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Compact Size of Multiband Planar Monopole Antenna for Portable Device Applications

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ABSTRACT: The proposed planar antenna features F and U shaped strips on the patch, along with U shaped slits on the ground plane, catering to WLAN/Bluetooth/WiMAX/HYPERLAN applications. Initially designed for a resonance frequency of 2.4 GHz using standard formulae, the rectangular patch antenna boasts dimensions of $38.60 \times 46.70\,\text{mm}^2$, totaling $1803\,\text{mm}^2$. However, employing the covering electrical length technique, the proposed antenna effectively reduces size for multiband applications. The lengths of the strips determine the resonance frequencies, while the U shaped slits facilitate the adjustment of resonance frequencies as required. Following parametric optimization, the rectangular patch antenna becomes suitable for multiband operation, shrinking in size by up to 71.47% compared to its original form. The proposed antenna achieves resonance at 2.45 GHz, 3.55 GHz, and 5.37 GHz, effectively covering WLAN, Bluetooth, Zigbee, WiMAX, and HYPERLAN frequencies. Despite size reduction, the antenna maintains acceptable gain, ensuring its viability for multiband operations. The compact dimensions of the proposed planar antenna measure $39.5 \times 13\,\text{mm}^2$, making it ideal for integration into small portable devices such as mobile handsets, laptop computers, and USB dongles. Following fabrication, various parameters of the antenna are measured using a Vector Network Analyzer (VNA), including reflection coefficient, Voltage Standing Wave Ratio (VSWR), and impedance.

1. INTRODUCTION

From the last ten years as opposed to involving single band for single radio wire, the multiband receiving wire turns out to be extremely well known by utilizing cuts, spaces, and halfway ground plane. The size of receiving wire decreases by taking the assistance of slits, slots, surface current dispersion, and deserted ground structure. The multiband receiving wire is appropriate for various bands in a few compact development gadgets, for example, PC, cell sets, stylish telephones, and USB dongle application.

Present days multiband patch antenna turned out to be well known because of the activity of various frequencies in single patch, so it decreases the size and is effectively comfortable with any electronic circuits. We have some standard formulae for getting required single frequencies yet on the off chance that we need multiband antenna, and there are some procedures to bring multiband applications. The idea of capacitance and inductance is utilized. There is conversely connection between recurrence capacitance and inductance.

$$Fc = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Fc — Centre frequency, L — Inductance, C — Capacitance.

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The bandwidth upgrades are contrarily related with quality factor of antenna. The quality factor relies upon the copper size of antenna. The data transfer capacity can be improved by including space in copper layer, so diminishing copper region implies quality factor diminishes.

$$Bandwidth = \frac{1}{Q.F.} \tag{2}$$

$Q.F.$ — Quality factor.

Above formulae for center frequency and bandwidth are useful for obtaining the desired outcome from a single frequency. The small remote device is essential for communicating with web applications using a multiband antenna. The device has the capability to access multiple bands with an appropriate size, making it portable and convenient for use wherever needed.

Several antennas have been studied in [1, 2] for multiband application. U shaped and L shaped branches have been used to get multiple resonance frequencies [3]. U and L shaped slots are used to required bands [4].

The key dimensions of the right-angle structure and custom-designed U-shaped slot for enhancing bandwidth with optimal radiation characteristics have been determined through practical methods. In this study, the achieved bandwidth is approximately 2.4 times greater than that of a standard unslotted rectangular microstrip antenna [5]. The incorporation of stair-shaped slots on the ground plane has improved the bandwidth by around 7.3% by lowering the quality factor [6]. A wider bandwidth with satisfactory gain has been obtained by introducing a meandered microstrip feed along with a partial ground plane [7]. Further bandwidth enhancement of up to 12% has been accomplished by adding two parasitic elements to the proposed antenna [8].

Various antenna designs have been introduced, such as using series capacitors to reduce antenna size and employing double circular slot ring resonators to achieve multiband operation [9]. A square-shaped slot on the ground plane reduces the antenna size and supports multiband performance [10]. The addition of coupled circular rings on the ground plane minimizes the antenna size while maintaining the reference frequency band [10, 11]. Meandered slots contribute to size reduction [12], while a spiral planar inverted-F structure is used to decrease the size of patch antennas [12, 13]. Additionally, defected microstrip structures have been applied to further minimize antenna size [14]. These techniques have been proposed for multiband operation, bandwidth enhancement, and antenna size reduction across applications such as GSM, WiMAX, WLAN, Bluetooth, Zigbee, and HyperLAN.

The proposed antenna provides sufficient gain while maintaining a compact planar monopole design. There is a direct correlation between the gain and the size of the antenna, which depends on the electrical length. An increase in electrical length enhances current distribution, achieved by introducing cuts, slots, and branches in various planar monopole patch antennas. Planar monopole antennas offer several advantages, including ease of fabrication, multiband capabilities, compact size, lightweight design, and compatibility with electronic circuits. The F-shaped and modified U-shaped slots are optimized to achieve resonance at 2.45 GHz. Adjusted U-shaped slots incorporated into the ground plane enable resonance at 3.55 GHz and 5.37 GHz. These U-shaped slots in the ground plane are responsible for bandwidth enhancement, utilizing the concept of the quality factor.

2. ANTENNA DESIGN AND SIMULATION APPROACH

Conditions (1)–(6) are utilized for the proposition of rectangular microstrip patch antenna. The feed length is 9 mm, and width is 1 mm as shown in Figure 1.

The Width of the patch (Wp): The width of the microstrip patch antenna is given in "Equation (1)".

$$Wp = \frac{C}{2 * Fr\sqrt{\frac{\varepsilon r+1}{2}}} \tag{3}$$

Effective dielectric constant (*εreff*):

$$\varepsilon reff = \frac{\varepsilon r + 2}{2} + \frac{\varepsilon r - 1}{\sqrt{1 + \frac{12h}{W}}} \tag{4}$$

where *εreff* is the effective dielectric constant, εr the dielectric constant of substrate, h the Height of dielectric substrate, and W the Width of the patch.

Effective length (*Leff*):

$$Leff = \frac{C}{2 * Fr\sqrt{\varepsilon reff}} \tag{5}$$

Calculation of patch length (ΔL):

$$\frac{\Delta L}{h} = 0.414\left(\frac{(\varepsilon reff + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon reff - 0.258)\left(\frac{W}{h} + 0.8\right)}\right) \tag{6}$$

Length of substrate (Ls):

$$Ls = Lp + 6h \tag{7}$$

Width of substrate (Ws) :

$$Ws = Wp + 6h \tag{8}$$

Initially, the dimensions of rectangular patch antenna are calculated with the help of standard formulae as shown in Table 1. The designed rectangular patch antenna is suitable for 2.4 GHz resonance frequency by the proper adjustment of microstrip line [15].

TABLE 1. Rectangular patch antenna with dimensions.

Parameters	Calculated values
Resonant Frequency (fr)	2.4 GHz
Substrate	FR4
Dielectric constant (εr)	4.4
Substrate Height (h)	1.6 mm
Feed	Microstrip line
Patch Width (WP)	36.10 mm
Patch Length (LP)	27.4 mm
Substrate Length ($Lsub$)	38.60 mm
Substrate Width ($Wsub$)	46.70 mm
Length of Ground Plane ($Lsub = Lg$)	38.60 mm
Width of Ground Plane ($Wsub = Wg$)	46.70 mm

The design of the microstrip patch antenna with a structured microstrip line feed is illustrated in Figure 1. The proposed antenna is implemented using a microstrip line feed on an FR-4 dielectric substrate with a thickness of 1.6 mm and dimensions of $46.70 \times 38.60 \times 1.6\,\text{mm}^3$. The antenna is fed through a microstrip line feed and features a full ground plane with dimensions identical to those of the FR-4 substrate. The substrate has a relative permittivity of 4.4 and a loss tangent of 0.02, respectively [16, 17].

Based on the optimized parameters of the proposed rectangular patch antenna with a microstrip line feed, the Zigbee band ($fc = 2.4$ GHz) has been successfully achieved. The proposed rectangular microstrip antenna is designed with an enhanced microstrip line feed, and various antenna parameters are simulated using Computer Simulation Technology (CST) Studio Suite 14.0. Figure 2 illustrates the reflection coefficient, which is ≤ -10 dB for the microstrip line-fed MSA, showing a value of up to -19.5 dB for the Zigbee band. The primary objective is to design a multiband planar monopole antenna that supports

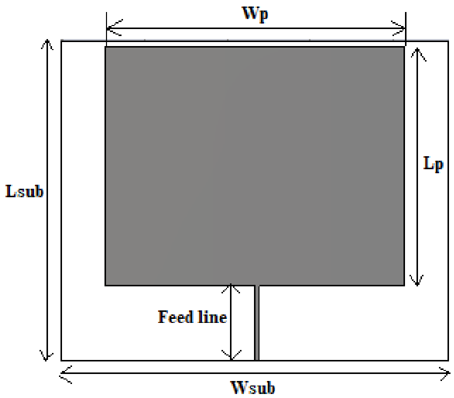


FIGURE 1. Rectangular patch antenna.

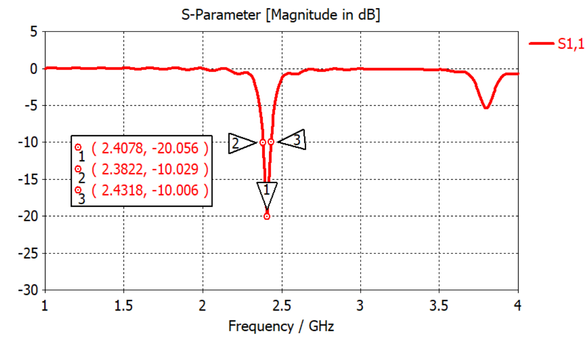


FIGURE 2. Reflection coefficient versus frequency graph for rectangular microstrip patch antenna.

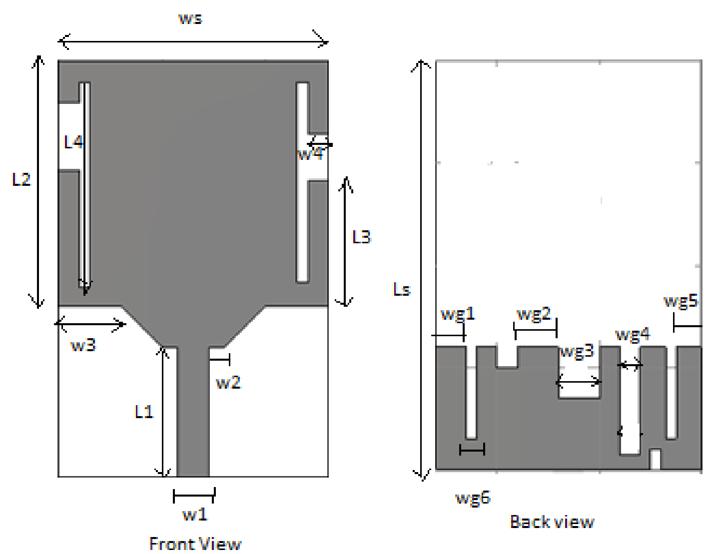


FIGURE 3. Planar monopole antenna using C shape slot & DGS (Antenna 1).

applications such as WLAN, Bluetooth, Zigbee, WiMAX, and HYPERLAN [18, 19].

Figure 3 shows that of asymmetrical C shaped slots on patch in front view and defected ground structure on the ground plane in back view to obtained the multiband antenna.

Table 2 shows that the microstrip line is connected to the patch on the front side of the antenna, with dimensions typically set to 3 mm to achieve a characteristic impedance of 50 ohms for the resonant frequency. This configuration places both the radiating patch and microstrip line on the same side, which is why it is referred to as a 'planar antenna' [22].

All simulations for the proposed antenna were performed using the CST Microwave Studio software. The simulated return loss results are shown in Figure 5.

An analysis of Figure 3 indicates that the C-shaped slot helps generate specific resonant frequencies, particularly at 3.52 GHz, while the defected ground structure contributes to resonances at 2.53 GHz and 5.36 GHz.

The achieved frequency bands are as follows:

TABLE 2. Antenna parameters (units in mm).

Design Parameters	Dimensions in mm	Design Parameters	Dimensions in mm
$W1$	3	$Wg1$	3
$W2$	1.5	$Wg2$	4
$W3$	6	$Wg3$	4
$W4$	2	$Wg4$	2
$L1$	12.5	$Wg5$	3
$L2$	23.5	$Wg6$	1
$L3$	12	Ls	40
$L4$	17.75	Ws	26

- The first band spans from 2.32 GHz to 2.73 GHz, offering a bandwidth of 410 MHz, which covers Zigbee, Bluetooth, and WLAN applications.
- The second band ranges from 3.39 GHz to 3.64 GHz, providing a bandwidth of 250 MHz, suitable for WiMAX applications.

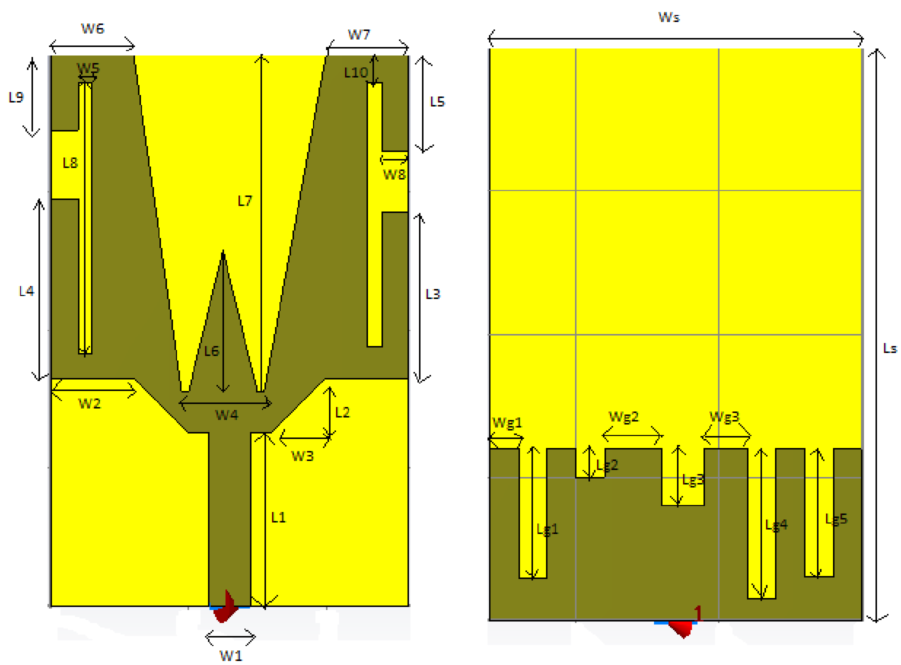


FIGURE 4. Planar monopole antenna using DGS, C and W shaped slots (Antenna 2).

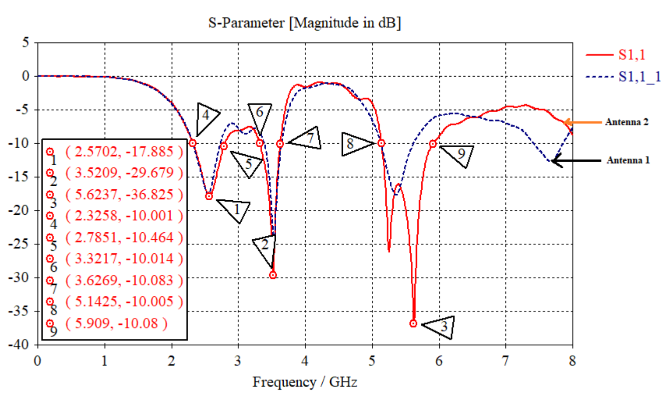


FIGURE 5. Comparative reflection coefficient versus frequency graph between planar antenna 1 and antenna 2.

- The third band extends from 5.13 GHz to 5.61 GHz, delivering a bandwidth of 480 MHz, catering to HYPERLAN 1 requirements.

Figure 5 clearly shows that the HYPERLAN 2 application, which ranges from 5.72 GHz to 5.85 GHz, is not covered. To address this, a portion of the copper in the middle of the patch is removed, and a W-shaped slot is added. This modification does not affect the other resonating frequencies but plays a role in enhancing the bandwidth of the proposed planar antenna. By removing the copper from the patch, the quality factor is directly affected, as it influences the bandwidth of the planar antenna.

A W shaped slot is added where it is shown in Figure 4. This W shaped slot is responsible for enhancing the bandwidth by reducing the quality factor. There is a direct relation between storage factor and portion of copper on patch and ground plane. The copper portion is responsible for reducing or increasing the storage factor. This technique is used to increase or decrease the bandwidth of antenna.

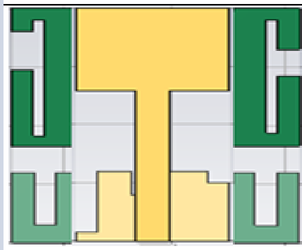
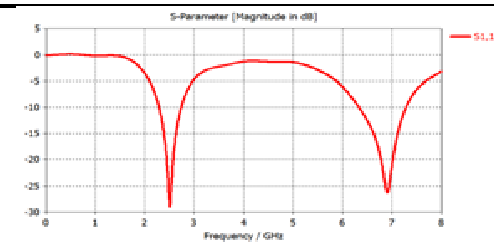
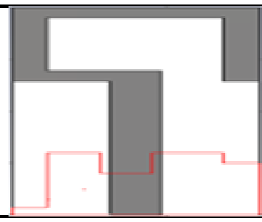
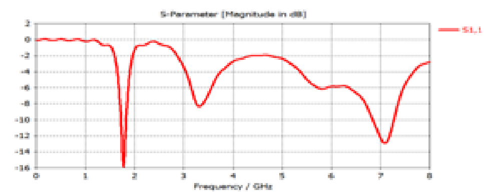
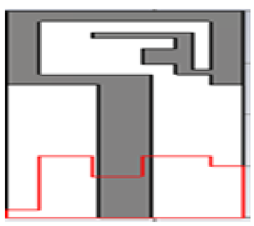
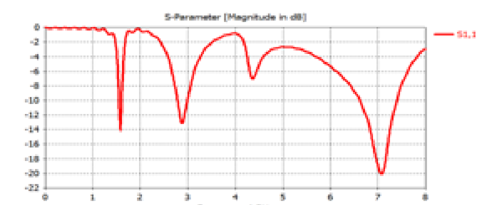
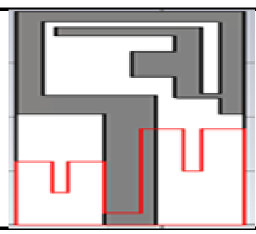
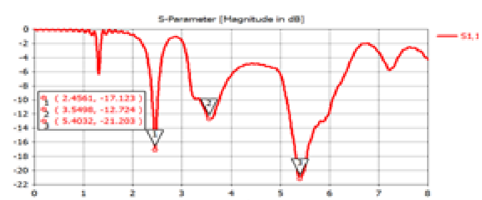
Table 3 shows measurements of fix and ground of planar antenna 2 by including W formed space. The microstrip line is connected to the front side of the antenna, set at a distance of 3 mm to achieve a characteristic impedance of 50 ohms for the entire frequency range. This configuration ensures that the radiating patch and microstrip line are located on the same side of the antenna.

TABLE 3. Antenna parameters (units in mm).

Design Parameters	Dimensions in mm	Design Parameters	Dimensions in mm
$W1$	03	$L7$	24.5
$W2$	06	$L8$	19.75
$W3$	04	$L9$	5.5
$W4$	05	$Wg1$	02
$W5$	01	$Wg2$	04
$W6$	06	$Wg3$	03
$W7$	06	$Lg1$	09
$L1$	11.5	$Lg2$	9.05
$L2$	04	$Lg3$	03
$L3$	12	$Lg4$	10.5
$L4$	13	$Lg5$	03
$L5$	07	Ls	40
$L6$	10.25	Ws	26

From Figure 5 in antenna 2 graph, it is observed that the W shaped slot is responsible for enhancing the bandwidth from 5.14 GHz to 5.90 GHz for covering the HYPERLAN 1 and HYPERLAN 2 application. The lower frequency band spans from

TABLE 4. Evolution process of planar antenna 2 to reduce the size.

Evolution process	Return loss
	
Improvement in Parameters	In patch and ground plane there is no copper portion so added square shaped patch along with microstrip line by sustaining same portion and remaining portion is removed. By doing this process two resonance frequencies come in picture.
	
Improvement in Parameters	By adding the inverted U shaped strip are responsible to produced two resonance frequencies and produce third resonance frequency but it is not acceptable.
	
Improvement in Parameters	By adding F shaped strip with inverted U shaped strip are accountable to obtained three resonance frequencies with increasing the electrical length.
	
Improvement in Parameters	But three frequencies does not resonates in proper range so these resonance frequencies are shifted towards the desirable location by using the defected ground structure.

2.32 to 2.78 GHz, providing a bandwidth of 460 MHz, which encompasses Zigbee, Bluetooth, and WLAN applications. The second frequency band ranges from 3.32 to 3.62 GHz, offering a bandwidth of 300 MHz, suitable for WiMAX applications.

This designed planar antenna is suitable for multiband operation, but main intension is to again reduce the size of antenna for the USB dongle application or portable devices.

From Figure 5 there are comparative results between planar antenna 1 and antenna 2 where it is given by blue dotted and red lines in the graph, respectively.

From Table 4 in both the patch and ground plane, areas without copper have been modified by adding a square-shaped patch along with the microstrip line, while the remaining sections are removed. This modification results in the appearance of two resonance frequencies. The introduction of an in-

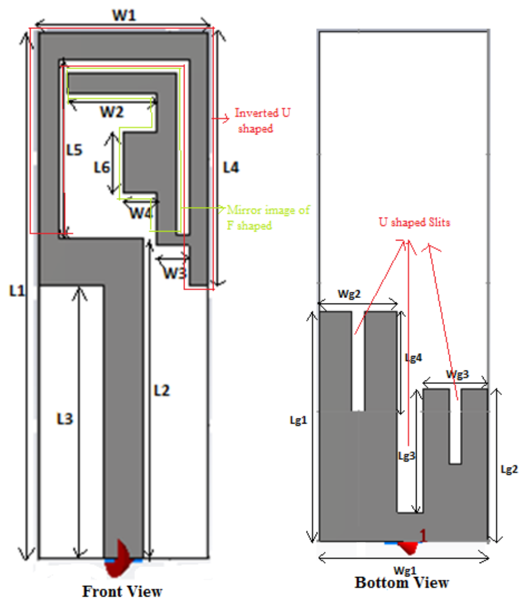


FIGURE 6. Geometry of the proposed antenna.

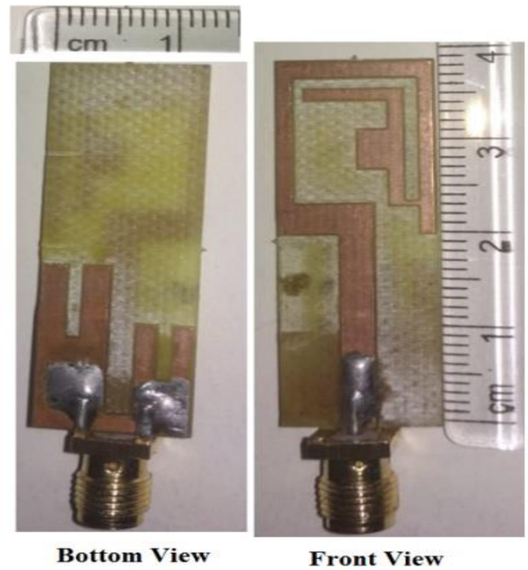


FIGURE 7. Photos of the proposed planar antenna.

verted U-shaped strip is responsible for generating these two resonance frequencies. Furthermore, adding an F-shaped strip alongside the inverted U-shaped strip leads to the emergence of three resonance frequencies due to the increased electrical length [23]. However, these three frequencies do not initially resonate within the desired range. To shift the resonance frequencies to the target range, a defected ground structure (DGS) is implemented. The DGS plays a crucial role in altering the transmission line parameters, such as capacitance and inductance. There is an inverse relationship between the resonance frequency and the capacitance and inductance, as demonstrated in Equation (1).

The overall dimension of proposed planar antenna is $39.5 \times 13.5 \times 1.6\,\text{mm}^3$, and the planar antenna comprises perfect representation F molded and upset U formed on the front view as in Figure 6. The incomplete ground plane is utilized with U formed cuts to bring the 3.5 GHz and 5.37 GHz frequencies. The U formed cuts are utilized to accomplish required bandwidth.

The proposed antenna showcases its physical parameters in Table 5. It employs a microstrip line matching technique with a width of 3 mm to achieve a $50\,\Omega$ impedance match for the SMA connector. Given that the SMA connector itself has an impedance of $50\,\Omega$, the microstrip line is designed to match this impedance accordingly for effective impedance matching.

3. SIMULATED AND MEASURED RESULTS

The designed antenna is manufactured using a printed circuit board (PCB) prototype machine, and its performance is evaluated using a Vector Network Analyzer (VNA). A calibration trainer kit is employed to calibrate the VNA, enhancing the accuracy of the measuring device and ensuring the quality of the measured results.

Figure 7 illustrates the front and base perspectives of the planar monopole antenna, showcasing the placement of the SMA connector soldered onto both the patch and ground plane. The fabricated multiband planar monopole antenna is as shown in Figure 7 along with front view, bottom view, and centimetre scale.

TABLE 5. Antenna parameters (Units in mm).

Design Parameters	Dimensions in mm	Design Parameters	Dimensions in mm
$W1 = Wg1$	13	$L5$	13.5
$W2$	6.85	$L6$	4.5
$W3$	2.5	$Wg2$	06
$W4$	2.5	$Wg3$	05
$L1$	39.5	$Lg1$	17.8
$L2$	24	$Lg2$	11.8
$L3$	20.5	$Lg3$	9.6
$L4$	19	$Lg4$	08

Figure 7 presents the front and rear views of the planar monopole antenna, featuring an SMA connector soldered to both the patch and ground plane. The SMA connector plays a critical role in evaluating the performance of the fabricated patch antenna by enabling connection to a Vector Network Analyzer.

Figure 8 illustrates the reflection coefficient, highlighting three resonance frequencies at 2.45 GHz, 3.55 GHz, and 5.37 GHz. A modified ground plane, along with the combined design of an F-shaped structure and an altered U-shaped form, is used to generate these distinct resonance frequencies. The 2.45 GHz resonance frequency ranges from 2.39 to 2.50 GHz, providing a bandwidth of 110 MHz, which covers applications such as Zigbee, Bluetooth, and WLAN. The second frequency band spans from 3.23 to 3.78 GHz, offering a bandwidth of 550 MHz, suitable for WiMAX. The third band ranges from

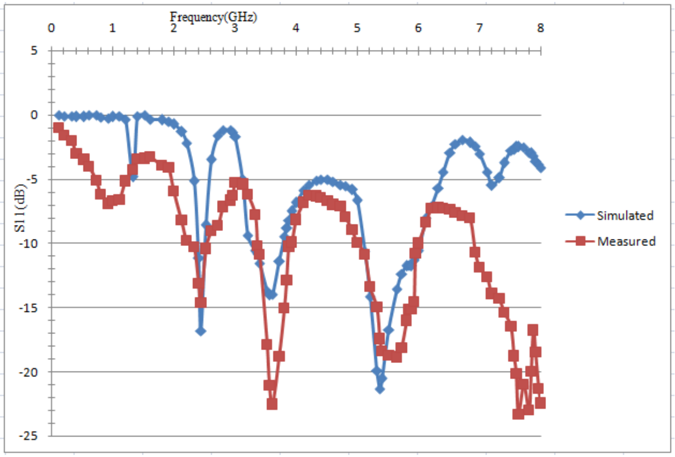


FIGURE 8. Comparative result of reflection coefficient versus frequency to designed and fabricated planar antenna.

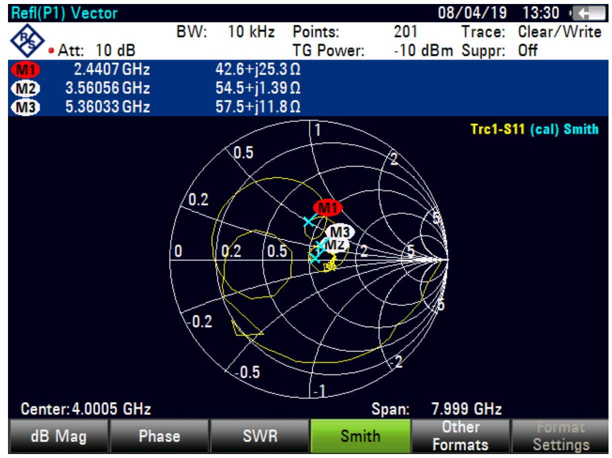


FIGURE 9. Impedance for the proposed antenna.

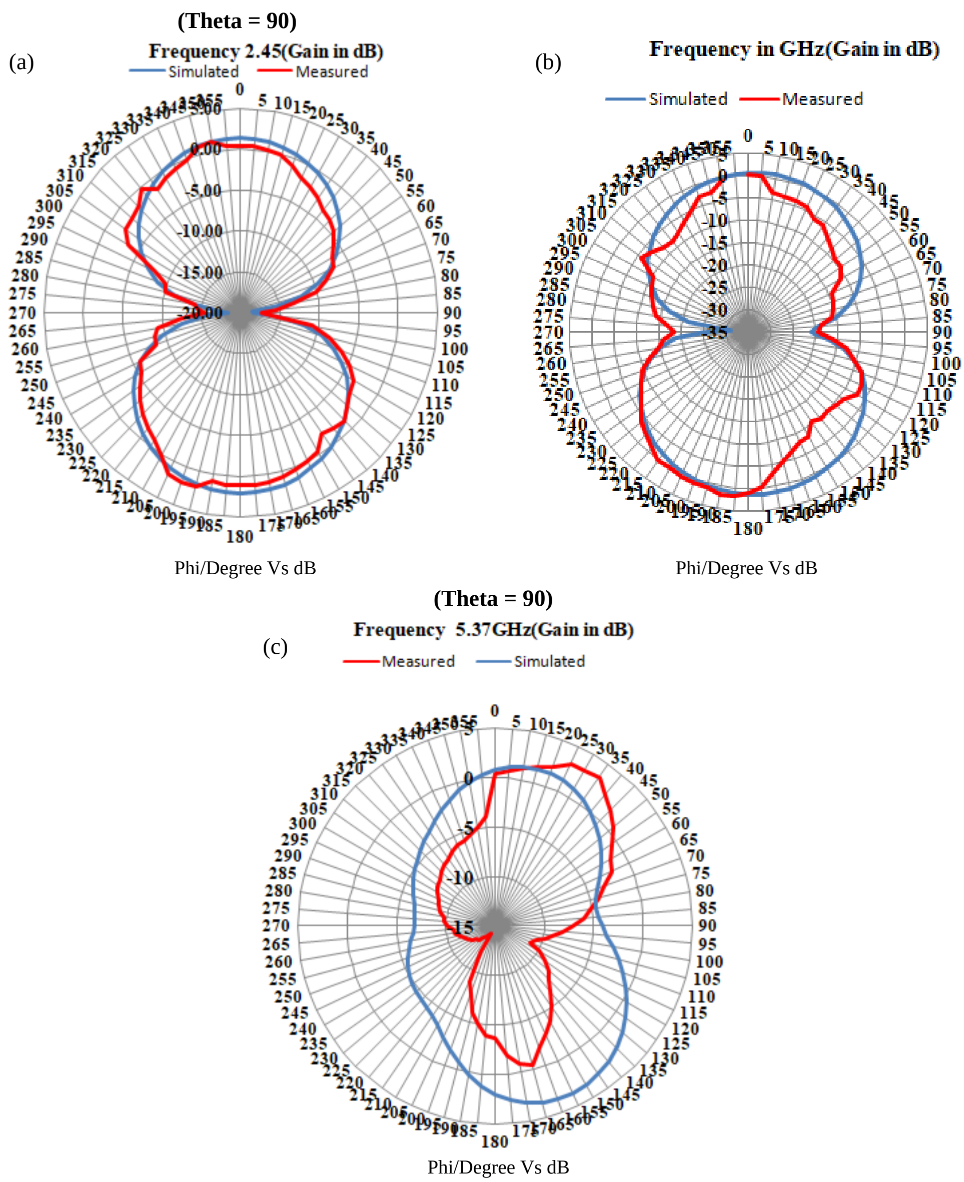


FIGURE 10. Measured polar radiation patterns of antenna at (a) 2.45 GHz, (b) 3.55 GHz, (c) 5.37 GHz frequencies.

TABLE 6. Comparison with proposed antenna and the works by other authors.

References	Designed technique	Size reduction in %	Return Loss	Gain
[20]	two meander slits on the common ground (2024)	83.37%	2.46 GHz-, 3.47 GHz, 5.45 GHz, −15 dB, −13 dB and −22 dB respectively	2.46 GHz-, 3.47 GHz, 5.45 GHz 1.43 dB, 1.44 dB, 3.63 dB respectively
[21]	Hexagonal patch with two pairs of mirror-imaged modified L-shaped resonator slots (2020)	67.38%	3.71 GHz, 4.21 GHz, 5.16 GHz, −13 dB, −16 dB, −18 dB respectively	3.71 GHz, 4.21 GHz, 5.16 GHz, 2.19 dB, 1.8 dB, 4.1 dB respectively
[9]	Modified double circular slot ring resonator (MDCSRR) on ground plane and inter digital capacitor (IDC) on patch (2018)	68.83%	3.2 GHz, −20 dB, 5.4 GHz, −16 dB, 5.8 GHz −19 dB respectively	3.2 GHz, 5.4 GHz, 5.8 GHz 3.28 dB, 2.76 dB, 3.1 dB respectively
[10]	Square shaped slot at the ground plane (2017)	90%	3.62 GHz−48.05, 7.06 GHz−28.79, 7.82 GHz−16.29 respectively	3.62 GHz −4.8 dB
[16]	Circular ring on ground plane (2015)	42%	2.45 GHz and −50.34 dB	2.23 dB
[18]	pair of mirrored L-shaped strips (2015)	20%	2.45/3.5/5.5 GHz bands −18, −40 and −20 dB respectively	2.45/3.5/5.5 GHz bands 3.2/3.5/5.4 dB
Proposed antenna	F and U shaped strips on patch and U shaped slits on ground plane	71.03%	2.45/3.5/5.5 GHz −16, −22 and −19 dB respectively	2.45/3.5/5.5 GHz 2.0/2.17/3.45 dB respectively

5.11 to 6.02 GHz with a bandwidth of 910 MHz, covering HYPERLAN1 and HYPERLAN2. The bandwidths of these three distinct frequency bands are beneficial for various applications, ensuring the required data transmission capacity for multiband operations.

Figure 8 shows that the three resonance frequencies — 2.45 GHz, 3.55 GHz, and 5.37 GHz — are well suited for multi-band operation, covering the necessary bandwidths. The reflection coefficients of the proposed planar monopole antenna from both measured and simulated results are closely aligned. As observed in Figure 8, the antenna effectively covers the required resonance frequencies with corresponding bandwidths, confirming its capability for multiband operation.

Figure 8 presents the simulated results related to resonance frequencies and bandwidth. The measured frequency range for the 2.45 GHz resonance frequency spans from 2.32 to 2.52 GHz, providing a bandwidth of 200 MHz, which covers Zigbee, Bluetooth, and WLAN applications. For the 3.59 GHz resonance frequency, the measured range extends from 3.36 to 3.88 GHz, offering a bandwidth of 520 MHz suitable for WiMAX. The third measured frequency band ranges from 5.12 to 6.08 GHz, with a bandwidth of 960 MHz, covering both HYPERLAN1 and HYPERLAN2.

Figure 9 shows the measured impedance of the proposed antenna, which closely matches the characteristic impedance of 50 Ω at the respective resonance frequencies. The source impedance is derived from the SMA connector through the microstrip line feed, which typically has a value of 50 Ω. From Figure 9, it can be observed that the source impedance and load impedance are well matched, allowing for efficient power transfer in the outward direction. The impedances at the resonance frequencies of 2.45 GHz, 3.55 GHz, and 5.37 GHz are 42.6 Ω, 54.5 Ω, and 57.5 Ω, respectively, all of which are close to the 50 Ω characteristic impedance.

From Table 6, it is observed that there are several techniques to reduce the size of planar antenna, but in proposed antenna easy method is given to reduce the size of antenna by increasing the electrical length of strip. The twice of electrical length of strips is equal to the wavelength of antenna which is responsible for resonating respective frequencies.

Figure 10 illustrates the polar radiation pattern of the planar antenna, showing how electromagnetic waves are radiated in different directions for each center frequency. The antenna demonstrates an omnidirectional radiation pattern across multiple resonance frequencies, ensuring uniform signal coverage.

The patch significantly influences the polarization characteristics, determining whether the polarization is vertical or horizontal. The measured gains at the corresponding center frequencies are 2.03 dB for 2.45 GHz, 2.25 dB for 3.55 GHz, and 3.72 dB for 5.37 GHz.

Furthermore, the polar radiation patterns presented in Figure 10 highlight the maximum gain achieved at each resonance frequency. These gain measurements were performed in an anechoic chamber at IIT Kanpur, India. The recorded peak gains for the resonance frequencies of 2.45 GHz, 3.55 GHz, and 5.37 GHz are 2.0 dB, 2.17 dB, and 3.45 dB, respectively. Antenna easy method is given to reduce the size of antenna by increasing the electrical length of strip. The twice of electrical length of strips is equal to the wavelength of antenna which is responsible for resonating respective frequencies.

4. CONCLUSION

The proposed planar antenna achieves a size reduction of up to 71.49% compared to a conventional rectangular patch antenna, primarily due to variations in the lengths of its F-shaped and U-shaped strips. This paper presents an innovative antenna design incorporating F-shaped structures combined with inverted U-shaped elements and a modified ground plane. These design features are carefully optimized to achieve three distinct resonance frequencies: 2.45 GHz, 3.55 GHz, and 5.37 GHz, accomplished by increasing the antenna's electrical length.

Specifically, the F-shaped and inverted U-shaped elements contribute to achieving the 2.45 GHz resonance frequency. Furthermore, the inclusion of U-shaped slits in the ground plane facilitates the tuning of resonance frequencies at 3.55 GHz and 5.37 GHz by modifying transmission line parameters such as capacitance and inductance.

Notably, the antenna design delivers a satisfactory gain, exceeding 2 dB for all central frequencies—2.45 GHz, 3.55 GHz, and 5.37 GHz. The strong correlation between fabrication and simulation results confirms the reliability and effectiveness of the proposed design.

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