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A Coplanar Waveguide-Fed Highly Efficient Miniaturized Conformal Triple Band Antenna for Bio-Medical Applications

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A compact co-planar waveguide (CPW) based triple-band printed conformal antenna for on-body applications is presented in this research. In order to accomplish impedance matching, a coplanar structure is employed with the ground on the same plane, and this is printed on the top layer of a polyimide substrate of 0.6 mm thickness. The proposed conformal antenna consists of two identical patch elements. The radiating element is made up of two split ring resonators positioned on the top of the feeding element. The suggested on-body antenna has an overall miniaturized size of only 35 × 37.5 mm^2, making it ideal for use in the biomedical field. The designed antenna is capable to cover various spectrum spanning from 2.387-2.618 GHz, 4.2-4.64 GHz, and 6.23-6.56 GHz with a 2:1 voltage standing wave ratio. The designed antenna is fabricated and antenna parameters are measured which is correlated with simulated results. The antenna achieves a total gain of around 5 dBi with radiation efficiency of up to 95 % over the various operating spectrums. To validate the conformality over curved surfaces, the fabricated prototype of the proposed antenna is bent at 30°, 45, 90° angles and the measured results are compared with simulation results of the bending analysis. Furthermore, to validate the on-body performance of the antenna Specific Absorption Rate has been calculated through simulation and it is found to be lower than 1 W/Kg over all three bands of spectrums which proves that the proposed bio-medical antenna could be a viable candidate for microwave imaging applications.

Keywords: Printed antenna, Conformal antenna, On-body antenna, Triple-band, SAR, Bio-medical.

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1. INTRODUCTION

The demands for wearable devices are increasing very rapidly with the recent advancement in wireless communication technology due to its important applications in various sectors, most importantly for biomedical equipments in health sectors. With this remarkable growth in flexible and wearbale printed electronics, the high performance efficient flexible/conformal/wearbale antennas are distinctly sought after to fulfil the advanced requirements of various applications. In recent years, deploying microstrip (printed) antennas for health monitoring applications has been the subject of substantial study in the field of biomedical applications. Because of their intended application in Implantable medical devices (IMDs), the antennas need to be small, lightweight, and human-body-conforming. The wirelessly connected medical implants might be placed almost anywhere in the body. However, these IMDs have short battery lives and need to be recharged regularly. There is a solution to this issue in the form of on-body devices [1] that strengthen the communication between the medical practitioner and patient without the need for wires to the batteries. When used for on-body applications, the implemented antennas should have certain characteristics such as compact size, capability to operate at multiple bands, higher operating bandwidth, high efficiency, Conformal structure, acceptable specific absorption rate (SAR) etc. for real-world applications. Several antennas with high bandwidth, efficiency, and compact size etc. are reported in literature [2-5] but these designs are neither conformal nor suitable for on-body applications. Afterwards, conformal or flexible antennas are proposed but they are applicable only for off-body communications [6-8]. In literature some printed flexible/wearbale antenna designs are also reported for wireless body area network [9-10], health monitoring [11], telemedicine devices [12], telemetry services [13], and biomedical [14] applications.

The Wideband and UWB antennas suffers from interference due presence of other co-existing narrow

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bands within wide frequency spectrum, hence UWB antenna needs to be integrated wirh filters or it should operate with notched bands.

In order to reduce these design complexity and cost, we have proposed a triple-band antenna that is printed on a 0.6 mm thick polyimide substrate for conformal biomedical applications. As, the antenna operates at separate multiple bands, so there is relatively less possibility of intereference with other nearby bands compared to UWB antennas. The developed conformal antenna functions at 2.5 GHz, 4.5 GHz, and 6.5 GHz covering the frequency spectrums from 2.387-2.618 GHz, 4.2-4.64 GHz, and 6.23-6.56 GHz, respectively to be utilized for Medical Implant Communication Service (MICS) and Industrial, Scientific, and Medical (ISM) bands applications. The antenna achieves gain of up to 5 dBi with a high radiation efficiency of around 92 % which is substantial for recent and advanced wireless communication systems. Further, the performance of the antenna is validated by calculating Specific Absorption Rate (SAR) for all the bands of resonance which ensures the proposed design could be useful for biomedical applications.

This research would make significant contributions, some of which are noted below.

i. The proposed antenna has been printed on a very thin (0.1 mm thickness) polyimide bio-compatible substrate with superior radiation characteristics.

ii. Because of the Co-planar structure, maximum radiation is achieved above the surface of the proposed antenna which prevents unwanted radiation of EM signals.

iii. As the antenna is printed on a thin substrate, the designed antenna could be folded as much as possible without degrading the performance.

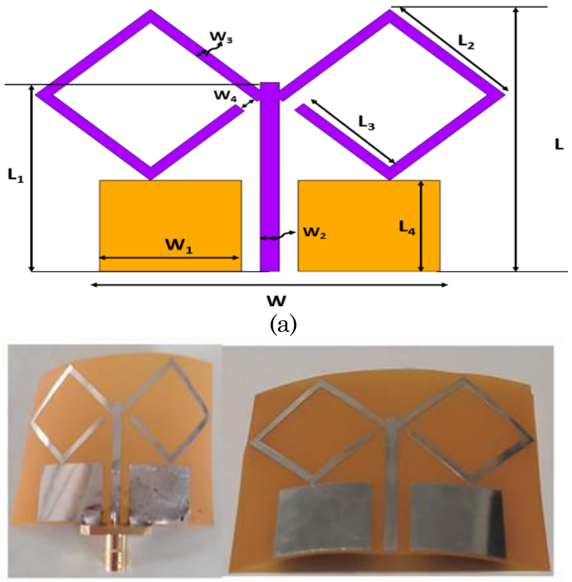
iv. The designed antenna not only covers the ISM band (2.45 GHz), but it also covers other useful spectrums (5.5 GHz and 6.5 GHz) for modern wireless applications.

v. With such a low profile, the proposed antenna archives a maximum gain of up to 5 dBi and radiation efficiency of around 92 % over the desired band of operation.

2. DESIGN AND METHODOLOGY

The suggested antenna is completely printed on a polyimide substrate of 0.6 mm thick with a dielectric constant of 3.5. Initially, two complimentary split ring resonators (CSRRs) are located at the left and right top edges of the feeding strip whose length is $L_1 \times W_2 = 27 \times 27$ mm^2. To reduce the overall dimension of the antenna two CSRRs are rotated with an angle of 45° as shown in Figure 1 (a). Because of the coplanar waveguide (CPW) configuration of the proposed antenna, its two grounds have been printed on the substrate's top surface. The suggested antenna is prototyped, and its meaningful performance is verified by measuring and analyzing its antenna characteristics. Figure 1 (b) depicts the final product of the fabricated antenna prototype. The dimensions of proposed antenna's different structural parameters are $L = 37.5$, $L_1 = 27$, $L_2 = 12.235$, $L_3 = 9.1195$, $L_4 = 13$, $W = 35$, $W_1 = 15$, $W_2 = 27$, $W_3 = 0.94$, $W_4 = 1.3591$ [all dimensions are in mm].

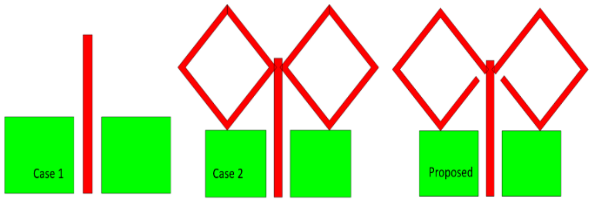
The progressive design evolution of the CPW Antenna is demonstrated in Figure 2 (a) and the corresponding variations in reflection coefficients for different stages of modifications are shown in Figure 2 (b). Initially, a single microstrip line is designed and named case 1. As shown in Figure 2 (b), the design specified in case 1 suffers from an impedance matching problem and is not able to resonate at all anywhere in the spectrum ranging from 0 to 10 GHz with below – 10 dB reflection coefficient. Then two concentric square elements have been added (case 2) at the top corner of the microstrip line as shown in 2 (a). However, the structure in case 2 provides single band resonance only at 5 GHz. Finally, a small opening has been made at square elements (proposed antenna) as shown in Figure 2 (a) to behave like a split ring resonator (SRR). The proposed antenna is now able to yield resonance at three bands centered at 2.45 (2.387-2.618 GHz), 4.5 (4.2-4.64 GHz), and 6.5 GHz (6.23-6.56 GHz) with significantly well improved reflection coefficients at each resonant frequency [depicted in Figure 2(b)].



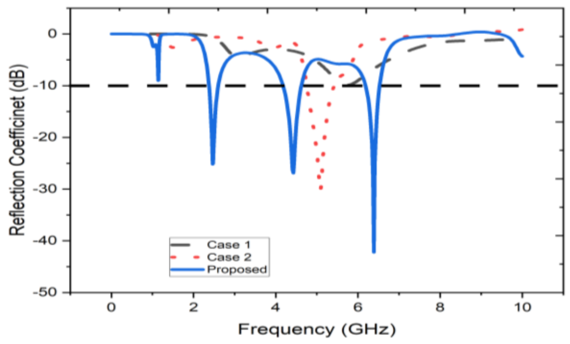
(a)

(b)

Fig. 1 – Proposed CSRR-inspired Antenna (a) structural view (b) fabricated prototype



(a)



(b)

Fig. 2 – (a) Design evolution of the proposed antenna (b) Reflection coefficients of Case 1, Case 2, and proposed CPW antenna

3. RESULTS AND DISCUSSIONS

Figure 3 depicts the proposed antenna's reflection coefficient characteristics. The S-parameter of the proposed antenna is measured using a well calibrated Anritsu MS2037C combinational vector network analyzer. Across all three frequency ranges, the antenna's reflection coefficient is more than 10 dB. The first band includes the conventional ISM band at 2.45 GHz, and the remaining two bands (4.5, 6.5 GHz) covers the spectrum for wireless applications.

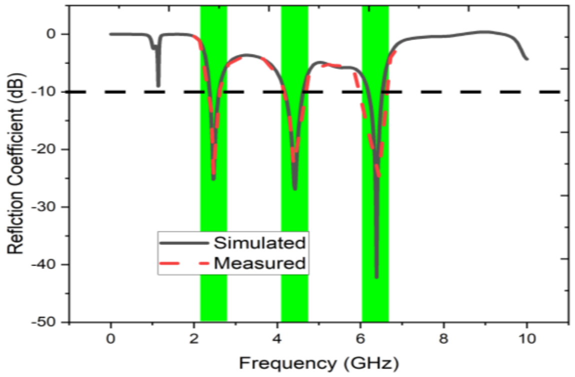


Fig. 3 – Reflection Coefficient of the proposed antenna

The radiation performance parameters (Radiation patterns, gain, and radiation efficiency) of the proposed antenna are also measured and compared with simulation results. The radiation parameters are measured in anechoic chamber. The photograph of the measurement setup in anechoic chamber is depicted in Figure 4. Radiation patterns of the recommended design in two dimensions at frequencies of interest are shown in Figures 5 (a-c) for 2.5, 4.5, and 6.5 GHz. It is noticed that the antenna exhibits omni-directional radiation pattern with cross polarization better than 25 dB over the complete band spectrums. The antenna also achieves an overall gain of around 3.25-5.5 dBi with peak radiation efficiency up to 95 % as shown in Figure 6 (a) and (b), respectively in the desired band of spectrums which is highly acceptable for the antenna to be operated for bio-medical applications.

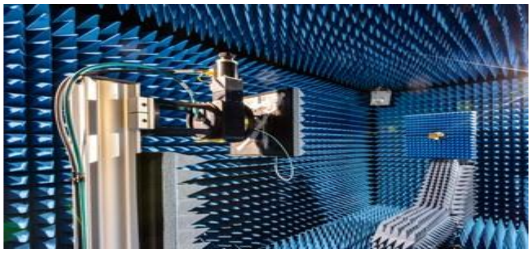
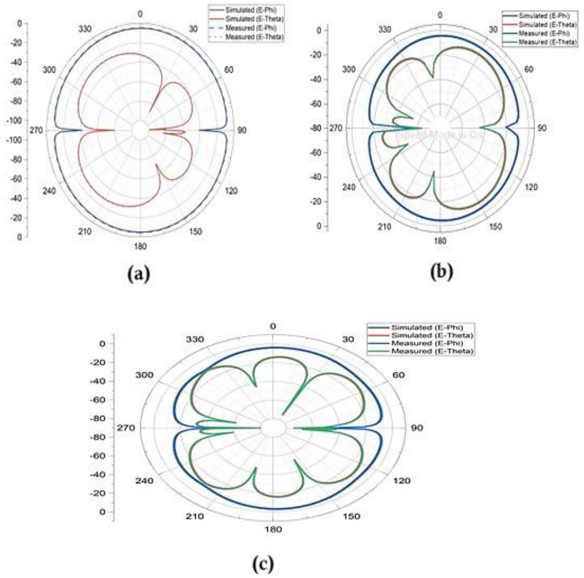


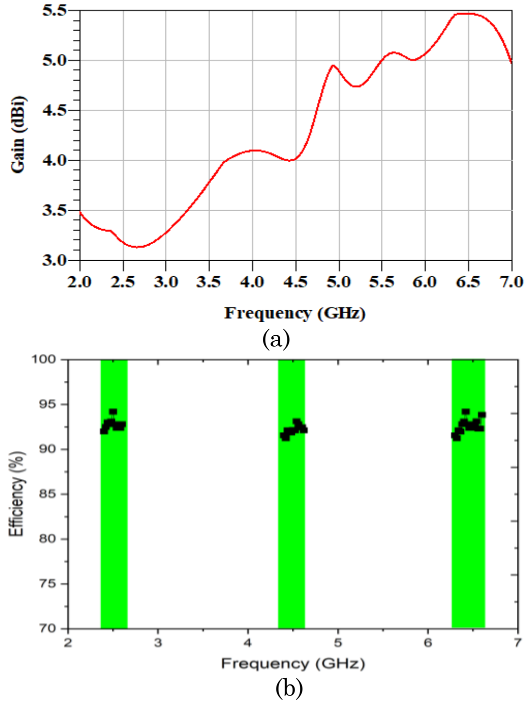
Fig. 4 – Measurement setup in anechoic chamber



(a) (b)

(c)

Fig. 5 – Simulated and Measured Radiation Pattern of the proposed antenna (a) 2.5 GHz, (c) 4.5 GHz (d) 6.5 GHz



(a)

(b)

Fig. 6 – Radiation Performance (a) Gain, (b) Efficiency

4. ON-BODY ANALYSIS

This section presents the on-body analysis of the proposed antenna by showcasing the antenna attached to human phantom model to judge its adaptability for weable applications by calculating its specific absorption rate (SAR). The results of a study assessing the proposed antenna's adaptability under a range of deformation conditions and in relation to a number of anatomical locations on the human body are shown in Figure 7. The phantom's model was built via CST MWS, and it consists of four different layers representing skin, fat, muscle, and bone. Materials and design parameters for the human body phantom are consistent. The SAR analysis of the propsed conformal antenna is depicted in Figure 8. Table 1 lists the primary features of every layer in particular. Using a simulation study, we examine the impact of stacking on antenna performance. The 1g and 10g of body tissue employed in this study did not have a specific absorption rate (SAR) higher than the maximum value authorized by the Federal Communication Commission (FCC) as shown in Table 2.

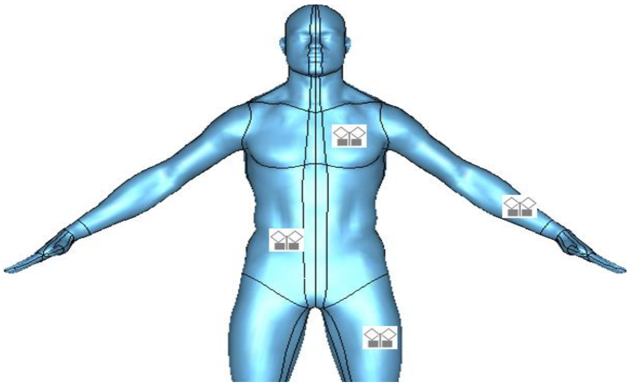


Fig. 7 – On-Body analysis of the proposed wearable antenna

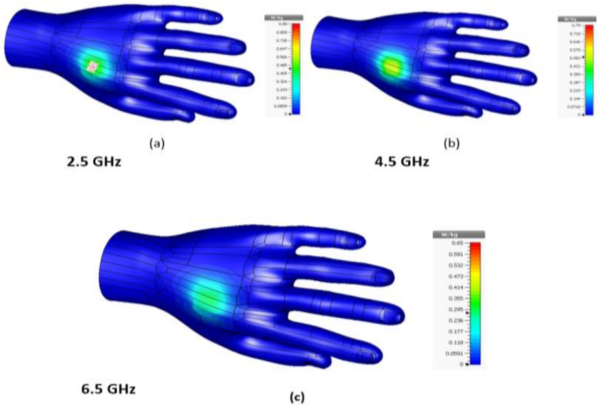


Fig. 8 – SAR analysis of the conformal antenna

Table 1 – Conductivity features of human tissue

Name of the Human Tissue	Skin	Fat	Bone	Muscle
Dielectric constant (ξ_r)	30.95	5.152	12.362	51.9856
Conductivity (S/m)	5.4856	0.09	3.758654	1.92583
Loss tangent	0.3654	0.198654	0.27	0.256478
Density (Kg/m^3)	1100	1100	1850	1060

Table 2 – Antenna absorption rate at different body locations at various frequencies

Frequency of Operation	Position	SAR (1g)	SAR (10g)
2.5 GHz	Chest	0.786	0.661
	Stomach	0.7785	0.782
	Hand	0.857	0.552
	Thigh	0.75	0.5102
4.5 GHz	Chest	0.798	0.789875
	Stomach	0.8796	0.89965
	Hand	0.7546	0.75548
	Thigh	0.7985	0.56528
6.5 GHz	Chest	0.785	0.658
	Stomach	0.6525	0.7854
	Hand	0.65123	0.8546
	Thigh	0.72564	0.75648
	Chest	0.8654	0.79865

5. CONFORMABILITY ANALYSIS

This section examines the antenna's durability by experimenting with different bending angles. The angle has been varied from 30° to 90° as shown in Figure 9 (a) – (e) and the corresponding reflection coefficient is plotted as illustrated in Figure 10. Clearly, the antenna's malleability does not come at the expense of its signal-sending efficiency. Table 3 compares the performance of the designed antenna with other antennas presented in the previous studies. The antenna comparison is done with respect to the size of the antenna, frequency of operation, application, and conformability. The proposed antenna is smallest in dimension and displays superior performance in terms of supporting the spectrum of multiple operating bands, conformability. The antenna communicated in this research could find its place in on-body wearable applications.

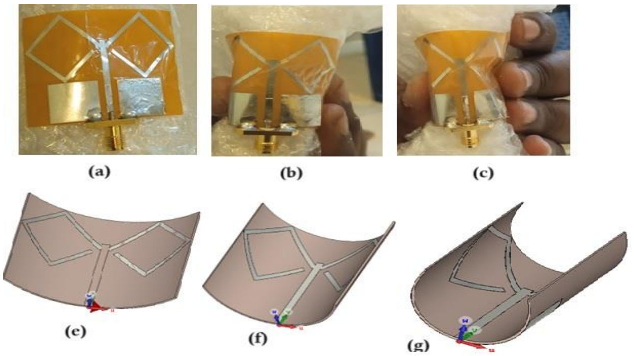


Fig. 9 – Various bending configurations of the proposed antenna (a) –(c) Measured (30°, 45, 90°) (d)–(f) Simulated (30°, 45, 90°)

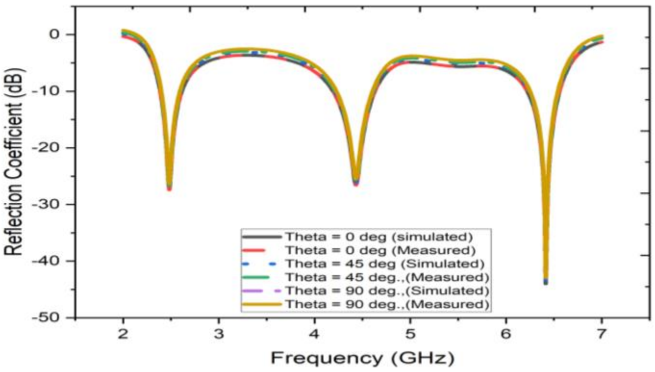


Fig. 10 – Conformal Analysis of the proposed antenna

Table 3 – State of Art Comparison with antennas presented in the literature

Ref.	Antenna size (mm^2)	Frequency of Operation (GHz)	Application	Confor-mability
[2]	300 × 300	0.34 -10.28	UWB	No
[3]	65 × 45	1.8-11	UWB	No
[4]	50 × 41	3-11.4	UWB	No
[5]	22 × 19	4.2-5.0, 8-12.2	Communication	No
[6]	75 × 75	1-6	Communication	Yes
[7]	92 × 25	0.984-1.052	RFID, Sensing	Yes
[8]	37 × 63.6	2-12	UWB	Yes
[9]	62 × 42	2.36-2.40	WBAN	Yes
[10]	86 × 72	3.5-10.6	WBAN	Yes
This Work	**35 × 37.5**	**2.45, 4.5, 6.5**	**On-Body**	**Yes**

6. CONCLUSION

A CSRR-inspired, CPW-structured triple-band antenna for wearable applications is presented in this article. The ground planes are printed on the top half of the 0.6 mm thick polyimide substrate, which allows for impedance matching. The suggested on-body antenna has an overall size of around 35 × 37.5 mm^2, making it very compact for use in the medical field. The developed antenna has a voltage standing wave ratio of 2:1, making it suitable for use across a wide frequency range (2.387-2.618 GHz, 4.2-4.64 GHz, 6.23-6.56 GHz). Two split ring resonators mounted on top of the feeding element form the radiating component. Overall, the antenna can reach a gain of around 5 dBi over its wide range of frequencies of operation, with a radiation efficiency of up to 95 %. The antenna's performance has been analyzed when attached to the human body. The proposed bio-medical antenna has a Specific Absorption Rate (SAR) of less than 1W/Kg throughout all three bands of spectra, as shown by both simulation and measurement findings. The proposed triple band conformal antenna could be a promising choice for weable biomedical applications due tp its attractive chatracteristics.

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Компланарна хвилеводна високоефективна мініатюрна конформна тридіапазонна антена для біомедичних застосувань

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У роботі представлена компактна тридіапазонна друкована конформна антена на основі копланарного хвилеводу (CPW) для застосування в медицині. Щоб досягти узгодження імпедансу, компланарна структура використовується із заземленням на одній площині, і це друкується на верхньому шарі поліімідної підкладки товщиною 0,6 мм. Пропонована конформна антена складається з двох однакових накладних елементів. Випромінювальний елемент складається з двох розділених кільцевих резонаторів, розташованих у верхній частині живильного елемента. Запропонована накладна антена має загальний мініатюрний розмір лише 35 × 37,5 мм^2, що робить її ідеальною для використання в біомедичній галузі. Розроблена антена здатна охоплювати різний діапазон діапазону від 2,387-2,618 ГГц, 4,2-4,64 ГГц і 6,23-6,56 ГГц із співвідношенням стоячих хвиль напруги 2:1. Розроблена антена виготовляється, параметри антени вимірюються, що корелюється з результатами моделювання. Антена досягає загального посилення близько 5 дБі з ефективністю випромінювання до 95 % у різних робочих спектрах. Для підтвердження конформності на вигнутих поверхнях виготовлений прототип запропонованої антени згинається під кутами 30°, 45, 90°, а результати вимірювань порівнюються з результатами моделювання аналізу вигину. Крім того, щоб перевірити ефективність антени, за допомогою моделювання було розраховано питомий коефіцієнт поглинання, і виявлено, що він нижчий за 1 Вт/кг у всіх трьох діапазонах спектру, що доводить, що запропонована біомедична антена може бути використана для застосування в мікрохвильовому діапазоні.

Ключові слова: Друкована антена, Конформна антена, Тридіапазонна антена, SAR, Біомедицина.