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A Compact Coplanar Waveguide Fed Wideband Monopole Antenna for RF Energy Harvesting Applications

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Abstract—For energy harvesting applications a new design of a coplanar waveguide (CPW) fed monopole antenna is presented. It covers almost all useful band ranges from 900 MHz–9.9 GHz (Radio, GSM, ISM, UWB bands). It also provides band reject characteristics for the range 3.1 GHz–5.6 GHz (HIPERLAN, C-Band, and W-LAN) to avoid interference from this range. The new design is based on the modification of coplanar waveguide (CPW) structure and optimizing the gap between patch and CPW ground for covering the ultra wideband (UWB) range and other useful ranges (Radio, GSM and ISM). Bandwidth enhancement and impedance matching for UWB range have been obtained by chamfering the corners, cutting two slots in CPW ground and dual stubs. The new design incorporates a parasitic patch above the antenna patch for tunning the desired band rejection. The entire design has been optimized at various stages during its evolution. The structure is compact in size $50 \times 40 \times 1.6\,\text{mm}^3$. It may also be used for mobile, military and satellite applications.

1. INTRODUCTION

1.1. RF Energy Harvesting and Its Demands on Antenna Specifications

In the field of wireless communication the emerging technologies need compact and miniature devices. Such devices have small batteries that need to be charged well in time. Day by day increase in the usage of data demands that the batteries be charged frequently. A possible solution is that the batteries are charged automatically by any technique (for example by energy harvesting technique). RF energy is present in the ambient practically everywhere. Therefore research is being conducted throughout the world to harvest this energy. Any RF energy harvesting module will draw RF energy from an available source and convert it into usable energy for a given application. Most common source is the ambient. A RF energy harvesting module is the combination of a receiving antenna, RF-DC converter circuit and impedance matching circuit. Such a combined structure (device) has been named as RECTENNA by the researchers [1–4]. So a miniaturized structure of antenna is needed to capture energy and to feed it to the rectifying block of RECTENNA. For maximizing energy output of the antenna the input should be maximized. However, at any given place, the environment will have limited RF energy per unit area. Therefore for given dimensions, the energy capturing area of the antenna should be as large as possible. In the ambient RF energy is present in various frequency bands such as 900 MHz–2 GHz (Band for radio & television applications, GSM), 2.1 GHz–2.6 GHz (ISM band for various applications) and 3.1 GHz–10.6 GHz (ultra wideband for satellite applications) [5]. Narrow band systems such as WLAN (3.1 GHz–4.4 GHz), HIPERLAN (5.1 GHz–5.3 GHz), C-BAND (4.4 GHz–5 GHz) may provide interference. The rectifying block should incorporate a band reject filter to stop these narrow bands. Additionally a band reject filter may have to be included after the rectifying diodes to suppress internal

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harmonics generated by the diodes. Therefore, RF energy harvesting imposes 3 major demands on an antenna

(i) Large energy capturing area.
(ii) Resonance at 900 MHz–2 GHz band, 2.1 GHz–2.6 GHz and 3.1–10.6 GHz band.
(iii) With rejection of 3.1 GHz–4.4 GHz band, 5.1 GHz–5.3 GHz band, 4.4 GHz–5 GHz band.

For band rejection of the band which provides interference for this application, band-stop filter may be used. However, this will make the antenna structure complex. Also for particular this application at the converter side a band-stop filter for rejecting the harmonics by rectifying diodes is needed, so it is favorable if we eliminate the band reject filter circuit at the antenna side to avoid the complexities. A parasitic element along with the antenna patch may be a good candidate for this purpose [6].

Microstrip antenna structures for the above mentioned particular ranges are available [7–10]. Planar antennas for UWB applications have also been reported [11–15]. The antenna design may be transformed into another dielectric material by using the transformation formulae for antenna dimensions and feed line dimension [16, 17]. This paper presents a coplanar monopole antenna structure for the band from 900 MHz–9.9 GHz with band rejection from 3.1 GHz–5.6 GHz. Although the antenna is designed for RF energy harvesting application, it may also be used for mobile, satellite and military communication applications. The new design of the antenna has been simulated and optimized with the simulation software ANSYS HFSS $^{\mathrm{TM}}$16. In the next section the antenna design and the simulated and measured results of the reflection coefficient (S_{11}) and radiation patterns are given.

2. ANTENNA DESIGN

2.1. Motivation behind the Design

Present day electronic systems frequently use sensors, sensor networks and communication devices. Some of these sub-systems may be remotely situated (physically) and may be difficult to power by physical wires. The wireless energy transfer is then the only means to supply energy to such sub-systems. If the energy is to be harvested from the ambient then Rectennas are preferred. Antenna is a major functionary part of any Rectenna. This motivated us to develop an antenna structure for application in Rectennas. The scope of this paper is only the development of antenna structure suitable for the energy harvesting module and not the whole module of the Rectenna. The essentials for designing this type of antenna is already explained in Subsection 1.1 as 3 major demands of the antenna design.

Thus the motive of this paper is to design a microstrip/monopole/slot antenna that would be able to receive an appropriate level of energy from almost all useful bands, e.g., Radio, GSM, ISM, UWB, so that the device remains activated in all the places where the RF spectrum is in use.

2.2. Design Specifications

This work has been focused on evolving a single structure for antenna that will capture energy from 900 MHz to 3.1 GHz and 5.6 GHz to 9.9 GHz bands and simultaneously reject energy from 3.1 GHz to 5.6 GHz. This means a wideband antenna (0.9 GHz to 9.9 GHz) with a band rejection from 3.1 GHz to 5.6 GHz. It should also maximize the utilized area for capturing the radiation energy falling on the structure.

2.3. The New Design

Methodical investigations have led to a new design (shown in Fig. 1). The proposed antenna structure consists of a coplanar ground with chamfered corners and unsymmetrical gap between patch and ground edges. A parasitic patch has been added for tuning the band rejection range. The structure has two unsymmetrical slots in the ground for enhancing the bandwidth as well as two unsymmetrical stubs along the feed line for impedance matching. FR4 has been selected as the substrate material. It has permittivity 4.4, loss tangent 0.001 and thickness 1.6 mm. Substrate size is 50×40 $(L \times W)$ mm^2. The width of feed line, W_l, is 3 mm, and the gap between the line and the CPW ground plane (g) is 0.5 mm.

The optimized parameters of the proposed antenna are:

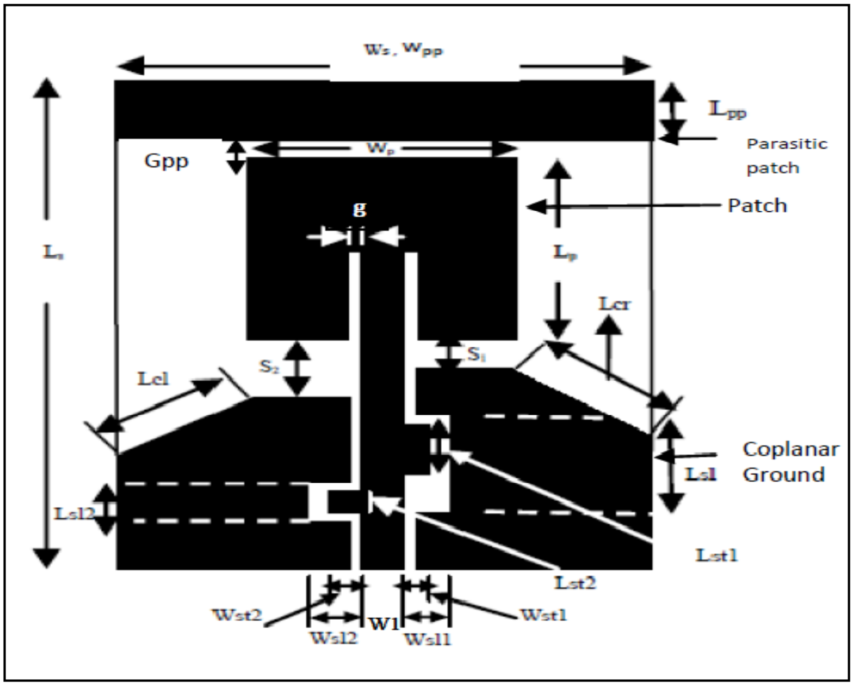

Figure 1. Proposed monopole antenna structure.

$L_p = 20\,\text{mm}$, $W_p = 20\,\text{mm}$, $L_s = 50\,\text{mm}$, $W_s = 40\,\text{mm}$, $W_{pp} = 40\,\text{mm}$, $L_{pp} = 5.4\,\text{mm}$, $G_{pp} = 0.4\,\text{mm}$, $S_1 = 3.2\,\text{mm}$, $S_2 = 6.2\,\text{mm}$, $L_{cl} = 8.2\,\text{mm}$, $L_{cr} = 7.1\,\text{mm}$, $L_{sl1} = 10\,\text{mm}$, $W_{sl1} = 3.3\,\text{mm}$, $L_{sl2} = 4\,\text{mm}$, $W_{sl2} = 4.3\,\text{mm}$, $L_{st1} = 5.4\,\text{mm}$, $W_{st1} = 1.5$, $L_{st2} = 2.6\,\text{mm}$, $W_{st2} = 1.5\,\text{mm}$.

2.4. Development of the New Design

For a rectangular patch antenna, the basic design formulae are [20]

$$w = \frac{c}{2f_l}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

$$L_p = \frac{c}{2f_l\sqrt{\varepsilon_{re}}} - 2\Delta l \tag{2}$$

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{w}{h}\right]^{-0.5} \tag{3}$$

$$\Delta l = 0.412h\frac{(\varepsilon_{re} + 0.3)\left(0.264 + \dfrac{w}{h}\right)}{(\varepsilon_{re} - 0.258)\left(0.8 + \dfrac{w}{h}\right)} \tag{4}$$

where the symbols have their usual meaning.

The design started with a rectangular patch with the coplanar ground for UWB antenna [18]. Due to its monopole structure simulation results showed a passband from 0.94 GHz to 8.22 GHz with a band rejection from 2.82 GHz to 6.96 GHz as shown in Fig. 2.

To improve the results, the gap between the patch and ground has been optimized, and the corners of the ground plane have been chamfered. Cutting slots in the ground plane (on both the sides of the feed line) and optimization of various dimensions further improved the results. A parasitic patch has been added in the design and optimized to tune the band of frequencies to be rejected [6]. This also increased the area for collecting the energy.

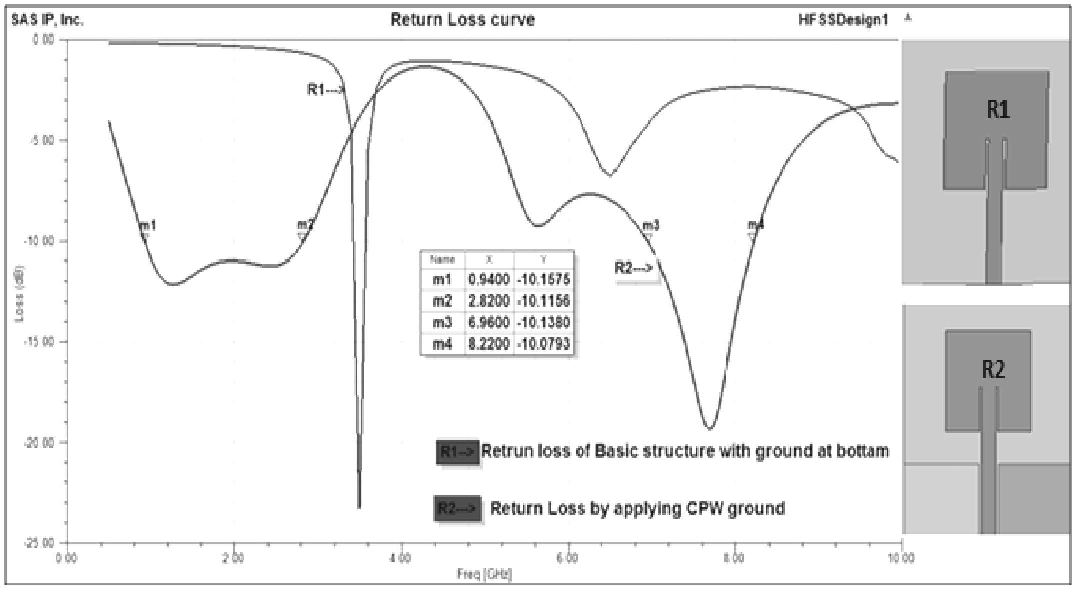

Figure 2. Simulated return loss curve of basic structure with conventional ground and effect of applying CPW ground.

3. PARAMETRIC ANALYSIS

ANSYS HFSS ™16 software has been used for analyzing the 3D structure. Initially a monopole structure with coplanar ground has been constructed for the designed resonant frequency (2.4 GHz). After that the parametric study has been applied at the four parts of the structure as mentioned in Subsections 3.1, 3.2, 3.3 and 3.4.

3.1. Effect of the Gap between the Patch and CPW Ground (S_1, S_2)

By keeping other parameters constant, S_1 and S_2 have been varied from 1 to 10 mm. The asymmetrical gap between the patch and the ground at the right and left sides of line feed have shown a remarkable effect on the resonance characteristics of the antenna for ISM band and Ultra wide band range. The optimized curve for $S_1 = 3.2$ mm and $S_2 = 6.2$ mm has been marked as R3 in Fig. 3.

3.2. Effect of Chamfering of Corners of Ground (L_{cl} and L_{cr}) as well as the Gap between the Parasitic Patch and Resonant Patch

The corners of the CPW ground have been chamfered. The cutting length (diagonal length) is $L_{cl} = 8.2$ mm and $L_{cr} = 7.1$ mm at which the maximum enhancement in the ISM band has been noticed (Fig. 3). The parasitic patch of optimized dimension is added to tune the required rejection band. According to the theory two resonant frequencies are separated according to the coupling between the two patches [19]. So controlling the gap between these two patches will control the range of frequencies which has to be rejected. The effect of varying Length (L_{pp}) of the Parasitic Patch and of the gap between parasitic patch and resonant patch has been shown in Fig. 3. The parasitic patch is added for tunning the band reject range from 3.1 GHz–5.6 GHz. By adjusting the gap (G_{pp}) between the resonant patch and this parasitic patch the desired range of rejection has been tuned.

3.3. Effect of Cutting Slots in the CPW Ground

Effect of Cutting Slots of the dimensions (L_{sl1}, L_{sl2}, W_{sl1}, and W_{sl2}) in CPW Ground Edges is shown in Fig. 4. These slots will change the path of current consequently enhance the bandwidth in ultra wide band range. The optimized values $L_{sl1} = 10$ mm, $W_{sl1} = 3.3$ mm, $L_{sl2} = 4$ mm, $W_{sl2} = 4.3$ mm show

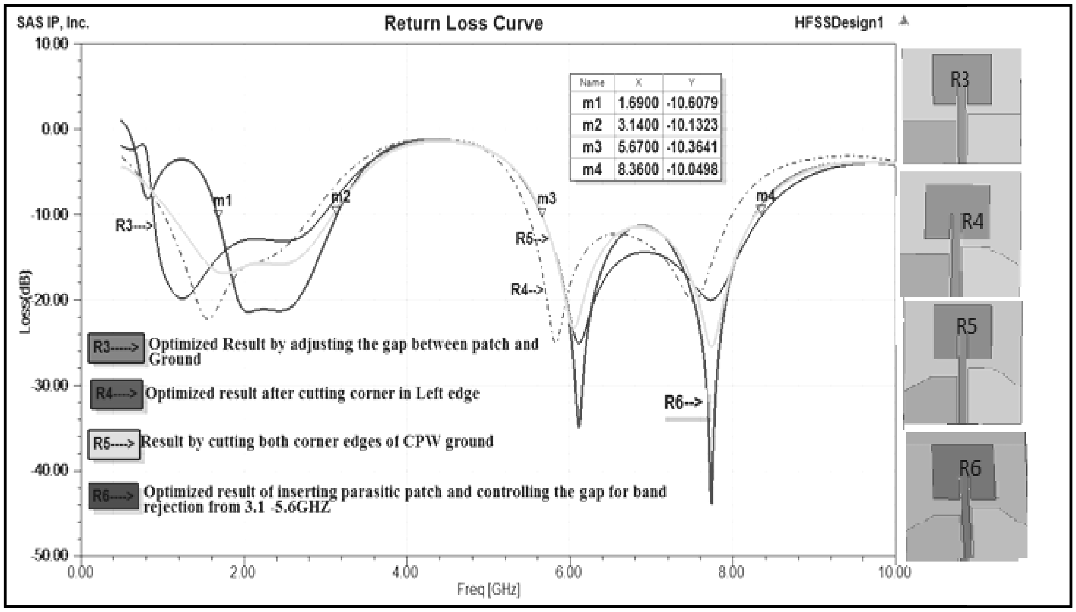

Figure 3. Optimized simulated return loss curve for the CPW ground structure after chamfering & adding optimized parasitic patch structure.

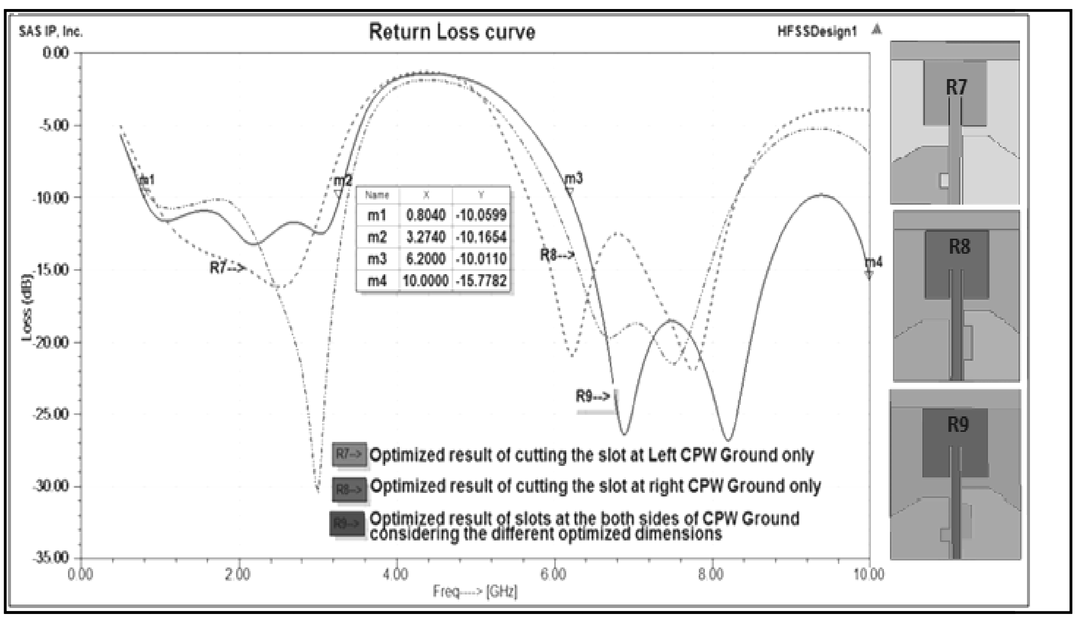

Figure 4. Simulated return loss curve for optimized results by introducing slots in the CPW ground for enhancing the range of UWB.

the maximum enhancement in the Ultra wideband range from 5.6–8.3 GHz to 6.2–10 GHz. At the cost of some impedance mismatching.

3.4. Effect of Stubs in the Feedline for Impedance Matching

Effect of adding stubs of the dimensions (L_{st1}, L_{st2}, W_{st1} and W_{st2}) to the Feed Line is shown in Fig. 5. To improve the impedance mismatching produced by the above optimized slots the stubs are added.

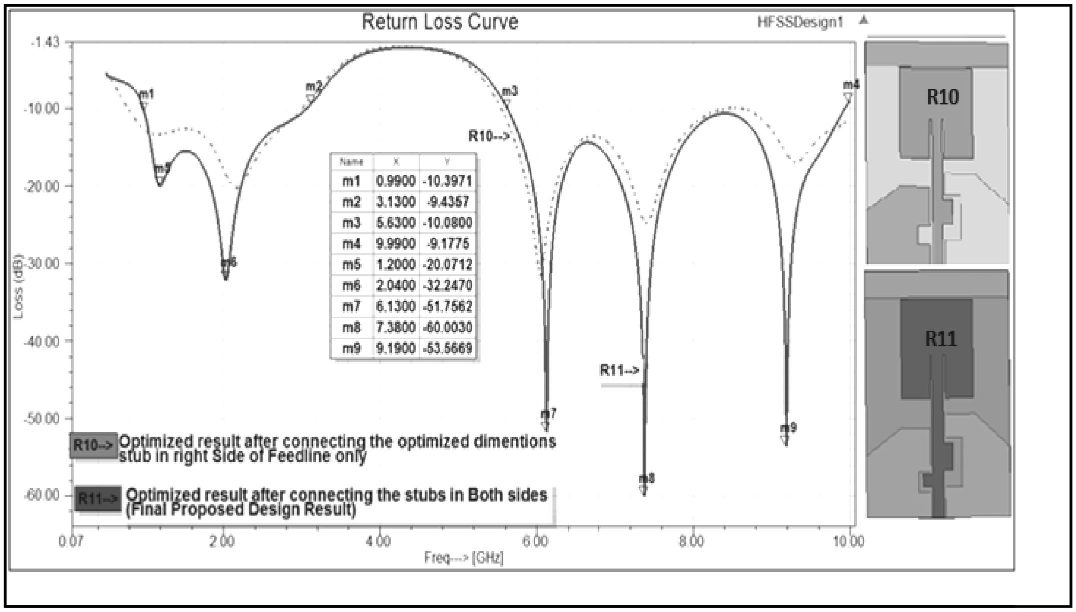

Figure 5. Simulated return loss curve for the optimized result of connecting the stubs in the feed line.

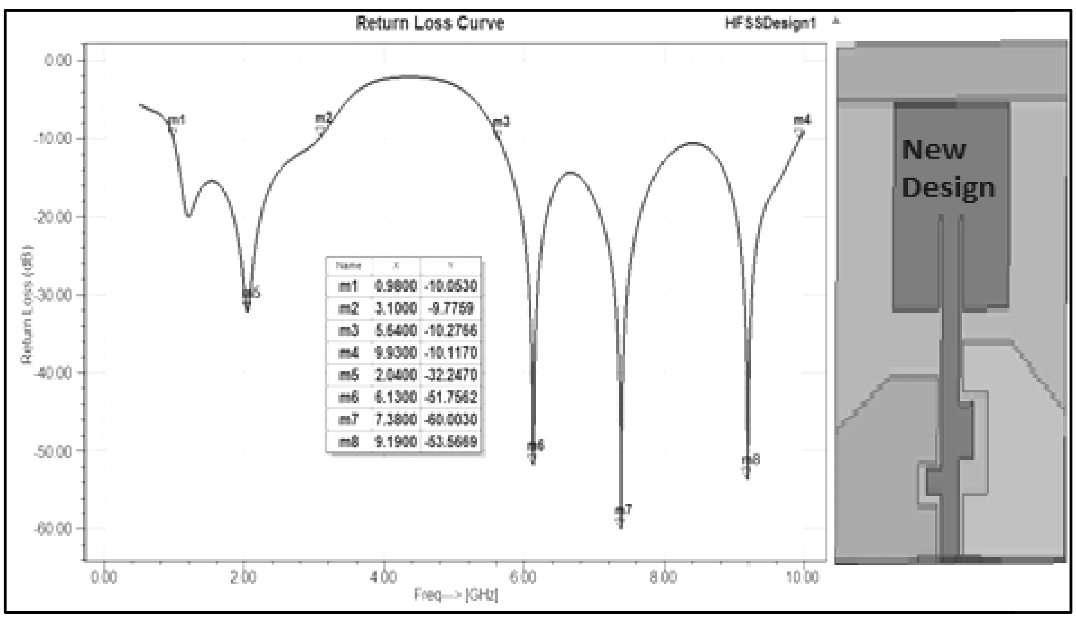

Figure 6. Simulation result for S_{11} of the new design.

The optimized dimensions of stubs $L_{st1} = 5.4\,\text{mm}$, $W_{st1} = 1.5\,\text{mm}$, $L_{st2} = 2.6\,\text{mm}$, $W_{st2} = 1.5\,\text{mm}$ shows the desired result in the ultra wide band range, i.e., from 5.6–9.9 GHz with good return loss values.

The return loss curve for the optimized final new design is shown in Fig. 6. As shown in Fig. 6 the new proposed design is resonant from 900 MHz–9.9 GHz with the band reject form 3.1 GHz–5.6 GHz (WLAN & HIPER LAN). This band has been rejected because it provides only interference for the RF energy Harvesting Application.

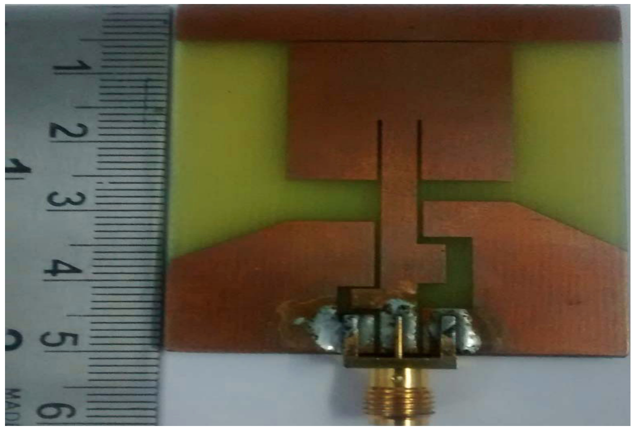

Figure 7. Photograph of fabricated antenna.

4. RESULTS

4.1. Experimental Verification

For experimental verification of the results, the new design structure has been fabricated, shown in Fig. 7. Simulation of the proposed design showed a maximum gain of 7 dBi at resonant frequency 6.2 GHz, impedance matching of the desirable frequencies and rejection of the unwanted band. Measurements of fabricated antenna have proven the predictions.

4.2. Return Loss Curves: Simulated and Measured

As shown in Fig. 6 (simulated results) and Fig. 8 (measured results) the measured results match the simulated ones. These results indicate that the proposed monopole antenna works on multiple bands of frequencies from 900 MHz–9.9 GHz and also rejects band from 3.1 GHz to 5.6 GHz.

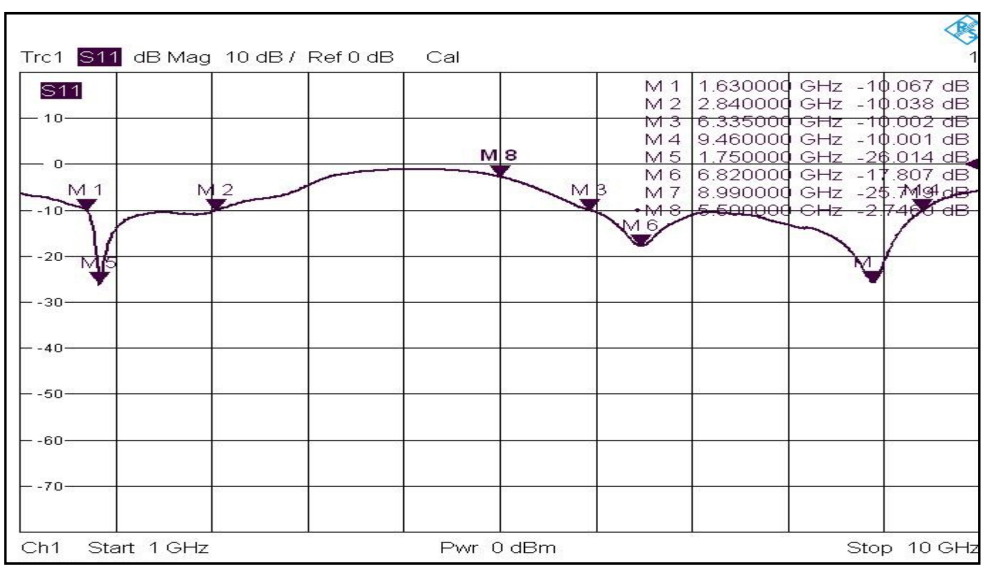

Figure 8. Measured results of S_{11} parameter of the proposed design.

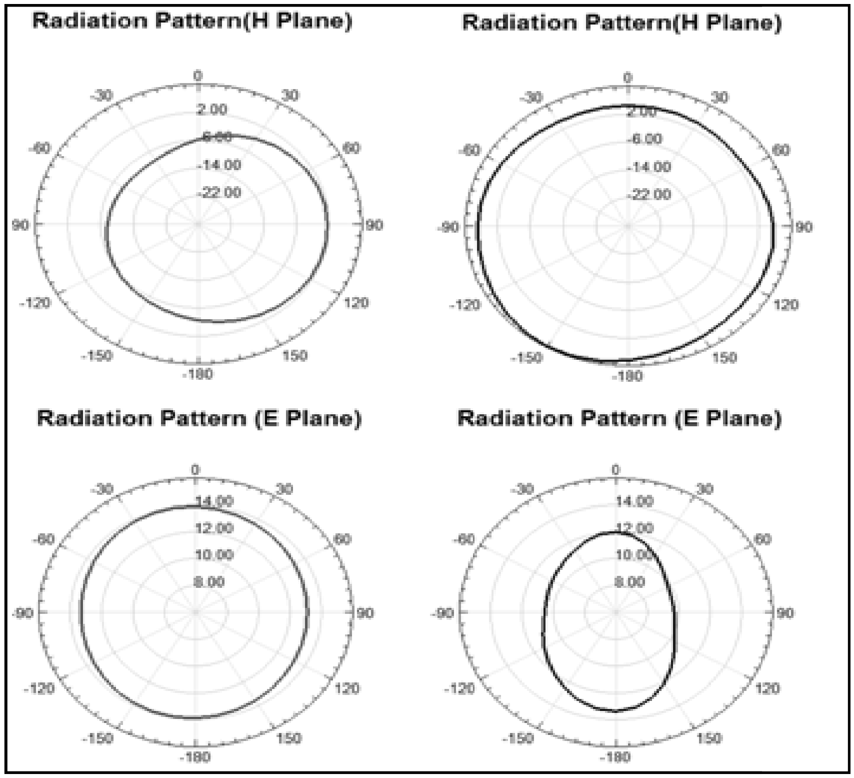

Figure 9. Measured radiation pattern (H-plane & E plane) for frequencies 2.03 GHz, & 6.1 GHz.

4.3. Measured Radiation Patterns (E-plane & H-plane)

For the fabricated antenna, measured radiation patterns for resonant frequencies 2.03 GHz and 6.1 GHz E-plane & H-plane are shown in Fig. 9, respectively. These patterns are shown as sample measured patterns for the proposed design because it is not possible to show all the results. The sample patterns indicate that the antenna has omnidirectional characteristics.

The radiation patterns show asymmetrical characteristics because the CPW ground dimensions are asymmetrical around the feeding point of the center of the symmetric shaped radiating patch. The ground also places its effect on the radiation pattern.

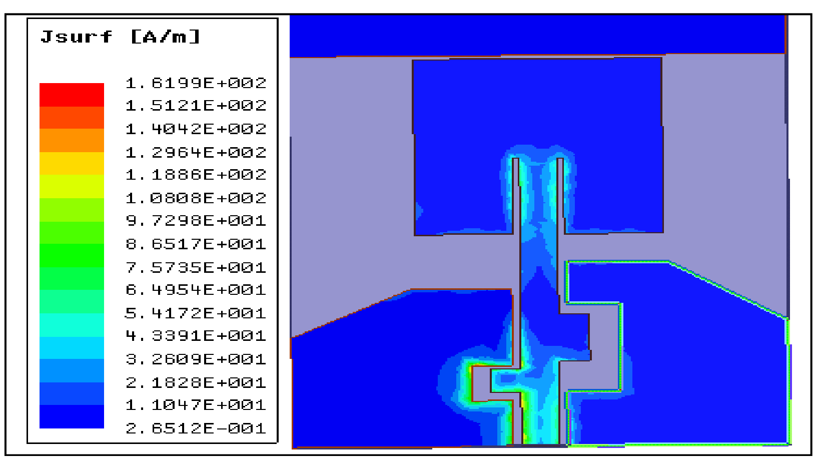

Figure 10. Simulation result of new design for current distribution at one of the resonant frequency 2.4 GHz.

4.4. Current Distribution

The current distribution for only one resonant frequency (2.4 GHz) is shown here in Fig. 10. It indicates that at the resonant frequency surface current is only at the radiators edges.

4.5. Gain and Radiation Efficiency

The result of total gain has been plotted. The proposed antenna has shown the maximum gain of 7 dBi at 6.2 GHz and from 2 dBi to 4 dBi for other resonant frequencies as shown in Fig. 11. Radiation efficiency of the structure is seen about 87% maximum.

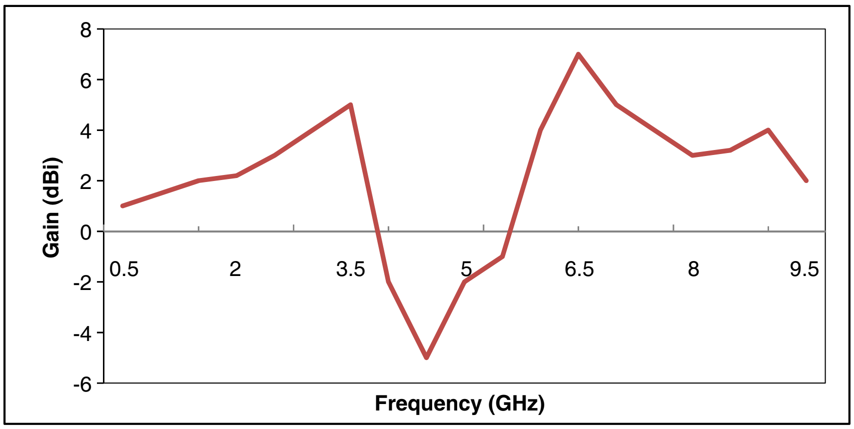

Figure 11. Gain of antenna structure.

5. DISCUSSIONS AND CONCLUSION

In this paper a compact coplanar waveguide fed wideband monopole antenna for RF energy harvesting applications has been proposed. It has been designed particularly for RF energy harvesting applications due to two reasons, firstly because the area of capturing radiation energy through receiving antenna is more due to parasitic patch, resonant patch & the coplanar ground above the substrate, and secondly it is resonant on almost all the bands available in the RF spectrum. The proposed antenna is compact in size ($50 \times 40 \times 1.6\,\text{mm}^3$) and used for a wide range from 900 MHz to 9.9 GHz with band reject (3.1–5.6 GHz) characteristic. For RF energy harvesting purposes WLAN & HIPERLAN (3.1–5.6 GHz) band is less useful because it provides interference due to weak strength of signals.

The tuning slots in the coplanar ground are responsible for the bandwidth enhancement of UWB range, and the stubs in feed line are responsible for impedance matching. The designed UWB monopole antenna shows omnidirectional radiation patterns, good radiation efficiency of 87% and gain (2–7 dBi for different frequencies). The proposed antenna has the perfect impedance matching for the GSM, ISM, and UWB ranges and rejects the interference by HIPERLAN and WLAN range.

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REFERENCES

1. Yang, X.-X., J.-S. Xu, D.-M. Xu, and C.-L. Xu, “X-band circularly polarized rectennas for microwave power transmission applications,” *J. Electron.*, Vol. 25, No. 3, 389, 2008.

2. Gao, Y.-Y., X. Yang, C. Jiang, and J.-Y. Zhou, "A circularly polarized rectenna with low profile for wireless power transmission," *Progress In Electromagnetics Research Letters*, Vol. 13, 41–49, 2010.
3. Huang, F. J., C.-M. Lee, C.-L. Chang, L.-K. Chen, T.-C. Yo, and C.-H. Luo, "Rectenna application of miniaturized implantable antenna design for triple-band biotelemetry communication," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 7, 2646, 2011.
4. Takhedmit, H., L. Cirio, S. Bellal, D. Delcroix, and O. Picon, "Compact and efficient 2.45 GHz circularly polarised shorted ring-slot rectenna," *Electron. Letters*, Vol. 48, No. 5, 253, 2012.
5. Federal Communications Commission, First report and order, Revision of Part 15 of commission's rule regarding UWB transmission system, FCC, 02-48, Washington, DC, 2002.
6. Jung, J., H. Lee, and Y. Lim, "Compact band-notched ultra-wideband antenna with parasitic elements," *Electron. Letters*, Vol. 44, No. 19, 1104, 2008.
7. Choi, S. T., K. Hamaguchi, and R. Kohno, "Small printed CPW-fed triangular monopole antenna for ultra-wideband applications," *Microw. Opt. Technol. Lett.*, Vol. 51, No. 1, 1180, 2009.
8. Medeiros, C. R., J. R. Costa, and C. A. Fernandes, "Compact tapered slot UWB antenna with WLAN band rejection," *IEEE Antennas and Wireless Propagation Letters*, Vol. 8, No. 1, 661, 2009.
9. Jang, J.-W. and H.-Y. Hwang, "An improved band-rejection UWB antenna with resonant patches and a slot," *IEEE Antennas and Wireless Propagation Letters*, Vol. 8, No. 1, 299, 2009.
10. Zha, F. T., S. X. Gong, G. Liu, H. Y. Yang, and S. G. Lin, "Compact slot antenna for 2.4 GHz/UWB with dual band-notched characteristic," *Microw. Opt. Technol. Lett.*, Vol. 48, No. 1, 1859, 2009.
11. Lin, C.-C., Y.-C. Kan, L.-C. Kuo, and H.-R. Chuang, "A planar triangular monopole antenna for UWB communication," *IEEE Microw. Wireless Compon. Lett.*, Vol. 15, No. 10, 624, 2005.
12. Foudazi, A., H. R. Hassani, and S. M. A. Nezhad, "Small UWB planar monopole with added GPS/GSM/WLAN bands," *IEEE Trans. Antennas Propag.*, Vol. 60, No. 6, 66, 2012.
13. Qing, X. and Z. N. Chen, "Compact coplanar waveguide-fed ultra-wideband monopole-like slot antenna," *Microwaves, Antennas & Propagation*, Vol. 3, No. 5, 889, 2009.
14. Li, W.-T., X.-W. Shi, T.-L. Zhang, and Y. Song, "Novel UWB planar monopole antenna with dual band-notched characteristics," *Microw. Opt. Technol. Lett.*, Vol. 52, No. 1, 48, 2010.
15. Ammann, M. J. and L. E. Doyle, "Small planar monopole covers multiband BRANs," *Proc 30th European Microwave Conf.*, Vol. 2, 242–246, Paris, France, 2000.
16. Mathur, D., S. K. Bhatnagar, and V. Sahula, "Quick estimation of rectangular patch antenna dimensions based on equivalent design concept," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 1469, 2014.
17. Mathur, M., A. Vats, and A. Agrawal, "A new design formula for feedline dimensions of the microstrip patch antenna by using equivalent design concept," *IEEE Proc. of International Conference on Signal Processing and Communication Systems*, 105–110, Jaypee, Noida, India, 2015, ISBN-No. 978-1-4799-6761-2/15, available: http://ieeeexplore.ieee.org/DOI:10.1109/ICSPCom.-2015.7150629.
18. Reed, J. H., *An Introduction to Ultra Wideband Communication Systems*, Prentice Hall PTR, Upper Saddle River, NJ, 2005.
19. Volakis, J. L., *Antenna Engineering Handbook*, McGraw-Hill Education, New York, 2009.
20. Garg, R., P. Bhartia, I. Bahl, and A. Ittipiboon, *Microstrip Antenna Design Handbook*, Artech House Publisher, Boston, London, 2001.