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Design a compact CPW monopole antenna on rubber substrate for ISM band application

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ABSTRACT

One of the most challenging works on compact antenna design is to maintain the flexibility orientation. This paper demonstrates a coplanar waveguide (CPW) fed monopole antenna with rubber substrate at 2.45 GHz center frequency for ISM band application. The proposed antenna attained the realized gain at 4.06 dB with the radiation efficiency around 90% at peak value and the bandwidth of 541.5 MHz. The antenna was designed using the CPW structure. CST microwave studio applied to design the proposed antenna simulation. The main purposed of this study is to improve the antenna performances specially the bandwidth, gain, and radiation efficiency. Moreover, another aim of that antenna design is to reduce the antenna size and thickness upon the existing related design with rubber substrate.

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1. INTRODUCTION

Compactness in the antenna design is a popular research interest in the field of wireless body area network (WBAN) application. Besides, coplanar waveguide (CPW) antenna is widely used due to the advantages of improving radiation efficiency and the bandwidth, while reducing the radiation loss and substrate dielectric losses. This CPW antenna feeding technique has much better outcomes compared to the microstrip feed line due to its reduction leakage and minimum dispersion [1].

In [2], a microstrip patch antenna on rubber substrate with defected ground structure (DGS) was designed while, antenna bandwidth at 101 MHz. Enclosed with this bandwidth, antenna showed some positive performances that the improvement of surface current, radiation efficiency and return loss, however it reduced other performances that was lower bandwidth and larger dimensions which ultimately reduced the gain (3.42 dBi) whereas, these performances can be improved by designing a CPW antenna.

A compact antenna design was presented in [3] with meta-surface on rogers' substrate for ISM band application. It presented a CPW monopole antenna design which antenna gain was only 3.3 dBi, reflection coefficient (S_{11}) was -20 dBi and the efficiency was around 88%. Upon overall observation of this antenna, it showed that this antenna had better efficiency, but lower gain. Whereas in [4] the design of two-sided CPW monopole antenna with asymmetric meandered structure with a compact size and designed for three bands (ISM, WLAN, and X-Band) applications was proposed but the antenna gain was not mentioned in the paper.

The antenna designed in [5-13], are all single-band for ISM band application at 2.45 GHz center frequency. The CPW structure was proposed to get a wide bandwidth for antenna design. Besides, in general, modern systems require the wide bandwidth response introduced by various methods mentioned in [14-16]. The design of asymmetric coplanar feed [17] developed the fractional bandwidth that is up to 100%, but achieved limited gain. CPW feeding on antenna design applied in [5-12, 16, 18-21] achieved wide bandwidth with compact size, high antenna gains and lower reflection co-efficient. The antenna design with CPW structure [14, 20], antennas obtained better impedance bandwidth but low gain. In [18-20, 22, 23] all of the antennas were designed for multiband applications, such as worldwide interoperability for microwave access (WiMAX), industrial scientific and medical (ISM) band, wireless fidelity (Wi-Fi), satellite radio-frequency identification (RFID), wireless local area network (WLAN). Nevertheless, these antennas could not satisfy the output performances. Although in [24], this antenna attained high gain and wide bandwidth, but antenna size was large compared with others. As mentioned earlier, most of the antennas were designed with CPW structure for single or multi bandwidth applications using different substrate such as roger, Teflon, FR-4, ceramic, and textile. However, it presented in this paper is the new avenue to design a CPW antenna on a rubber substrate.

Rubber [25] is an alternative material for flexible substrate. It is better than any other flexible material due to low production cost, high elasticity, weather-proof and environment friendly. In FR-4 substrate, the permittivity can be varied by insertion of glass microsphere. In contrast, permittivity of rubber material can vary by the inclusion of carbon black. Glass microsphere is a fragile material and difficult to control with the risk of being broken. On the other hand, carbon black has much more reliability for filling material than fragile glass microsphere.

In this proposed antenna, it is aimed to enhance the expected outcomes from the design mentioned in [2]. The antenna gains in [2] was lower than proposed antenna. It is also a wealthy development that the efficiency can be increased by using CPW structure. That means the CPW antenna has achieved the improvement of overall antenna performances. In this paper, a CPW antenna design has been presented to increase antenna gain, efficiency, and bandwidth. This paper is organized as follows: section 1 will present the introduction. Section 2 will discuss the antenna design methods. The simulation results will be described in Section 3 and at finally, the conclusion will describe in section 4.

2. ANTENNA DESIGN

The layout of the proposed antenna is presented in Figure 1. It is a complete design from the evolution stages shown in Figure 2. The geometrical and dimensional views of the proposed antenna are given in Figure 1. The proposed antenna was designed with two layers using different type of components; the CPW monopole antenna placed as a metal sheet on the top layer and the dielectric substrate located at the bottom of the antenna which used by rubber material. The permittivity of the rubber substrate, ε_r was equal to 3 and loss tangent (tanδ) was equal to 0.02. In addition, the thickness of the dielectric layer and the copper were 1.88mm and 0.035mm, respectively. In the existing work [2], a microstrip antenna with three layers was developed to consist of a copper sheet, a dielectric substrate and a ground plane. In contrast, the proposed CPW antenna consists of two layers where the ground structure was designed on the same layer with patch shape.

Figure 2. illustrates the evolution process of the proposed CPW monopole antenna. CST microwave studio was used to simulate the designs in four stages. The first stage mainly concentrated on designing a standard patch antenna with the CPW structure, followed by the second stage where inset fed was included in the antenna design. In the third stage, slots on feedline were constructed to obtain a narrow way intended for effect on flowing the current distribution. Finally, the optimized design was obtained in the fourth stage where the proposed antenna was simulated on ISM band frequency.

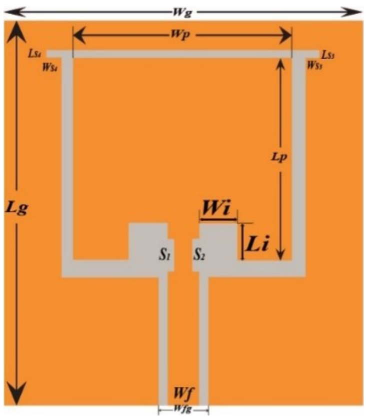
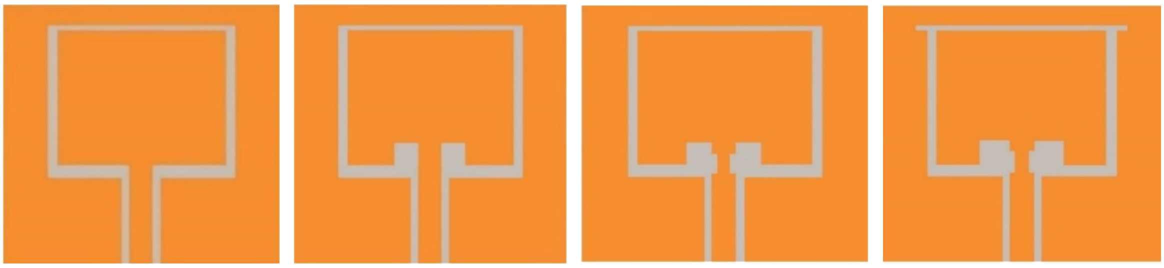


Figure 1. The layout of proposed antenna



(a) (b) (c) (d)

Figure 2. Evolution stages of proposed antenna; (a) Ant 1, (b) Ant 4, (c) Ant 4, and (d) Ant 4

Table 1 presents the proposed antenna dimensions. Here, A' is exposed as calculated values, and A'' is exposed as optimized values. The width of the ground gap is referred as Wf_g. Furthermore, the optimized dimensions have been calculated by (1-4) and presented in Table 1. The antenna geometry was calculated using the following equations. In [14], the CPW structure included, and the expected resonant frequency was achieved by optimizing the calculated dimensions. The width (W) of the patch antenna can be calculated as:

$$W = \frac{c}{2fr\sqrt{\frac{\epsilon r+1}{2}}} \quad (1)$$

Here, f_r is the antenna resonant frequency and ε_r is the dielectric constant of antenna. The length of patch antenna (L) is given by:

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

Here, L_{eff}, ΔL are the effective length and length extension of antenna. The value of ground length (L_g) and ground width (W_g) can be calculated using (3) & (4) [26]:

$$W_g = 12h + W_p \quad (3)$$

$$L_g = 12h + L_p \quad (4)$$

In this paper, the advantage of using CPW structure is that it can utilize the patch antenna pattern with flexible material. By using only two layers, hence reducing the overall thickness of the proposed antenna.

Table 1. The dimensions (A' = Calculated, A'' = Optimized) of the proposed antenna (in mm)

	A'	A''		A'	A''		A'	A''		A'	A''		A'	A''		A'	A''
Lp	34	32	W_g	56	55	Li	6	5	Wf	4.73	-	Ws_1/Ws_2	1	-	Ws_3/Ws_4	2.25	-
Wp	43	33.5	L_g	54.5	52	Wi	1	-	Wf_g	7.73	-	Ls_1/Ls_2	4.5	-	Ls_3/Ls_4	1	-

2.1. Parametric study

A parametric study was performed to identify the optimization of antenna dimension and size. Figure 3 shows the improvements in terms of return loss and resonant frequency between the four antennas. Ant 1 is the initial stage of the proposed design, where the frequency resonated at 4.45 GHz. This frequency can operate in C band application, but it was not the required frequency of the proposed antenna. For Ant 2, we include the inset fed, and the resonating frequency shifted to 2.58 GHz. this antenna can operate in S-band applications. To improve the resonant frequency of Ant 2, we proposed Ant 3. The evolution of that design allows the frequency to be shifted at 2.55 GHz with the return loss at around -26 dB. Finally, Ant 4 improved the resonant frequency of 2.45 GHz with the enhancement of the return loss at -31.17 dB. These analytical study shows the resonant frequency can be controlled by varying the antenna dimensions.

2.2.1. Effects of inset feed (*Li*)

The proposed design (Ant 4) was developed to utilizing the inset feed, and its characteristics depend strongly on the value of the inset feed length (*Li*). The variation of (*Li*) effects on the depth of return loss. So, improvement (decrease) in the return loss can be acquired by varying the length of inset feed. Decreasing the value of (*Li*) from 6 mm to 5 mm gradually improves the return loss (depth) as observed in the parametric study of Figure 4.

The return loss decreased to -31.03 dB when the value of length (*Li*) was 5 mm. The reflection coefficient was improved at -24.80 dB for 5.5 mm and -21.14 dB for 6 mm. These value of inset feed 5, 5.5, 6 mm was only chosen due to keep the resonant frequency at 2.45 GHz with stable condition and otherwise it did not pursue the concern of parametric study.

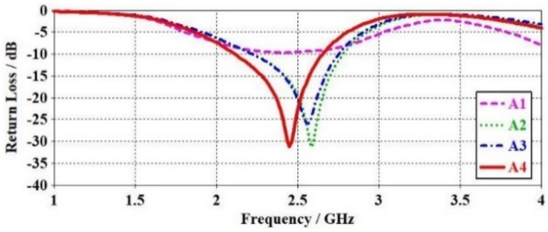


Figure 3. Comparison study of the return loss between Ant 1 to Ant 4

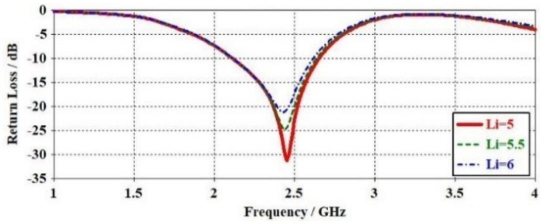


Figure 4. Effect of the variation on the inset feed length at reflection coefficient was improved shorter inset from 6 mm to 5 mm

2.2.2. Effects of the slot width (Ws_3/Ws_4)

In the proposed design, four slots were utilized to build the intended structure on the antenna. Slot 3 and slot 4 were applied to increase the surface current distribution, placed to the right and left corner between ground and patch shape. By changing the Ws_3/Ws_4 values, the resonant frequency can be shifted to the right or left side with the same reflection coefficient (S_{11}) shown in Figure 5. It was observed that the resonant frequency moved to the left side by increasing the width of slots (Ws_3/Ws_4). The resonant frequency was shifted to 2.40 GHz for the width of slots Ws_3/Ws_4=3.25 mm (22 mm in figure value) and the resonant frequency was at 2.45 GHz for Ws_3/Ws_4=2.25 mm (21 mm). Meanwhile, the resonant frequency shifted to the right side as the resonant frequency (f_r) was at 2.50 GHz for Ws_3/Ws_4=1.25 mm (20 mm) and 2.53 GHz for Ws_3/Ws_4=0.25 mm (19 mm). It was also observed that the resonant frequency (f_r) moved to the right side by decreasing the width of slots (Ws_3/Ws_4).

It is observed from these parametric studies that the Ant 4 was the best antenna design where resonant frequency reached at 2.45 GHz with the better return loss of -31.17 dB and it is proved by above mentioned parametric studies. Nevertheless, Ant 4 achieved the higher bandwidth with the wide frequency range where the center frequency was 2.45 GHz. The impedance matching and current distribution also better at Ant 4 compared between others antenna design.

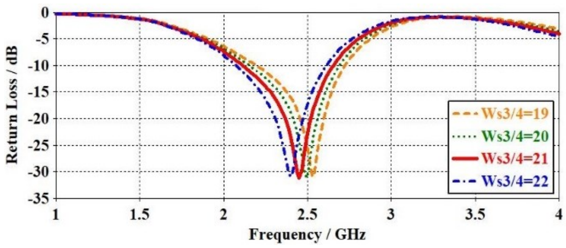


Figure 5. Effect of the variation on the width of slots at reflection coefficient, Ws_3/Ws_4 = 2.25 mm (21 mm) is the desired value of slot width which appeared for 2.45 GHz resonant frequency

3. RESULTS AND ANALYSIS

The patch width and length calculated by (1) and (2). Furthermore, the ground width (W_g) and ground length (L_g) calculated by using (3) and (4) resultant value inserted in Table 1. Figure 6 and Figure 7 are the graphical view of reflection coefficient (S_{11}) and voltage standing wave ratio (VSWR) for Ant 4. The CPW fed monopole antenna design has resulted with an increment to the bandwidth. In [2], antenna flexibility has significant consideration in antenna design for WBAN application. This paper has focused on the improvement of the return loss and bandwidth those are suitable for WBAN application. The bandwidth was 101 MHz in [2], which has been outdone in proposed design with CPW structure. The bandwidth increased by developing the CPW structure in this work at 541.5 MHz. The range of the bandwidth at the proposed antenna is 2.1121-2.6536 GHz which covers full ISM band (2.40-2.50 GHz) and can operate at WLAN (2.412-2.462), Wi-Fi (2.40-2.497), LTE (2.49-2.68) applications. The proposed antenna must operate at 2.45 GHz resonant frequency, which is the center frequency of the ISM band and the reflection coefficient (S_{11}) is -31.17 dB.

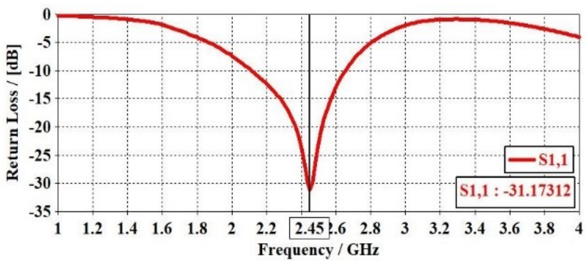


Figure 6. Return loss (S_{11}) at proposed antenna (Ant 4)

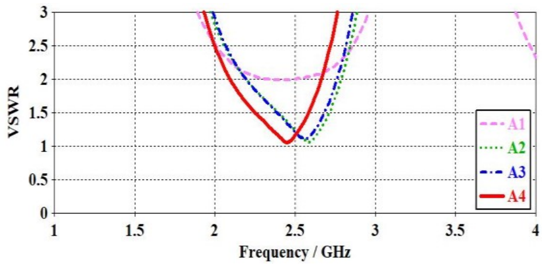


Figure 7. The VSWR of proposed antenna (Ant 1-Ant4)

The VSWR of the proposed antenna (Ant 4) in Figure 7 is 1.05, which is very close to 1. The analysis from Figure 7, Ant 1 got the consequence of VSWR which was above 2 and it was not ideal outcome of the VSWR. In Ant 2 & Ant 3, VSWR were around 1 but resonant frequency more than 2.50 GHz. Lastly, at Ant 4, the VSWR was the better outcome with the expected resonant frequency of 2.45 GHz. It also observed that the VSWR is almost similar with slight variation among the existing works. As shown in Figure 8, the proposed antenna has achieved better directivity than the CPW antennas in some of the reference papers. The directivity of proposed antenna reached at 4.66 dBi in the design of Ant 4.

The realized gain was obtained at 4.06 dB as shown in Figure 9 (a), and this value is better than the value of realized gain in [2]. The meaningful achievement in this work was to improve the realized gain by design CPW antenna with the same dielectric substrate. Consequently, the realized gain within the operational band of the proposed antenna achieved the requirements for the expected system.

The radiation pattern in polar form is shown in Figure 9 (b). This figure presents the H- plane and E-plane radiation pattern at 2.45 GHz of resonant frequency. E-plane and H-plane have taken at 0° and 90° phase angle respectively and stable condition has been ensured. The surface current is shown in Figure 10 (a) and a high value of the current distribution with the CPW fed antenna has been achieved, that is 75.7 A/m and it is a better result in comparison to that of other antenna designs with CPW structure. The maximum efficiency (Peak value) of this work is around 90% of 2.45 GHz resonant frequency, and this value over the efficiency of [2] is shown in Figure 10 (b). So, it is another achievement to get around 90 % radiation efficiency in Ant 4.

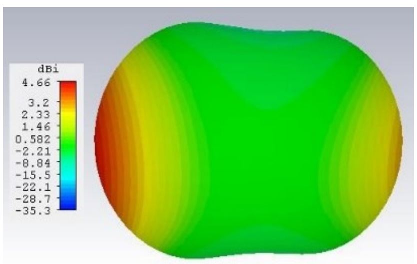
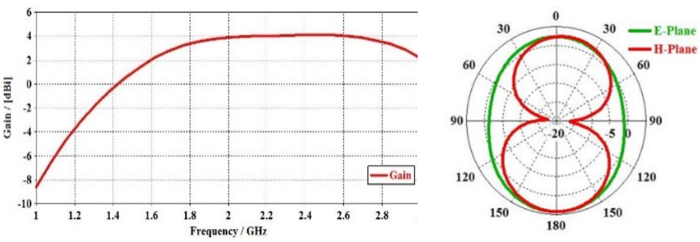


Figure 8. 3D radiation pattern of proposed antenna at Ant 4



(a) (b)

Figure 9. (a) Realized Gain at the proposed antenna, and (b) Radiation pattern at 2D of antenna at Ant 4

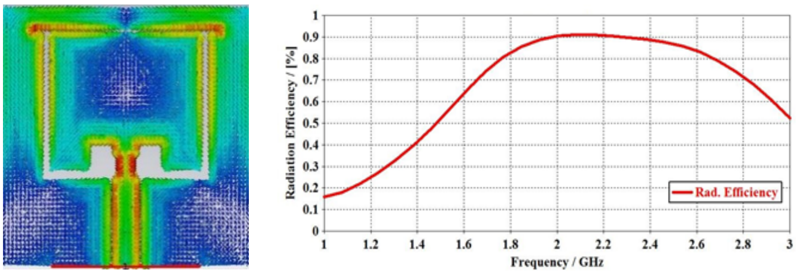


Figure 10. (a) The surface current of proposed antenna at Ant 4, and (b) The radiation efficiency of the proposed antenna at Ant 4

3.1. Bending formulation

The bendability is one of the unique features for a flexible antenna. The flexible antenna should be capable of presenting good performance at the bending condition. It is necessary to investigate the effect of bending on rubber-based antenna. The return loss and resonant frequency are required to be evaluated at bending condition since these properties are affected by geometrical changes that may occur while bending. In this bending analysis, 60° degree preferred as cylindrical angle and it also proved that this antenna could operate on bending condition.

The resonant frequency was fixed for testing the impact of bending that conducted using CST software. The bending effect on the proposed antenna was tested in two different directions that are E and H-planes shown in Figure 11. This proposed model allowed for prediction of performance of the antenna when it was bending. The width of the radius is shifted based on the changing of bending angle as well. During the antenna bent at the H-plane, the width of the antenna was used as the length of the arc, while the length of the antenna was used at the E-plane bending.

Figure 12 shows a plot of measured return losses on E and H-plane bending. The resonant frequency was shifted slightly to a higher value with the bending of the antenna along these planes as expected. The effect of bending on the resonant frequency is predicted by [25],

$$f = \frac{1}{2\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m}{2\theta a}\right)^2 + \left(\frac{n}{2b}\right)^2} \quad (6)$$

The resonant frequency is f, where ε is the substrate permittivity, μ is the permeability. The radius of cylinder is mentioned by a, b is the length of patch antenna and θ is the bending angle. In addition, m and n are using as propagation modes. In Table 2, some of the output performances mentioned at different bending conditions are presented. Here, the bandwidth (BW) and Antenna Q are inversely proportional to each other. The following equation is exactly proved by the getting output performances,

$$BW = \frac{VSWR-1}{Q\sqrt{VSWR}} \quad (5)$$

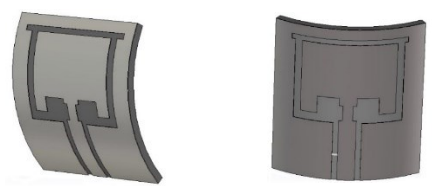


Figure 11. Bending angle (60°) of the designed antenna; (a) E-Plane (Vertically), and (b) H-Plane (Horizontally)

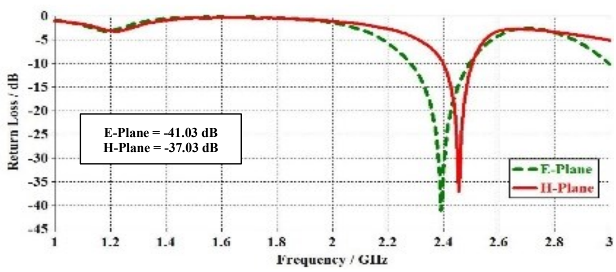


Figure 12. Return loss (S_{11}) at bending conditions

The gain, directivity and radiation efficiency are presented in the Table 3 at the bending conditions of the proposed antenna. It is observed that the results of the H-plane show the slight difference from that of flat condition and E-plane bending. During the bending conditions, resonant frequency moved to left side at E-plane and it was decreased to 2.40 GHz but at H-plane condition, resonant frequency remained at 2.455 GHz. For this situation, H-plane performance has slight difference with flat condition while E-plane output performance has much difference. The summary of comparison has been described below in Table 4, where the performance of the proposed antenna and that of presented in [2] has been shown.

Table 2. Results of comparison between flat and bending conditions on return loss, bandwidth, and *Q* factor

	Angle θ	Resonant Frequency (GHz)	Return Loss (dB)	Bandwidth (MHz)	*Q* Factor
Flat	-	2.45	-31.17	541.5	4.52
E-plane	60°	2.40	-41.03	213	11.21
H-Plane	60°	2.455	-37.03	105	23.27

Table 3. Comparison between radiation characteristics simulated for flat and bending conditions

Bending condition	Angle θ	Gain (dB)	Directivity (dBi)	Radiation Efficiency (%)
Flat	-	4.06	4.66	87.86
E-Plane	60°	3.33	3.79	89.99
H-Plane	60°	4.14	4.92	83.13

Table 4. Comparison between [2] and this work

Experiment Name	[2]	Proposed work
Return loss in dB	-37.33	-31.03
Bandwidth in MHz	101	541.5
VSWR in ratio	1.03	1.05
Surface current in A/m	172	75.7
Rad. Efficiency in %	60%	87.86%
Gain in dBi	3.42	4.06

The comparison study considered the different aspects such as size of antenna, dielectric characteristics, frequency, substrate material etc. It is observed that the proposed design (Ant 4) enhanced the antenna performances in these aspects, better antenna efficiency, wide bandwidth, high realized gain, and compact size have been attained by CPW monopole antenna. The bandwidth has been improved in this work with 541.5 MHz. The radiation efficiency attained around 90%, which was previously obtained around 60% in [2]. In this work, same dielectric material as rubber with the same thickness of the material of 1.88 mm has been applied. In this study, Rubber material has been chosen as substrate material and this is the first effort to use rubber material for design a CPW antenna. In Table 5, the proposed design (Ant 4) has achieved higher gain compared with other benchmarking papers.

Table 5. Comparative study on different natures and proposed antenna design

Ref.	[2]	[7]	[1]	[4]	[5]	[6]	This Work
S_{11}	-37	-47	-50	-32	-37	-27	-31.03
BW (MHz)	101	2800	50	870	10	19	541.5
Gain (dBi)	3.42	2.1	-	-	-	-	4.06
Dielectric Material	FR-4	FR-4	FR-4	FR-4	FR-4	FR-4	Rubber
Rad. efficiency	60%	90%	-	-	-	68%	87.86
Number of Band	Single	Single	Single	Multi	Single	Single	Single

4. CONCLUSION

CPW monopole antenna for ISM band application is discussed in this paper by using the rubber material as the dielectric substrate. The paper analyzes the performance of the proposed antenna as the first attempt to use rubber material in CPW antenna design. By comparing the main achievements of the proposed antenna with the performances of the existing antenna design, it has been observed that the antenna proposed in this paper has achieved wider bandwidth, better efficiency, higher gain. The antenna thickness also has been compressed into two layers due to its being a CPW monopole antenna. In contrast to another conventional antenna of three layers designed as normal patch antenna with ground plane. The proposed antenna (Ant 4) results are more desirable to be used for ISM band application.

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