A Novel Miniaturized Isotropic Patch Antenna for X -Band Radar Applications Using Split Ring Resonators

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Abstract – *A new circular patch antenna with a novel metamaterial structure that achieves high bandwidth and positive gain across the operating band. The proposed antenna was Designed by incorporating three split ring resonators into the patch and fabricating it with 15 ×10 ×1.6 mm3. The use of a metamaterial structure with negative permittivity and permeability reduced mutual coupling in a wideband antenna. The designed antenna shows the isotropic nature at 9.71 GHz in the operating band from 8.80 to 12.89 GHz for X band applications specifically for detecting objects using radars. The optimetrics technique analyzed impedance matching with a good return loss of -30 dB. In comparison to previous works, miniaturization achieved up to 81.94%. The efficiency of 95.6% and isotropic pattern were also achieved at 9.71 GHz using HFSS020R2.*

Keywords: *Metamaterial, X-band, impedance matching, mutual coupling, isotropic, gain*

1. INTRODUCTION

In wireless communication systems, especially military radar systems, transmitting and receiving antennas should possess a good gain with an anisotropic pattern. It can receive and send the signal without delay, and loss transfers data in all directions. But practically, it is not possible to design an antenna with broadband properties like an Isotropic pattern, i.e., it should radiate in all directions equally with positive gain for wideband applications like X-band. Devices with fast communication and a high data rate are required in the new communication era, with no data loss. The antenna should have high signal strength and equally transmit signals in all directions with less return loss. The literature survey clearly explains the contribution of different researchers to achieve this challenge.

For wide bandwidth communication applications, designing antennas play a crucial role. Antenna size should be small enough to be compatible with all wearable intelligent device applications quickly, so miniaturization of the antenna is another challenge for wideband applications with good signal strength.

Many methods are introduced by designing a miniaturized antenna for Wideband applications with good signal strength, i.e., high gain with low return loss. One is by taking another artificial material on the antenna. There are remarkable changes observed performance characteristics of the antenna. The maximum of wideband application antennas in the literature shows the band. Still, with low signal strength and high return loss, those are not suitable for radar and satellite applications with high data rates and loss in data.

The key objective of the proposed work is to design a miniaturized antenna for wideband application within good gain and minimum return loss. A metamaterial structure achieves a compact antenna with a positive gain throughout the band. The proposed antenna is also easy to fabricate and compatible with all planar structured device applications, especially for satellite and radar applications with highly rigid surfaces.

Many researchers worked to increase the bandwidth by using substrates [1-3]. Typically, available materials have properties of positive permittivity & permeability. Metamaterials are created by introducing new materials with negative permittivity and permeability [4-6].

Researchers who utilized these new artificial materials to design antennas observed a significant improvement in antenna parameters.

O. Borazjani [7] used a 4x9 array E.B.G. layer to improve bandwidth for X band applications and achieved improvement up to 1.6G Hz with a simple design. Lin Peng [8] used Mushroom-Type E.B.G. Complementary ring resonator-type meta structures for dual/triple band applications. Ahmad A. Gheethan [9] used a 2x2 collection split ring resonator M.N.G. Deepa Pattar [10] to reduce the mutual coupling of linearly and circularly polar antenna arrays SRR&CSRR to design an antenna. With this, they achieved the X band with a good gain of about 10dbi. They returned a loss of 17db. It reduced a mutual coupling up to 6db.N. A. Estep [11] used a complementary split-ring resonator with negative index material between (permittivity and permeability) from 4.2 to 4.6GHz used to X Band applications. Prince Jain [12] used an I-shaped meta-structure for X-band applications that resonates between 5 to 15 GHz. They observed the FOM for meta-structure, which performs the Structure.

Bhaskar Reddy [13] used a complementary loaded octagonal split ring resonator at operating frequency band 3. 33 GHz.they achieved five bands used for Satellite, Wi-MAX, and X -Band Applications. Mohamed Lashab [14] explained electrically small antennas with different meta structures explained clearly. Ampavathina Sowjanya [15], Microstrip bandpass filters designed using split-ring resonators for X band Applications.

Researchers added artificial material to the antenna to improve parameters like gain, bandwidth, and efficiency. But not able to distribute signals in all directions with good strength in a wide bandwidth range with positive gain used for radar applications. Work has been investigated, analyzed, and validated. The proposed antenna CP-TCSSR structure attains an excellent wide band, size reduction, positive gain over a frequency band, and isotropic pattern at a particular frequency 9.71GHz. The unique feature of the proposed antenna is most appropriate for defense tracking and weather monitoring applications. The S.R.R. (split-ring resonator) is excited by the impedance matching the 50ohm transmission line with dimensions of 15 mm and a width of 10 mm in the proposed antenna. The proposed antenna operated at a wideband frequency from 8.80 to 12.89 GHz with positive gain all over the band and optimized using the ground plane length. Here By varying the ground plane sizes, we finally optimized at 3mm ground length and achieved the highest gain at 12 GHz at 3.74 dB.

2. MATERIALS AND METHODS

Metamaterials with unique electromagnetic properties enable many advantages in antenna design in satellite applications. While using the antenna for wideband applications, there is an effect of mutual coupling, removed by negative index materials. The capacitive and inductance nature of the Metamaterial gives the bandgap frequency,

$$Fr = \frac{1}{2\Pi\sqrt{Lc}} \quad (1)$$

2.1. DESIGN METHODOLOGY

These steps must be followed while designing the antenna for desired applications. The proposed antenna design methodology with metamaterial structure is explained clearly in Fig.1.

- First, we must select the operating frequency for a particular application for antenna design.
- Design an antenna using a high-frequency structure simulator and evaluate the antenna.
- Design the miniaturized metamaterial structure by satisfying the artificial material properties as -ε and -μ.
- Now, optimize the antenna parameters by varying the position of the meta structure on the antenna until the desired antenna requirements are met.
- Simulate and analyze the results. Fabricate the antenna with the final consideration of the design structure.

Finally, the miniaturized antenna is designed for a wide band with positive gain and low return loss.

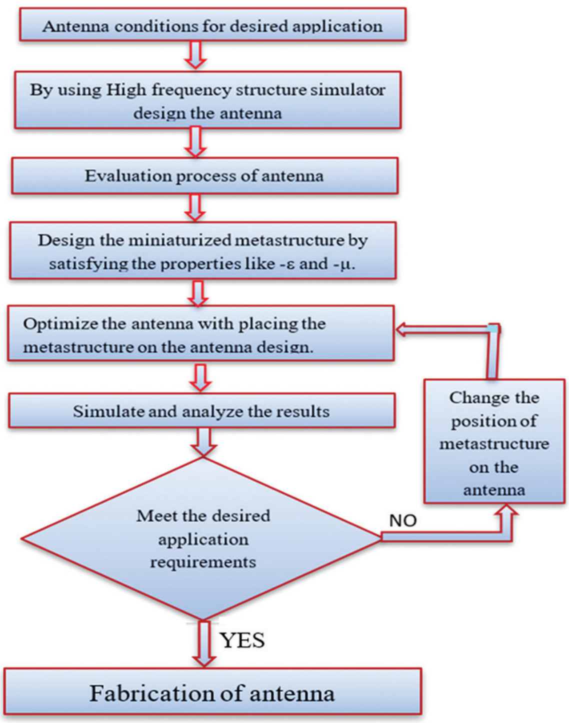


Fig. 1. Design methodology structure of an antenna

2.2. ANTENNA DESIGN & CONFIGURATION

In this session, we proposed a miniaturized antenna with a length of 15 mm and a width of 10mm circular antenna with FR4 Epoxy as substrate ε_r=4.4 with 1.6 mm thickness. The circular patch is designed with a radius of 1.8 mm, a feed line of 6mm, and a width of 1 mm is used.

Consider the circular antenna with the radius 'r' and effective radius 'a_r' taking the effective radius into account, antenna radiation characteristics are improved in relationships of the return losses, gain, and bandwidth [27]. The design formulas are below.

$$a = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[ln ln\left[\frac{\pi F}{2h}\right]+1.7726\right]\right\}^{\frac{1}{2}}} \quad (2)$$

$$F = \frac{8.791\times10^{9}}{f_r\sqrt{\varepsilon_r}} \quad (3)$$

$$\varepsilon_{eff} = \frac{1}{2}(\varepsilon_r + 1) + \frac{1}{4}\frac{(\varepsilon_r - 1)}{\sqrt{1+\frac{12h}{a}}} \quad (4)$$

$$a_r = \frac{1.8412\,c}{2\pi f_r\sqrt{\varepsilon_r}} \quad (5)$$

2.3. DESIGNING OF THE PROPOSED ANTENNA

The antenna was designed with the dimensions shown in Table 1. This antenna is made from a circular patch with a radius of R1=1.8 mm. Regarding that patch, We added three split ring resonators of various radii, R2, R3 & R4, with 2.18 mm,3 mm & 4 mm, respectively. The 6mm length and 1mm width feed line excited the patch. We take a rectangular ground plane of dimensions 10 mm x 3 mm.

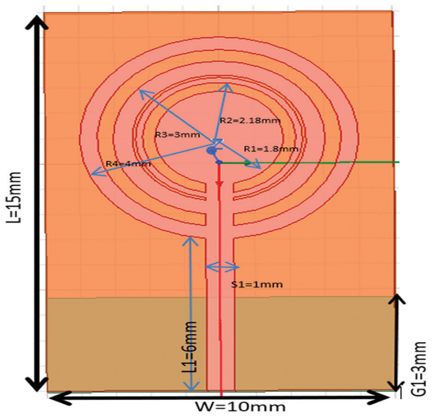


Fig. 2. Proposed antenna front view

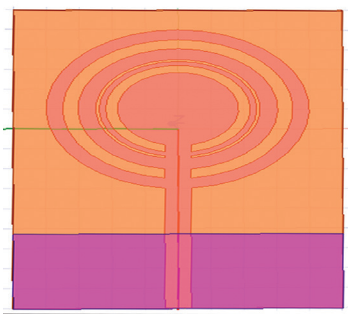


Fig. 3. Proposed antenna bottom view

Fig. 2, 3 signifies the front and bottom view of the proposed design antenna. This Structure, wide bandwidth operated in the region of the X band from 8.80 to 12.89 GHz frequency with a positive gain of 3 dB all over the band. Return loss is observed as very low at 9.71 GHz and 12 GHz ranges. Ground plane length G1 also varied and got optimized at 3 mm.

Table 1. Proposed antenna dimensions

S.NO	Parameter (mm)	Proposed Antenna
1	L	15
2	W	10
3	L1	6
4	S1	1
5	G1	3
6	R1	1.8
7	R2	2.18
8	R3	3
9	R4	4

2.4. DESIGN PRINCIPLE

The design of a circular patch antenna is considered an equivalent circuit as follows.

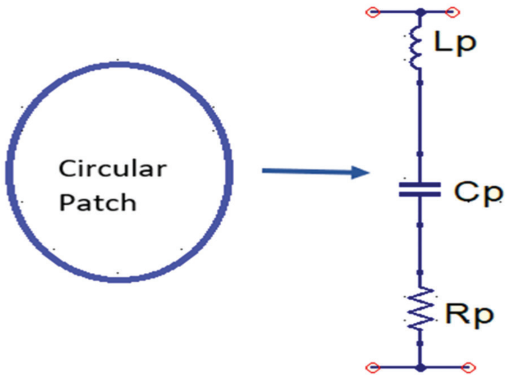


Fig. 4. Patch equivalent circuit

Fig. 4 shows the series combination of the circular patch's inductance, capacitance, and resistance, denoted by Lp, Cp &Rp, respectively

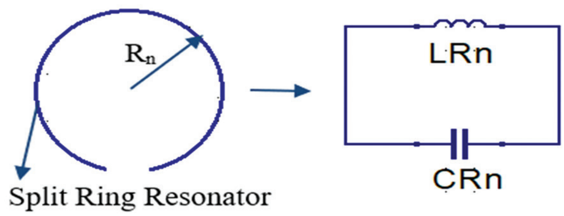


Fig. 5. Three split ring resonators equivalent circuits

Fig. 5. represents the S.R.R. (Split Ring Resonator) equivalent circuit with radius Rn, where 'n' characterizes the nth ring resonator. Each ring resonator has a parallel combination of inductance LR_n and capacitance CR_n. Here are three-ring resonators with three different radii, R_2, R_3 & R_4, and having a similar variety of inductance & capacitance LR_2 & CR_2, LR_3 & CR_3. LR_4 & CR_4, respectively. Fig. 6 shows the equivalent circuit of the antenna.

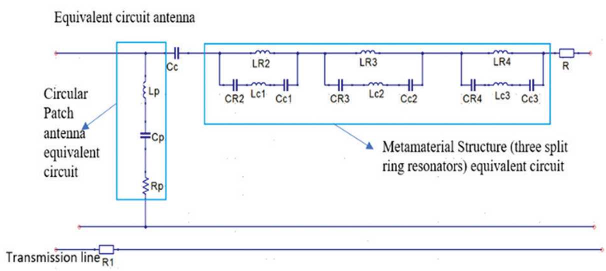


Fig. 6. Equivalent circuit of the proposed antenna

The coupling capacitor is denoted by the term Cc in this context. Each ring resonator is connected in series.

The resonance frequencies are [19],

$$F_Z^2 = \frac{1}{2\Pi\sqrt{LR_2CR_2}} \quad (6)$$

$$F_Z^3 = \frac{1}{2\Pi\sqrt{LR_3CR_3}} \quad (7)$$

$$F_Z^4 = \frac{1}{2\Pi\sqrt{LR_4CR_4}} \quad (8)$$

$$Fz_1 = \frac{1}{2\pi}\sqrt{\frac{CR_2+Cc_1}{Cc_1CR_2(Lc_1+LR_2)}} \quad (9)$$

$$Fz_2 = \frac{1}{2\pi}\sqrt{\frac{CR_3+Cc_2}{Cc_2CR_3(Lc_2+LR_3)}} \quad (10)$$

$$Fz_3 = \frac{1}{2\pi}\sqrt{\frac{CR_4+Cc_3}{Cc_3CR_4(Lc_3+LR_4)}} \quad (11)$$

$$F_M = \frac{1}{2\pi\sqrt{\left(L_{eq}+\left[\left(\frac{Lt_1}{Lt_2}\right)\left(\frac{Ct_1}{Ct_2}\right)\right]+\left[\left(\frac{Lt_3}{Lt_4}\right)\left(\frac{Ct_3}{Ct_4}\right)\right]\right)}} \quad (12)$$

$$L_{t1} = LR_2\ LR_3 + LR_3\,Lc_2 + LR_3\,Lc_1 + Lc_1Lc_2 \quad (13)$$

$$L_{t3} = LR_3\ LR_4 + LR_3\,Lc_3 + LR_4\,Lc_2 + Lc_2Lc_3 \quad (14)$$

$$L_{t2} = LR_2 + LR_3 + Lc_2 + Lc_1 \quad (15)$$

$$L_{t4} = LR_3 + LR_4 + Lc_3 + Lc_2 \quad (16)$$

$$C_{t1} = CR_2\ CR_3\,CR_1 + CR_2\,Cc_2Cc_1 + CR_2\,Cc_2\,CR_3 + Cc_1CR_3\,Cc_2 \quad (17)$$

$$C_{t2} = CR_2\ CR_3 + CR_2\,Cc_2 + Cc_1\,CR_3 + Cc_1 \quad (18)$$

$$C_{t3} = CR_2\ Cc_2CR_4 + CR_2\,Cc_2Cc_3 + CR_4\,Cc_3\,CR_3 + Cc_2CR_4\,Cc_3 \quad (19)$$

The following circuit component parameters are as LR3=2.5 nH, LR4=7.0 nH, LR4=12.0 nH, Lc1=1.75 nH, Lc2=0.5 nH, Lc3=0.02 nH, CR2=0.108 pF, CR3=0.029 pF, CR4=0.05 pF, Cc1=1.6 pF, Cc2=0.0362 pf. The resonance frequency of metamaterial structure F.M. is 8.524 GHz. The patch circuit frequency can be expressed as follows,

$$F_p = \frac{1}{2\pi\sqrt{\left(L_p+\left[\left(\frac{C_PC_C}{C_P+C_C}\right)\right]\right)}} \quad (20)$$

The antenna's resonance frequency was 10.39 GHz, with the values of Lp, C_P & C_C as 2.5nH,1.5 pF & 0.1 pF respectively.

Half power frequencies in L.C.R. series circuits are $F_{.M.}$ & $F_{.P.}$ taken as,

$$F_0 = \sqrt{F_M . F_P} \quad (21)$$

3. RESULTS

This session covered S11 parameter extraction based on ground length, antenna gain, and antenna radiation pattern, as it varies with operating frequency. The session concludes by discussing the comparison of simulated and measured results.

3.1. ANTENNA'S GROUND PLANE OPTIMIZATION

The antenna must be effective enough to transmit the signal. Impedance matching is critical in many of the techniques used for this. We used simple optimetrics by varying the antenna length factor from 3 mm to 5 mm.

G1 is 3mm in length and has a wide bandwidth range from 8.80 GHz to 12.89 GHz with a return loss of -25 dB.

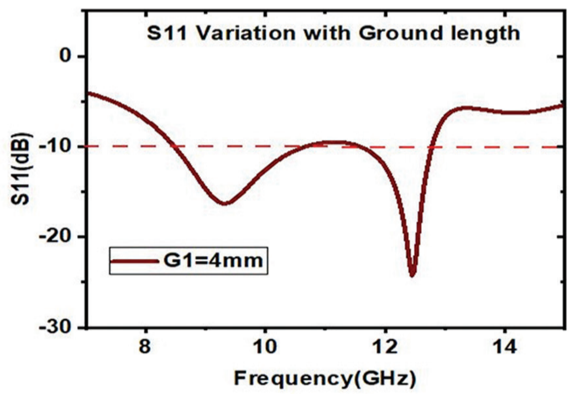


Fig. 7. Ground plane effect on S11 at G1 is 4 mm

By changing the length G1 of the ground plane to 4mm and observing the antenna resonating at frequencies 8.43 GHz to 10.64 GHz, and 11.58 to 12.92 GHz with -17 dB & -29 dB, respectively shown in Fig. 7.

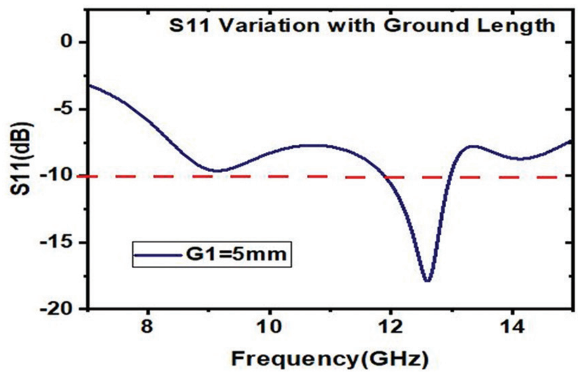


Fig. 8. Ground plane effect on S11 at G1 is 5 mm

By Changing the length G1 of the ground plane to 5mm, then observed antenna resonating at dual-band frequencies from 11.8 to 13 GHz with return loss -18 dB, respectively, shown in Fig. 8.

3.2. REFLECTION COEFFICIENT S11 EXTRACTION

The proposed antenna is operated at a frequency from 8.80 GHz to 12.95 GHz.

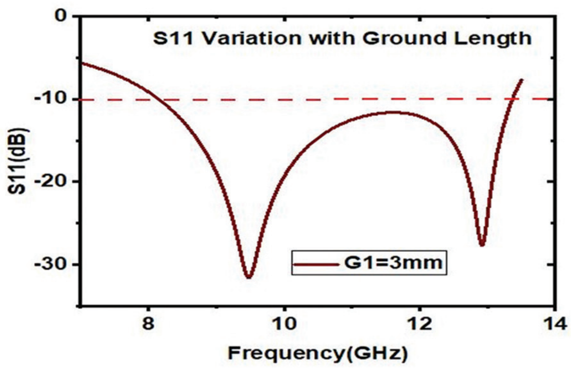


Fig. 9. S11 plot of the antenna at G1=3mm

The circular patch antenna with TSRR got optimized at 3mm. Fig. 9 shows the S11 plot of an antenna at an optimized ground length of 3mm, where achieved wide bandwidth with good Return Loss of -31 dB at 9.8 GHz and -24 dB at 12.5 GHz.

3.3. PROPOSED ANTENNA VOLTAGE STANDING WAVE RATIO (VSWR)

The crucial parameter,i.e., impedance matching, is measured with the VSWR

The VSWR of proposed antennas also varied at the acceptable value, i.e., 1.5 at the 9.71 GHz frequency range shown in Fig.10.

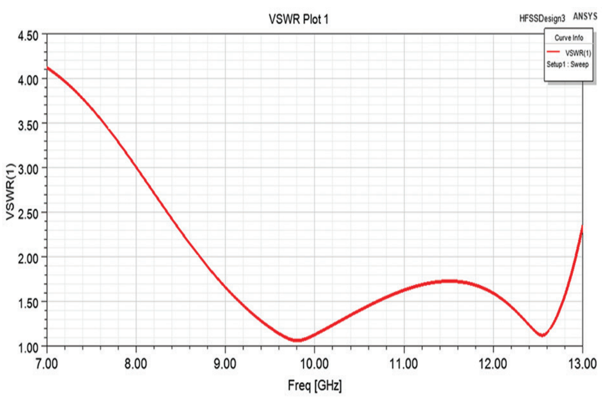


Fig. 10. VSWR plot of antenna

3.4. ANTENNA'S GAIN

The gain of the proposed antenna is positive throughout the operating band. Below, Fig. 11 & 12 shows the gain plots of the antennas at 9.71 GHz & 12 GHz, respectively.

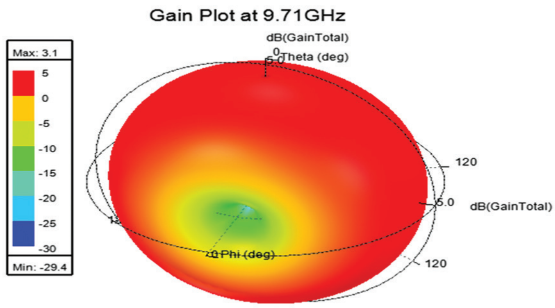


Fig. 11. Proposed antenna's gain plot at 9.71 GHz

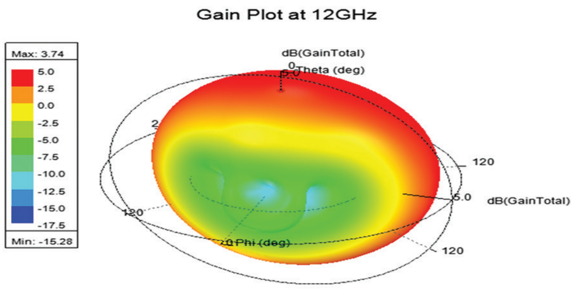


Fig. 12. Proposed antenna's gain plot at 12 GHz

The circularly polarized patch antenna has good immunity to signals in all directions, and its gain makes orientation in a particular focus possible. Fig. 11 shows a 3.1 dB gain of 9.71 GHz, and Fig. 12 offers the highest gain at 12 GHz at 3.74 dB for the proposed antenna.

3.5. GAIN VS. FREQUENCY PLOT

The below fig 13. represents the plot for frequency vs. gain.

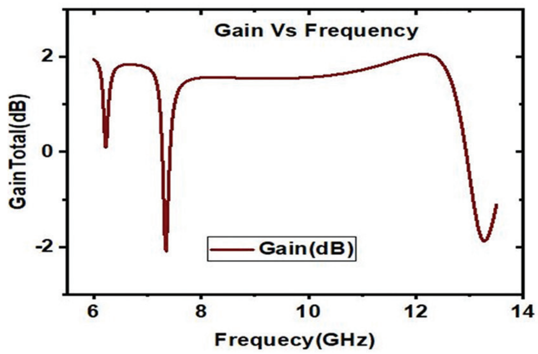


Fig. 13. Gain vs. Frequency plot

Here proposed antenna achieved a positive gain all over the X- band from 7.76 to 12.8 GHz. At phi 0 degrees and theta 0-degree direction, we got a maximum increase of 2 dB at 12 GHz.This is used for military and commercial applications.

3.6. RADIATION PATTERN

A circular patch has the advantage of having the signal distribution with equal signal strength in all directions possible.

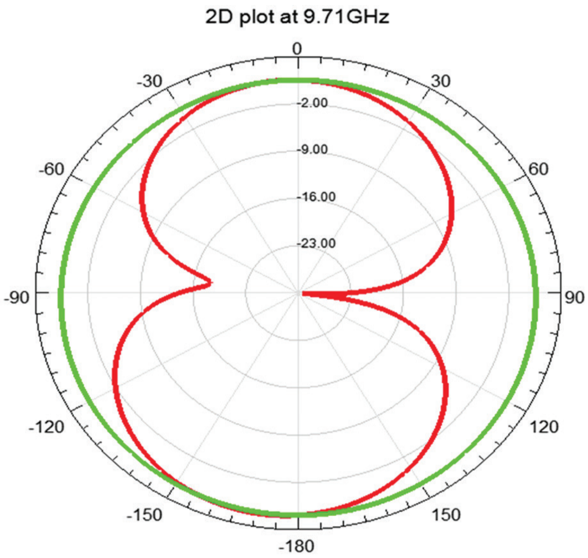
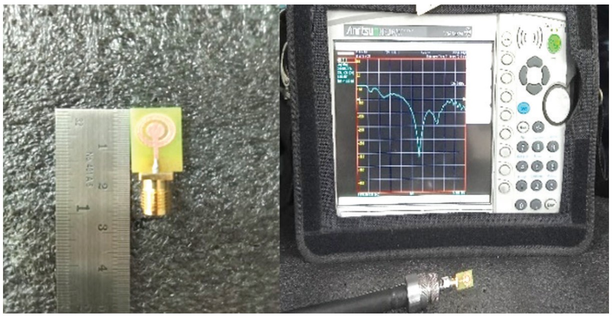


Fig. 14. Proposed antenna radiation pattern at 9.71 GHz

This determines the signal strength towards the particular direction, which detect the object's location. Isotropic pattern radiates equally in all directions, taking as a reference for other sources to compare. The proposed antenna got an isotropic radiation pattern at 9.71 GHz, which is the unique advantage of the proposed antenna used for Radar applications.

4. FABRICATION RESULTS

The designed and simulated antenna with dimensions 15 x 10 mm^2 is fabricated using substrate FR4 Epoxy of thickness 1. 6 mm. The front view of the fabricated antenna is shown below in Fig. 15.



a) b)

Fig. 15. Fabricated Antenn a) prototype b) vector analyzer setup

Vector Network Analyzer used for testing the Fabricated antenna. The below fig shows the comparison of the simulated and fabricated results.

Fig. 16 shows the simulated and measured parameters S11 & VSWR are compared and achieve the appropriate, acceptable range.

The comparison of the measured frequency band 9.41 GHz-12.95 GHz to the simulated frequency band 8.80 GHz - 12.89 GHz, covering extra X-band, is achieved.

5. DISCUSSION

Table 2. gives the comparison of results thus obtained by the proposed antenna and previous works. Compared to the [7,13,21], The bandwidth has been increased. And antenna has a higher gain than previous works [20,21]. Compared to [7,20,21], miniaturization of the antenna also achieved an average of 81.94%.

5.1. LIMITATIONS

The Proposed antenna operated at X-band applications with an average gain of 3 dB. The proposed antenna is an isotropic radiation pattern for satellite and radar applications and was non-isotropic at the remaining bands.

Table 2. Comparison of proposed work with previous works

Ref	Dimensions (mm)	Frequency Bands	Gain
[7]	30×40	9.7 GHz	0.7 dBi
[10]	13x13	9.5 GHz	4 dBi
[12]	50 × 45	4.5 to 5.33 GHz 6.98 to 13.65 GHz	15.1 dBi
[13]	15x15	3.33 GHz, 5.01 GHz, 5.28 GHz, 7.46 GHz & 9.48 GHz	0.4, 0.28, 3.49, 4.19 & 2.05 dBi
[17]	24 x50	2.01 to 2.15 GHz, 7.83 to 8.52 GHz, 9.91 to 10.01 GHz, 11.21 to 12.84 GHz	Five dBi
[18]	29.5 x 22	3.5 GHz, 4.41 GHz, 5.8 GHz, 8.26 GHz, 10.48 GHz 13.35 GHz and 14.42 GHz	2.68 dBi
[19]	45 × 31	2.2 GHz to 9.8 GHz	5 dBi
[20]	30x30	8 to 12 GHz	2 dBi
[21]	20x30	8 to 12 GHz	2 dBi
Proposed	15x10	8.80 to 12.89 GHz	3.74 dBi

6. CONCLUSION AND FUTURE SCOPE

In this paper, a Miniaturized Metamaterial-based X-band range antenna is fabricated and simulated. We got wideband nature by adding Three split-ring resonators to the circular patch. The proposed Structure has been miniaturized by 81.94%, adding Split rings to the circular patch. Because of the circular patch signal strength equal, i.e., isotropic in all directions, achieved at 9.71 GHz frequency and addiction of negative index materials, mutual coupling at the wideband is reduced and achieved a positive gain of 3dB all over the X band ranging from 8.80 GHz to 12.89 GHz, And also discussed the optimetrics of the Ground plane. The efficiency of the antenna is 95.6%. The Fabricated and simulated results are nearly identical and valid for X-band applications. Adding metasurfaces and fractal techniques will improve the antenna's gain. It will be helpful in Radar array applications.

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