

Design of Planar Triple-Band Electrically Small Asymmetrical Antenna for ISM, WLAN, and X-Band Applications



Payal Bhardwaj and Ritesh Kumar Badhai

Abstract In this paper, we proposed a novel printed monopole antenna with the asymmetric meandered structure on the two sides of coplanar waveguide (CPW) feed line. The proposed antenna has the compact size of $0.095 \lambda \times 0.095 \lambda \times 0.005 \lambda$, where λ corresponds to the wavelength in free space at the lowest operating frequency. The proposed antenna exhibits three resonances around 2.38, 5.52, and 7.72 GHz. The proposed antenna shows the good impedance matching, wide bandwidth, good radiation efficiencies, and radiation pattern at the resonating bands. The proposed antenna is fabricated on FR-4 substrate and found the good agreement between simulated and experimental results. The proposed triple-band antenna with a relatively low profile and compact size is useful for various biomedical applications covering the ISM (Industrial, Scientific, and Medical) band ranging from 2.4 to 2.48 GHz and 5.15 to 5.82 GHz, WLAN, Wi-Fi, and Wi-Max. It also covers the X-band downlink frequency range from 7.25 to 7.75 GHz and uplink 7.9 to 8.4 GHz frequency ranges.

Keywords Asymmetrical antenna · Biomedical applications · Coplanar waveguide (CPW) feed · ISM band · Multifrequency antenna

P. Bhardwaj (✉)

Department of Electronics and Communication Engineering, Birla Institute of Technology,
Deoghar Campus, Deoghar 814142, India
e-mail: payalrashi@gmail.com

R. K. Badhai

Department of Electronics and Communication Engineering, Birla Institute of Technology,
Patna Campus, Patna 800014, India
e-mail: riteshkbadhai@bitmesra.ac.in

1 Introduction

Earlier, much of the development of microstrip antenna was subject to military and aerospace applications, increasing its span to communication applications like WLAN and Wi-Fi. In the recent era, there has been a gradual improvement in wireless communication systems related to biomedical fields and therefore antennas intended for biomedical applications have achieved considerable attention. The antenna systems designed for biomedical applications are either implanted in-body or worn on-body and off-body. The wireless links remove the need for cables making the communication simple and cost-effective [1]. On-body communication is established between wearable electronic sensors attached to the human body, while off-body communication establishes the link between sensors and external devices. The size reduction or miniaturization, circular polarization, good impedance matching, and efficiency are, therefore, essential requirements for antenna design.

The microstrip patch antenna is chosen for the design due to its advantages of being low profile, conformal to planar structures, and simplicity of fabrication [2]. The patch antennas can sometimes be operated at more than one frequency, one dominant mode frequency, and the other corresponding to higher order modes. The radiations with same polarizations can be obtained at multiple frequencies if patches are stacked and fed properly [3, 4]. Many multiple frequency antennas have been studied for biomedical applications but have large volume [5] and complex structure [6].

The size of an antenna is one of the main constraints in the design for biomedical applications, a printed antenna with a size $12 \times 12 \times 0.65 \text{ mm}^3$ and coplanar waveguide feed (CPW) has been designed in this paper. The coplanar waveguide feed structure is used to obtain high-frequency response [7] and good impedance matching [8, 9], reducing back radiations and making it easier to integrate with microwave circuits. Many CPW-fed antennas have been studied for their dual-band operation [10–12] and wireless applications [13–16]. CPW feed simplifies the antenna structure along with providing good radiation properties and high-frequency response, thereby increasing the system accuracy. The proposed antenna is based on the meandered structure with an improvement in the gain, impedance matching, and radiation characteristics. The structure resonates at multiple frequencies embodying the function of multiple antennas and can be used for transmission in ISM as well as in X-band. Another major improvement in the structure is the ease of fabrication and it is an extremely miniaturized size which is a challenge in most biomedical antenna designs. The electrically small antenna may be defined as one whose largest dimension is not more than one-tenth of a wavelength ($\lambda/10$) [17]. The proposed antenna exhibits electrically smaller size based on the fact that the size of the antenna is inversely proportional to the number of meandered turns. In the proposed structure the number of turns has been increased resulting in an electrically small antenna with increased path length, thereby obtaining lower resonating frequency.

2 Antenna Design

We propose a CPW feed asymmetrical antenna for triple frequency operations. The proposed multifrequency antenna structure shown in Fig. 1 comprises of multiple slotted conducting patches on one side of the CPW feed and a single-slot patch on the other side; a CPW feed line. The proposed antenna structure has a compact size of $12 \times 12 \text{ mm}^2$. The proposed structure is printed on a glass epoxy FR-4 substrate with a height of 0.65 mm and relative permittivity of 4.4. Copper has been used as a radiating material for both patches as well as the ground plane. The antenna resonates at 2.38, 5.52, and 7.72 GHz and has a good impedance matching at all the bands. It also exhibits good radiation patterns and antenna gains over the operating bands.

The coplanar waveguide feed structure can be analyzed by using the following Eqs. (1)–(5):

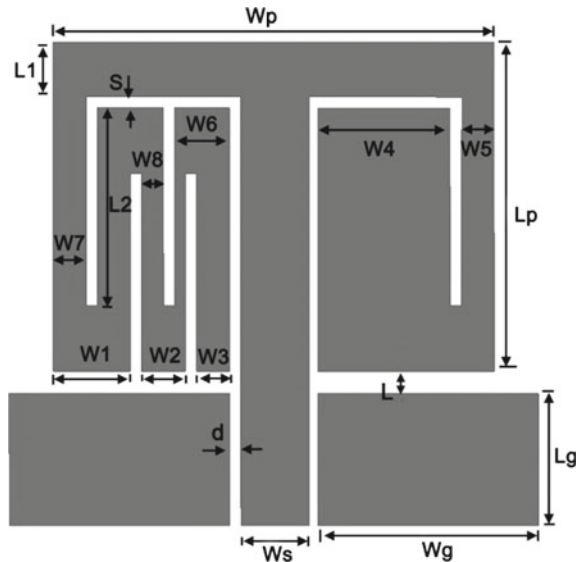
$$\epsilon_{eff} = 1 + \frac{\epsilon_r - 1}{2} \frac{K(k_2)}{K(k'_2)} \frac{K(k'_1)}{K(k_1)} \tag{1}$$

$$k_1 = \frac{W_s}{W_s + 2d} \tag{2}$$

$$k'_1 = \sqrt{1 - k_1^2} \tag{3}$$

$$k_2 = \frac{\sinh\left(\frac{\pi W_s}{4h}\right)}{\sinh\left(\frac{\pi(W_s + 2d)}{4h}\right)} \tag{4}$$

Fig. 1 Proposed asymmetric patch monopole antenna geometry



$$k'_2 = \sqrt{1 - k_2^2} \quad (5)$$

In the above equations, $K(k_1)$, $K(k_2)$, $K(k'_1)$ and $K(k'_2)$ are the first complete elliptic integral of the first kind and its complement, ϵ_{eff} , W_s , d , and h are the effective dielectric constant, the width of the CPW feed, the gap between the CPW feed and the ground and the substrate thickness, respectively.

The width and length of the meandered patch responsible for the three resonating frequencies are approximated and computed using the following Eqs. (6)–(11):

$$W_M = 0.042 \lambda_g \quad (6)$$

$$L_2 = 0.054 \lambda_g \quad (7)$$

$$W_1 = 0.021 \lambda_g \quad (8)$$

$$W_2 = 0.012 \lambda_g \quad (9)$$

$$W_3 = 0.009 \lambda_g \quad (10)$$

where λ_g is the guided wavelength given by

$$\lambda_g = \frac{\lambda}{\sqrt{\epsilon_{eff}}} \quad (11)$$

The structure of the proposed antenna has been developed in the progressive manner shown in Fig. 2. The process begins by designing the symmetric planar structure on both sides of the feed line with conventional inset feed antenna as shown in Fig. 2a. The distance between the patch and the ground is taken to be 1 mm and the feed gap between the feed line and the ground is 0.3 mm. As shown in Fig. 3, the antenna resonates at a single frequency of 3.4 GHz. It deviates from the desired frequency of operation in ISM band and makes the antenna suitable for only single-band operation. It is seen that no resonance occurs at ISM band. In the next step, for the antenna to resonate at multiple frequencies the conducting patch is meandered with strip on both sides of the feed line. The gap between the patch and the ground is reduced to 0.5 mm, while the gap between the feedline and the ground is reduced to 0.2 mm Fig. 2b. Reduction in the gap between the patch and the ground lowers the resonant frequency and frequency corresponding to other high order mode is obtained.

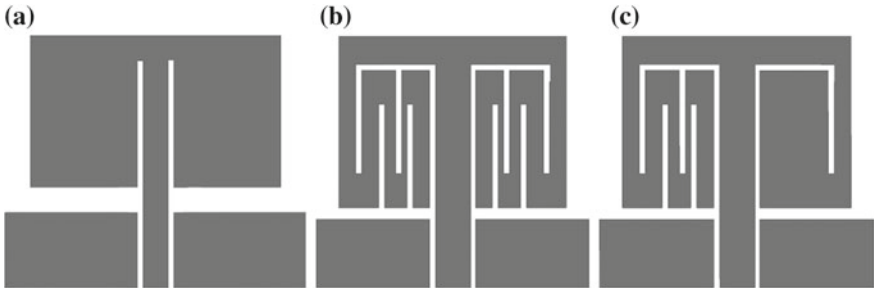
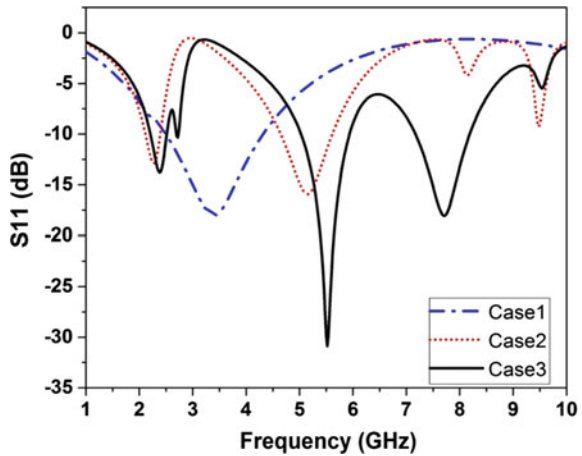


Fig. 2 The three structures of on-body monopole antenna: **a** Case 1: plane symmetric structure, **b** Case 2: meandered symmetric structure, and **c** Case 3: proposed antenna

Fig. 3 Comparison of the reflection coefficient of Case 1: plane symmetric structure, Case 2: meandered symmetric structure, and Case 3: proposed antenna



When the patch antenna with the meandered structure on both sides of the feed-line is used, it is observed that antenna resonates at dual frequencies 2.26 GHz and 5.18 GHz. Out of the two bands, only one lies in the ISM band with -15.8 dB return loss. In order to include higher order bands and frequencies close to ISM band, the asymmetric structure with meandering on one side of the patch and planar patch on the other side is used Fig. 2c. From the comparison of the simulated return loss S_{11} of the three antenna structures Fig. 3, it is observed that the proposed antenna demonstrates sharp and well-defined curves at desired frequencies. Further, by selecting a proper distance between the ground and CPW feed, a good impedance matching and resonating frequencies have been obtained. The detailed dimensions of the proposed antenna are presented in Table 1.

Table 1 Dimensions of the proposed antenna

Parameter	Dimension (mm)	Parameter	Dimension (mm)	Parameter	Dimension (mm)
Lp	7.5	W1	1.75	W7	0.7
Wp	10	W2	1	W8	0.5
Lg	3	W3	0.75	L1	1.25
Wg	5	W4	3	L2	4.5
Ws	1.55	W5	0.75	L	0.5
d	0.2	W6	1.25	S	0.25

3 Parametric Study

3.1 Effect of the Distance Between the Patch and the Ground (L)

By changing the distance between the patch and the ground, while keeping the distance between the feedline and the ground fixed. The gap “L” has a significant effect on impedance matching and bandwidth. As depicted in Fig. 4, it can be observed that with increasing value of “L”; impedance matching improves for the lower resonant band but decreases at higher bands. The large separation between ground and patch (L) also reduces the resonance frequency of higher order modes. The reflection coefficient and bandwidth for three different value of “L” are given in Table 2. From these analysis, optimum value of $L = 0.5$ mm is considered for the proposed antenna.

Fig. 4 Comparison of reflection coefficients for varying distance “L” between patch and ground at $L = 0.5$ mm, $L = 1$ mm, and $L = 1.5$ mm

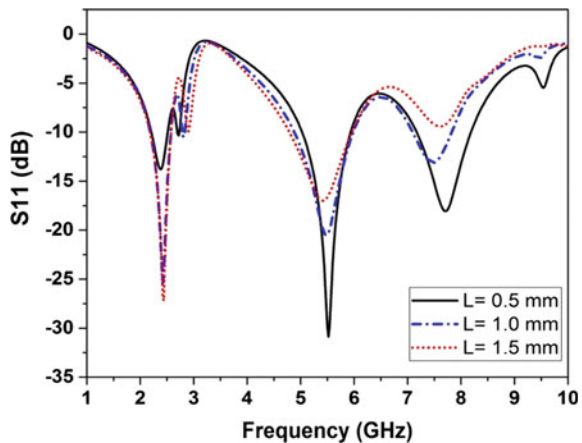
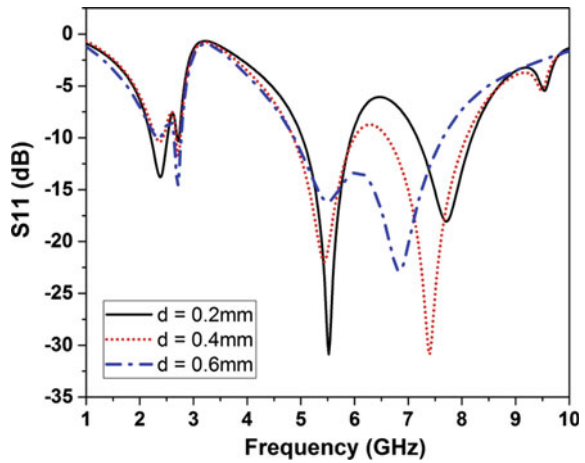


Table 2 Antenna characteristics for various values of “L”

Varying component (mm)	Resonant frequencies (GHz)	Reflection coefficient S11 (dB)	Bandwidth (MHz)
L = 0.5	(a) 2.38	-13.79	280
	(b) 5.52	-30.84	860
	(c) 7.72	-18.05	960
L = 1.0	(a) 2.42	-25.43	370
	(b) 5.5	-20.46	1060
	(c) 7.5	-13.11	740
L = 1.5	(a) 2.44	-27.19	360
	(b) 5.4	-16.97	1140

Fig. 5 Comparison of reflection coefficients for varying distance “d” between feed and the ground at $d = 0.2$ mm, $d = 0.4$ mm, and $d = 0.6$ mm



3.2 Effect of the Feedgap (D)

By changing the distance between the feedline and the ground keeping the distance between the patch and the ground fixed. The feedgap “d” has a significant effect on capacitive coupling between the feed line and the ground plane. From Fig. 5, it is observed that for $d = 0.4$ mm antenna resonates at 5.4 GHz and 7.4 GHz and for $d = 0.6$ mm the antenna becomes wideband operating within 4.88 GHz to 7.64 GHz band, while for $d = 0.2$ mm antenna gives the better impedance matching for all three resonating bands and covers the desired operating bands. The reflection coefficient and bandwidth for three different values of feedgap “d” are given in Table 3.

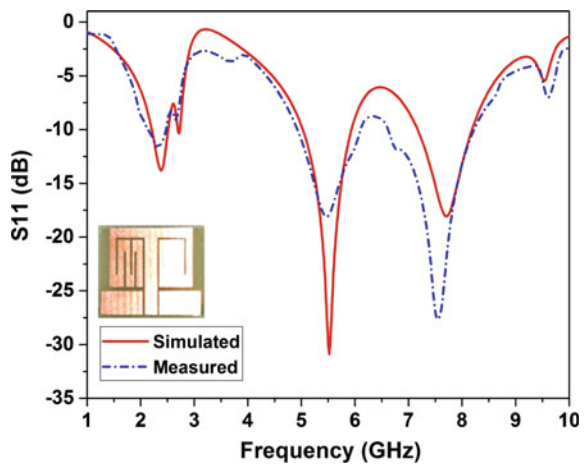
Table 3 Antenna characteristics for various values of “*d*”

Varying component	Resonant frequencies (GHz)	Reflection coefficient S ₁₁ (dB)	Bandwidth
<i>d</i> = 0.2 mm	(a) 2.38	−13.79	280 MHz
	(b) 5.52	−30.84	860 MHz
	(c) 7.72	−18.05	960 MHz
<i>d</i> = 0.4 mm	(a) 2.38	−10.378	1100 MHz
	(b) 5.42	−20	1420 MHz
	(c) 7.39	−16.413	
<i>d</i> = 0.6 mm	(a) 2.699 Wideband frequency range 4.88–7.64 GHz	−14.78 (<−10)	120 MHz 2.76 GHz or 2760 MHz

4 Results and Discussions

The proposed antenna is fabricated on glass epoxy FR-4 substrate. To estimate the performance of the proposed antenna, the fabricated antenna is connected to the vector network analyzer (VNA). Figure 6 illustrates the result of the simulated and measured reflection coefficient S₁₁ for the proposed planar asymmetric antenna structure. It can be seen that the proposed antenna resonates at three different bands; the first band operates at 2.4 GHz band with a bandwidth of 300 MHz (2.20–2.50 GHz) which is useful for biomedical applications. The second band of antenna resonates at 5.52 GHz band with a bandwidth of 870 MHz (5.05–5.92 GHz) which covers all three bands (UNII 1, UNII 2, and UNII 3) of WLAN applications. The third band of the proposed antenna resonates at 7.72 GHz with a bandwidth of 1.05 GHz

Fig. 6 Simulated and measured reflection coefficients |S₁₁| of the proposed antenna



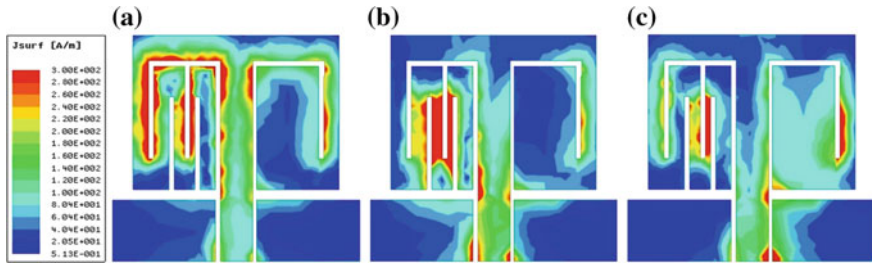


Fig. 7 Current distribution of the proposed antenna at **a** 2.38 GHz, **b** 5.52 GHz, and **c** 7.72 GHz

(7.10–8.15 GHz) covers C-band fixed satellite (7 communication). The current distributions of asymmetric patch monopole antenna are shown in Fig. 7 at 2.38, 5.52, and 7.72 GHz. The surface current shows information about the effective electrical length and resonating mode of the antenna. From Fig. 7a, it is seen that the surface current distributed is dominated on the left side of the feed and having the longest electrical length on the patch surface without any null point due to which it resonates at the fundamental resonant frequency of 2.38 GHz. Similarly, in Fig. 7b, the strong surface current flows near the second and fourth slot on the left side of the feed which produces the second resonating mode at 5.52 GHz, while due to the shortest electrical length, the right side of the patch having a large influence on the third resonating mode at 7.72 GHz.

Figure 8 illustrates the plots for E-plane and H-plane radiation patterns of the proposed antenna for frequencies 2.38, 5.52, and 7.72 GHz. The E-plane pattern has the dual directional cone-shaped pattern and the H-plane pattern is an omnidirectional pattern. It also shows the good co-relation between co and cross-polarizations.

5 Conclusions

A compact asymmetric antenna with CPW feed has been proposed with a simple structure and small volume to be printed on an area of 12 mm × 12 mm. The antenna resonates at three frequencies 2.38, 5.52, and 7.72 GHz. The comparison of structures has demonstrated a considerable improvement in the reflection coefficient of the asymmetric structure at higher resonating frequencies. The compact size and multiple resonating frequencies of the antenna can effectively cover the applications ranging from WLAN to portable medical diagnostic applications.

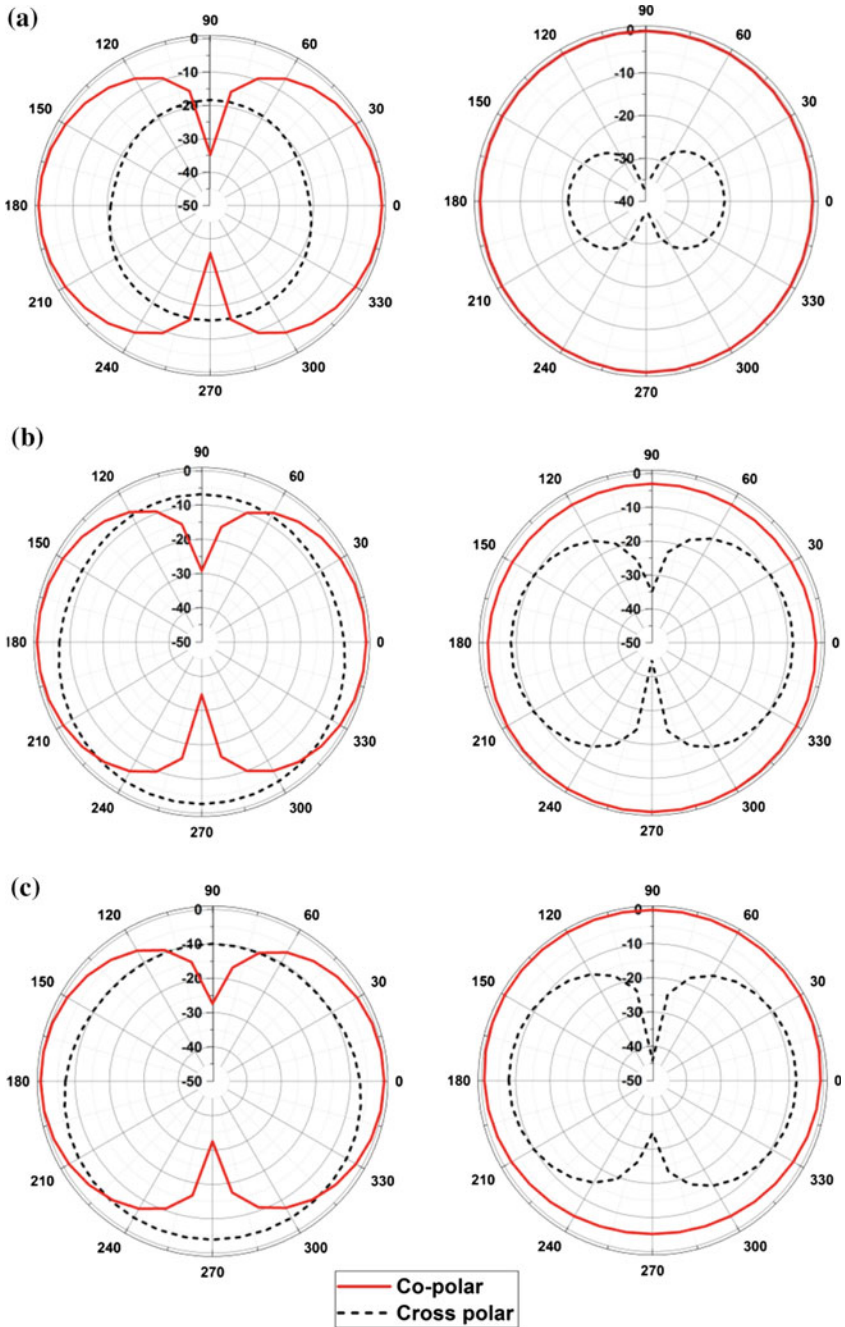


Fig. 8 Normalized radiation patterns of the proposed antenna for E-plane and H-plane at a 2.38 GHz, b 5.52 GHz, and c 7.72 GHz

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