excited with signals of uniform amplitude but there is a phase difference between the array's neighboring elements, this creates multiple beams and variations of the beam pattern of the antenna.

The steps to evaluate the array factor for a phased array antenna involve first defining the arrangement of the array, and then evaluating the radiation pattern of a single element.

The phase excitations and amplitudes of signals to all elements should be defined, the array factor is calculated and multiplied by the pattern of a single element to get the overall radiation pattern of the array, which is called pattern multiplication. The overall radiation pattern can be analyzed to find the gain, main lobe, and nulls of the array.

5G has been widely used for high-speed and low-latency communications. The mm-wave frequencies are used for 5G wireless communications [19].

The use of 5G communications by scientists has unknowingly created a 5G wireless grid that is capable of providing power to many devices with enhanced capability as compared to any other existing technology. In the current scenario, the trend is going very much towards the Internet of Things which requires many IOT devices.

It is expected to deploy around 40 billion IoT devices by 2025, this requires a large number of batteries that have to be recharged and replaced continuously, to achieve this RF energy harvesting is required to a much extent.

The spectrum for 5G communication as per ITU comprises the following bands: 3.4–3.6 GHz, 5–6 GHz, 24.25–27.5 GHz, 37–40.5 GHz, and 66–76 GHz, and the FCC has declared the spectrum of 27.5–28.35 GHz for 5G [20].

A major drawback of using 5G frequencies is that despite having a large gain [21] they furnish a low angular coverage area, the angular positions of sources and harvesters are generally not fixed so this requires an antenna with large angular coverage, and a multibeam antenna can be used to fulfil such requirement.

Beam-forming networks are quite complex and they can be used by mapping feed lines to different directions for getting a large angular coverage.

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There are only a few literature present related to RF energy harvesting for higher frequencies as compared to their low-frequency counterparts more specifically for frequencies of 24-28 GHz and above, a comparison is presented for higher frequencies as in [22-24] but they suffer from small angular coverage.

The concept of UAV was introduced to improve the service quality of communication in areas that were overloaded at ground levels. It includes large-scale directional antennas for the transmission of energies [25,26].

The phased array antenna [27] are designed in this paper, by varying the phase of input for different antenna elements, a multiple-beam pattern can be obtained.

An antenna working at 5G frequency has to go through many challenges that may include signal attenuation due to free space propagation and other environmental conditions [28].

Numerical approaches and simulation tools like MATLAB or electromagnetic simulation software (e.g., CST Studio Suite, HFSS) are frequently used for array factor analysis.

This analysis aids in optimizing the array design for desirable performance characteristics such as beam scanning, beam shaping, and sidelobe suppression, it is an important milestone in the development of phased array microstrip antennas, which are utilized in a wide range of applications including radar, communication systems, and satellite communications.

In this paper, first of all the array factor is calculated for linear isotropic array, the pattern for microstrip antenna array is further evaluated followed by the pattern for phased antenna array, and the theoretical results obtained after calculations on MATLAB software are plotted, Further, CST Microwave studio which is an electromagnetic simulation software is used, where the actual antenna array with similar parameters as above is designed and simulated for radiation pattern and other results.

In the next section, theoretical and simulated outcomes are collated. The last section deals with the design of the final phased array without phase shift and then with phase shift and formation of multiple beams with large bandwidth.

2. ARRAY FACTOR FOR ISOTROPIC ANTENNA ELEMENTS

Consider an array of N isotropic elements as illustrated in Fig.1, they are organized along the z axis. The elements are separated by a distance‘d’ with an inter element phase difference of ‘β’.

The first element is assumed to be isotropic with normalized field of unity, after that the phase shift factor ‘β’ will be included along with spacing ‘d’ and angle ‘θ′ as in Fig.1.The array factor of this N element isotropic array will be given by [8]

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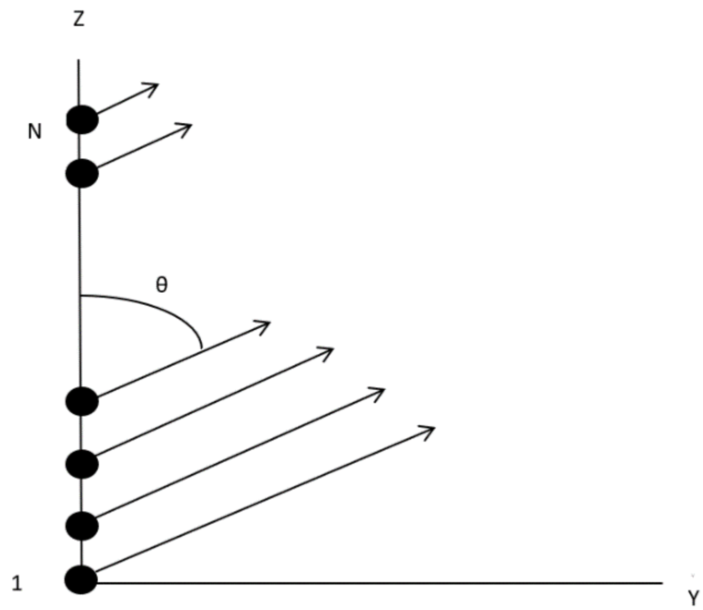

Figure 1: N isotropic Antenna Elements along z axis

$$AF = 1 + e^{j(kdCos\,\theta+\beta)} + e^{j2(kdCos\,\theta+\beta)} + \cdots + e^{j(N-1)(kdCos\,\theta+\beta)} \quad (1)$$

$$AF = \sum_{n=1}^{N} e^{j(n-1)(kdCos\,\theta+\beta)} \quad (2)$$

where $k = \frac{2*\pi}{\lambda}$ and λ is the operating wavelength

Now its defined

$$\psi = kd\ Cos\ \theta + \beta \quad (3)$$

So, array factor becomes

$$AF = \sum_{n=1}^{N} e^{j(n-1)\psi} \quad (4)$$

$$AF = \frac{e^{jN\psi}-1}{e^{j\psi}-1} \quad (5)$$

$$AF = \frac{\sin(\frac{N}{2}\psi)}{\sin(\frac{1}{2}\psi)} \quad (6)$$

The maximum value of above expression is N, so the normalized array factor reduces to

$$(AF)_n = \frac{1}{N}\frac{\sin(\frac{N}{2}\psi)}{\sin(\frac{1}{2}\psi)} \quad (7)$$

The pattern will be a broadside pattern, so the maximum radiation occurs for ‘θ′ equals 90 degrees which implies from (7) that the equation is maximum for ψ =0 degrees, thus β equals zero degrees from (3) so to receive a broadside pattern all elements should be excited by an equal phase.

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The radiation pattern of isotropic antenna array whose array factor is given by (7) is plotted on MATLAB software as below which shows maximum radiation for ′θ′ equals 90 and 270 degrees as in Fig.2. The number of elements ‘N’ is taken as four.

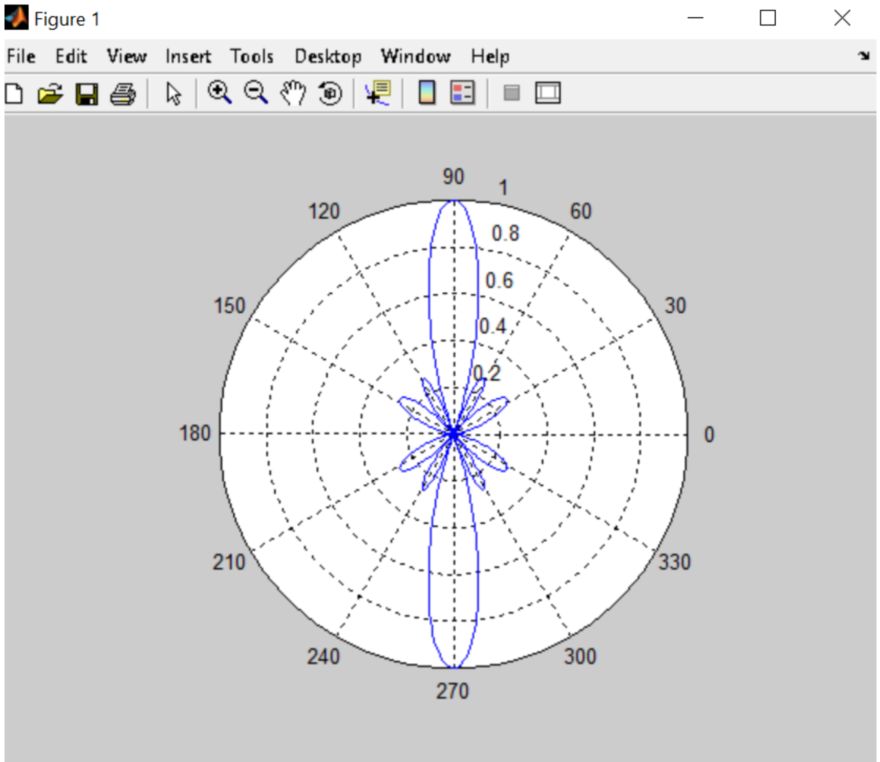

Figure 2: Radiation Pattern for Isotropic Array Antenna

3. ARRAY FACTOR FOR PHASED ARRAY MICROSTRIP ANTENNA

The isotropic antenna elements in the array defined as in above section are now going to be replaced by micro strip antenna patches, placed along Z axis only, the steps involved in designing the MATLAB code for determining the array factor having micro strip patch antenna elements are depicted as in flowchart of Fig.3.

The design process begins with determining the number of patch antenna elements.

Taken as N=4, the spacing between the elements is kept to be 0.76 λ and initially phase difference between adjacent elements is kept to be zero degrees.

The array factor for a single microstrip patch antenna element is given as [8]

$$AF = \sin\theta \frac{\sin\left(\frac{kh}{2}\sin\theta\right)}{\frac{kh}{2}\sin\theta} \frac{\sin\left(\frac{kh}{2}\cos\theta\right)}{\frac{kh}{2}\cos\theta} \qquad (8)$$

h= height of substrate used to take as 0.51 mm

$k = \frac{2*\pi}{\lambda}$ Calculated for a frequency of around 28 GHz that is used for 5G applications.

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The above equation (8) shows that maximum array factor is obtained at ‘θ′ equals 90 degrees that denotes a broadside pattern.

The radiation pattern plot for single element micro strip antenna from the array factor as in (8) as plotted on MATLAB software is as shown in Fig.4.

The pattern is having a maximum at ‘θ′ equals 90 degrees which is a single element microstrip antenna pattern.

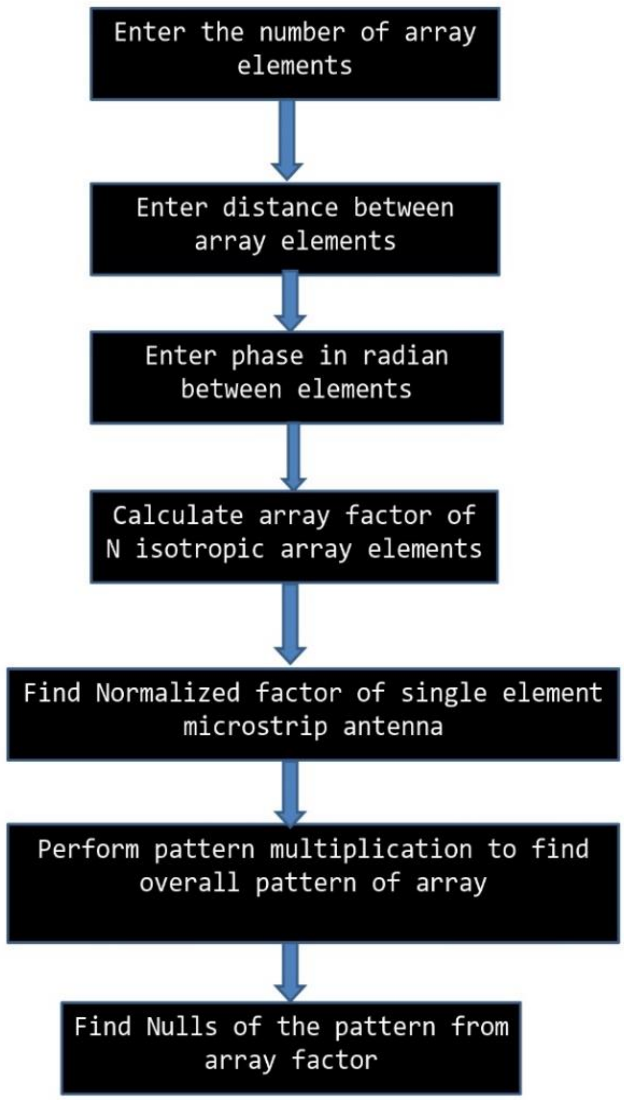

Figure 3: Flowchart for Calculating Array Factor of Microstrip Antenna Array

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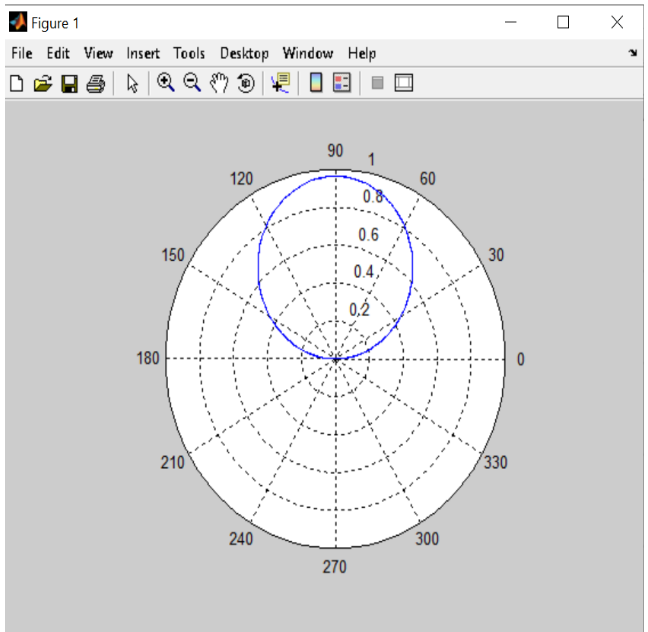

Figure 4: Single Element Microstrip Antenna Pattern

Now as per the flowchart of Fig.3, the combined array factor of the microstrip antenna array will be calculated as pattern of single microstrip antenna element as in equation (8) multiplied by the overall array factor as in equation (7) that comes out to be

$$(AF)_n = \frac{1}{N}\frac{\sin(\frac{N}{2}\psi)}{\sin(\frac{1}{2}\psi)} * \sin\theta * \frac{\sin\left(\frac{kh}{2}sin\theta\right)}{\frac{kh}{2}sin\theta}\frac{\sin(\frac{kh}{2}cos\theta)}{\frac{kh}{2}cos\theta} \quad (9)$$

The multiplied radiation pattern as obtained for the overall array factor as in equation (9) for above antenna array as plotted on MATLAB is given as in Fig.5.

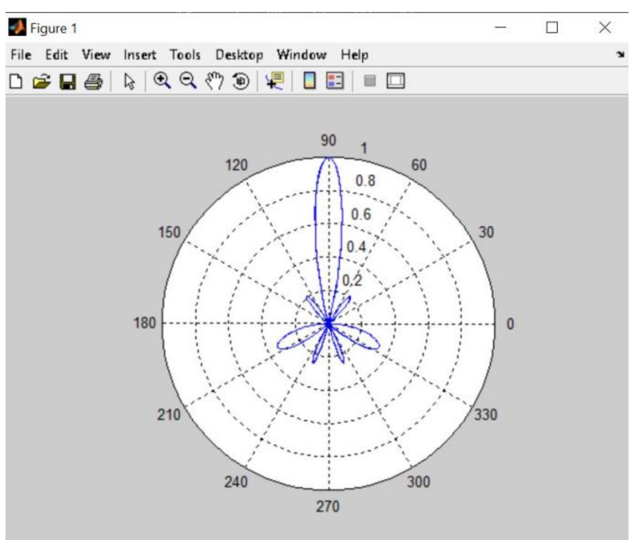

Figure 5: Overall Microstrip Antenna Array Pattern

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Now, in the given array, we keep a phase difference of β equals 1.76 radians between the adjacent elements, so the pattern no longer remains broadside, the angle ψ changes and the single beam broadside pattern splits in two multiple beams as in Fig.6. The array now becomes a phased array.

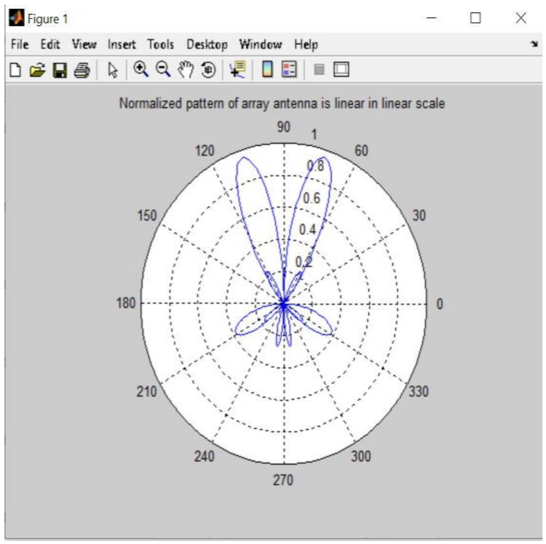

Figure 6: Microstrip Antenna Phased Array Pattern

4. SINGLE PATCH ANTENNA DESIGN

In the above sections, the array was positioned and the array factor was calculated mathematically and plotted, now the same micro strip antenna will be designed on CST software and simulated for the radiation pattern.

The antenna design started with only one patch segment antenna. The patch was designed for a frequency of 28 GHz that can be used for 5G applications. The edge impedance of the patch was around 150 ohms, so in order to feed the patch from a 50-ohm impedance line, a quarter wave matching transformer was used for feeding between the patch and 50-ohm feed line. Fig. 7 depicts the antenna design. Rogers RT Duroid 5880 LZ was utilised as the design substrate with 1.96 as dielectric constant and a height of 1.27 mm. The dimensions of Fig.7 are as given in Table 1.

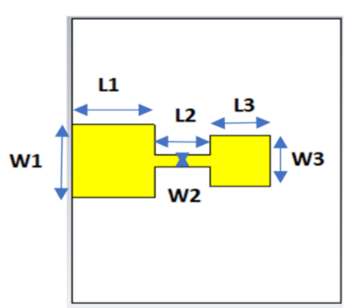

Figure 7: Single Patch Antenna Design

Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
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Table 1: Dimensions of the patch as in Fig.7

Dimensions in mm			
W1	4.2	**L1**	4.1
W2	0.7	**L2**	2.2
W3	2.95	**L3**	2.95

The simulation of the above single element patch was done and the graph of Return loss and frequency is as plotted in Fig.8. The minimum value is found to be -45.34 dB positioned at frequency of around 27.5 GHz.

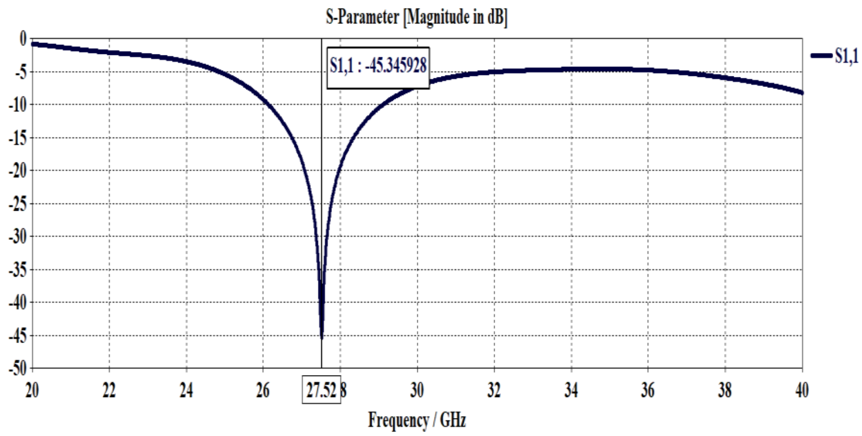

Figure 8: Return Loss vs Frequency Graph for Single Patch

The radiation pattern curve is also simulated, the element is placed along Z axis on CST software also, the pattern is broadside with a maximum at 'θ′ equals 90 degrees as in Fig.9. The pattern is nearly similar to the pattern as obtained in Fig.4 by MATLAB simulation.

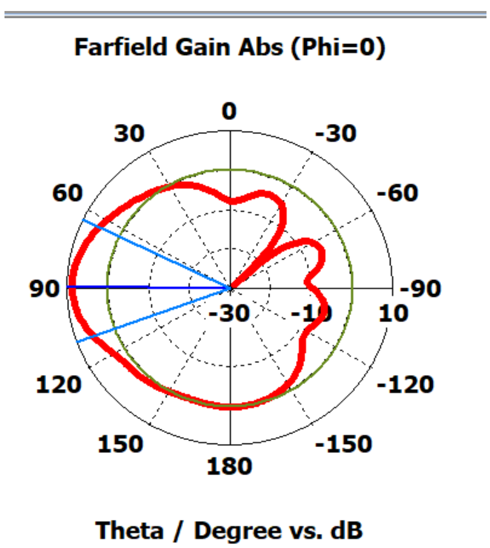

Figure 9: Broadside Pattern for Single Patch Antenna

Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
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5. ANTENNA ARRAY DESIGN

Antenna array is formed having four elements fed with same input phase using corporate feeding. The array was designed at a frequency of 28 GHz with a spacing of 0.76 λ between the elements. The antenna design is as depicted in Fig.10. The back side is having full copper. There is a 50-ohm feed line that is further divided using quarter wave matching transformers.

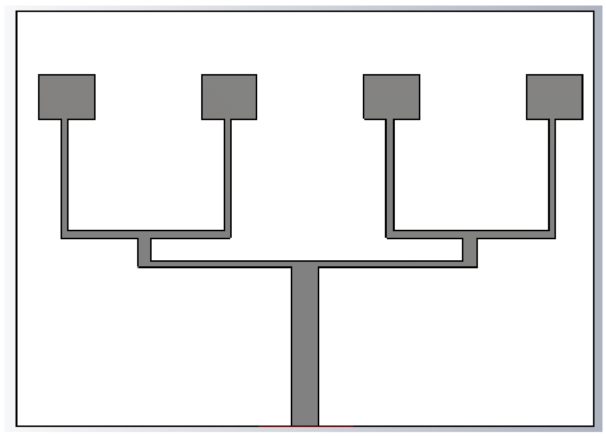

Figure 10: Microstrip Patch Antenna Array

The substrate used in above section was having a large thickness, and the size of feed line became more than the patch, so the feed line might also radiate so the substrate was changed to one having lower thickness. Rogers RT Duroid 5880 LZ was utilised as the design substrate with 2.2 as dielectric constant and a height of 0.508 mm the design was simulated and the graph of return loss and frequency is shown in Fig.11. The return loss is -32.2 dB positioned at a frequency of 27.9 GHz. The overall size of antenna is 36 * 25 mm2.

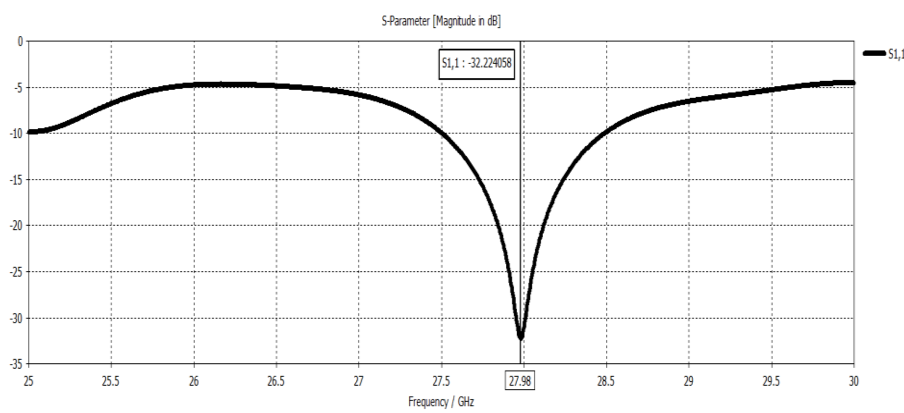

Figure 11: Graph of Return Loss for Microstrip Patch Antenna Array

Fig. 12 conveys that the pattern is broadside pattern, with a maximum at ‘θ′ equals 90 degrees. The pattern is very much similar to that obtained in Fig.5 after MATLAB simulation.

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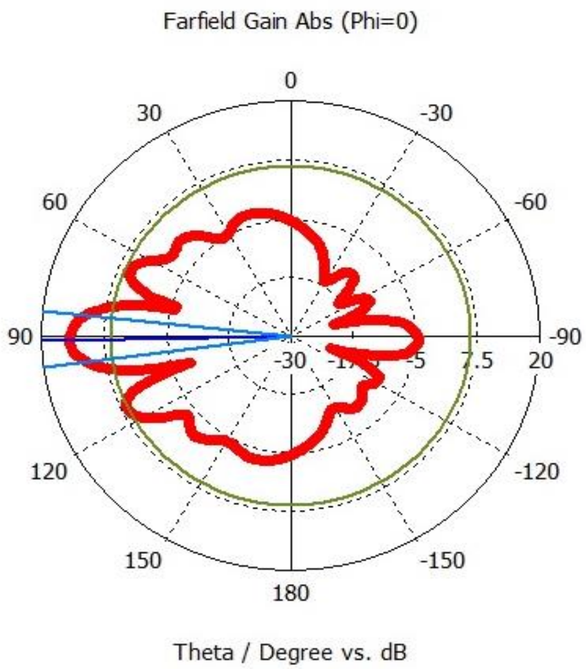

Figure 12: Broadside Pattern for Patch Antenna Array

6. PHASED ARRAY ANTENNA DESIGN

A phase shift was introduced between the elements by varying the length of feed line. There is a difference of around 2.41 mm in length between two adjacent elements, corresponding to a phase shift of 1.8 radians, as in Fig.13.

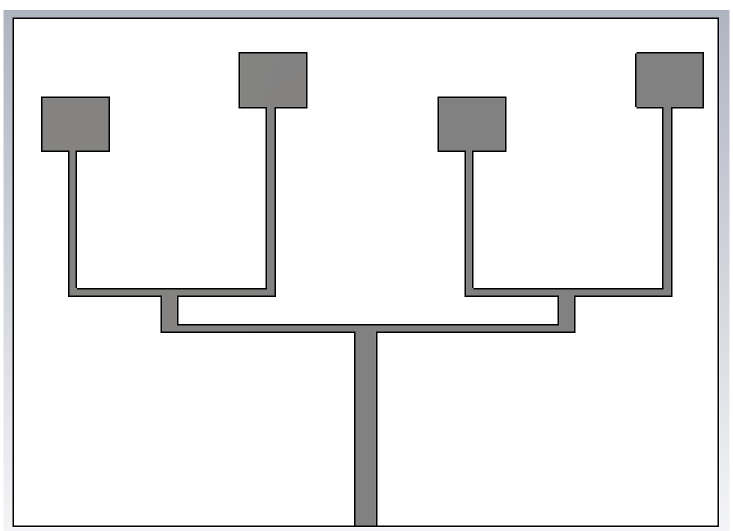

Figure 13: Phased Microstrip Patch Antenna Array

Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
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Now the current path has phase difference and generates two resonant frequencies at 25.1 GHz and 26.4 GHz respectively.Fig.14 depicts a 10 dB impedance bandwidth of 1.8 GHz from the graph of return loss.

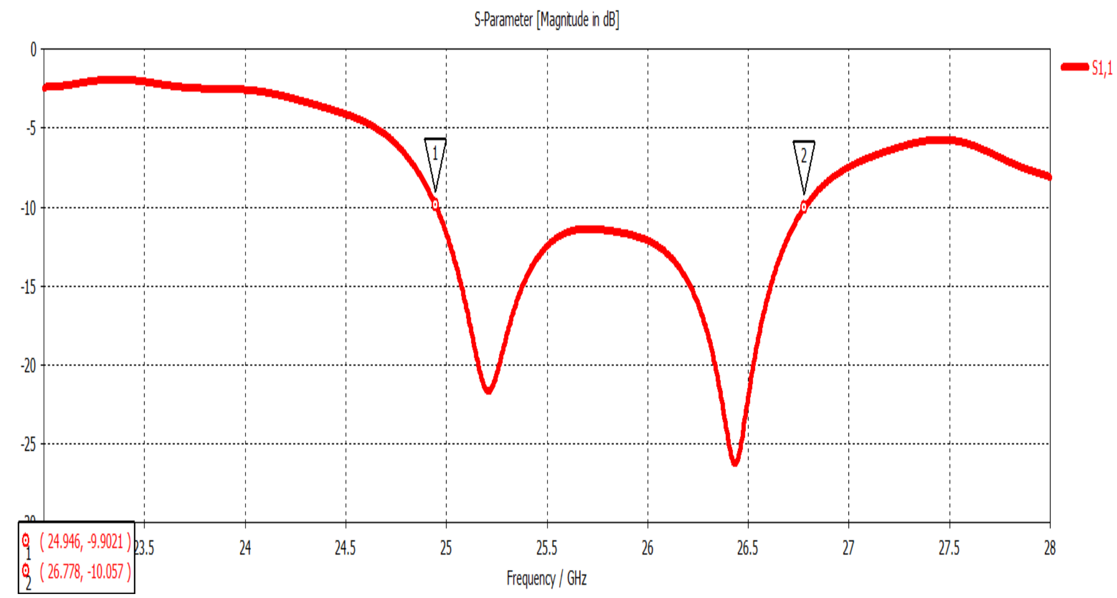

Figure 14: Graph of Return Loss for Microstrip Patch Antenna Phased Array

A radiation efficiency around 93.8 % at 26 GHz frequency appears as in Fig.15 from the graph of variation of radiation efficiency with frequency.

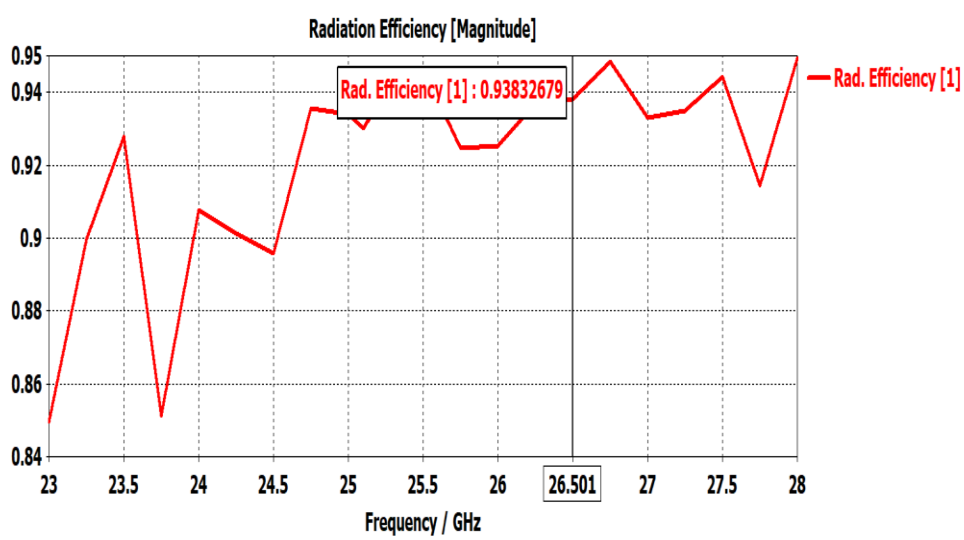

Figure 15: Variation of Radiation Efficiency with Frequency Graph for Phased Microstrip Patch Antenna Array

Fig.16 depicts that the maxima shift from 'θ′ equals 90 degree and splits in different beams, the pattern is no longer a broadside pattern for the phased array.

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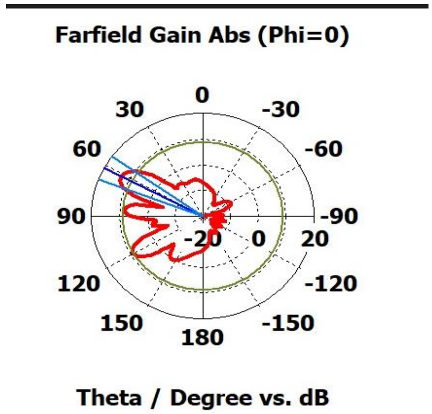

Figure 16: Pattern for Phased Antenna Array

7. COMPARISON OF THEORETICAL AND SIMULATED RESULTS

The radiation pattern was calculated from array factor for the micro strip antenna array, the MATLAB software was used to perform the calculations, first of all the pattern of isotropic antenna was obtained as in Fig.2, then using pattern multiplication technique, the pattern for entire micro strip antenna array was obtained by multiplying the pattern of single micro strip antenna array to pattern of isotropic antenna array. Fig.5 depicts the antenna array pattern.

The antenna array with same parameters was designed on CST software, keeping position of array same, with same number of elements and their spacing, the radiation pattern was obtained from CST software as in Fig.12.

The comparison of pattern obtained from theoretical calculations and actual simulated antenna array is as shown in Fig.17. As seen from comparative plot, both the patterns are broadside with variations as obtained between the theoretical and simulated results.

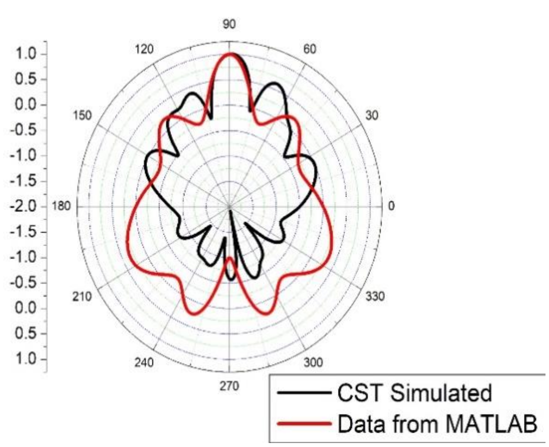

Figure 17: Comparative Patterns from Simulated and Theoritical Reuslts

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The phased array antenna is one having certain phase shift between the elements of antenna, the phase shift ‘β’ was introduced in the MATLAB code and obtained pattern as in Fig.6.

The phase shift between the elements was also introduced in the simulated array on CST software by varying the feed line length between the elements and the pattern obtained as in Fig.18. The pattern no longer remains broadside now

The comparative plot between the theoretical and simulated results is as shown in Fig.18.

As per the ideal MATLAB calculations two perfect symmetrical beams should be obtained, but on actual simulation, the results are a little varying, which are nearly same to theoretical results.

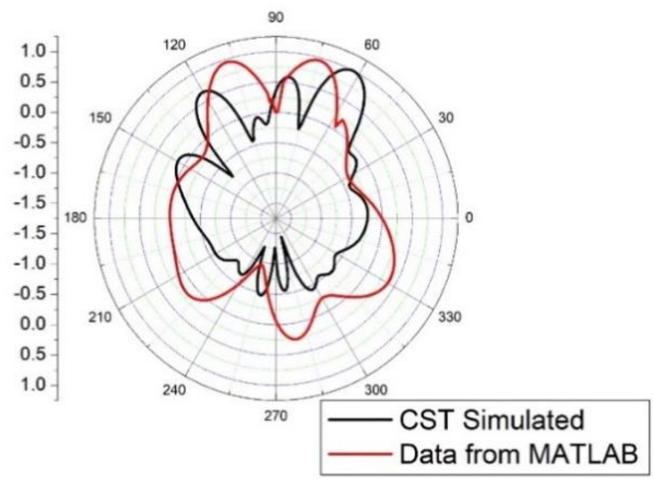

Figure 18: Comparative Patterns from Simulated and Theoritical Reuslts for Phased Antenna Array

The pattern obtained from MATLAB calculations are ideal, they are calculated simply by mathematical equations and performing pattern multiplication and numerical calculations, the effects and losses of Electromagnetic signals are not taken into account.

The actual simulation on electromagnetic CST software, involves actual antenna design, taken into account the return loss, radiation efficiency and other parameters, the radiation pattern is obtained which is nearly similar to the plots obtained after actual calculations on MATLAB, thus the mathematical equations stand verified.

8. DESIGN OF MULTI BEAM PHASED ARRAY ANTENNA

The above method discussed compares the theoretical and simulated results, thus proving the validity of method. The array factor as calculated above is for a conventional patch element antenna but using the concept of above that to form multiple beams, phase shift is required, substrate used was Rogers RT Duroid 5880 dielectric 2.2 and thickness 0.508 mm. The above designed array was extended to 24 elements using corporate

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feeding but with no phase shift as shown in Fig.19. The overall array size is 58 X 34 mm with an inter-element spacing of 0.8 λ in horizontal direction and 0.4 λ in the vertical direction

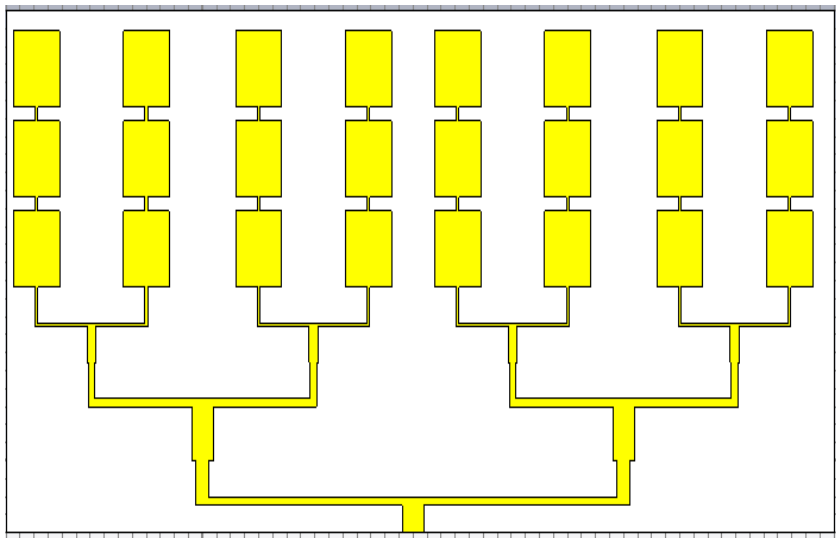

Figure 19: 3 X 8 designed array without phase shift

The above array design was simulated with a minimum on S11 curve at 25.65 GHz with a value of -67 dB as shown in Fig.20 with a 10 dB impedance bandwidth of 3 GHz (25-28 GHz)

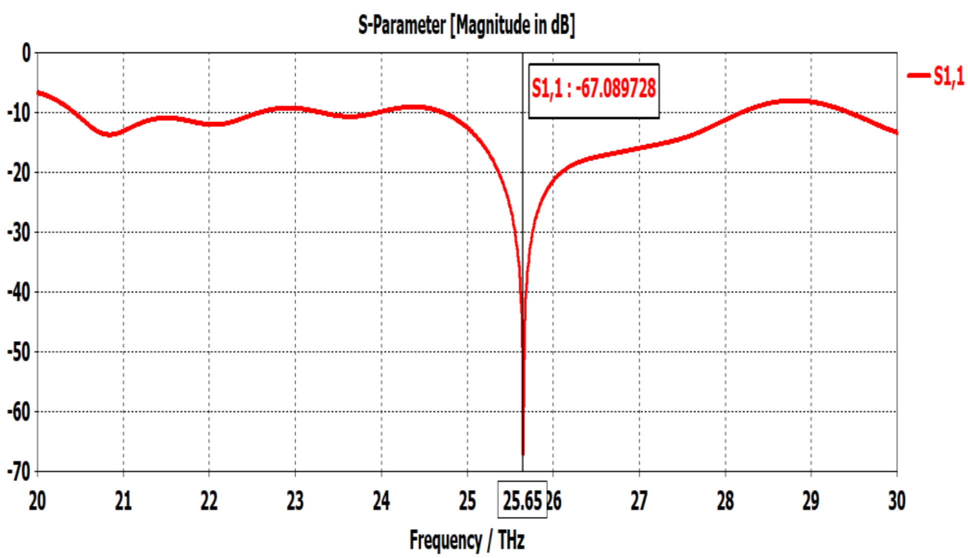

Figure 20: Graph of Return Loss for Array Antenna

Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
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The peak gain obtained was 11.28 dB as shown in Fig.21 at a frequency of 23.5 GHz

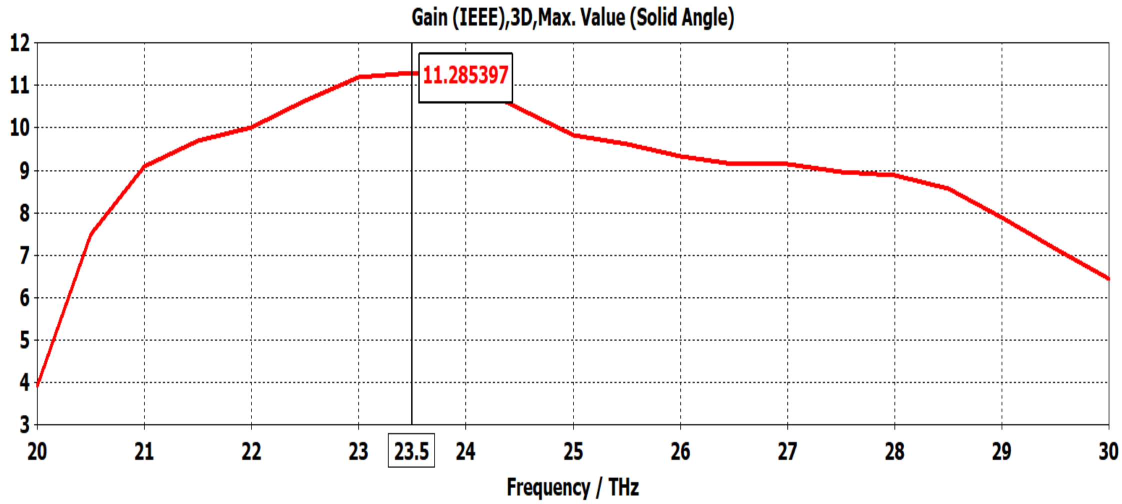

Figure 21: Gain vs Frequency Curve for Array Antenna

The above designed array does not include phase shift between elements, after certain phase analysis, the array was fed with a rat race hybrid ring that provides 180 degree phase shift.

Fig.22 depicts the feed line connected at port 1 of ring that is divided in ports 2 and 4 equally but with 180 degree phase shift and no output at port 3 so it is terminated by 50 ohms matched impedance as shown in blue colour.

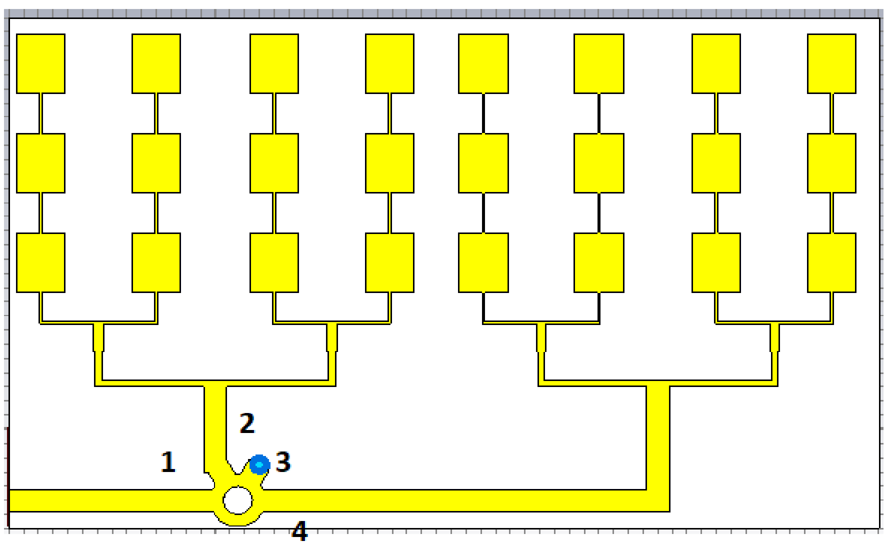

Figure 22: Phased Array Antenna Fed by Hybrid Ring

The above array design was simulated with a minimum on S11 curve at 27.27 GHz with a value of -35 dB as shown in Fig.23 with a large 10 dB impedance bandwidth for the entire range of 20-30 GHz

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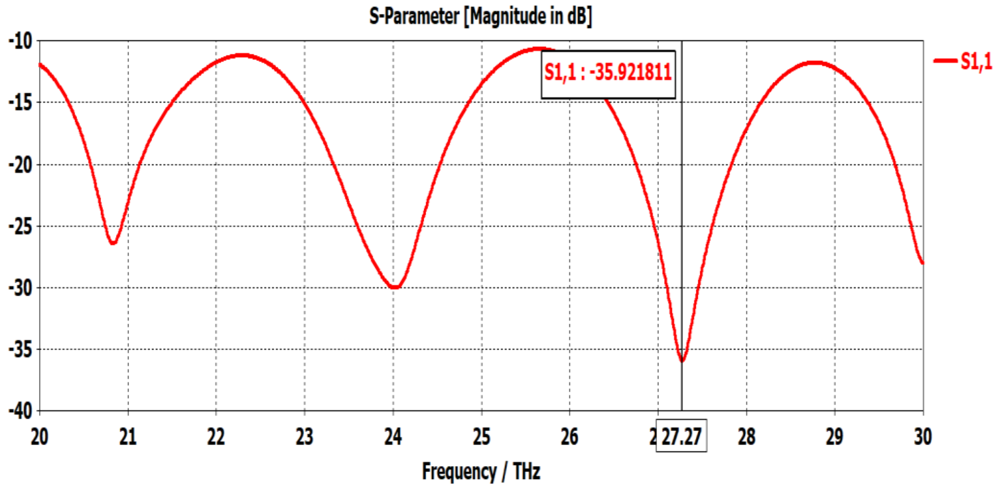

Figure 23: Graph of Return Loss for Array Antenna

The simulated radiation pattern of phased array shows two beams at theta equals +30 degree and -30 degrees, the 3 D pattern plot and polar plot are as depicted in Fig. 24 and Fig.2

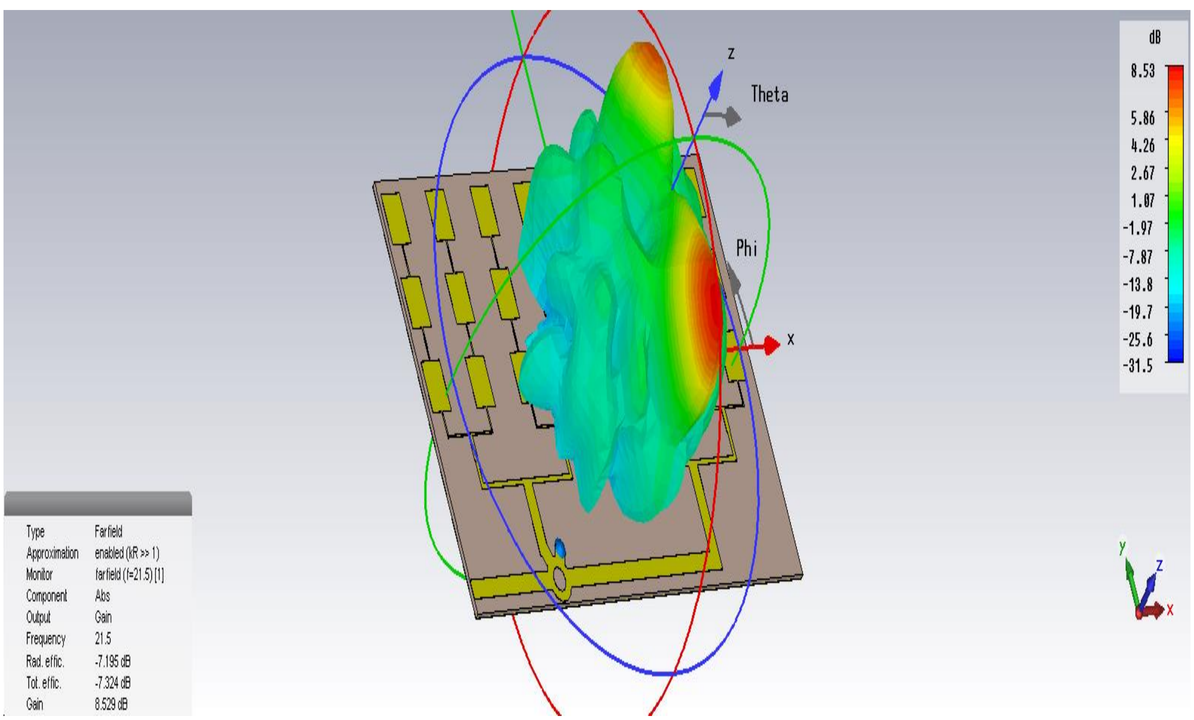

Figure 24: 3D Pattern for Phased Array Antenna

Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
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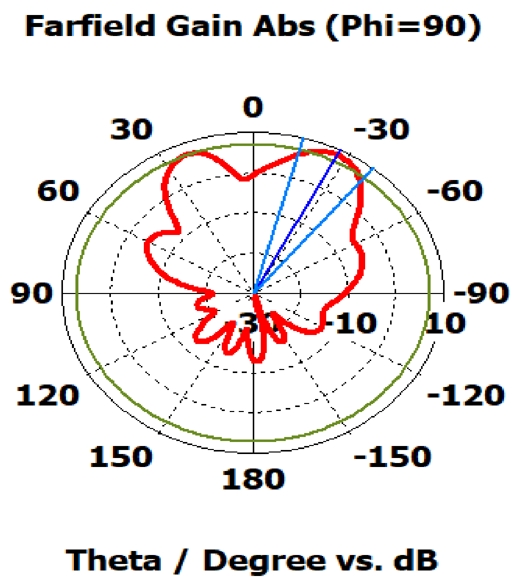

Figure 25: Polar Plot for Phased Array Antenna

The peak gain obtained has now reduced after phase shift to 8.52 dB as compared with normal array antenna as shown in Fig.26 at a frequency of 21.5 GHz.

The increase in bandwidth causes a reduction in gain. The comparison table of proposed design with other designs present in literature is also given in Table 2.

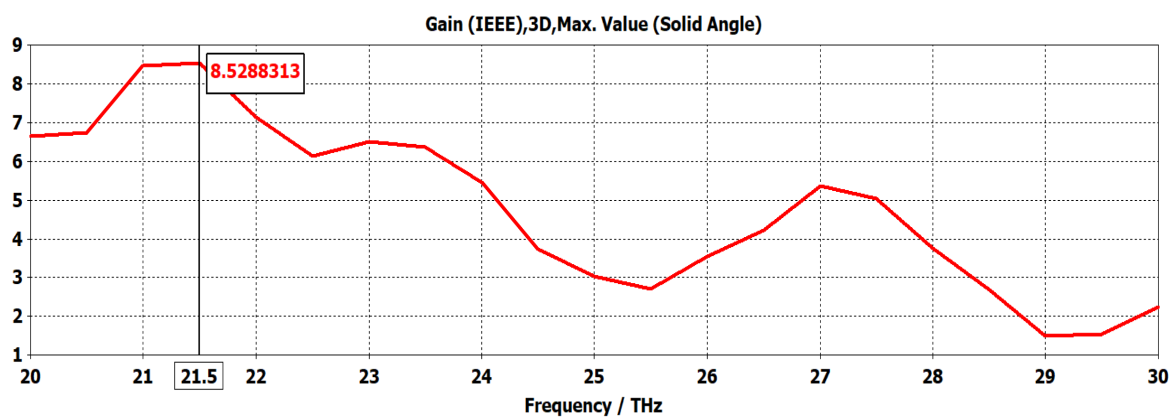

Figure 26: Gain vs Frequency for phased array

Table 2: Comparison of Proposed design with other designs

	S11 (dB)	Bandwidth	Gain	Size	Frequency of operation
[29]	-	400 MHz	5 dB	8 X 8 array	28 GHz
[30]	-27	27.2-29.2 GHz	10.33	130 X 42 mm	28 GHz
[31]	-11	2.2 GHz	2.6 dB	11 X 8 mm	28.3 GHz
[32]	-22	27-29.5 GHz	14.6 dB	52 X 29.96 mm	28 GHz
Proposed	-35.9	20-30 GHz	8.52 dB	58 X 34 mm	28 GHz

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9. CONCLUSION

An antenna array's radiation pattern is calculated by multiplying the array factor by the pattern of a single micro strip antenna, which is called pattern multiplication. The theoretical pattern is obtained by designing the MATLAB code, and after the required calculations, the pattern is plotted. The same array with the same parameters as used in theoretical plotting was simulated on CST software, taking into account the electromagnetic radiation. The theoretical and simulated results have a small variation as theoretical results are calculated on exact formulas without taking into account the losses caused by electromagnetic signals. The pattern is broadside when there is no phase shift between adjacent elements, and the main beam splits in multiples when a phased array is designed. The pattern is broad, having a large beam width when there is only a single element, but as we design a micro strip antenna array, the maximum remains the same, but now the beam width is reduced and the gain increases, as can be seen in the above plots. When we introduce the phase shift between antenna elements, the pattern shifts in multiple beams and the gain reduces, as can be seen above. The main objective in many designs is to avoid grating lobes. If the spacing between the elements is kept less than λ, grating lobes are avoided. The final designed array states that without phase shift a broadside pattern is obtained but for requirements of 5G or other applications, multiple beams are required in different directions, obtained only by phased array antennas.

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