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High-Gain Circularly-Polarized Elliptically-Annular Antenna-Array with Reduced Side-Lobe Level

Rabindra Kumar, Archana Kumari, Neha Kumari, Priyanka Mondal, Pradip Kumar Jain

Abstract: *A single feed microstrip patch elliptically annular antenna array has been proposed for high gain circularly polarized (CP) radiation. An array of* 2×2 *elliptically annular patches antenna resonates at a frequency of 3.77 GHz which can be used in satellite communication and radar application. A corporate feed network with quarter-wave transformer has been used for uniform excitation of all the array elements. Thus a good circular polarization is obtained by using a single feed with enhanced gain 15.62 dB compared to single patch. The radiation pattern, axial ratio and input impedance of the proposed elliptically annular antenna array is compared with single element elliptically annular antenna. A substantial gain enhancement with low side lobe level (SLL) is observed keeping circular polarization intact. Further, simulated and measured results of the proposed antenna array have been compared and found that axial ratio and gain are in good agreement.*

Keywords : Planar antenna array; coaxial feed; corporate feed; Axial ratio; elliptical annular ring; Circular polarization..

I. INTRODUCTION

Circularly polarized antennas have been effectively used in present days for their stable signal transmission and reception properties in inclement weather and flexible orientation between transmitters and receivers. Also, circular-polarization (CP) is more resilient to signal degradation due to atmospheric circumstances (rotation of signal polarization) and are not observed by the Faraday rotation due to earth's magnetic field while passing through ionosphere.

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It is well-known that circularly polarized patterns can be achieved from circular or square patches using dual-orthogonal feeds [1], [2] elliptical shaped antennas [3].

But, the patch antennas suffer from inherent low gain. It can be alleviated by exciting TM_{12} mode of annular elliptical ring microstrip antenna [4], [5].

Moreover, the CP is achieved using a single feed only. It is due to the existence of two spatially orthogonal degenerate modes (even and odd), with different resonant frequencies. A mode chart of confocal annular elliptical resonators is

calculated to evaluate resonant frequencies for a given outer and inner eccentricity [6].

In this paper, a design of circularly polarized 2×2 elliptical annular ring antenna array at 3.77 GHz is presented. The patches are excited uniformly. A suitable feed network is designed for impedance matching between the 50 Ω probe and the patches. The design is optimized through HFSS simulator and the prototype is experimentally verified. The paper is organized as follows: Section II describes single element antenna and its performance matrices; Section III deals with the design of 2x2 antenna array along with the feed network. Section IV contains fabrication and measurement results. Finally, it has been concluded in section V.

II. SINGLE PATCH ELLIPTICAL ANNULAR RING ELEMENT

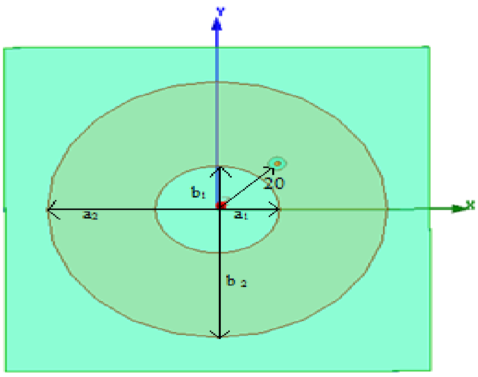

Fig.1 Single Elliptical annular ring antenna.

The substrate size of Single Elliptical annular ring antenna is 120×120×1.542. Semi major axis of the inner ellipse a_1 = 14.5 and semi minor axis of inner ellipse=13.4, a_2 = semi major axis of outer ellipse= 40, b_2= semi minor axis of outer ellipse= 39.5. All dimensions are in mm.

A. Design of single elliptical annular ring element

The schematic of a single annular antenna is shown in Fig.1. The dimension of elliptical annular patch at the desired radiation frequency can be derived with the help of the circular patch design. Major outer radius a_2 of the elliptical annular patch (Fig. 1) can be obtained as [8]:

$$a_2 = \frac{F}{\left(1+\frac{2h}{\pi\varepsilon_{re}F}\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right)^{1/2}} \quad (1)$$

where h is thickness, ε_{re} is the effective dielectric constant of the substrate and F is a function defined as

$$F = \frac{\chi_{mn} \times 3\times10^{11}}{2\pi f\sqrt{\varepsilon_{re}}} \quad (2)$$

The TM_{1n} modes show maximum radiation in the boresight direction, hence typically TM mode radiation is selected here [5]. For TM modes, the roots of the characteristic equations, which has form of the Bessel function can be obtained as χ_{mn} = 5.33 for the TM_{120} mode, and f_r is the radiation frequency of the patch.

It has been shown by Bhattacharya and Shafai [4] that the ratio between the major and minor axes of the outer ellipse lies in the range of 0.98 to 0.99 for producing good circularly polarized radiation. Hence, the minor outer radius b_2 of the elliptical patch can be obtained by typically selecting the ratio of b_2/a_2 as 0.9875.

The choice for inner radius has been selected using the formula for ring width W [1] as

$$W = a_2 - a_1 = b_2 - b_1 \cong \lambda_g/2 \quad (3)$$

The ratio of $a_2/a_1 \cong b_2/b_1$ should lie in the range of $1.3 \leq a_2/a_1 \leq 3.0$.

The effective minor radius is calculated by equation given below [7]:

$$b_e = b\left[1+\frac{2h}{\varepsilon_r \pi b}\left\{\ln\left(\frac{b}{2h}\right)+(1.41\varepsilon_r+1.77)+\frac{h}{b}(0.268\varepsilon_r+1.65)\right\}\right]^{1/2} \quad (4)$$

The effective dielectric constant of the elliptic patch can be obtained using the expression given below [7]

$$\varepsilon_{re} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left\{1+\frac{10h}{2b_2}\right\}^{-1/2} \quad (5)$$

Selecting parameters as h = 1.542 mm substrate thickness, ε_r = 2.55 relative permittivity of the substrate, f_r = desired operating frequency= 3.8 GHz and following the approach discussed, using expressions (1) to (4), the annular elliptical ring antenna dimensions are found as:

a_1=semi major axis of inner ellipse =14.5 mm,
b_1=semi minor axis of inner ellipse =13.4 mm,
a_2 = semi major axis of outer ellipse = 40 mm,
b_2= semi minor axis of outer ellipse = 39.5 mm

B. Simulated results of the single elliptical annular ring antenna

The simulated results of single annular ring patch element are shown below. Co-axial feeding scheme is used for the excitation of the annular elliptical ring microstrip patch antenna where the feeding point is positioned at a radial distance of 20 mm from the center of the ellipse while considering the angular separation of 45^0 with respect to the major axis. The 3D-EM simulator HFSS from ANSYS is used for simulations with appropriate size of radiation boundary. The simulated S-parameter is shown in Fig.2 shows a good impedance matching. The radiation pattern is shown in Fig.3 ensures that the maximum radiation is in broadside direction and the obtained broadside gain is 11.47 dBi. It can be seen from Fig.4 that CP is also attained in broadside direction and the corresponding axial ratio is 2.9 dB.

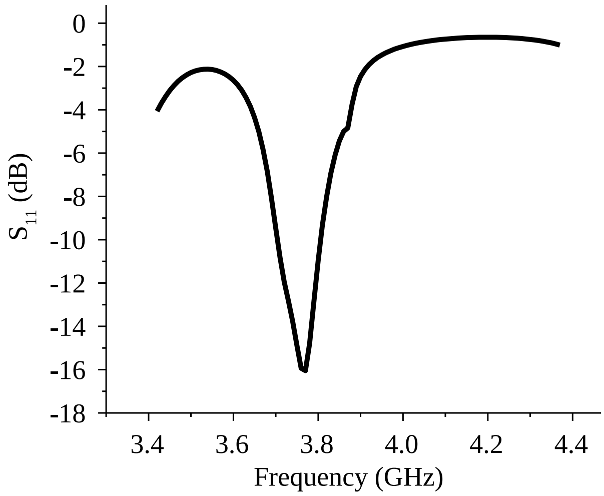

Fig.2. Simulated S_{11} of single element

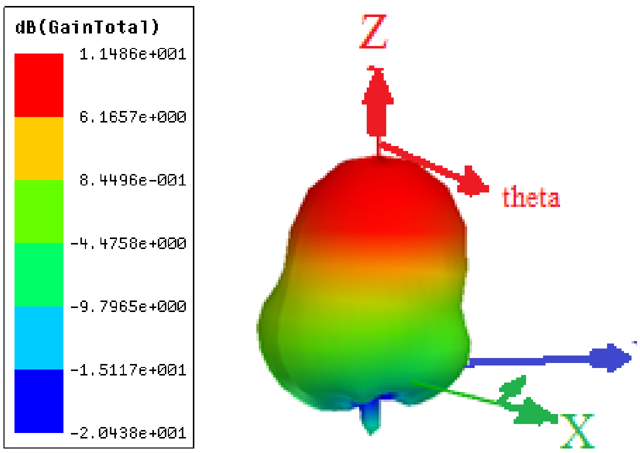

Fig.3. 3D radiation pattern of single element

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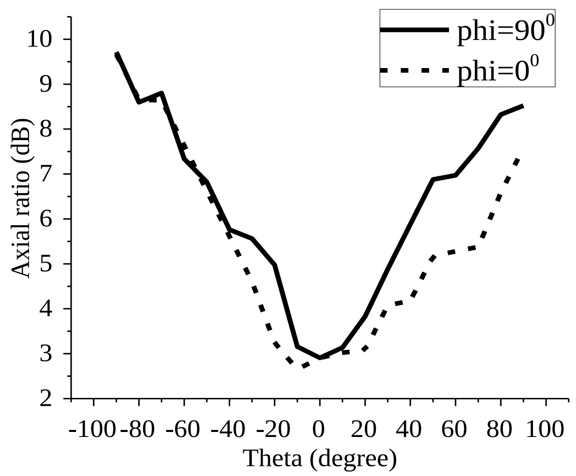

Fig.4. Simulated axial ratio for the single element

C. Parametric study of single patch antenna for low SLL

Here we have done a parametric study for SLL at TM_{12} mode by choosing different substrate materials with different dielectric constants due to which the size of antenna also got changed by using formula (1). The fundamental (TM_{11}) mode of circular patch antenna is useful where broadside gain is desired. Moreover, other TM_{1m} modes (m=2, 3,…) radiate in the broadside direction with high directivities, but higher order modes are avoided due to occurrence of side-lobes in the radiation pattern. Generally, all TM_{1m} modes radiate normal to the plane, but on considering higher values of m, the SLL begins to appear and gets closer to the main lobe, and hence beam-width becomes narrower. In a practical antenna design, it is found that the SLL of TM_{12} mode can be further reduced by using a substrate with high value of the dielectric constant and finite ground plane [9]. The designed antenna has high gain with a substrate of high value of dielectric constant.

- For RT/duroid 5880 substrate material with ε_r = 2.2, the Gain obtained was 11.72dBi but due to TM_{12} mode SLL also appeared over here at $\Phi = 90^\circ$, and no SLL was seen for $\Phi = 0^\circ$. Plot of radiation pattern and Gain is shown in Fig.5.
- For FR4 substrate material with ε_r = 4.4, since the SLL has reduced significantly to negligible, but at the same time gain has reduced to a very low value i.e. 6.9dBi, thus making it less efficient. Plot for radiation pattern and gain total is shown in fig.6.

  As SLL for TM_{12} mode can be reduced by Selecting a high value of dielectric constant. This has been explained in detail in theory part of section 4. Thus we are in need to select a substrate material in between these two dielectric constants which can provide both low SLL and high gain at the same time.

- Hence we have selected Neltec Substrate with ε_r = 2.55, for this, Gain obtained was 11.47dBi and at the same time SLL has also reduced. The radiation pattern and Gain plot has been shown in Fig.7

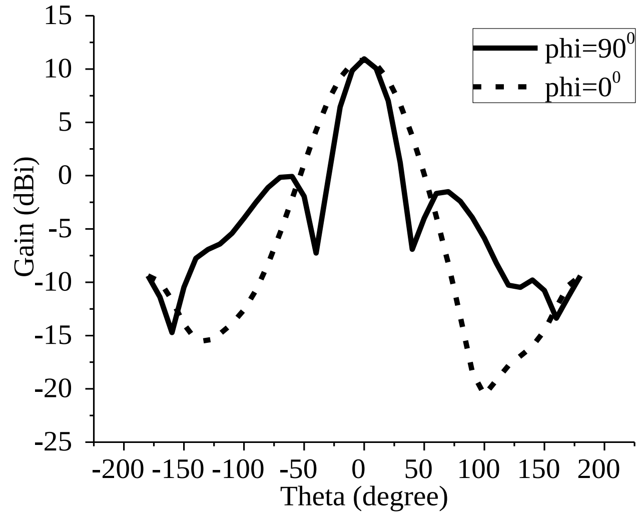

Fig. 5. Simulated Gain plot of substrate RT/duroid 5880 (ε_r =2.2).

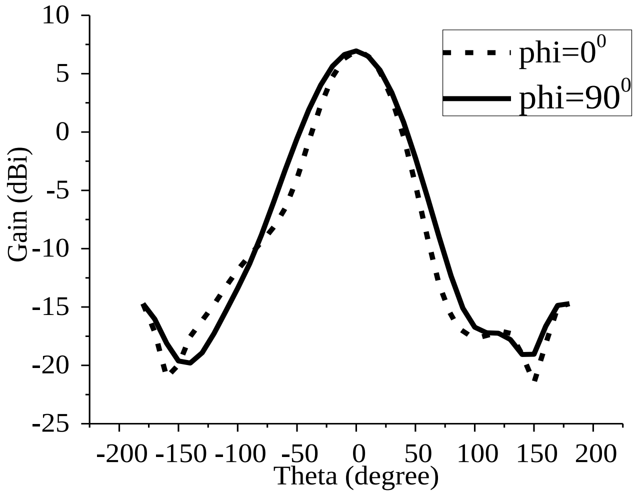

Fig. 6. Simulated Gain plot of Substrate FR4(ε_r =4.4)

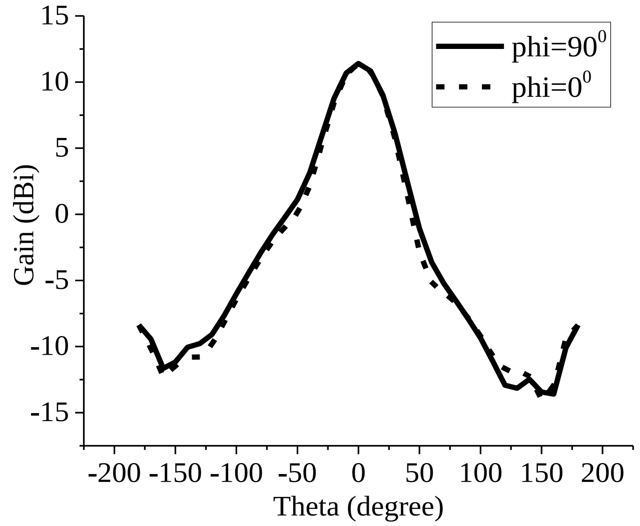

Fig.7. Simulated Gain plot of substrate Neltec(ε_r = 2.55)

III. DESIGN OF AN ANTENNA ARRAY

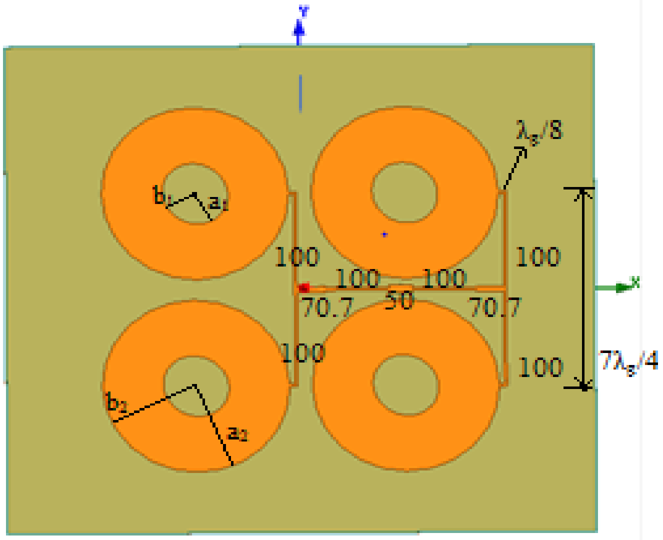

Fig.8. Schematic structure of 2×2 array.

The substrate size taken is $((250\times225\times1.542)mm^3$

A. Design layout of 2×2 antenna array

The elliptical annular ring element has been used in section 2 for the array design. The inter-element spacing is chosen to be $\frac{7}{4}\lambda_g$to avoid mutual coupling between antenna array elements. Here each single elliptical annular ring patch is rotated by 45°clockwisewith the major axis to connect microstrip lines with edge feeding. It is found that the impedance is minimum at the center and maximum at the edge of each individual patch, which makes it possible for edge feeding at an optimized point so that there is a proper matching and hence it results good reflection coefficient. The antenna input impedance at the edges is found to be nearly equal to 100 Ω. All the elements are connected using 100 Ω microstrip lines. Hence the equivalent impedance at the junction of each pair of 100 Ω lines is found to be 50 Ω. After this a quarter-wave transformer is placed between a 50Ω equivalent impedance and 100 Ω microstrip line and hence resultant impedance is obtained using formula given below:

$$Z=\sqrt{Z_{in}\times Z_{out}}=\sqrt{50\times100}=70.7\Omega$$

As a final step of corporate feeding two pairs of 100Ω lines from each side are connected resulting in an equivalent impedance of 50Ω where the coaxial feeding is given.

Here, wavelength λg in the dielectric medium is calculated using the formula given as:

$$\lambda_g=\frac{3\times10^{11}}{f_r\sqrt{\varepsilon_r}}mm$$

Although there are small side-lobes on both sides of the main lobe, there is maximum radiation in the broadside direction and gain is15.76 dBi as shown in Fig.10. The substrate size taken is $(250\times225\times1.542)mm^3$ .Total length of 100 Ω line = 2λg, width of 100 Ω line = 1.2 mm, length of 70.7 Ω line = λg/4, width of 70.7 Ω line = 2.36 mm, width of 50 Ω line = 3.8 mm.

B. Simulated results of antenna array

The designed array antenna has been fabricated using the same substrate together with finite ground plane.

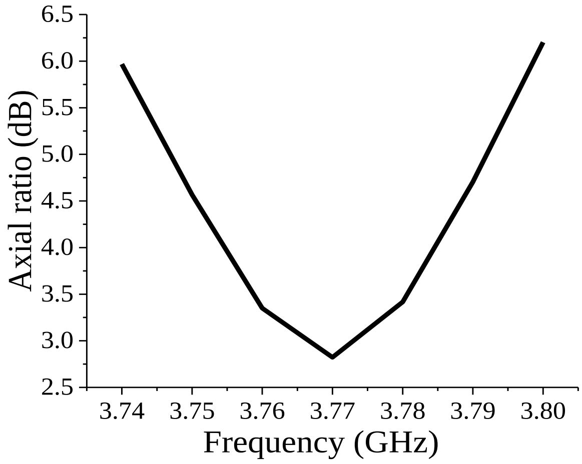

Fig.9. Simulated Axial ratio of array

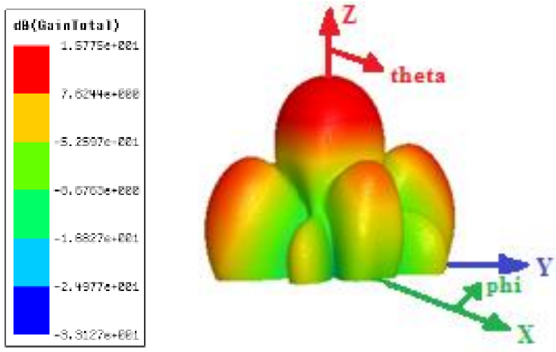

Fig.10. 3D Radiation pattern of antenna array

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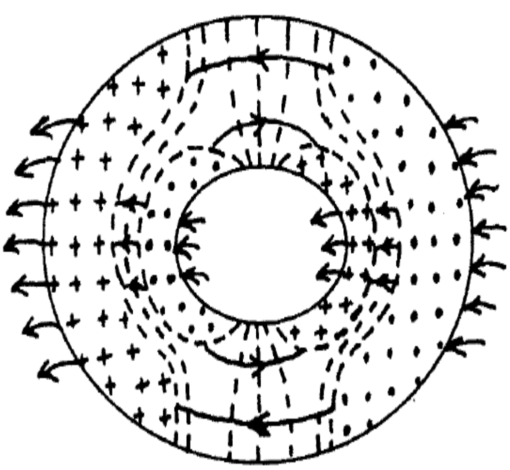

J_S = →→→

H = ─ ──

E_Z = ••••• +++

Fig.11.Modal field patterns(Surface Current, Magnetic Field and Electric Field distribution) for TM_{12} mode[5]

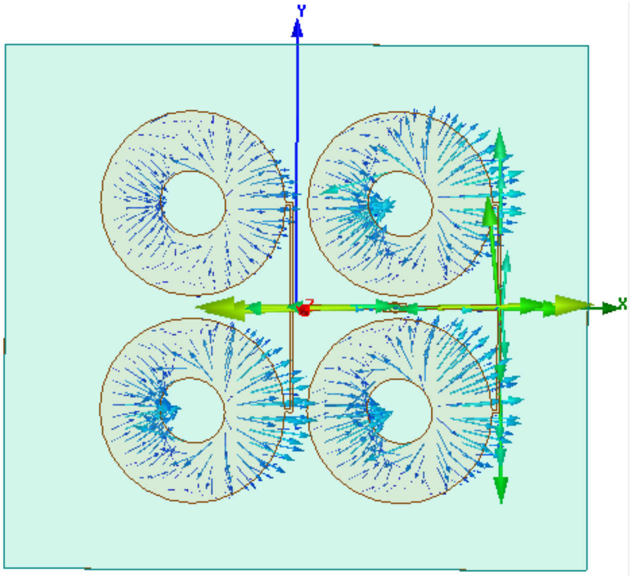

Fig.12. Simulated surface current distribution for TM_{12} mode

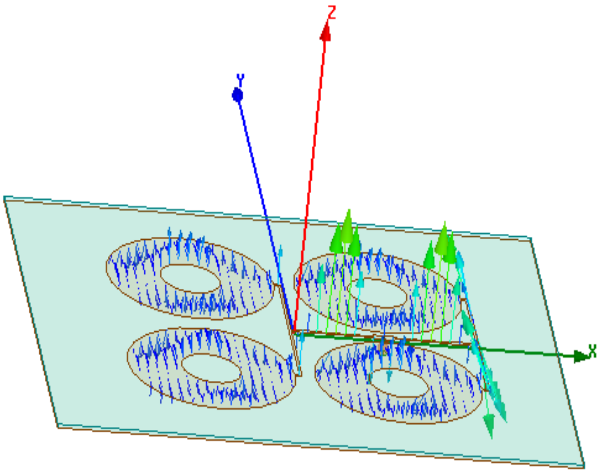

Fig.13 . Simulated Electric Field distribution for TM_{12} mode.

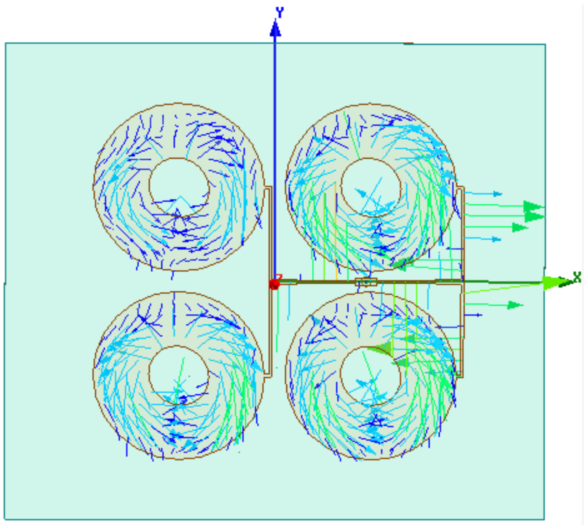

Fig.14 . Simulated Magnetic Field distribution for TM_{12} mode

Fig.12, 13, 14 have been verified with the modal field pattern shown in Fig.11 which demonstrates TM_{12} mode.

IV. FABRICATION AND MEASUREMENT RESULTS OF ANTENNA ARRAY

In this section the annular elliptical ring antenna array was fabricated using the same substrate. An image of the fabricated antenna array is shown in Fig.15. For S-parameter measurement of the given antenna array was measured with Agilent Technologies N5222A, Programmable Network Analyzer (PNA) in the antenna laboratory. Simulated and measured S_{11} are shown in Fig. 16 which shows a good impedance matching between simulated and measured results. The impedance bandwidth is measured around 100 MHz The radiation pattern has been measured in both E-plane and H-plane and the normalized radiation pattern are shown in Fig.17. The measured axial ratio in broadside direction is obtained as 2.04 dB and the measured axial ratio bandwidth is 20.0 MHz

Transmitting gain (G_t) of the antenna was measured using a Horn antenna. Power calculation was done using ***Friis transmission*** formula given by:

$$P_r = G_t G_r P_t \left(\frac{\lambda}{4\pi r} \right)^2 \tag{6}$$

where, P_t = Power transmitted, P_r = Power received, G_t = Gain of transmitted antenna, G_r = Gain of receiving antenna, r = distance between transmitting and receiving antennas, and λ = wavelength at the operating frequency.

We have considered P_t = -28.5 dBm, obtained P_r = 10.49 dBm at 3.77 GHz at a distance of 190 cm.Thus the gain of fabricated antenna is found to be 14.53 dBi while the gain of simulated antenna was found to be 15.78 dBi

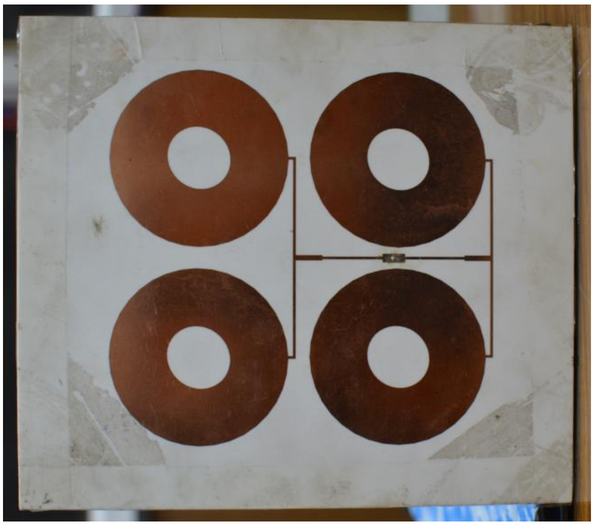

Fig.15. A photograph of fabricated antenna array

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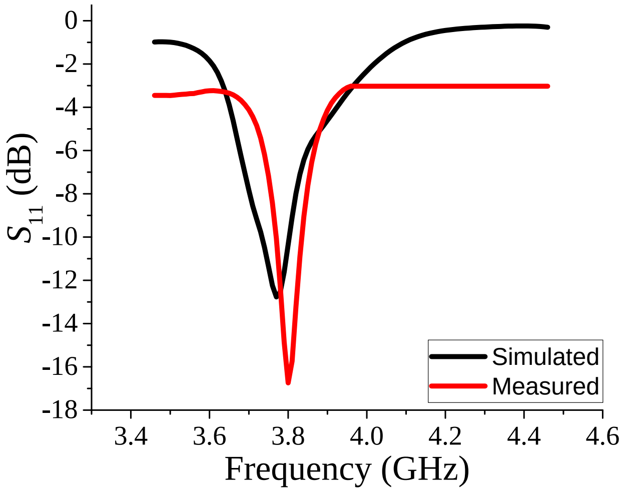
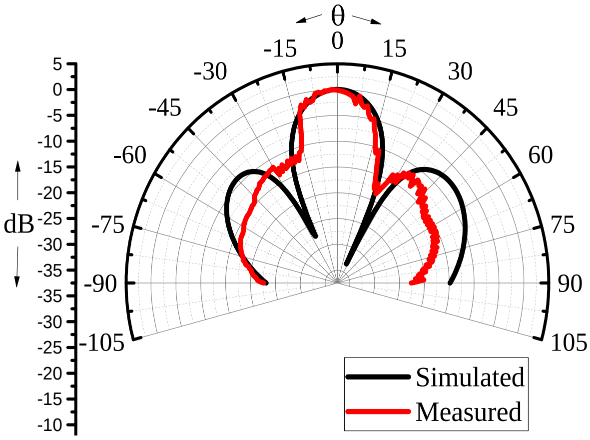
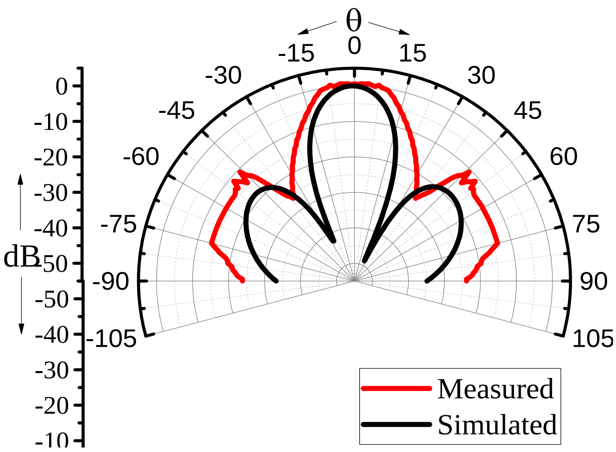


Fig.16. Simulated and measured S_{11}



(a)



(b)

Fig.17. Measured and Simulated normalized radiation patterns at the plane (a) X-Z and (b) Y-Z

Table I: Comparison between single patch and (2×2) antenna array

Antenna	Return Loss (dB)	Gain (dBi)	Axial Ratio (dB)	Side-lobe Level in E-plane (dB)
Single Patch antenna	-11.94	11.470	2.9	0
2×2 antenna array (Simulated)	-13	15.782	2.75	-18.279
2×2 antenna array (Measured)	-17.33	14.53	2.041	-14.4

V. CONCLUSION

Detailed design procedure, fabrication and measurements of an elliptical annular microstrip antenna array operating at frequency 3.77 GHz have been demonstrated. The experimental results show good agreement with simulated one. Single feed has been used for CP instead of two orthogonal feeds as used in other CP generation methods. The designed antenna is operating in TM_{12} mode where the side lobe levels appears to be very low due to the proper selection of the dielectric material of the substrate and using a finite ground plane. Also the proposed antenna array is capable of providing high gain at the same frequency as that of the single element antenna and the results of both are compared. Future research work may be devoted to explore other gain enhancement methodologies for achieving high gain at other frequencies.

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