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Design Analysis and Performance Evaluation of Annulus Patch Antennas

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Abstract- The paper presents a detailed investigation of various types of circular ring patch antennas and their importance in Wireless Communications, especially under satellite Frequency Applications. The main focus is considered on the typical resonant frequencies, design parameters, theoretical foundations on the shape, equivalent circuits and various applications of the ring patch antennas. Design, simulation and comparison of different structures of patches with annulus patch were also presented to justify the investigation.

Index Terms- Microstrip Patch antennas, Microwave Frequency, Wireless Communications, Circular Ring patch.

I. INTRODUCTION

From the past few decades, planar antennas were considered as the best choice of interest to meet the requirements and specifications of microwave frequencies in wireless communications. The main reason for opting the planar microstrip antennas is their weight and compact in size, economic in terms of cost and fabrication [1]. Microstrip Antennas are available in different shapes like ring, rectangle, square circle, triangle, ring, etc. Out of these shapes, ring shape has gained unusual importance for its smaller size, flexible and miniaturization for array structures, wide bandwidth and less stored energy [2]. For Obtaining wide as well as multi-band features, ring structures are included with other geometric elements and one of the interesting features of ring patch antennas is that separation of resonant modes depends on the ring outer to inner radii ratio [3]. The circular polarisation can be easily attained with ring patches related to other shapes by simply making slots or extending the patch dimensions. Although, theoretical analysis of ring patch antennas is not a recent problem but the importance of the analyses for the designs is mandatory to fulfil the conditions and limitations of any application. The theoretical foundations for the ring patches were initiated since the usage of the ring structure has begun. From different ring structures, annular ring is most widely used shape due to its fringing effect at both inner and outer radii and high radiation performance [4].

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Ring antennas act as a transitional configuration between a patch and in print loop in both geometrical as well as electrical cases. The ring structure can also be used to determine the material dielectric constant and as a radiator for medical applications [5]. The Ring structures can be of square, triangle, rectangle or circular shapes. The circular or annular ring shape is most widely used as it minimises the open-end loading effect observed in other patch structures. Apart from this, the annular ring which possess several advantages than other structures of microstrip antennas. This paper carries out the investigation of the work done by various authors on annular ring microstrip antennas from the past few decades and the justification of the investigation through simulation and comparison of annular ring patch antenna with other structures of microstrip antennas.

II. INVESTIGATION

In this section, the work carried out by various authors on annular ring patches was presented. In [1] a multiband circular ring patch antenna was proposed on a patch shape configuration method with constant layout dimensions. The applications of the proposed antenna are confined to 4G wireless communications having 3 bands with their centre frequencies at 6.86GHz, 12.37GHz and 13.75 GHz having bandwidths of 270MHz, 460MHz and 480 MHz respectively and the VSWR have been maintained approximately at 1. In [6] the application is focused on C-band satellite communications and X-band under Radar applications with a rectangular patch with two concentric circular ring slots and two diamond shaped patches near the feed line. The designed is made as to obtain circular polarisation using two concentric ring circles and the enhancement of antenna gain by two diamond shaped patches. The proposed antenna provides dual bands having resonating frequencies at 6.6 GHz and 9.4GHz with S_{11} of -14.7dB and -20.9dB respectively. The bandwidths obtained are 6.38- 6.8 GHz and 9.2 TO 9.6GHz with gains of 4.77dB and 6.29dB respectively. In [7] a patch antenna with concentric annular ring slot was proposed which provides bidirectional circular polarisation radiation with dual bands operating at 2.45 GHz (ISM) and 3.5 GHz (5G) bands. The two-band operation was obtained with tunnelling annular ring slots in the base as well as to maintain circular polarisation two bend structures are loaded on each annular ring inclined at 45^0. In [8] a simple single feed circular patch antenna is proposed with asymmetrical ring-shaped arc slot pairs with extended narrow slots are implanted on both patch and ground which provides dual or multi band circularly polarized radiation. The arc slots embedded increase the impedance bandwidth through the mutual coupling between arc slot resonance and circular patch fundamental resonance and the two extended narrow slots provide circular polarisation.

An extensive parametric analysis has been done on each and every parameter dimension to obtain the optimum results. In [9] the importance of a ring structure has been proved by loading a simple co-axial fed conventional circular patch antenna with a ring. This made the antenna configuration to obtain better performance than a conventional patch antenna which includes greater impedance bandwidth, high gain, surface waves excitation reduction with improvement in efficiency.

In [10] a novel technique has been implemented using short pins between the patch and ground and loading a circular patch with an annular ring which enhanced impedance bandwidth making the antenna broadband in nature. In [11] full wave analysis of a probe fed spherical circular patch antenna loaded by a circular ring was performed in frequency domain using Galerkin's moment method and vector Legendre transform which provided broadening of impedance bandwidth. In [12] full wave analysis of Circular ring patch antennas on double uniaxial anisotropic substrate were theoretically defined with particular cases of one-layer substrate and adjourned substrate. The observations of analyses include the relation between the resonant frequency and substrate permittivity rather than with its height. The operating frequency and radiation pattern were determined by Hankel Transform domain and Hertz Vector Potentials whose numerical results shown that these depend on antenna geometrical parameters. In [13] different novel and miniaturized ring patch antennas were designed to obtain single and multi-band operations by etching various structures in the patch as well as ground of the patches. The designs have provided very efficient results with variations in the dimensions of the rings patches and cross slot structures. In [14] monopole like broadband omnidirectional radiation characteristics were obtained by centre feeding a coupled annular ring patch. The obtained various parameter results were simulated and measured at 5.8 GHz resonant frequency with gain 5.7 dBi and -10dB S_{11} bandwidth of 12.8%. In [15] a triple band compact size single layer probe fed concentric annular ring patch antenna was designed to provide 6.38, 6.30 and 35% of impedance bandwidths at 1.17GHz, 1.428 GHz and 1.9 GHz respectively. The multiband operation was obtained by etching a cross slot in ground and embedding a simple circular patch to concentric ring patch loaded with dual stub. In [16] a novel UWB circular ring structure antenna was designed and analysed for biomedical applications. The proposed antenna resembles like Ashoka chakra and provides compact size. The design was analysed putting on tri-layered human phantom model examining on arm and head at three different frequencies. In [17] ring patch antenna was designed with frequency independent tunability as peculiar feature for WLAN and WIMAX applications. The Dual-band operation was introduced by loading the patch with a gap. Independent frequency tunability was also obtained by etching peripheral trenches at particular positions on the patch. In [18] an annular ring patch was proposed with DGS to promote multiband operation. The antenna performs at 3 different resonant frequencies of S/C/X bands providing circular polarisation using wave port excitation. In [19] a simple ring-shaped patch antenna was designed operating between 2 to 5 GHz for WLAN, WIFI applications. The frequency tunability was achieved by introducing slots at particular locations.

III. MATHEMATICAL INVESTIGATION

The Mathematical analyses regarding the design of annular ring patch has begun around 1980s by James W. Mink [20] providing the theoretical as well as experimental work on a simple ring patch antenna. The paper presents a theoretical expression for the electric and magnetic fields in cylindrical coordinates by using Bessel functions and Taylor's series expansion. The evolution of circular ring antennas was from the ring resonators. The fundamental field expressions were considered based on the ring resonators. The magnetic currents and propagated fields were experimentally verified. The resonator operating frequency was computed with stationary principle and the numerical results were compared with experimental data for testing accuracy [21,22]. Out of numerous mathematical models/methods for the analysis that are followed since from the initial investigation, some important methods were discussed here. The basic mathematical analysis of circular ring microstrip antenna was performed to determine resonant frequency using planar wave guide model, radiation characteristics were derived from the magnetic current equations and radiating fields using electric vector potentials derived from magnetic currents [23]. The development of the annular ring patch improved to obtaining dual frequencies and detailed analysis of patch design and its radiation characteristics were proposed in [24] which include supressing unwanted modes, input impedance model, radiation patterns, etc., providing good agreement between theoretical and measured values. In [25] the methods required for improving the patch characteristics were investigated numerically as well as experimentally stating that the resonant frequency and impedance depend on design geometry. As in [25] was proposed for a printed square ring antenna, the same was implemented for annular ring in [26] through FWSD moment method solution in which the probe feed and ring patch connection was modelled using mode expansion function. Another approach for numerical analysis is done majorly through the Hankel Transform domain [2, 12, 27, 28] and Hertz Vector potentials [2, 12, 28] where the equivalent circuit of the patch and field expressions were obtained. Cavity model analysis [29, 30] can also be used to derive various field expressions and current expressions based on magnetic currents on the peripherals of the wall. The model also determines the design requirements like effective dielectric constant, Mode dependent resonating frequency and effective geometry dimensions.

IV. COMPARISON OF ANNULUS WITH OTHER BASIC PATCH ANTENNAS

There are numerous structures available for microstrip antennas like rectangular, Square, Triangular, Circular, Ring, etc. out of these patch shapes, annular ring is most widely used one. To justify this statement, comparison and analysis of annular ring patch with other basic patch shapes like rectangular and circular patch antennas were performed operating at a frequency f_0 = 15 GHz, dielectric medium RT duroid with permittivity value ε_r = 2.2 and depth h = 1.59mm.

Inset microstrip feed technique was used for proper impedance matching. The antennas were designed and simulated using CST 2017. The mathematical design equations for each patch antenna are considered from [5, 30, 31]

A. *Rectangular Patch Antenna*

Width $W_o = \frac{c}{2*f_o*\sqrt{\frac{\varepsilon_r+1}{2}}}$ (1)

Length $L_0 = L_{eff} - 2 * \delta l$ (2)

Where

c = 3* 10^{10} is velocity of light in cm/sec.

$L_{eff} = \frac{c}{2*f_o*\sqrt{\varepsilon_{reff}}}$ is the operative length of the patch fringing effect.

$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}[1 + 12 * \frac{h}{w}]^{\frac{-1}{2}}$ is the effective dielectric constant.

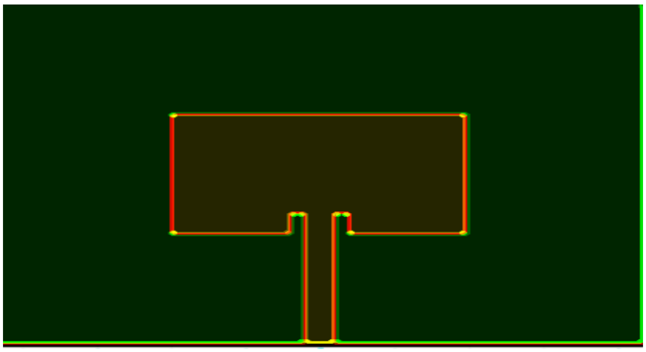


Fig.1. Rectangular patch antenna structure

$\delta l = 0.41 * h * \frac{(\varepsilon_{reff}+0.3)*(\frac{W}{h}+0.264)}{(\varepsilon_{reff}-0.258)*(\frac{W}{h}+0.8)}$ is the normalised extended length.

The substrate and ground dimensions are given by

$Length\ L_g = L + 6 * h$ and

$Width\ W_g = W + 6h$

The substrate thickness $h = \frac{0.0606*\lambda}{\sqrt{\varepsilon_r}}$.

By substituting the specified design values, we get the geometry dimensions as W = 0.79 cm, L = 0.59cm, L_g = 1.59 cm, W_g = 1.74 cm, L_{eff} = 0.721 cm.

B. *Circular Patch antenna*

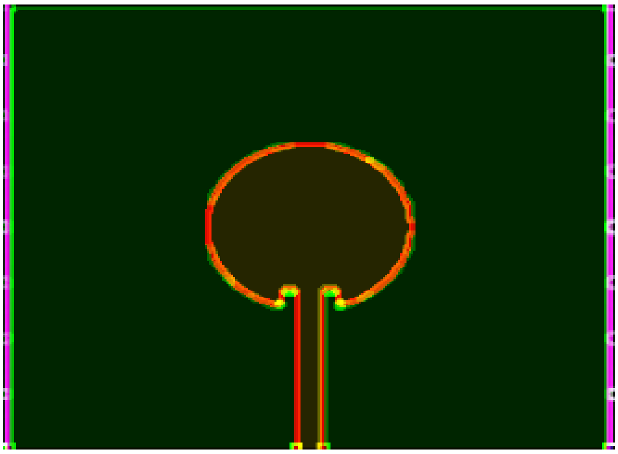


Fig.2. Circular patch antenna structure

The resonant frequency expression is given by

$$f_{rnm} = \frac{\chi_{nm}*c}{2*\pi*a*\sqrt{\varepsilon_r}} \quad (3)$$

Where c = 3* 10^{10} is velocity of light in cm/sec

$a = \frac{F}{\{1+\frac{2*h}{\pi*\varepsilon_r*F}[1.7726+ln(\frac{\pi*F}{2*h})]\}^{\frac{1}{2}}}$ is the radius of the patch

$$F = \frac{8.791*10^9}{f_0*\sqrt{\varepsilon_r}} \quad (4)$$

χ_{nm} is the first order Bessel function root and depends on the mode of the patch. For TM_{10} the value of χ_{nm} = 1.841.

The operative radius with fringing is

$$a_e = a\{1 + \frac{2*h}{\pi*\varepsilon_r*a}[1.7726 + \ln(\frac{\pi*a}{2*h})]\}^{\frac{1}{2}} (5)$$

The geometric dimension values of circular patch antenna for the specified design are a = 0.35 cm, F= 0.395 and a_e = 0.45 cm.

C. *Ring Patch Antenna*:

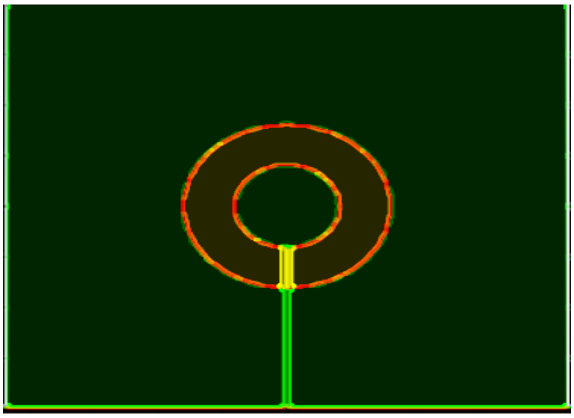


Fig.3. Annular patch antenna structure

The mathematical analysis of a ring patch was similar to circular patch

Resonant frequency $f_{rnm} = \frac{\chi_{nm}*c}{2*\pi*a*\sqrt{\varepsilon_r}}$ (6)

Where

c = 3* 10^{10} is velocity of light in cm/sec

χ_{nm} is the first order Bessel function root and depends on the mode of the patch.

For TM_{11} the value of χ_{nm} = 0.6773.

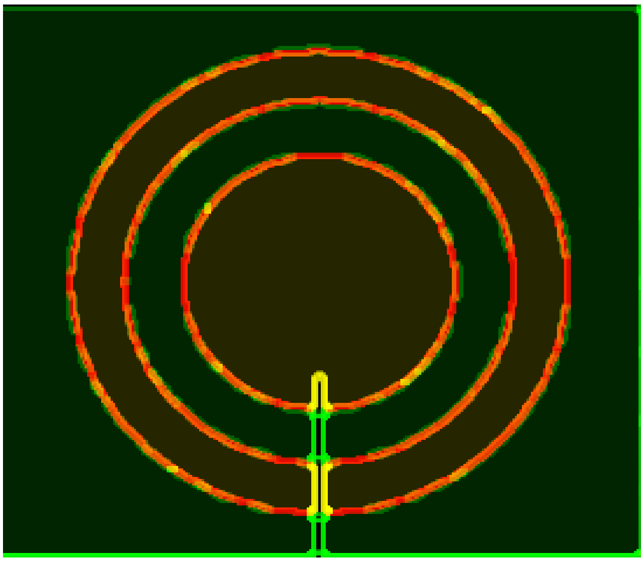
$$\chi_{nm} = K_{nm} * a$$

Where n indicates azimuthal variation and m indicates field variation across the ring width.

The above expressions provide accurate values when $\frac{b-a}{b+a} < 0.35$ and $b = 2 * a$ conditions are met. 'a' and 'b' are the inner and outer radii of the ring.

If the fringing effect is also considered then the resonant frequency is given by

$$f_{rnm} = \frac{\chi_{nm} * c}{2 * \pi * a * \sqrt{\varepsilon_{re}}} \quad (7)$$



Here $\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 10 * \frac{h}{w}\right]^{\frac{-1}{2}}$ is the effective dielectric constant.

w = b-a is the width of the ring.

The computed geometrical values from mathematical expressions are b= 0.323 cm and a= 0.1618cm.

D. Ring loaded circular patch

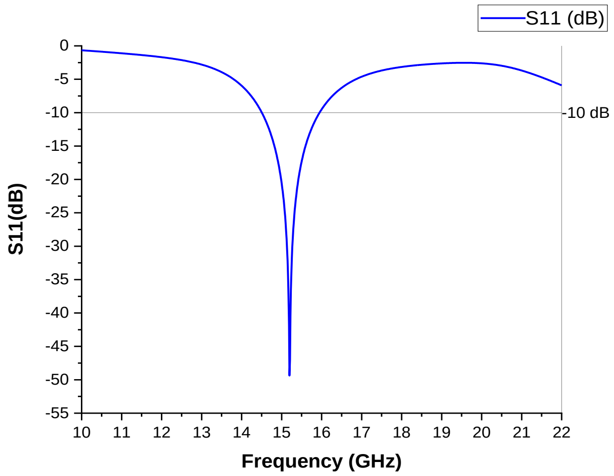
Fig.4. Circular patch with loaded annular ring antenna structure.

The performance characteristics of circular patch antenna can be improved through loading an annular ring with a width of annular ring and the separation between the loaded ring and patch are maintained at 0.15 cm. The annular ring is etched away at the feed point. The outer radius and inner radius of the loaded ring are 0.3cm and 0.15 cm respectively.

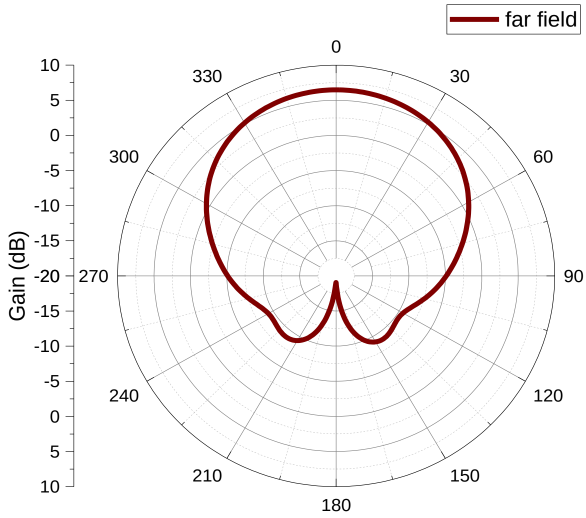
V. RESULTS AND DISCUSSIONS

The antenna structures discussed in the above section were designed and simulated using CST 2017. This section provides analysis of the EM fields as well as comparison of the ring patch with other patch antennas. The patches were inset fed for proper impedance matching and examined that width and depth of the microstrip line inset feed decides the impedance matching of feed and patch.

The designed rectangular patch resonated at a frequency of 15.196 GHz having good return loss of -49.369 dB with an impedance bandwidth of 1.46 GHz [(15.951 – 14.505) GHz]. The gain provided by the antenna is 6.48dBi. The 3dB angular beam width is 89.2^0, sidelobe lobe level of -15.4dB and the directivity is 6.39dBi.

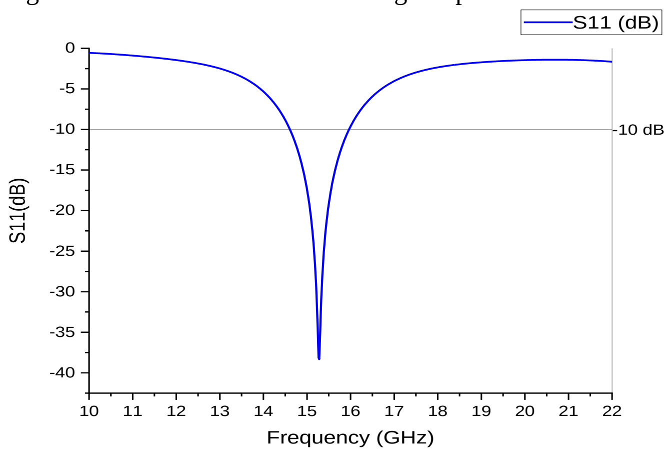


(a) Return loss plot



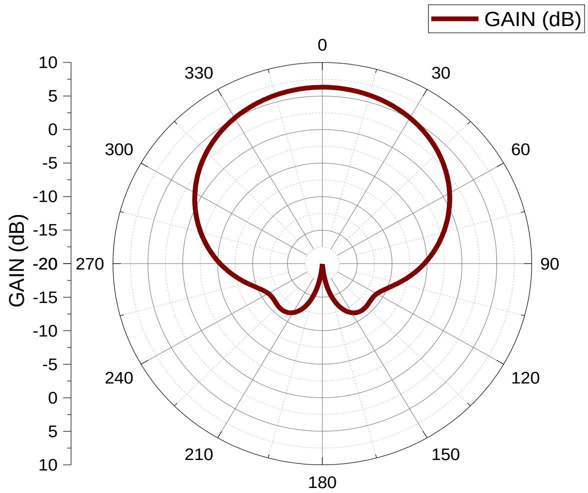
(b) Far field polar plot

Fig.5. Performance metrics of rectangular patch



(a) Return loss

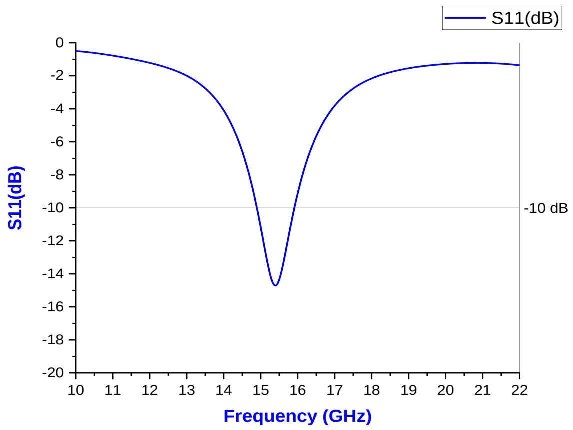
The proposed circular patch resonates at 15.28GHz with S_{11} =-38.32 dB and the -10dB bandwidth is 1.357 GHz [(15.965 to 14.608) GHz]. The realized gain is of 6.31dBi, beam width 92.3^0, side lobe level -17.3 dB and 6.27dBi.



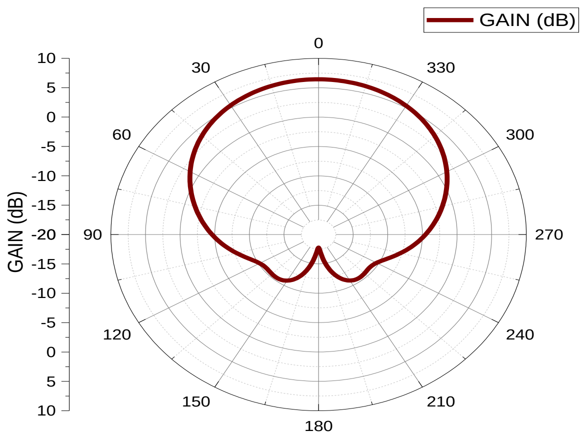
(b) Far field polar plot

Fig.6. Performance metrics of circular patch

The ring antenna provided a return loss of -14.71 dB at an operating frequency of 15.396 GHz with -10dB bandwidth of 1.013 GHz [(15.909-14.896) GHz], gain 6.43dBi, beam width 94.9^0, side lobe level -16.9 dB and directivity of 6.38dBi.

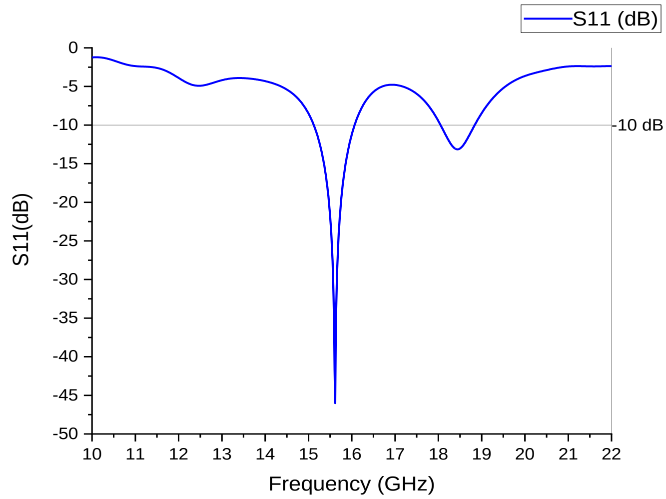


(a) Return loss

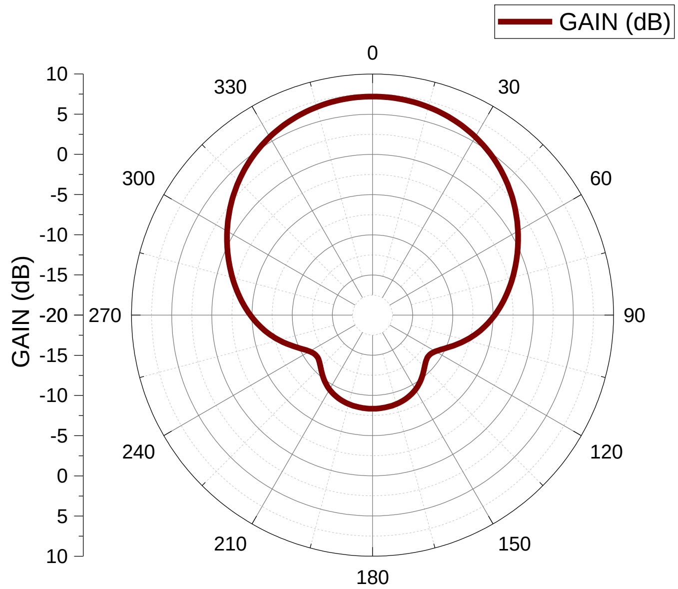


(b) Far field polar plot

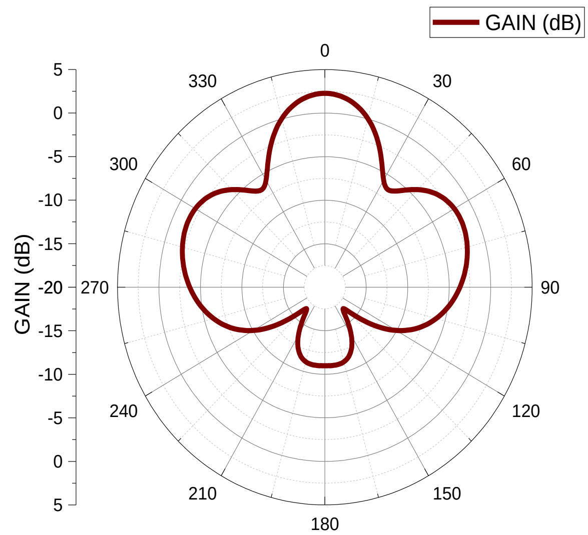
Fig.7. Performance metrics of annulus patch.



(a) Return loss



(b) Far field polar plot at band1



(c) Far field polar plot at band 2

Fig.8. Performance metrics of annulus loaded circular patch.

The ring loaded circular patch has shown tremendous improvement apart from the circular patch antenna. The dual band operation was observed with the resonating frequencies 15.616 GHz and 18.436 GHz with reflection losses of -46. 498dB and -15.431 dB respectively. The impedance band width at band1 is 943 MHz [(16.066-15.123) GHz] and at band 2 is 789MHz [(18.84 – 18.051) GHz]. The gain at centre frequency of band1 is enhanced to 7.19dBi, beam width 81.6^0, side lobe level -15.5 dB and directivity of 7.83dBi. The second band performance metrics are gain 2.26dBi, beam width 34.8^0, side lobe level -4.1 dB and directivity of 4.55dBi.

The parametric analysis was performed on the feed width of the patch(w_f). It is observed that the impedance matching of the patch will be mostly depend on the feed width

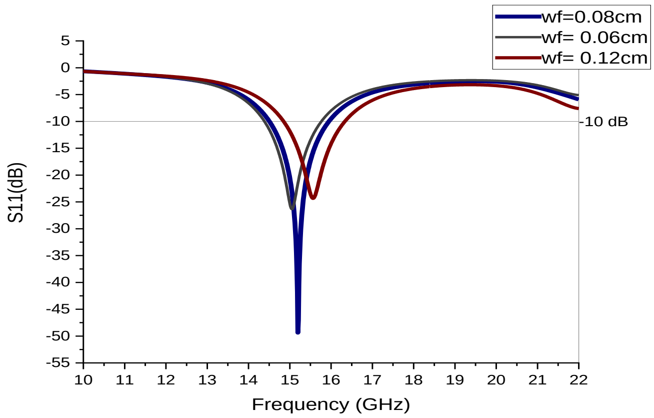


Fig.9. Return loss of S11 for various feed width values in ring patch

Table.1. Comparison of performance metrics of designed patch antennas

Parameter	Rectangular	Circular	Annular Ring	Ring Loaded Circular
Designed fr	15 GHz	15 GHz	15 GHz	15 GHz
Obtained f0	15.196 GHz	15.28 GHz	15.396 GHz	Band1: 15.616 GHz Band2:18.436 GHz
S11 (dB) at f0	-49.369	-38.32	-14.71	Band1: -46.498 Band2: -15.431
Impedance Bandwidth	1.46 GHz (15.951 – 14.505) GHz	1.357 GHz (15.965 – 14.608) GHz	1.013 GHz (15.909- 14.896) GHz	Band1: 934 MHz (16.066-15.123) GHz Band2: 789 MHz (18.84- 18.051) GHz
Gain (dBi)	6.48	6.31	6.43	Band1: 7.19 Band2: 2.26
Directivity (dBi)	6.39	6.27	6.38	Band1: 7.83 Band2: 4.55
Beam Width	89.20	92.30	94.90	Band1: 81.60 Band2: 34.80
Side Lobe Level (dB)	-15.4	-17.3	-16.9	Band1: -15.5 Band2: -4.1

VI. CONCLUSION

In this paper, the various designs of ring Microstrip Patch antenna were studied and surveyed in detail. The mathematical foundations and analyses were also studied which stated that most of the patch analysis used hankel transforms as well as vector potentials. The basic mathematical foundations were also discussed and simulation and analysis of patch antennas were compared. Annular ring loaded circular patch antennas shown better performance were analysed. The inset feeding has shown better performance results when compared with other feeding techniques.

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