Volume 10, Issue 4
August 2021

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

Design of Novel Multi-Band Antenna for Satellite Applications

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ABSTRACT

In this article, a multi-band novel antenna for satellite applications is presented. The characteristics of the tri-band are established by excitation of fundamental (TM10 & TM01) modes and one higher order (TM12) monde in a rectangular antenna with employing characteristic mode analysis (CMA) to modify the antenna structure. TM10, TM01, and TM12 modes are shifted to L1-band, L5-band, and S-band, respectively, for IRNSS (Indian Regional Navigation Satellite System) and GPS (Global Positioning Services) receiver applications, using parametric and surface current investigations. To verify the simulated results of the CMA approach, the final optimized antenna is simulated using FIT (Finite integration methods) with coaxial feed excitation. The proposed antenna is printed on low-cost FR4 dielectric material with relative permittivity ($\varepsilon_r = 4.3$) and loss tangent (0.025) on FR4. The hardware of the antenna is tested to validate simulated results by CMA and full-wave FIT methods. The operational frequencies that have been measured are the L1-band (1575 MHz) for GPS systems, the L5-band (1170 MHz), and the S-band (2490 MHz) for IRNSS applications, with bandwidths of 31.7 MHz (1557.2-1588.9), 32.2 MHz (1163.4-1195.6 MHz), and 40.5 MHz (2469.7-2510.2), respectively, and stable broadside radiation patterns for each band.

Keywords: *CMA, GPS, IRNSS, L1-band, L5-band, S-band*

1. INTRODUCTION

The Indian Regional Navigation Satellite System (IRNSS) is a self-contained regional navigation satellite system built by the Indian Space Research Organization and completely managed by the Indian government (ISRO) [1]. There is a limit to using GPS (Global Positioning Services) in hostile situations due to foreign government policy, and it also does not provide better accuracy for tracking and navigation applications. However, the Indian navigation satellite IRNSS, which uses seven satellite constellations with dual-frequency bands L5-band (1176.45 MHz) and S-band (248.08 MHz) for Standard Positioning Services (SPS) and Restricted Services (RS), SPS for civilians and RS for specific users up to 10 meter for the Indian region and 20 meter for India, provides better accuracy in real-time applications, position, and time velocity. SPS for civilians and RS for specific users up to 10 meter [2-4]. There are big challenges to the integration of the antenna in the limited space of IRNSS receiver systems due to antenna size. As a result, numerous academics and companies have begun developing multi-band antennas that are small in size, low in cost, and simple to integrate with circuits for GPS and IRNSS applications [5-7].

Microstrip antennas are more effective because of their low profile, compact size, and ease of fabrication. To obtain multi-band responses, various forms and types of antennas have been used. To achieve the required bandwidth, any microstrip patch antenna with a conducting element etched on a nonconductive dielectric material and a matching network with a sufficient dielectric thickness. The antenna performance like return loss, directivity, gain, and efficiency can be enhanced by reducing the dielectric losses due to surface wave propagation [8]. In the communication system, the IRNSS plays a very important role which will make the antenna more effective with multi-band properties. Antennas with different shapes like a spiral, bi-cone, helix, and meandering transmission lines are reported [9-10]. Also, it shows the multilayer structures with coaxial and aperture feeding techniques that have thickness variation of dielectric material for enhancement of bandwidth.

The common methods for designing multi-band antennas are shorting posts, etched slots, stacked patches, multi-conductor and PIFAs (planar inverted antennas) [11,13,14], and DRA antenna hybrid radiating modes reported in [12]. But these antennas increase volume and complexity and are undesirable for integration circuits. They are also responsible for distorted radiation patterns [11]. In this communication, a novel single-layer antenna is designed with exciting fundamental orthogonal modes (TM10 and TM01) and one higher-order mode (TM12), along with stable radiation patterns in the broadside direction using surface current and far-field study of characteristic modes.

Section 3 of this article explains the synthesis and optimization of an initial antenna design using characteristic mode analysis without excitation using the MOM (Method of Moments). Section 4 describes the validation of characteristic mode analysis using Full-Wave simulation by FIT (Finite Integration Technique) with coaxial feed excitation, and simulated results are compared to measured results. Section 5 summarizes the proposed antenna.

2. CHARACTERISTIC MODE ANALYSIS OF PROPOSED ANTENNA

The characteristics mode theory was developed by Garbacz, Harrington, and Mautz (CMT). This method is unaffected by different types of excitations and is solely

Volume 10, Issue 4
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ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

dependent on the shape of the conducting bodies. In microwave applications, it's a powerful tool for EM characterization of conducting bodies [4]. This concept identifies a series of orthogonal real-current modes for the conducting body [6]. The modes of analysis can be numerically calculated for any arbitrary shaped conducting body, as given as:

$$[X]\,\vec{J}_n=\lambda_n\,[R]\,\vec{J}_n \quad (1)$$

Where, $\vec{J_n}$ and λ_n are the current and eigen values, R and X, are real and imaginary components of the Z- matrix, respectively. The current properties of a conducting body as determined by

$$\vec{J} = \sum_{n=1}^{N} \alpha_n \vec{J} \quad (2)$$

Where α_n is weighting coefficient for each characteristic mode.

Modal significance (MSn) is given as:

$$MS=\left|\frac{1}{1+j\lambda_n}\right| \quad (3)$$

CA stands for Characteristic Angle.

$$\alpha = 180^{o} - \tan^{-1}(\lambda) \quad (4)$$

The modal significance (MS) value should be close to unit for resonant condition of conducting body, and corresponding Characteristic Angle (CA) should be close to 180° [6].

3. PROPOSED ANTENNA DESIGN BY CMA METHOD WITHOUT EXCITATION

The proposed antenna is designed in three steps (Antenna-1, Antenna-2, and Antenna-3) on a FR4 dielectric substrate using the CMA approach for L1-band, L5-band, and S-band, as illustrated in Fig.1.

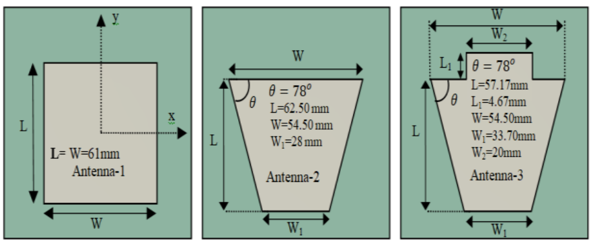


Fig.1. Schematics of Initial antenna designs by CMA (Dimensions)

3.1 PARAMETRIC STUDY OF ANTENNA-1

CST Software with MOM numerical methods is used to simulate the characteristic modes of the antenna-1 structure up to four modes without any excitation. The initial square antenna is designed and its parameters are calculated by the cavity model method for the fundamental mode (TM^{z}_{mnp}) as given by the following equation [15]:

$$(f_r)_{mnp} = \frac{1}{2\pi\sqrt{\mu\epsilon}}\sqrt{\left(\frac{m\pi}{h}\right)^2+\left(\frac{n\pi}{L}\right)^2+\left(\frac{p\pi}{W}\right)^2} \quad (5)$$

Where W, L, h denotes the antenna's width, length, and height, while m, n, and p denote the number of half-cycle field variations in the x, y, and z directions, respectively.

At L=W, antenna resonates fundamental orthogonal modes (TM10 and TM01) at same frequency, so we can calculate L parameter analytically for Antenna-1 using equation (5) for FR4 material.

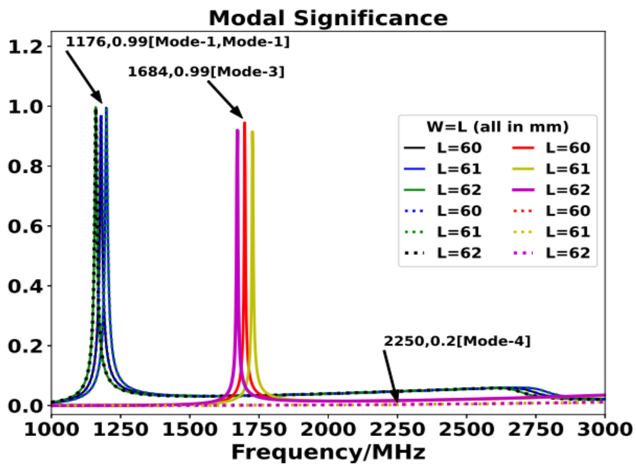
L-Parameter for TM^{z}_{010} $(mnp = 010)$ at L5 (1176.45MHz).

$$(f_r)_{010} = \frac{1}{2\pi\sqrt{\mu\epsilon}}\sqrt{\left(\frac{0\pi}{h}\right)^2+\left(\frac{1\pi}{L}\right)^2+\left(\frac{0\pi}{W}\right)^2} = \frac{1}{2L\sqrt{\mu\epsilon}} = \frac{C}{2L\sqrt{\varepsilon_r}},\quad L = \frac{c}{2(f_r)_{010}\sqrt{\varepsilon_r}} = \frac{3*10^8}{2*1176.45*10^6\sqrt{4.3}} = 61.48 \text{ mm}$$

And similar L value for mode TM^{z}_{001} $(mnp = 001)$ at L5 (1176.45MHz).

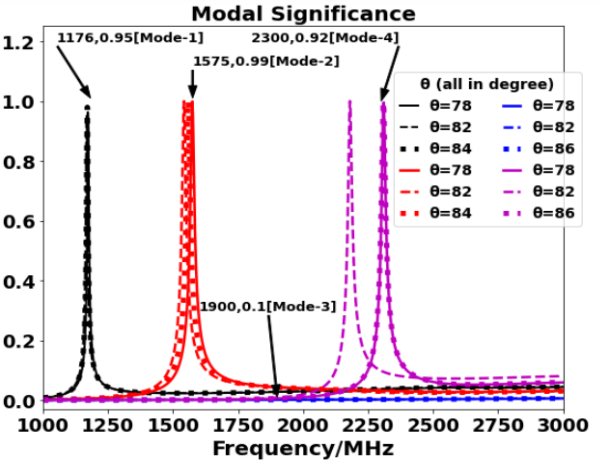
The antenna-1 is designed in the CST studio [17] and simulates up to four characteristic modes using analytical L values calculated from the cavity model method without any excitation. After parametric study of antenna-1, the fundamental modes (TM10 and TM01) are resonated at 1176 MHz for L = W = 61 mm, which is shown in the modal significant plot in Fig.2 (a). In this plot, only three modes resonate (due to MSn being close to one). The first and second modes are orthogonal at 1176 MHz, and the third mode is a higher order mode (TM12) at 1684 MHz the mode-4 is not resonant due to MSn = 0. The surface current distribution of antenna-1 is shown in Figure 3 (a). In this plot, the arrows of surface current for orthogonal modes (mode-1 and mode-2) are perpendicular to current nulls at the structure's corners, and for the third order mode (mode-3), there is one null point at the structure's center. As a result, the radiation pattern for orthogonal modes is hemi-spherical in nature with broadside direction, but for the third mode, their minimum radiation is at the center of the structure due to the available center nulls shown in Fig.4(a). Only a single band at L5-band (1176 MHz) is desirable for radiation in this step.

(a)

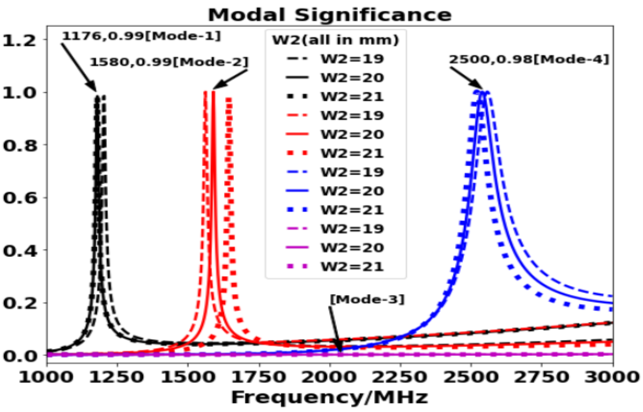


ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

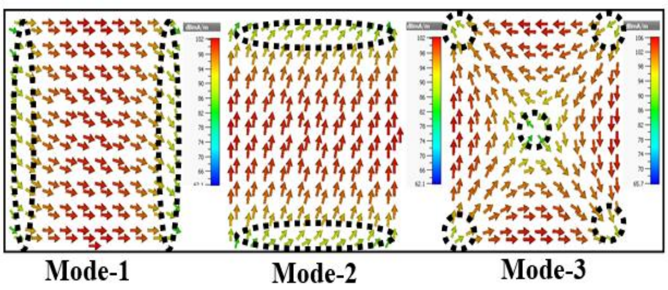


(b)

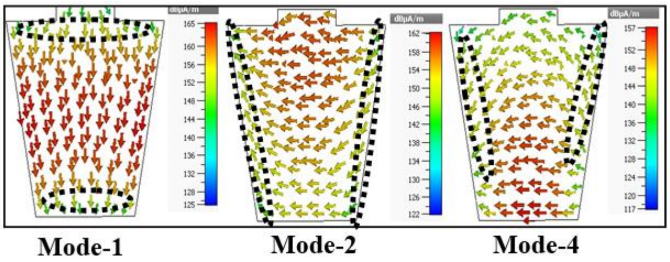


(c)

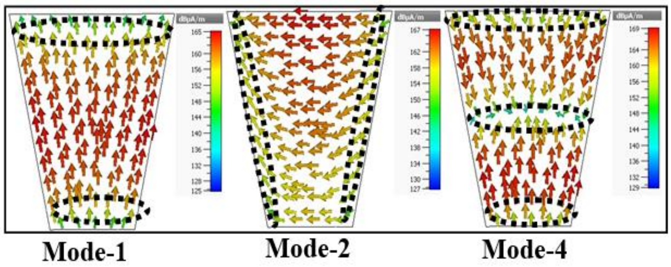
Fig.2. Modal Significant Plots for a) Antenna-1, b) Antenna-2, and c) Antenna-3



(a)



(b)



(c)

Fig.3. Surface current distribution for a) Antenna-1, b) Antenna-2, and c) Antenna-3, (**Black dashed shows current nulls**)

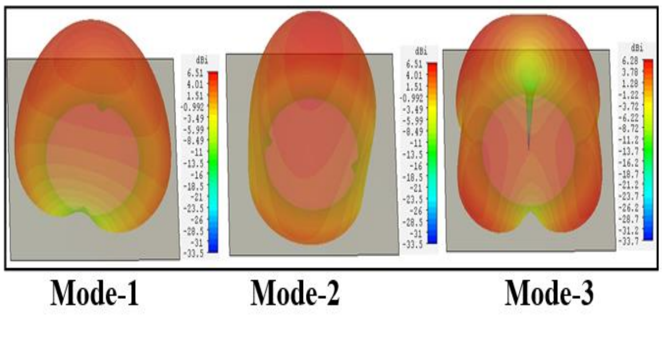
3.2 ANTENNA-2 PARAMETRIC STUDY

The antenna-1 design is further converted into the antenna-2 by parameter variation (78°, 82°, and 84°) to generate dual-band characteristics for the L1 and L5 bands with hemispherical radiation patterns by using CMA. The orthogonal modes (mode-1 and mode-2) are separated in such a way that one mode is resonated at 1176MHz and the other mode is resonated at 1575MHz by modification of the antenna-1 as shown in Fig.1 (b). The characteristic modes are resonated at 1176MHz, 1575MHz, and 2300MHz at =78° which is shown in Fig.2 (b), and their corresponding surface current distributions are shown in Fig.3 (b). In surface plots, the first and second orthogonal modes are orthogonal with different frequencies of 1176 MHz and 1575 MHz with corner current nulls. In this step, mode-3 is not resonant due to MSn=0. The mode-4 is resonated at 2300 MHz and the third higher-order mode is resonated with one center null, so both orthogonal modes have hemispherical radiation patterns in broadside radiation, as shown in Fig.4 (b).

3.3 PARAMETRIC STUDY OF ANTENNA-3

Finally, the Antenna-2 design is modified into Antenna-3, which generates tri-band characteristics in the L1-band, L5-band, and S-band for GPS and IRNSS applications, as shown in Fig.1 (c).

The characteristic modes are resonated (due to MSn closed to one) at 1176 MHz, 157 MHz, and 2500 MHz, shown in Fig.2 (c) and their corresponding surface current distribution plot shown in Fig.3 (c). Due to surface current nulls shifted toward the patch's corners, The L1-band, L5-band, and S-band radiation patterns are all broadside, which is the most required condition for navigation satellite receiver systems.

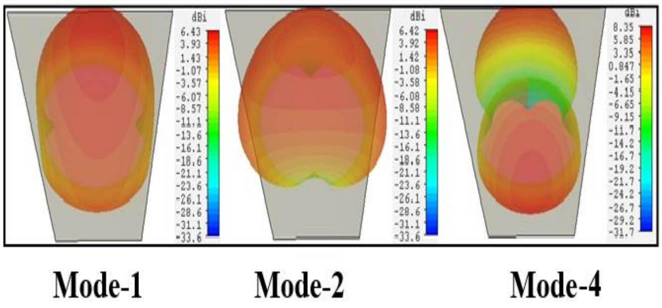


(a)

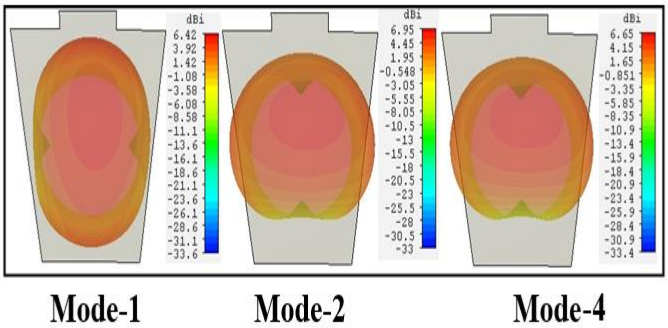
Volume 10, Issue 4
August 2021

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X



(b)



(c)

Fig.4. Radiation pattern for a) Antenna-1, b) Antenna-2, and c) Antenna-3

4. FULL-WAVE SIMULATION AND ANTENNA LAYOUT MEASUREMENT

The full-wave FIT method is used to simulate the optimized antenna design with coaxial feed line shown in Fig.5. The feed location has been chosen in such a way that all desire modes are excited simultaneously. The simulated S-parameter plot is shown in Figure 6 along with the measured results. A prototype of the proposed antenna was printed on a FR4 substrate with dielectric constants of 4.3 and loss tangent of 0.025, respectively, and a substrate volume of 100*100*1.6 mm^3, as shown in images in Fig. 8.

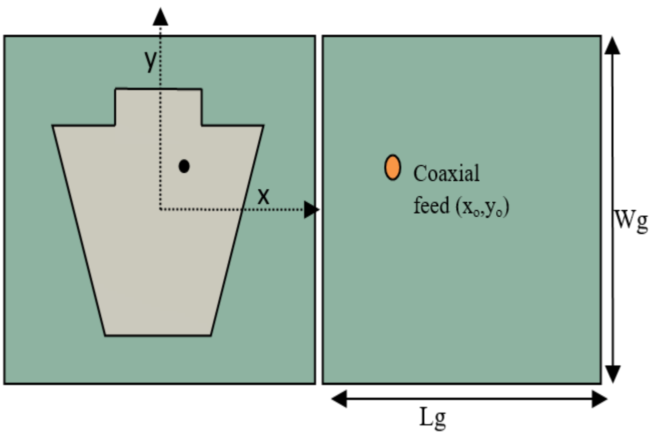


Fig.5. Design of the proposed antenna with feed

The proposed antenna's observed resonant frequencies are 1170 MHz, 1575 MHz, and 2490 MHz, with bandwidths of 31.7 MHz (1557.2–1589.9), 32.2 MHz (1163.4–1195.6 MHz), and 40.5 MHz (2469.7–2510.2), respectively. The measurement results are extremely similar to the modelling results, with slight deviations related to the measuring environment and fabrication. Figure 7(a,b,c) shows the far-field directional gain pattern at 1170, 1575, and 2490 MHz. Each band has hemispherical radiation characteristics, with a directive gain of 3.17 dBi for the L5-band, 2.15 dBi for the L1-bands, and 2.06 dBi for the S-band, making it suitable for GPS and IRNSS applications. Table 2 shows a compressive comparison based on GPS and IRNSS antenna applications.

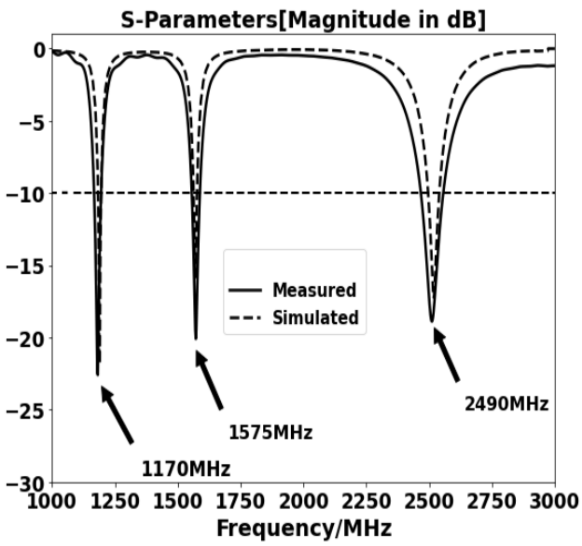


Fig.6. S11 Parameter of Proposed antenna

The dual band antenna is designed for the L5 and S bands on Rogger material reported in [1,16]. The single band antenna for the S-band IRNSS application is reported in [3]. The proposed novel antenna has additional features from earlier works, such as a tri-band operating frequency (L5-band, L1-band, and S-band), favorable bandwidth, broadside stable radiation patterns for each band, and it is designed on a low-cost FR4 material that is simple in nature for ease of fabrication and circuit integration.

TABLE1: Antenna dimension table

Parameters	Value (mm)	Parameters	Value (mm)
L_g	100	W_2	20
W_g	100	L_1	4.47
L	58.17	x_o	10
W	54.50	y_o	10
W_1	33.70	h	1.6

Volume 10, Issue 4
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ITEE Journal
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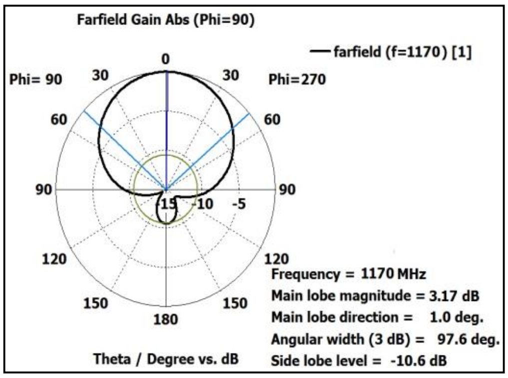
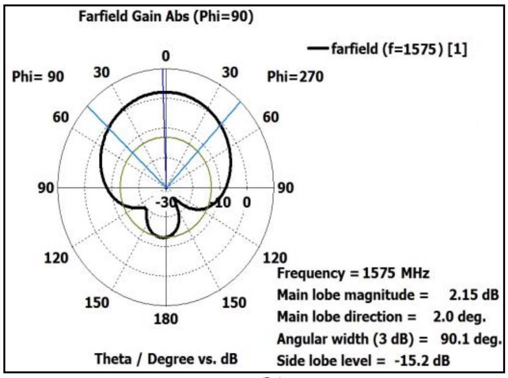
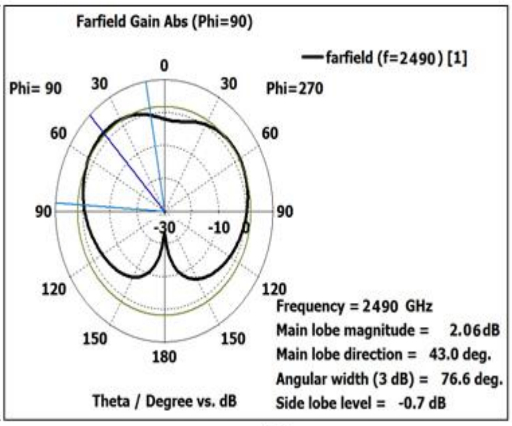
ISSN: - 2306-708X



(a)



(b)



(c)

Fig.7. Directive Gain of proposed antenna

Fig.8. Printed antenna on FR4 with coaxial feed

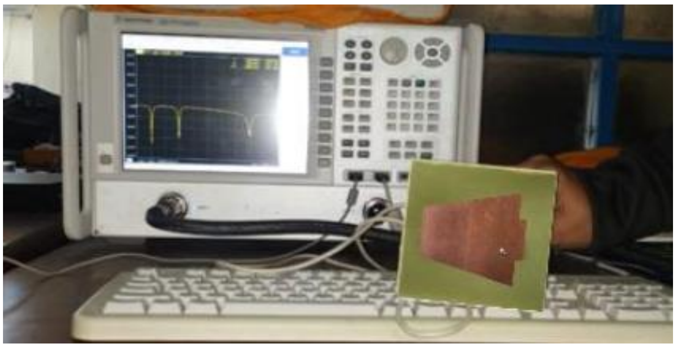


Fig.9 S11 measurements set-up with VNA

TABLE 2: Comparison of existing literature based on GPS and IRNSS applications

Ref.	[1]	[3]	[16]	**This work**
Frequency band	L5,S	S	L5,S	L1, L5,S
Bandwidth (%)	4.2,3.6	1.36	2.1,3.5	2.72, 2.3, 3.52
Volume (mm³)	100*100*4.7	100*100*1.6	114*114*1.6	100*100*1.6
Peak gain (dB)	1.02, 6.73	3.05	5.9,6.1	3.17, 2.15,2.06
Substrate	Rogger	FR4	Rogger	FR4

5. CONCLUSION

The design of a multi-band antenna for GPS and IRNSS applications is discussed by the author. In this study, the proposed antenna is built and tested using CMA and CST Studio Suite's Full-wave modelling. The designed antenna's operational frequencies are 1170 MHz, 1575 MHz, and 2490 MHz, respectively, with bandwidths of 32.2 MHz (1163.4-1195.6), 31.7 MHz (1557.2-1588.9), and 88.5 MHz (2469.7-2558.2). In this work, the initial antenna is optimized by the CMA method without excitation, and for validation of CMA, full-wave simulation has been used with a coaxial feed line. The full-wave simulation results are further validated by antenna layout measurement. So finally, a tri-band characteristic has been carried out with stable broadside radiation patterns for each desired band for IRNSS and GPS receiver applications.

ACKNOWLEDGEMENTS

This research supported by RTU (ATU) TEQIP-III and NPIU (TEQIP-III) in Rajasthan, India, under project sanction no. TEQIP-III/RTU (ATU)/CRS/2019-20/35.

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

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Dr. Jaget Singh has been an associate professor at Panjab University Chandigarh's University Institute of Engineering and Technology's Department of Electronics and Communication Engineering for the past 15 years. Electromagnetic field theory, microwave engineering, and antennas are among his scientific interests.