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Bandwidth Enhancement of CPW-Fed Elliptical Curved Antenna with Square SRR

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Abstract: The objective of this article is to design a novel coplanar waveguide fed elliptical curved antenna with split ring resonators to improve the bandwidth characteristics. Split ring resonators are etched on the ground plane nearer to the feed line, which exhibiting metamaterial properties to enhance the bandwidth. The metamaterial loading invoking the negative refractive index transmission line concept. A huge bandwidth of 17.9 GHz and an impedance bandwidth of 56% are attained from the current antenna model. The overall dimension of the antenna is around 40X44X1.6 mm on FR4 substrate material with permittivity 4.4. A peak realized gain of 6.2 dB and an average gain of 2.8 dB is attained in the operating band for the designed antenna model. The measured results are providing excellent correlation with simulation results obtained from HFSS and CST tools.

Keywords: Bandwidth enhancement, Coplanar waveguide (CPW), Elliptical antenna, Split ring resonator (SRR), High frequency structure simulator (HFSS), Computer simulation technology (CST).

1. Introduction

Generally wideband systems require compact antenna models with large bandwidth. The known fact is that the printed antennas are very much suitable for such kind of requirements and which enable to design the models at small size, simple orientation and low cost. The main drawback is the narrow bandwidth and which opposing the choice of printed antennas in specific applications. Many techniques are been proposed during last decade to improve the bandwidth characteristics of the antenna. Increase of substrate thickness [1], usage of stacked elements [2] and using magnetic dielectric materials will improve the bandwidth to certain extent [3]. In certain cases the impedance bandwidth is improved, but overall gain and size is not good [4-5]. Defected ground structure is one of the techniques to resonate additional bands and to improve the bandwidth of the antenna [6]. By using defected ground structure, we can attain better bandwidth, but considerable gain will be reduced. To improve the gain and directivity of the antenna, recently new types of composite structures are going to be used in the design. These new materials are called as metamaterials [7-8]. Metamaterials are engineered to provide material characteristics that cannot be found in nature.

Patch antennas with metamaterial characteristics offer many benefits including miniaturization, wide bandwidths and good radiation characteristics. The negative permittivity, permeability and negative refractive index are the properties of these materials [9]. The negative refractive index transmission line concept enabled design and development of advanced antennas with enhancement in performance characteristics [10]. The key deciding factors of refractive index are permittivity and permeability. Metamaterials are artificial structured materials, which possesses unnatural properties in the materials with negative permittivity and permeability. Split ring resonators and complementary split ring resonators are widely used structures to experience the metamaterial property in the substrate materials [11-12]. Researchers designed several models to enhance the antenna performance characteristics like gain, directivity and polarization with the placement of metamaterial concept in the structure [13-14]. The drawbacks in the current models available with split ring resonators concept in the wideband antennas are size, bandwidth and gain [15]. The key deciding factor of antenna performance characteristics is gain of the device. In general there is a tradeoff between gain and bandwidth. To overcome this problem of getting any one parameter low to improve other parameter was addressed and a novel structure was proposed to enhance the bandwidth and as well as to get desired gain in the operating band.

The proposed structure in this paper is a metamaterial inspired planar structure with coplanar waveguide feeding. Split ring resonators are been used in this design to attain the metamaterial nature and to enhance the radiation characteristics with minimum size. Curved elliptical shaped monopole antenna with coplanar wave guide feeding and split ring resonators with good impedance matching is providing improvement in the bandwidth characteristics in the proposed antenna. The ground plane with defected structure giving rise to additional resonances in the operating band and participating in the bandwidth enhancement.

2. Antenna geometry

A novel curved elliptical monopole antenna with SRR is proposed here to enhance the bandwidth. In this model, by employing a pair of ellipse-shape-combined design, a proper control on the lower and higher frequencies of the band is achieved. By this combination in the patch, additional resonances are excited, and hence the bandwidth is increased, especially at higher band. The multiband characteristic of the basic curved elliptical antenna shown in Fig. 1 (a) is modified by placing split rings on ground plane adjacent to feed line as shown in Fig. 1 (b). To enhance the bandwidth, pair of complementary split rings are added to the existing split rings as shown in Fig. 2.

$$Z_0 = \left(\frac{30}{\sqrt{\varepsilon_{eff}}}\right)\left(\frac{E(e'_0)}{E(e_0)}\right) \quad (1)$$

$$\varepsilon_{eff} = 1+\left[\frac{(\varepsilon_r - 1)}{2}\right] \left[\frac{(E(e_1)\,E(e'_0))}{((E(e'_1)\,E(e_0))} \right] \quad (2)$$

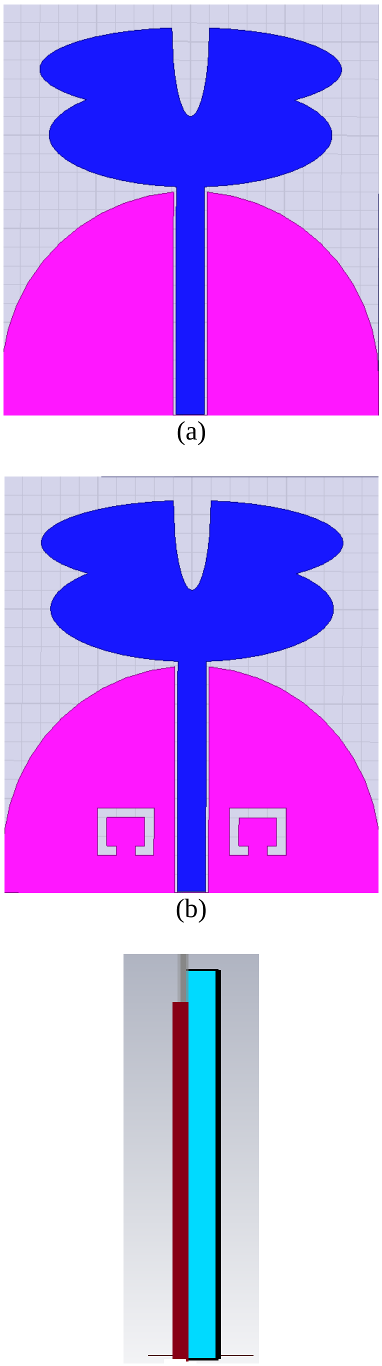

(a)
(b)
(c)

Figure.1 Antenna Iterations: (a) Elliptical curved antenna, (b) elliptical curved antenna with single split ring, (c) side view of the antenna

$$g_1 = 2\,S_1 + W_s \quad (3)$$

$$e^1{}_0 = \frac{w_f}{g_1} \quad (4)$$

$$e_0 = \sqrt{1-e^2{}_0} \quad (5)$$

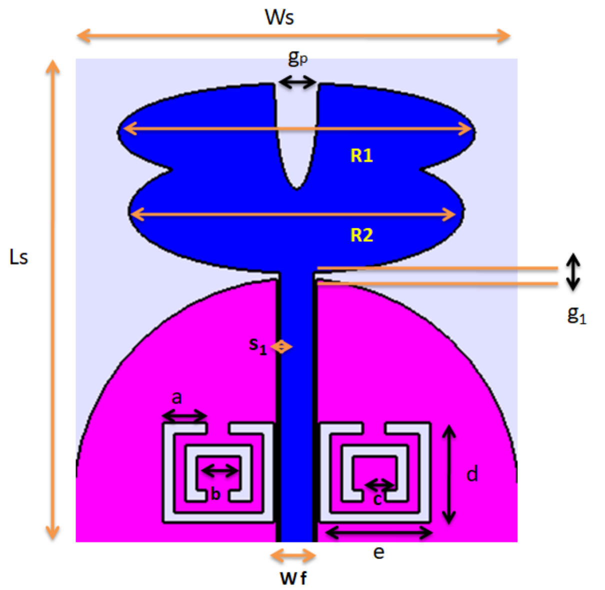


Figure.2 Proposed elliptical curved antenna with split ring resonators

Table 1. Antenna dimensions in mm

Parameter	Description	Dimension in mm
Ws	Width of the substrate	40
Ls	Length of the substrate	44
Wf	Width of the feed line	3
R1	Radius of upper ellipse	12
R2	Radius of lower ellipse	10
S1	Gap between feed line and ground	0.3
g1	Gap between radiating element and ground	0.56
gp	Gap between patch slot	3
a, d, e	Outer split ring dimensions	4, 9, 9
b, c	Ineer split ring dimensions	4, 2

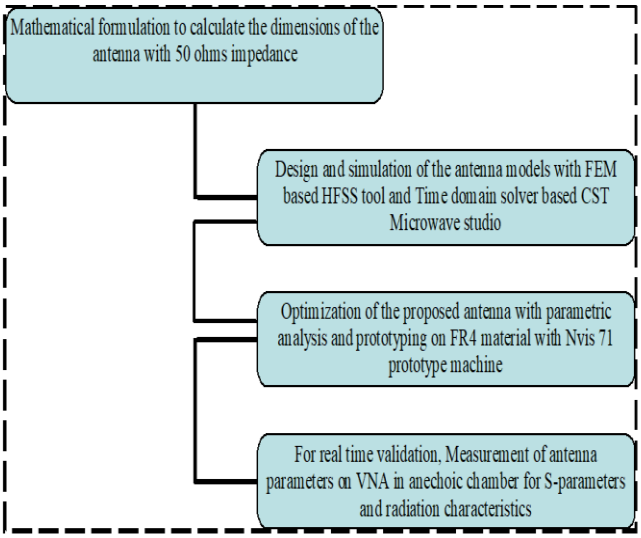


Figure. 3 Design methodology

$$e_1 = s_1 h_s \frac{\left(\frac{\Pi \ w_s}{4 \ h_s}\right)}{s_1 h_s \left(\Pi \ g_1 / \ 4 \ h_s\right)} \quad (6)$$

$$e^1_{\ 1} = \sqrt{1 - e^2_{\ 1}} \quad (7)$$

In the above equations, '*hs*' represents the height of the substrate, '*g1*' represents gap between ground plane and the elliptical patch element, '*w*' is the width of the feed line, '$\mathcal{E}$' is the dielectric constant of the substrate, 'ε_{eff}' is the effective dielectric constant, 'S_1' is the gap between ground and feed line. $E(e_1)$, $E(e'_0)$, $E(e'_1)$ and $E(e_0)$ are the first complete integral function and its complement forms. To achieve 50-ohm impedance, dimensions of the antenna are calculated from the above equations by considering FR4 substrate with dielectric constant 4.4 and loss tangent 0.02. Lumped port is used at CPW feeding in HFSS and waveguide port is used in CST Microwave studio. A detailed methodology of the work was given in Fig 3. A complete layout regarding design, simulation, prototyping and testing is presented in step wise.

The methodology that was followed in this work is categorized here in point wise.

1. Dimensional characterization is performed based on operating frequency and structure of the radiating element selected in the antenna model.
2. Design and simulation of antenna model with CST Microwave studio tool
3. Parametric analysis for optimization of the model at desired operating band
4. Prototyping the optimized model and real-time testing on VNA for validation.

2.1 Unit cell analysis

Split ring resonator is used to build left hand material. SRR unit is an artificial magnetic resonator which resonates at a frequency with a λ0 that is much larger than the SRR length. The resonance occurs when a time varying magnetic field is applied perpendicular to the plane that contains the SRR units. This results in inducing circulating surface currents on its rings, and the distribution of these currents shows that charges of opposite sign accumulated across the gaps and form a large distributed capacitance, which in turn results in producing very high positive and negative values of effective permeability at the vicinity of the magnetic plasma frequency where SRR strongly resonates. A

SRR unit cell consisting of two circular loops made up of metal material like copper with small gap between them. SRR can be modeled with LC resonant circuit and resonant frequency depends on the length of external ring, width of the strips and separation between parallel strips.

The permeability and permittivity of circular SRR can be extracted from simulated scattered parameter data S11 and S21. The equations for determining effective permittivity and permeability are

$$n = \pm \frac{1}{kd} \frac{cos^{-1}(1-{S_{11}}^2+{S_{21}}^2)}{2S_{21}} \quad (8)$$

$$z = \sqrt{\frac{(1+S_{11})^2-{S_{21}}^2}{(1-S_{11})^2-{S_{21}}^2}} \quad (9)$$

$$\epsilon_{eff} = \frac{n}{z} \quad (10)$$

$$\mu_{eff} = nz \quad (11)$$

Where ‘n’ is the refractive index, ‘z’ is relative impedance, ‘k’ is the wave number and‘d’ denotes dimension of unit cell. Transfer matrix method is used in the numerical calculation to find absorption loss

$$A = 1 - ({S_{11}}^2 - {S_{21}}^2) \quad (12)$$

To verify the antenna model performance characteristics, initially simulation of unit cell was carried on HFSS tool and presented in Figs. 5 and 6. Permeability and permittivity with respect to the unit cell analysis presented in this section showing the negative values.

3. Results and discussion

The reflection coefficient S_{11} will provide the information regarding the operating bands of the designed antenna model and bandwidth at resonant frequencies. Antenna model 1 resonating at multiband with quad band notching between 1 to 20 GHz as shown in the Fig. 4. Antenna model 2 also resonating at multiband with triple band notching in the prescribed range. The basic antenna model 1 notching the quad bands of 2.5-3.2 GHz, 6.2-.6.6 GHz, 7.6-9 GHz and 11.4-13.4 GHz respectively. The second model of split ring resonator based antenna notching the triple bands of 7.5-8.5 GHz, 11.6-13.2 GHz and 16-17 GHz respectively.

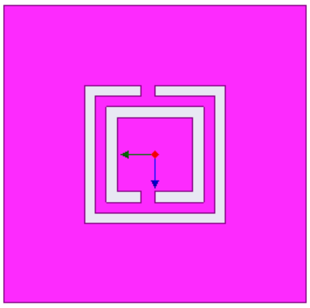


Figure.4 Unit Cell of Square SRR

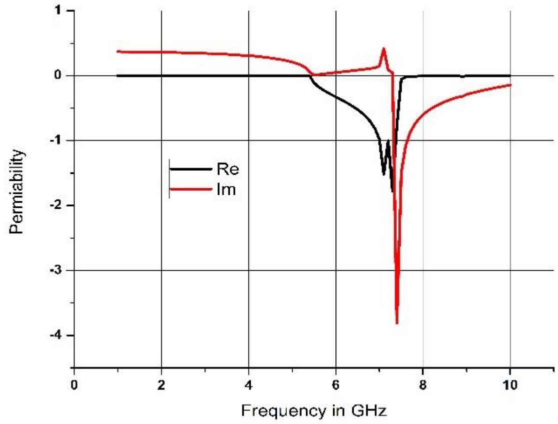


Figure.5 Frequency vs. permeability

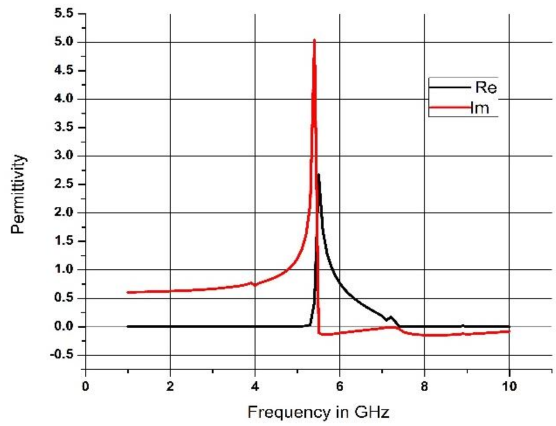


Figure.6 Frequency vs. permittivity

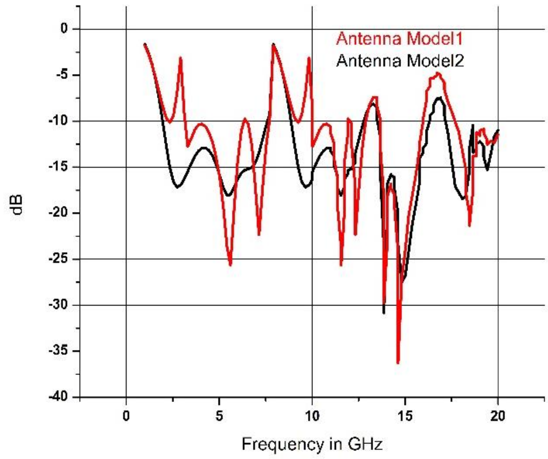


Figure.7 Reflection coefficient of antenna model 1 and 2

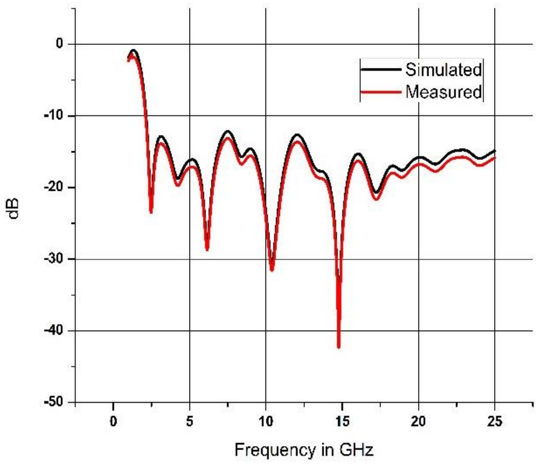


Figure.8 Proposed antenna reflection coefficient

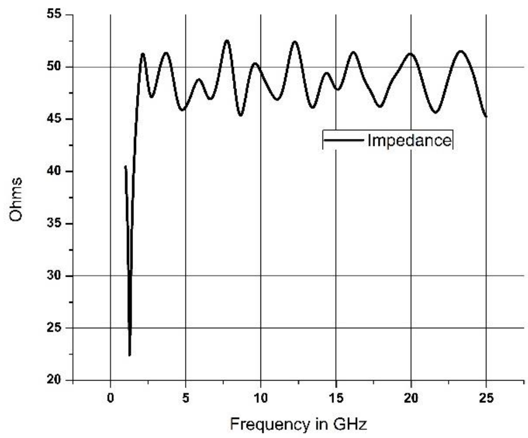


Figure.9 Proposed antenna impedance characteristics

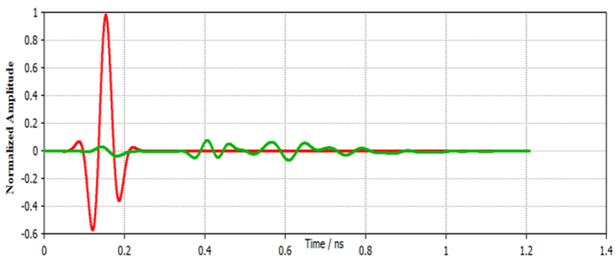
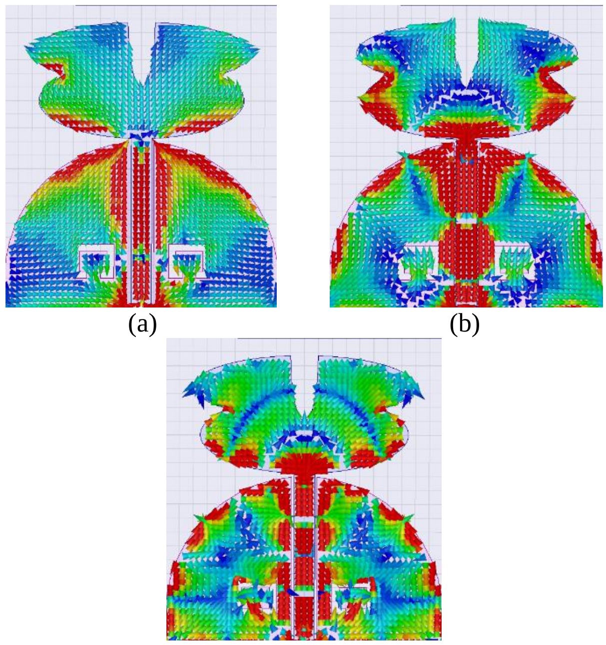


Figure.10 Time domain analysis

Single split ring is modified with complementary split ring resonator in the elliptical monopole antenna. The earlier models of 1 and 2 provided multiband characteristics, but the complementary split ring resonator based elliptical monopole is providing huge bandwidth of 22.9 GHz from 2.1 to 25 GHz. The proposed antenna reflection coefficient results of measured and simulation are shown in Fig. 8. An impedance bandwidth of 66% was achieved from the current antenna model.

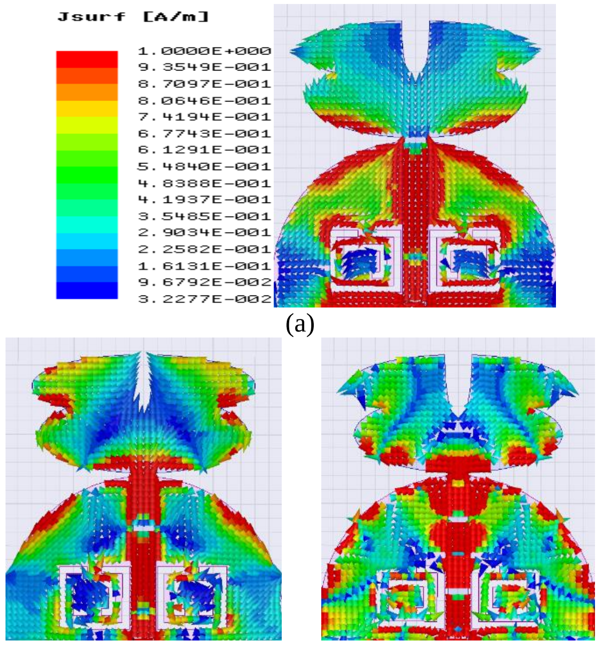
Fig. 9 presenting excellent impedance characteristics of the proposed antenna model, which is showing average impedance of 50 ohms in the operating band. The time domain analysis of the antenna model with CST tool is presented in Fig. 10.



(a) (b)

(c)

Figure.11 Surface current distribution of antenna model 2: (a) 5.6 GHz, (b) 10.6 GHz, and (c) 17.8 GHz



(a)

(b) (c)

Figure.12 Surface current distribution of proposed antenna: (a) 5.6 GHz, (b) 10.6 GHz, and (c) 17.8 GHz

The impulse response with respect to the input signal is presented in this result. Pulse distortion which is one of the characteristics of wideband signals is essentially determined by their wide bandwidth. To minimize reflection loss and to avoid pulse distortion good impedance match has to be maintained throughout the operating band. The main reason between the signal distortion as shown in Fig. 10 is due to mismatch between source pulse and the antenna.

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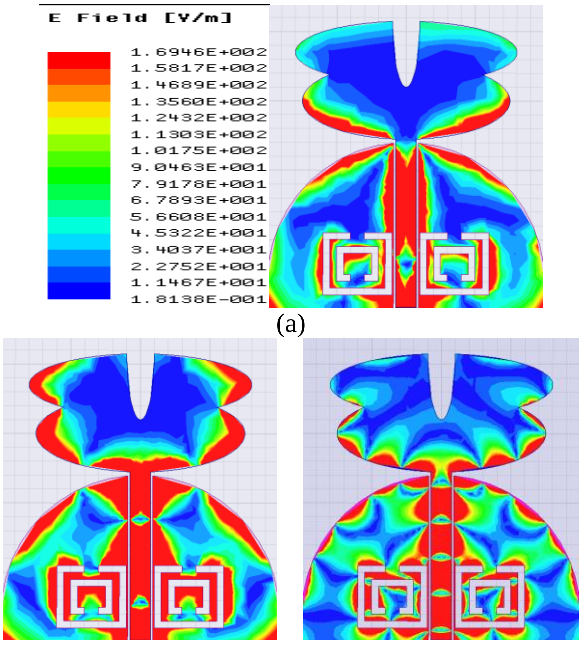

(b) (c)

Figure.13 Electric field distribution of proposed antenna: (a) 5.6 GHz, (b) 10.6 GHz, and (c) 17.8 GHz

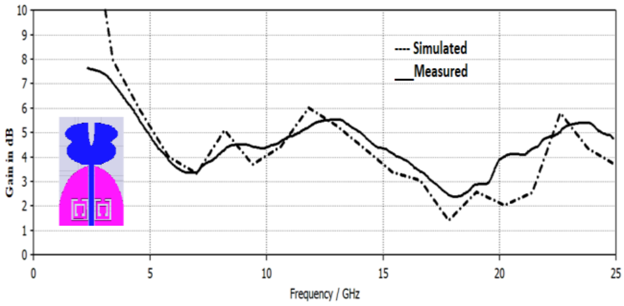

Figure.14 Gain vs. frequency

Figure.15 Prototyped antenna on FR4 substrate

Split ring resonator based multiband antenna model surface current distribution presented in Fig. 8. At lower bands of operation, the current density is low on the radiating element when compared with higher operating bands. Due to the single split ring slot on the ground plane the electrical length of the antenna is increased. The surface current distribution of the proposed antenna model is shown in Fig. 9. Most of the current density is focussed on the feed line at lower operating bands and in this case same magnitude with opposite direction of current on the feed line will lead to poor radiation at lower modes. The current distribution over the radiating structure at higher operating bands contributing more in the radiation of the proposed antenna.

The electric field distribution of the proposed antenna model is presented in Fig. 13. An equivalent electric field distribution can be observed at higher operating band rather than lower operating bands. The complementary split ring resonators guiding low electric density on ground plane and allowing maximum density over the radiating structure.

The measured and simulated gain characteristics of the proposed antenna are presented in Fig. 14. A good agreement can be observed between these two results. An average gain of 5 dB and average efficiency of 82% is attained in the operating band. The measured reflection coefficient results are collected from the prototyped antenna model shown in Fig. 15. R&S ZNB 20 vector network analyzer was used to measure the reflection coefficient results. The results obtained from the instrument are

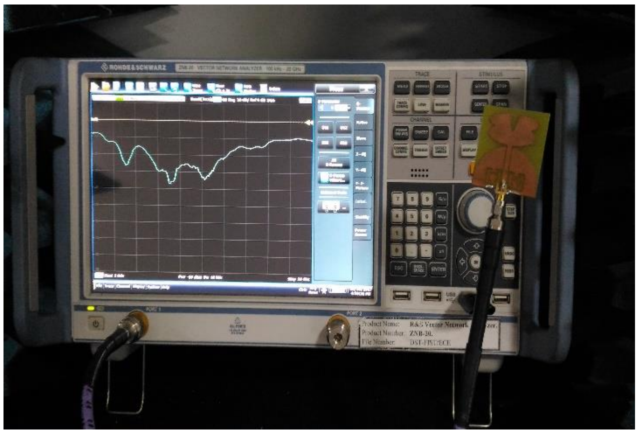

Figure. 16 Measured S11 on VNA

Table 2. Performance comparison of current antenna with literature

Model as per ref number	Size	Impedance Bandwidth%	Gain in dB	Bandwidth in GHz
[2]	56X54	60%	3.6	8
[3]	56X52	58%	3.8	12
[7]	62X56	64%	4.2	11
[9]	48X46	60%	3.2	9
[12]	62X60	58%	4.8	14
[14]	46X42	62%	3.8	16
Proposed Model	44X40	66%	5	22.9

almost matching with the simulation results obtained from HFSS tool.

Fig. 16 witness the measured results of S_{11} on vector network analyzer. The proposed antenna providing same kind of results in simulation and in real time measurement. The designed antenna is compared with other antennas from the literature and presented in Table 2. The proposed model is showing superior results when compared with other existing models.

4. Conclusion

This article proposes an elliptical monopole antenna with split ring resonators in the ground plane to enhance the bandwidth. In one way, these split ring resonators acting as defected ground structures and allowing antenna to resonate at additional bands. This causes enhancement in the bandwidth with 22.9 GHz at operating band from 2.1-25 GHz. The antenna model occupying compact size with stable radiation pattern and gain over the operating band. An average gain of 5 dB and efficiency more than 82% are key features of this proposed antenna. The prototyped antenna on FR4 substrate providing excellent correlation with simulation results obtained from commercial HFSS tool. The split ring resonators etched on the ground plane provided path for additional resonant frequencies and enhancement in the bandwidth. This model can be extended with multiple split ring resonators in the ground plane as well as additional strips on the back side of the feed line to enhance the impedance bandwidth. Conformal structure of this antenna model is also one of the challenging task to attempt for vehicular applications.

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