

Design, Analysis, and Optimization of Dual Side Printed Multiband Antenna for RF Energy Harvesting Applications

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Abstract—In this paper, the performance of a compact, multiband, and dual side printed microstrip patch antenna is introduced. The proposed antenna configuration is designed using a nested triangular patch and defected ground structure (DGS). A simple rectangular DGS is constituted in the ground plane, which helps to enhance the multiband characteristics of the antenna with its size. The proposed design exhibits compact size, better radiation, and reflection characteristics over a multiband frequency ranging from 1 GHz to 6 GHz. These entire bands are allied with various wireless communication services, such as GSM 1400 MHz and 1900 MHz, ISM, WLAN, Bluetooth, LTE, Wi-Fi, and GPS applications. The receiving Triangular Nested Patch (TNP) antenna offers omnidirectional radiation with 4.45 dBi gain at 5.8 GHz and maximum return loss -34.31 dB at 3.75 GHz. Moreover, extraction of parameters has been presented in this paper with the variation of feed width and ground length. The proposed design shows the enhancement of gain and improved return loss. A comparative analysis has also been shown with the four different antennas parameters. Furthermore, this paper also presents the compact structure to cover efficient frequency ranging from 1400 MHz to 5.8 GHz for radio-frequency energy harvesting applications.

1. INTRODUCTION

The exposure of many electronic appliances such as digital watches, LED pen drives, laptops, and mobile phones has changed human's day to day life. Energy consumption is also a significant issue for researchers. So, the requirement of energy has made researchers employ self-sustainable energy sources (such as RF signals) which can receive energy from the nearby surroundings through various energy conversion methods, for example, wind, solar, thermal, vibration, and Radio Frequency energy harvesting (RF-EH) techniques. The energy harvesting from available RF sources could also reduce dependence on battery, provided that there are numerous attractive features for the environment and deployment [1]. The RF energy harvesting is a green and self-sustainable resource, and it provides an unlimited RF energy supply that can be used to wirelessly power low power devices [1]. The widespread availability of RF signals provides an alternative solution for the replacement of batteries. In addition, it improves consistency, portability, and environmental friendliness. It also miniaturizes the antenna and the cost of the device. Furthermore, the limited availability of electrical batteries motivates researchers to investigate eminent alternative [2]. However, the antenna design also plays a vital role in harvesting energy from the ambient sources. A variety of antenna designs have been presented by the researchers. Existing antennas for energy harvester operate on a single frequency band which harvest the power from the available single source of energy. For an instance, the proposed harvesting system in [3] uses a simple rectangular microstrip patch antenna having the dimension $54 \text{ mm} \times 57 \text{ mm}$ operating at 2.4 GHz. The novel coplanar waveguide (CPW) [4] presented the article for 2.45 GHz Bluetooth/WLAN applications and microstrip patch antenna along with fractal geometry are implemented in [5]. During

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the practical execution, these harvesting systems could not harvest the abundant power available in other frequency bands, which is the major drawback of the existing single frequency band antenna for RF energy harvesting. To enhance the area of application apart from the single band, a dual-band and multiband antenna structure is also analyzed.

Dual-band differentially driven patch antenna has also been in the literature. The antenna design in [6] serves for the Wi-Fi frequency bands of 2.4 GHz and 5.5 GHz. For RF energy harvesting a dual-band planar antenna was presented in [6]. The antenna structure presented in [7] is a monopole type of antenna. It has three microstrip lines and shares an identical feed point. At the moment, the input impedance has completely matched with two frequency bands, and these bands have been analyzed through the antenna. The analyzed spectrum shows enough potential for multi-band frequencies. Among the increasing requirement of renewable energy sources, RF energy harvesting has been upgraded in recent times. It helps those types of systems which derive energy from existing RF signals in the context of distinct sources. A triple-band differential antenna for RF energy harvesting applications has been introduced in the work [8]. The proposed antenna operates in various GSM, lower, and higher frequency bands [8, 9] which is suitably considered for RF energy harvesting applications. Besides that in [9], textile antenna for single and dual frequency bands is also analyzed by using numerical analysis. Furthermore, harvesting RF energy by a multi-band planar antenna has also been presented in [10].

The primary contributions of the work reported in this paper are as follows:

- A double-sided printed multiband planar antenna with DGS is designed and fabricated, and the radiation characteristics of the proposed antenna are attained. Moreover, the results show better performance of the antenna than the designs reported in the state-of-art [11–19]. In these reported works, antennas present adequate gain, but most of them do not work on the antenna size. The proposed antenna fulfils these requirements.
- Parametric analysis is done with the variation of feed width and ground length. The results report compact antenna size compared to the designs reported in the work [11–15].

Antenna miniaturization is done with the help of DGS. This shows less complexity when it is implemented in compact electronic devices such as mobile devices, wearable devices, and wireless sensor devices. The proposed antenna also shows the multiband behavior of its structure to cover the higher frequency bands as well as lower frequency bands with a reasonable gain and higher return loss. These two considerations show that the proposed antenna is a good candidate against other antennas [11–19] in terms of antenna size and multiband characteristics. Apart from this, it can get RF power against all directions.

The paper is arranged as follows. Section 2 shows the literature about the existing work. Section 3 explains the proposed antenna structure, fabrication, and testing methods. Section 4 discusses the experimental results of the antenna, and Section 5 concludes the work analysis.

2. LITERATURE REVIEW

In the literature, numerous multiband antennas have been studied in addition to RF energy harvesting applications [11–15]. For example, at the operating range of 1.2 to 5 GHz the Archimedean spiral dipole antenna has been designed for wireless energy harvesting [11]. The proposed antenna geometry has been determined by the lower and higher frequency bands. In active region, the antenna radiates RF energy where the perimeter of one spiral is equivalent to one wavelength. The size of the planned antenna is 58 mm × 55 mm × 0.8 mm along with 4.5 dBi average gain. From the work [12], a rectangular antenna with a tri-stepped patch structure for RF harvesting has been proposed. To achieve proper impedance matching and make the best use of the omnidirectional gain of all mobile frequencies, a step-like structure has been considered. This antenna operates with the LTE, GSM900 and 1800, 3G, 4G, and ISM (2.4 GHz) systems. 130 mm × 60 mm size of the antenna has been considered. This is quite large for mobile operating bands. The observed gain of the antenna is higher than 3 dBi for the considered GSM1800, 3G, 4G, and ISM bands. The overall calculated gain has been extended 1.1 dBi for the required frequencies. The printed monopole antenna, offered in [13], consists of a circular patch along with cut in a ground plane. The proposed antenna offers to operate (0.81 to 5.2 GHz) with a peak gain of 4.3 dBi. The considered dimension of the antenna is 120 mm × 100 mm. This antenna structure

shows large antenna dimensions. A planar broadband folded dipole antenna from 800 MHz to 2.5 GHz with $300\ \Omega$ of input impedance for RF harvesting energy is presented in [14]. $144\ \text{mm} \times 114\ \text{mm}$ is the size of the simulated antenna. The analyzed gain of the antenna is compatible with or more than 1.5 dBi over the complete band; therefore, it is able to cover 3G, 4G, and Wi-Fi bands. A broadband omnidirectional antenna has also been presented in [15]. The gain of the triangular antenna is higher than 2 dBi for the (0.85 to 1.94 GHz) entire band of interest. Dimensions are considered $94\ \text{mm} \times 82\ \text{mm}$ for the designed antenna. All the studied structures show that the size of the proposed antenna is quite large. So, there is a need to design a compact antenna structure for efficient energy harvesting application. Some multiband configurations have also been reported in [16–19].

A printed dipole multiband antenna has been presented in [16]. Observed response at the dipole antenna has been achieved by adding metamaterial (MTM). This reflects dual-band characteristics of the antenna. Moreover, a tri-band antenna has been proposed here by the loading approaches: the first symmetric loading approach observes the response through changing the position of the MTM cells. And the second, asymmetrical loading of cells has been performed by posting the antenna of two MTM cells. The proposed antenna has been analyzed on both the GSM 900 and 1800 MHz bands. In [17], a quad-band printed antenna is introduced. The antenna structure derived from a consisting microstrip feed line ($50\ \Omega$) has three different sizes of monopole antennas that show proper radiation in the GSM 900 and 1800 MHz, 2.4 GHz (WLAN) and 3.5 GHz (Wi-MAX) frequency bands. U-shaped and L-shaped monopole antennas for RF energy harvesting are considered here. In spite of the excellent behavior of the considered antenna for mobile applications, it cannot be used for high-frequency applications. The asymmetric coplanar strip antenna is assumed to operate in three different frequency bands [18]. This antenna operates at 2.3 GHz, 3.5 GHz, and 5.3 GHz, respectively. The planned antenna does not achieve the high-power in GSM band. [19] presents the structure of a broad-side coupled antenna. The planned antenna structure has a coupled loop along with two branch lines, which covers the bands 694–960 MHz and 1710–2590 MHz, and the proposed structure does not cover high-frequency operations. That is the major drawback of the existing research.

3. ANTENNA DESIGN

The antenna considered is a conventional patch antenna, and the reason behind that is its eminent properties of light weight. A low cost dielectric substrate FR4 ($\epsilon_r = 4.2$ and $\tan \delta = 0.02$) with a thickness of 1.6 mm is used to design the antenna. It consists of a top conductor layer and a lower conductor layer which act as radiators and ground planes, respectively [20]. The two layers are separated by dielectric materials that reflect radiation from the designed patches and plains along the edge of the ground [21]. We have calculated the width and length of the patch through the following equations [22],

$$W = \frac{C}{2f_0 \sqrt{\frac{\epsilon_r + 1}{2}}} \quad (1)$$

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}} \quad (2)$$

$$\Delta L = 0.412h \frac{(\epsilon_{eff} + 0.3) \left(\frac{W}{h} + 0.264 \right)}{(\epsilon_{eff} + 0.258) \left(\frac{W}{h} + 0.8 \right)} \quad (3)$$

$$L_{eff} = \frac{c}{2f_0 \sqrt{\frac{\epsilon_r + 1}{2}}} \quad (4)$$

$$L = L_{eff} - 2\Delta L \quad (5)$$

Here a triangular nested patch shape multiband antenna has been designed to radiate EM waves due to this broadband feature. A rectangular patch on the ground plane is introduced behind the feed line.

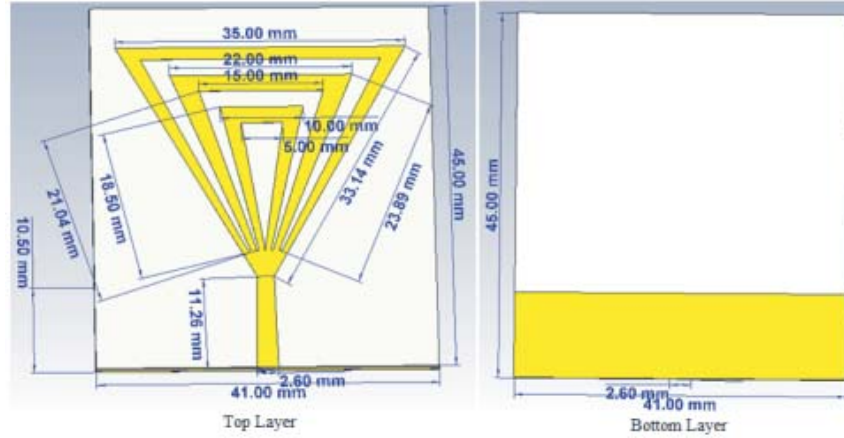


Figure 1. Geometry of the proposed TNP antenna.

A defect in the ground plane indicates the improvement in the gain at the higher frequency bands, better return loss (below -10 dB) at some specific bands such as 3.75 GHz, 5.18 GHz, and the compact antenna size. The proposed TNP multiband antenna configuration is shown in Figure 1. The antenna is fed by a $50\ \Omega$ microstrip feed line. To achieve multi-frequency band response, a rectangular slot DGS is applied on the ground plane. The main radiator component of the TNP antenna has a nested triangular shape attached to a microstrip feed line. The proposed design consists of three triangles where the inner triangle resonates near higher frequency due to its less surface space and the external triangle at a lower frequency with a larger surface area. Apart from this, the middle triangle plays a role to determine the resonating frequency by an antenna. The ground patch printed on the back of the substrate contains the DGS explained in Section 4.1.1.

3.1. Consumable Items, Testing and Fabrication Accessories

A dual side printed circuit board of FR4 substrate ($45\ \text{mm} \times 41\ \text{mm} \times 1.67\ \text{mm}$), PCB cutter, soldering iron with devices and etching solution (FeCl_3) has been bought locally. All the parameters of the antenna are measured with a vector network analyzer (VNA) acquired from Rohde & Schwarz and Spectrum analyzer (26 GHz) from Agilent Technologies.

3.2. PCB Preparation

A $45\ \text{mm} \times 41\ \text{mm}$ PCB is fabricated with the standard PCB fabrication procedure. The layer of excess copper on the PCB is etched by fecl_3 dilute. Once the PCB fabrication is done, $50\ \Omega$ SMA connector is added on the feed line. Now the complete PCB is shown in Figure 2.

4. RESULTS ANALYSIS AND DISCUSSION

The proposed antenna has a compact size of $45\ \text{mm} \times 41\ \text{mm} \times 1.67\ \text{mm}$. Both the simulated and measured results are presented here, and it demonstrates the broadband behavior of the planned antenna for efficient energy harvesting applications. A model of the planned antenna is fabricated (delineated in Figure 2) and tested. Measuring arrangement of the system consists of an R&S Vector network analyzer (VNA) and Device under test (DUT). Here we measure return loss (S_{11}) by the VNA. The analytical results of reflection coefficient are demonstrated in Figure 3.

The measured return loss shown in Figure 3 clearly indicates that the proposed antenna has a multiband characteristic. The resonance frequencies are located at 1.42 GHz, 1.9 GHz, 2.35 GHz, 3.75 GHz, 5.18 GHz, and 5.8 GHz, and the return loss readings at these frequency bands are -15.64 dB, -10.95 dB, -15.91 dB, -31.34 dB, -15.86 dB, and -10.28 dB, respectively. Compared to the simulated results, the measured reflection coefficient exhibits good agreement in resonant frequency

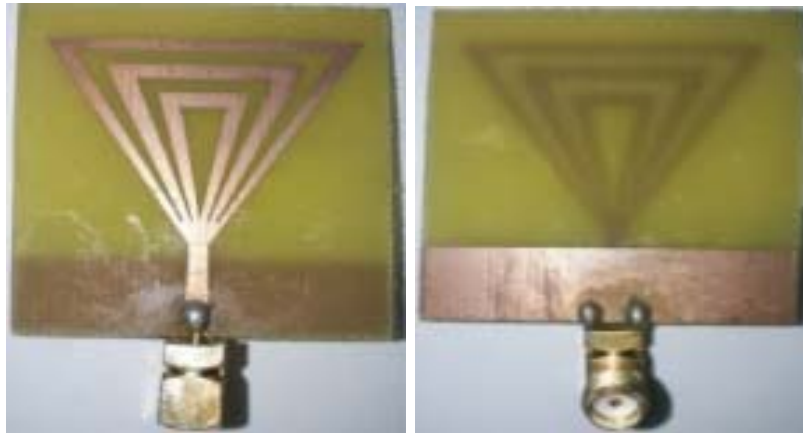


Figure 2. Fabricated TNP antenna (top and bottom layer).

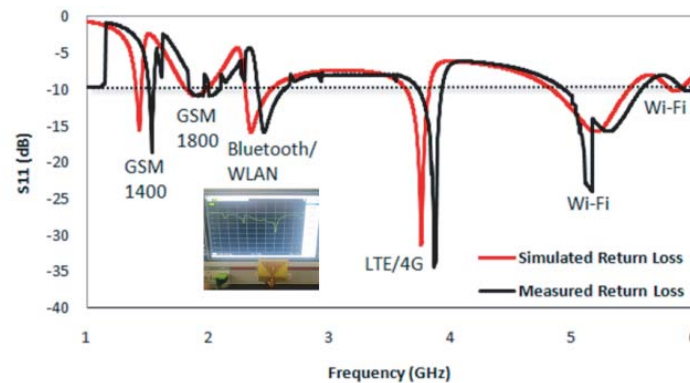


Figure 3. Measured reflection coefficients (S_{11}).

and bandwidth. The obtained result shows a good overall performance of the proposed antenna over the required frequency range: return loss better than -10 dB with impedance almost close to 50Ω . Good agreements are made between the simulated and measured results that satisfy the final agreement requirement. Parametric analysis of the antenna is also introduced in Section 4.1.

The analysis of receiving TNP multiband antenna is shown in Figure 4 depicting E plane and H plane. As demonstrated in Figure 4, the observed response of radiation pattern could be considered as omnidirectional. When the direction of the RF signal is not known, this type of antenna pattern is best suited for efficient harvesting.

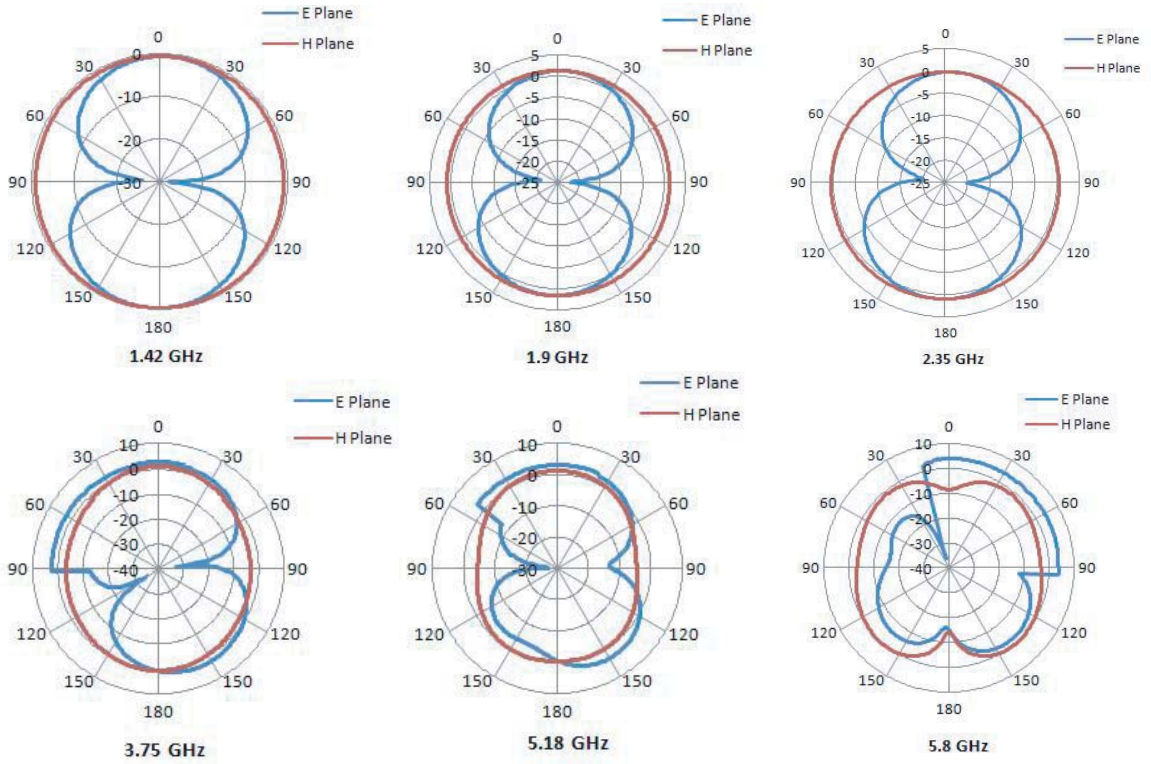
Table 1 shows the proposed antenna characteristics over the six operating bands. Apart from the characteristics of these six bands, it also represents excellent return loss (below -10 dB) at the considered frequencies; the analyzed (simulated) input impedance is totally matched to 50Ω . In addition, the antenna provides admissible directivity and gain corresponding to an omnidirectional antenna.

Figure 5 shows the characteristics of the simulated 3-D radiation pattern of the desired frequencies itemized in Table 1. As demonstrated from the figure, the radiation pattern of the first three frequencies (1.9 GHz, 1.42 GHz, and 2.35 GHz) indicates identical radiation in almost all directions, whereas for the other three bands (3.75 GHz, 5.8 GHz, and 5.18 GHz), the proposed antenna does not radiate uniformly in all directions.

In Figure 6, the feasible measurement setup is shown to evaluate the gain strength of the proposed antenna. This setup consists of a spectrum analyzer; the horn antenna with standard gain (in the transmitting end) and the TNP antenna (at the receiving end) are placed. For distinct frequency bands, the generated RF signal is transmitted through the horn antenna. To operate the antenna in

Table 1. Summary of the antenna.

Frequency (GHz)	Antenna Size (Wavelength)	Directivity (dBi)	Gain (dBi)	S_{11} (dB)	Input impedance
1.42	$0.21\lambda \times 0.19\lambda$	2.138	-0.269	-15.64	50Ω
1.9	$0.28\lambda \times 0.25\lambda$	2.276	1.756	-10.95	50Ω
2.35	$0.35\lambda \times 0.31\lambda$	2.278	0.880	-15.91	50Ω
3.75	$0.56\lambda \times 0.5\lambda$	4.556	2.644	-31.34	50Ω
5.18	$0.77\lambda \times 0.68\lambda$	3.977	3.264	-15.86	50Ω
5.8	$0.87\lambda \times 0.77\lambda$	5.232	4.45	-10.28	50Ω

**Figure 4.** Simulated gain (2D) of the TNP antenna E and H plane.

the far-field region, the horn antenna is positioned at a specified distance (2 meters) from the receiving TNP antenna.

From Figure 7, the measured gains at distinct frequency bands are analyzed. The overall obtained radiation patterns signify that the TNP antenna strongly shows the omnidirectional pattern of an antenna. The gains received at the considered frequency bands are -0.82 dB at 1.42 GHz, 1.005 dB at 1.9 GHz, 1.51 dB at 2.35 GHz, 3.547 dB at 3.75 GHz, 3.52 dB at 5.18 GHz, and 4.45 dB at 5.8 GHz.

Comparison of simulated and measured gains is reported in Figure 8. During the simulation, gains for the considered bands are -0.269 dB at 1.42 GHz, 1.75 dB at 1.9 GHz, 1.514 dB at 2.35 GHz, 2.64 dB at 3.75 GHz, 3.26 dB at 5.18 GHz, and 4.008 dB at 5.8 GHz respectively. Measurement of gain is done in an anechoic chamber. The gains received at the considered frequency bands are -0.82 dB at 1.42 GHz, 1.005 dB at 1.9 GHz, 1.51 dB at 2.35 GHz, 3.547 dB at 3.75 GHz, 3.52 dB at 5.18 GHz, and 4.45 dB at 5.8 GHz. With the analysis of these two responses, we have observed gain values during the measurement, which are quite variable due to human effects. It shows the maximum gain 4.45 dB at

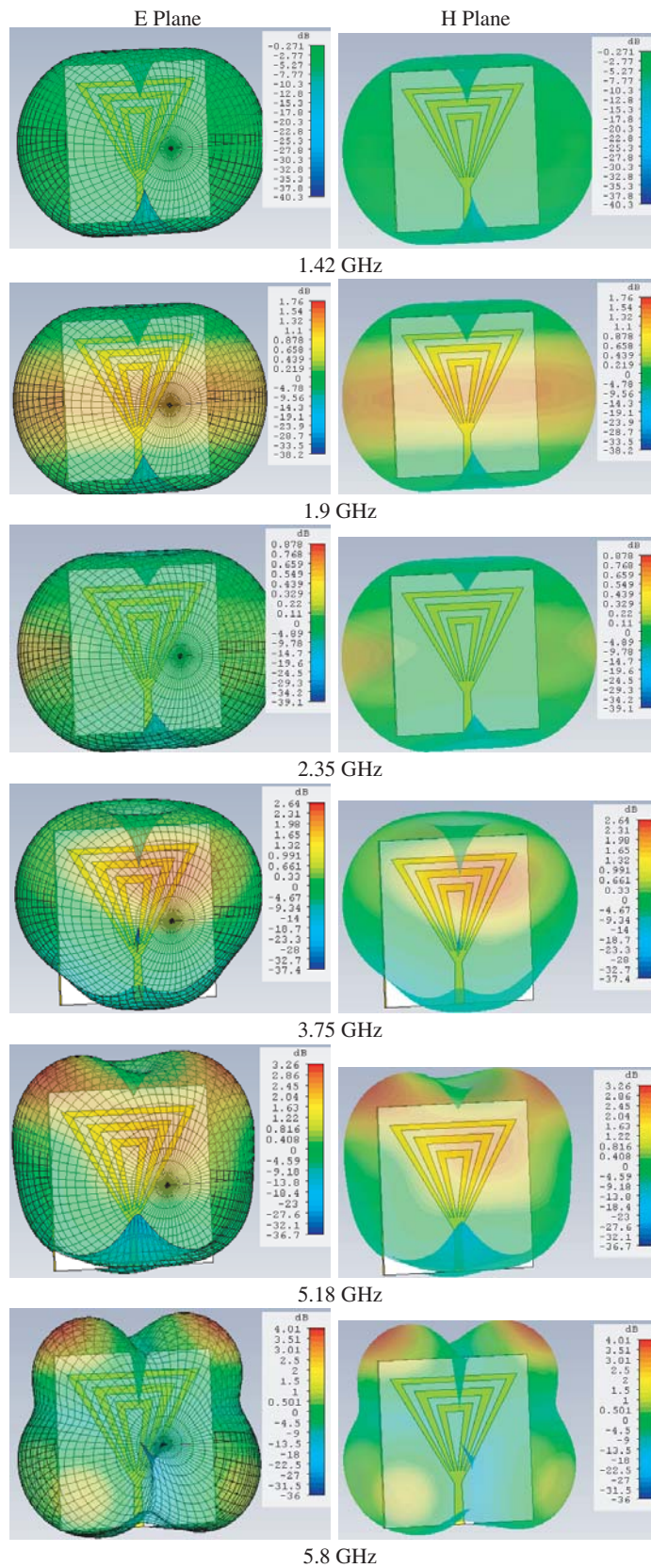


Figure 5. Simulated 3D radiation pattern (*E* plane and *H* plane).

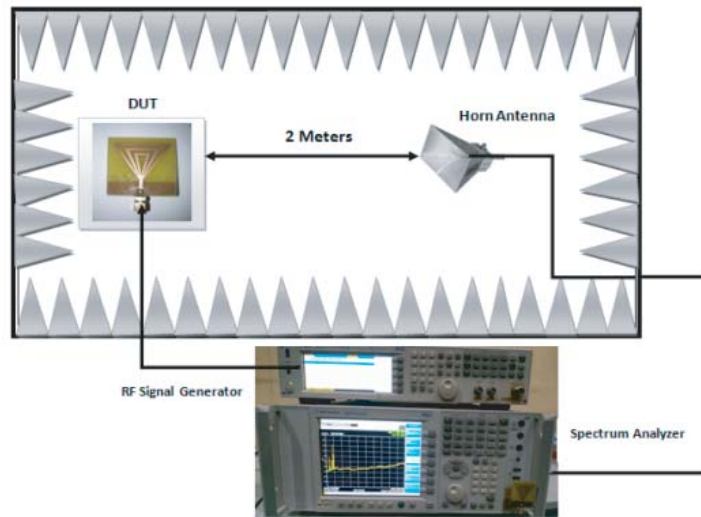


Figure 6. Set-up of anechoic chamber.

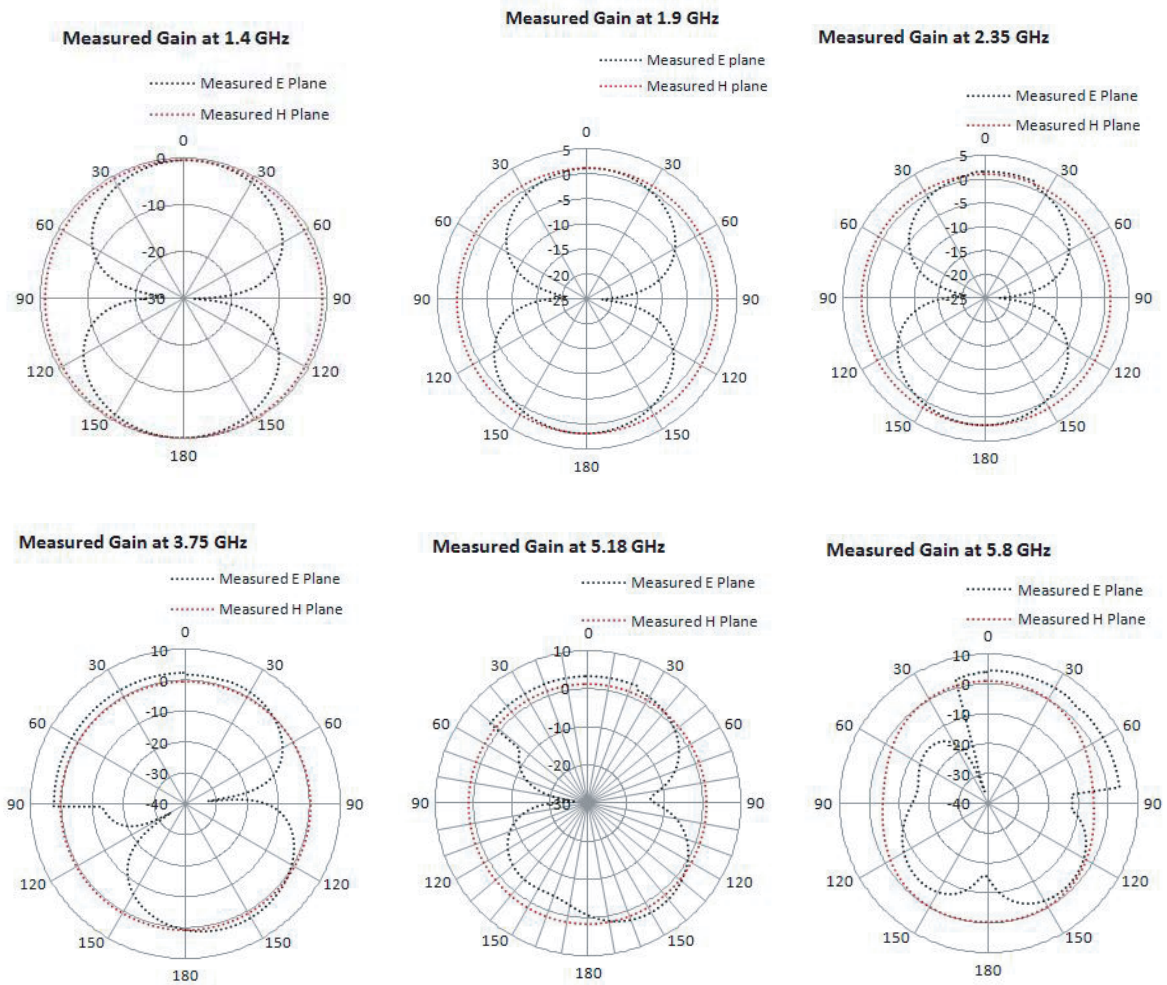


Figure 7. Measured gain of the TNP antenna fabricated on a FR-4 substrate.



Figure 8. Comparative analysis of gain.

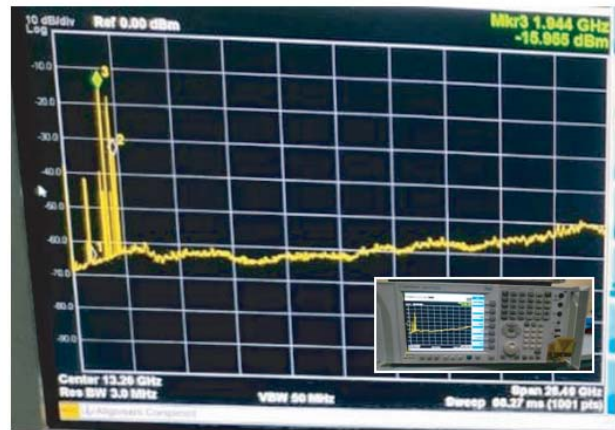


Figure 9. Received signal power of an antenna (Marker 1 — 67.156 dBm at 1.4 GHz, Marker 2 — 34.880 dBm at 2.42 GHz, Marker 3 — 15.955 dBm at 1.944 GHz).

5.8 GHz and sufficient gain at other frequency bands to receive the enough RF power for RF energy harvesting applications. Proposed antenna represents good candidature for efficient energy scavenging.

After the analysis of gain, we measure the received power of an antenna. As a result, the designed antenna structure is appropriate to receive RF power when the incident signals are not known (as shown in Figure 9). Received RF power is measured by spectrum analyzer. This power shows efficient reception of an antenna. The efficient power range during the transmission of cell phone data should be below -65 dBm to -67 dB. In our work, received RF power lies between the available ranges which is good for receiving maximum power for RF energy harvesting.

The very important parameters of an antenna used in energy harvesting are their radiator efficiency related to dielectric losses, conduction losses, and total efficiency, which takes into account the mismatch losses between the antenna and its feed. Efficiency is an important parameter in energy harvesting due to the very low power density of available sources. Figure 10 represents the radiation efficiency of the proposed antenna. This can be achieved by dividing the radiated power by the accepted power. The total efficiency of an antenna is the radiation efficiency multiplied by the impedance mismatch. So, it will be less than the radiation efficiency. Radiation efficiency of an antenna is the best way to predict the output behavior of proposed receiving antenna. This shows the proper reception of the available RF power.

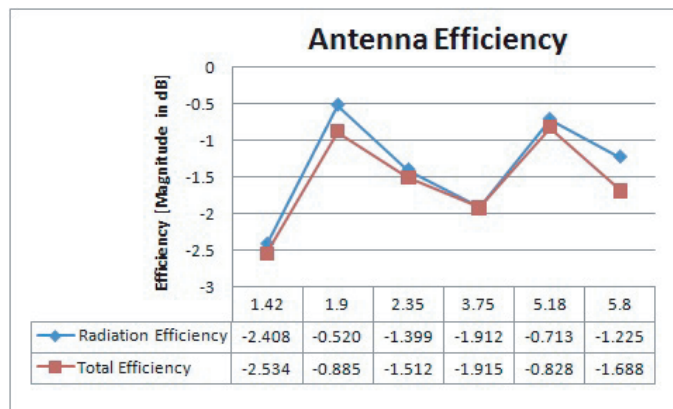


Figure 10. Radiation efficiency of the proposed antenna.

4.1. Parametric Analysis of the Proposed Antenna

There are a variety of parameters that can affect the outcomes of the antenna design, particularly the size of the feed and the dimensions of the ground patch concerning width and length. To identify their emphasis, parametric studies are performed using CST Microwave Studio.

4.1.1. Effect of Ground Patch

The techniques of defected ground structure (DGS) are designed in the ground plane just back on the feed line. The reason behind this design is that it shows the miniaturization in the antenna structure. This design is especially beneficial when it is implemented in compact electronic devices practically. The shape of the defect is rectangular as shown in Figure 2; this could be any type such as circle, triangle, and semicircle. During the parametric analysis, we change the DGS width with different intervals to enhance antenna return loss and gain characteristics. After the analysis, we observe a slight difference in return loss characteristics as shown in Figure 11. It has been observed that the change in ground length is of 7.50 mm while reporting the highest gain of 4.39 dBi at a frequency of 5.8 GHz. Due to the variation in the ground plane, scattering properties of the antenna can also get affected. So the size of the ground plane is designed as small as possible to keep the same construction and radiation properties. Figure 13 represents the gain plot with respect to the variation of ground length. It represents a quite enhancement in gain.

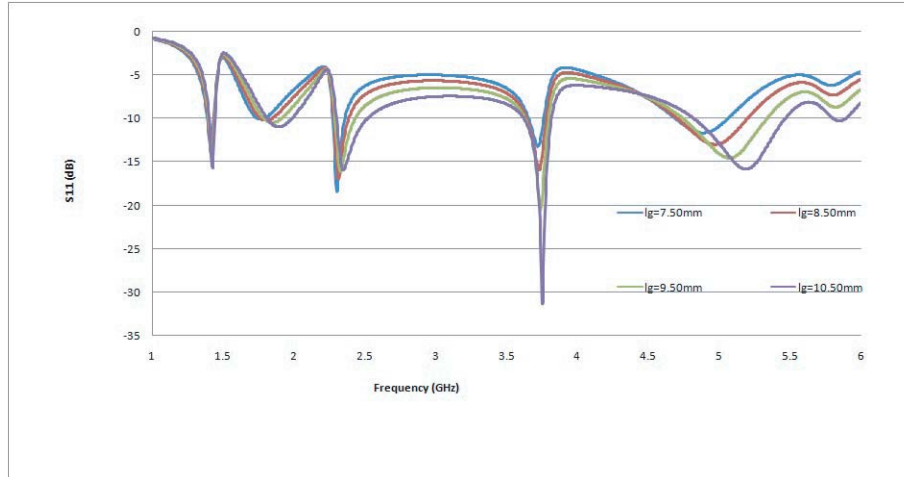


Figure 11. Simulated reflection coefficients for distinct values of ground patch length.

Table 2. Comparative analysis of the proposed antenna with the four different antennas.

Ref	Frequency (GHz)	Antenna footprint (mm)	Approach	Gain (dBi)	Application
[11]	1.2 to 5	58 × 55	Feed line Balun	4.5	EM Harvester
[12]	0.85 to 2.4	130 × 60	–	3	EM Harvester
[13]	0.89 to 5.5	100 × 120	DGS on the ground plane	4.3	EM Harvester
[14]	0.85 to 2.5	144 × 114	–	2	EM Harvester
[15]	0.85 to 1.9	94 × 82	–	2	EM Harvester
Proposed Work	1.4 to 5.8	45 × 41	DGS on the ground plane	4.45	EM Harvester

4.1.2. Effect of Feed Width

From Figure 12, the effect of feed line widths gives a better return loss for higher frequency range. For the lower frequency range, it shows bandwidth improvement (1.5 GHz to 3.75 GHz frequency bands as observed during the practical simulation).

From Figure 14, moderate gain is identified during the variation of feed width. So these exercises demonstrate that parametric analysis is useful for the improvement of antenna parameters.

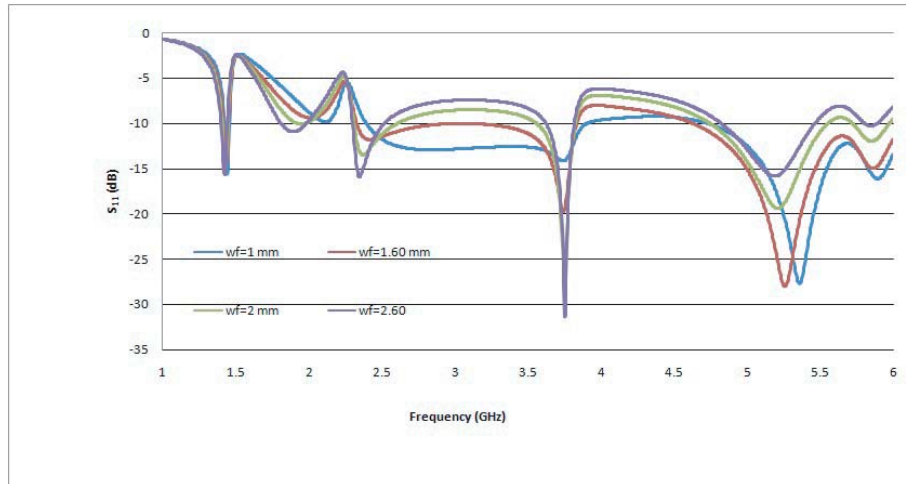


Figure 12. Simulated reflection coefficients for distinct values of feed width.

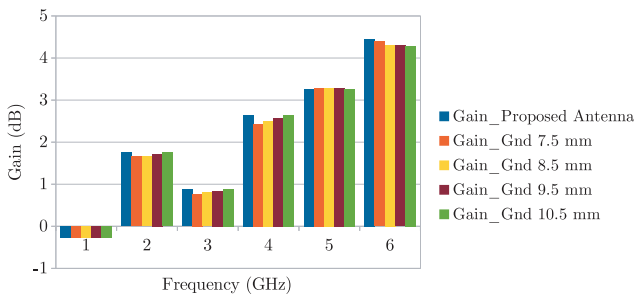


Figure 13. Gain plot with distinct ground length.

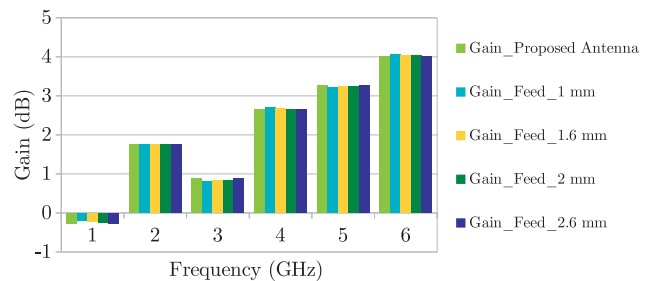


Figure 14. Gain plot with distinct feed width.

Table 2 shows the comparison between the proposed TNP antenna and the four different antennas presented in the literature (Section 2). The footprint, gain, and use of the operating standard of existing antennas are indicated accordingly. The proposed antenna shows a compact antenna size for lower and higher frequency bands against other existing antennas, which is a major contribution of the work. Apart from this, it also indicates a reasonable gain for efficient RF energy harvesting.

5. CONCLUSIONS

In this work, a compact TNP multiband antenna is designed, fabricated, and tested. The proposed antenna is quite simple to integrate with another electronic circuitry such as wearable devices and wireless sensor devices. The obtained simulation result shows multiband characteristics, excellent return loss, and omnidirectional radiation of the proposed antenna. The simulated antenna covers GSM 1400, GSM 1900, 2.4 GHz, 3.8 GHz, 5.2 GHz, and 5.8 GHz for RF energy harvesting applications. Measured return loss and gain are closely matched to the simulated results. This feature shows the interest to

obtain an RF signal from all directions through a novel antenna structure. Moreover, the proposed antenna has reported a proper balance between receiving the signal and availability of the RF sources. In addition, it shows compact structure which is the main implementation of the work. In the future, we will focus on enhancing the gain of omnidirectional TNP antenna for available RF signals along with complete rectenna circuit.

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