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A 2.45 GHz semi-flexible wearable antenna for industrial, scientific and medical band applications

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ABSTRACT

In this work, a compact size, wearable microstrip patch antenna is designed, simulated and fabricated for the Industrial, Scientific and Medical (ISM) band applications with the operating frequency at 2.45 GHz. A semi-flexible substrate material which is Rogers Duroid RO3003™ with a relative dielectric constant, ε_r of 3, loss tangent, tan δ of 0.010 and thickness, h of 1.52 mm has been proposed to ensure it can be worn on clothes. The antenna has a low-profile feature with 24 × 28 mm2 in dimension. Investigation of the antenna under bending condition on the approximate human arm size is also performed and analysed to ensure that the wearable antenna is applicable for on-body. The bending investigation shows that the initial resonant frequency of 2.45 GHz is shifted to 2.3 GHz. However, the reflection coefficient at 2.45 GHz is still greater than the -10-dB which implies that the antenna is still functional at that particular frequency. The Specific Absorption Rate (SAR) of the antenna has also been simulated to examine whether the antenna obeys the SAR limits under the FCC and CNIRP guidelines. The SAR values obtained show that the antenna obeys the standard for 1 mW input power. The SAR value for 1g of human tissue is computed at 0.03999 W/kg (FCC standard: 1.6 W/kg) while for 10g is at 0.01936W/kg (CNIRP standard: 2 W/kg).

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1. INTRODUCTION

Wireless communication technology has matured as a viable way to provide universal, unrestricted and convenient infrastructures [1]. Hence, the utilization of wireless radio system is increasingly essential for high speed data transmission in commercial, military and personal communications. The Industrial, Scientific and Medical (ISM) band which operates at 2.45 GHz is reserved internationally for the non-commercial use in the industrial, scientific and medical purposes rather than telecommunications [2]. The ISM bands are license-free and have low power consumption [3]. In order to take advantage of these features, there has been a growing research interest to integrate one or more ISM bands in a single device to improve its functionality [4-5].

Recently, intensive work has been devoted in the Wireless Body Area Network (WBAN) applications where ubiquitous computing devices are allowed to have on-body wireless communication with each other [6]. In order to cater to the needs, several frequency bands, other than the ISM band, have been assigned for WBAN systems known as the Medical Implant Communication System Band (MICS: 400 MHz) and the Ultra-wideband (UWB: 3.1 – 10.6 GHz), respectively [7]. The challenge lies in the integration of the on-clothing to achieve the “body-worn” communication systems [8]. A simple microstrip antenna consists of a radiating patch on one side of a dielectric substrate and a ground plane on the the other side [9 - 10].

Such antenna is suitable for body-worn applications since it mainly radiates perpendicularly to the planar structure and the ground plane efficiently shields the body tissues [11-12]. Therefore, the utilization of wearable textile materials as antenna substrate has been speedy [13-14]. Traditional antennas are rigid and inflexible which makes it not suitable for wearable applications [15]. Other considerations for body worn antennas are the radiation performance, small in size, robust, low-cost, consumes a small amount of power, comfortable to wear and ease of manufacture [16]. The behaviour of wearable antennas are mainly affected by the properties of the substrate materials [17]. For instance, the efficiency and bandwidth of the antenna are affected by the thickness and dielectric constant of the substrate material [18]. Moreover, wearable antennas are becoming lighter in terms of weight and can be integrated into or hidden inside clothing [19] or attached to clothing to improve wireless communication links [20].

Wireless Body Area networks (WBANs) are becoming increasingly crucial and play an important role in wireless communications systems. WBANs are revolutionizing in telemedicine communication system and health care sector by utilizing the human body itself as a transmission medium [21]. The challenge in designing the antenna for WBAN applications lies in the acceptability within the proximity of the human body and the effect of radiation properties to human body in terms of Specific Absorption Rate (SAR). In order to protect the human body from excessive radiation, standardised SAR limits have been introduced by the Federal Communications Commisison (FCC) and International Commission on Non-Ionizing Radiation Protection (CNIRP). The SAR value for 1g of human tissue is 1.6 W/kg according to the FCC standard while for 10g of human tissue is 2 W/kg based on the CNIRP standard [22].

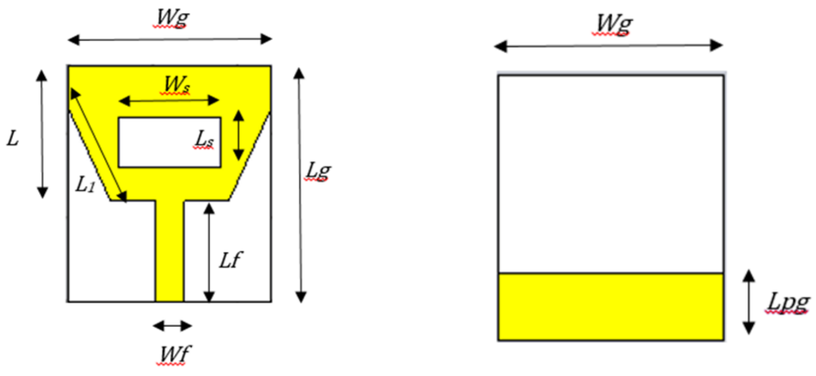
Therefore, a semi-flexible wearable microstrip patch antenna with Rogers Duroid RO3003 is proposed in this work as it offers a good solution in terms of flexibility and lighter weight structure that makes it conformable to human body. In addition, Rogers RO3003™ has the ability to produce an omnidirectional pattern since the human body will block the backwards radiation, which is commonly known as body shadowing effect [23]. The proposed antenna operates at 2.45 GHz for ISM band applications.

2. RESEARCH METHODOLOGY

This section will further explain the methods used in order to obtain the results of the work, starting from the design stage until the measurement stage.

2.1. Antenna Design and Configuration

The design and simulation of the antenna are done by using CST MWS® software. The dimensions of the antenna are optimized to achieve the required frequency at 2.45 GHz and also the best linear characteristics. The antenna is simulated on a semi-flexible, Rogers Duroid RO3003™ substrate with a relative permittivity, εr of 3, loss tangent, tan δ of 0.0010 and thickness, h of 1.52 mm. The substrate between the patch and ground plane of microstrip antenna plays an important role in antenna design as it dictates the bandwidth, size, gain and efficiency of that particular antenna [24]. Figure 1 shows the structure of the proposed antenna. The dimensions of the antenna are listed in Table 1.



(a) (b)

Figure 1. The wearable microstrip patch antenna with Rogers Duroid RO3003 substrate; (a) Top view (b) Bottom view

Table 1. Dimensions of the Wearable Microstrip Patch Antenna with a Rogers Duroid RO3003 Substrate

Parameter	Value (mm)	Parameter	Value (mm)
L	16	L_s	6
W	24	W_s	12
L_g	28	L_1	11
W_g	24	L_{pg}	7.1
L_f	12	h_t(copper)	0.035
W_f	3.5	h_s (substrate)	1.52

2.2. Antenna Simulation in Bending Condition

The bending investigation is conducted along the y-axis plane. CST MWS® software is used to simulate the antenna over a vacuum cylinder with a varying diameters, d of 70 mm, 80 mm and 100 mm as can be seen in Figure 2. The variation of diameters resulting in different antenna curvatures as depicted in Figure 3.

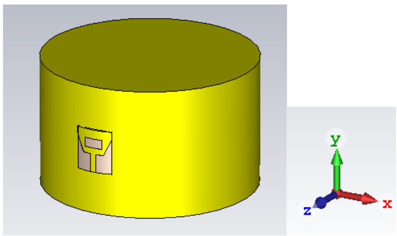


Figure 2. Antenna bending along the y-axis plane

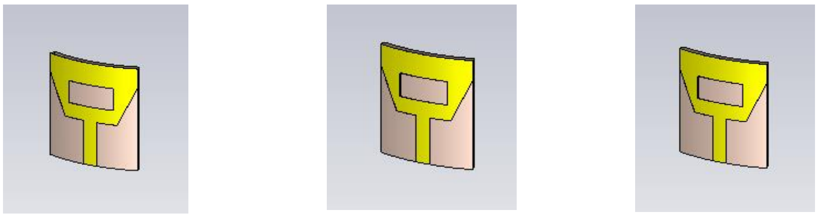
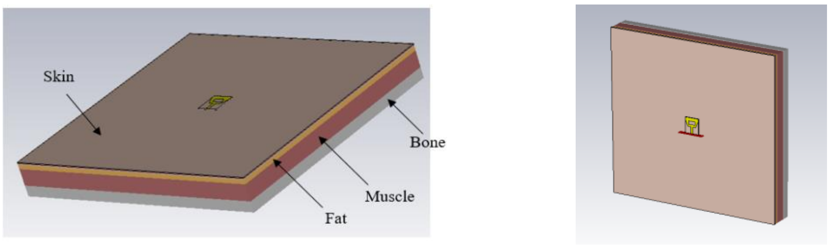

(a) (b) (c)

Figure 3. Variation of antenna bending on vacuum cylinder with varying diameters along the y-axis; (a) d = 70 mm (b) d = 80 mm (c) d = 100 mm

2.3. Antenna Simulation of Specific Absorption Rate (SAR) Level

As the antenna is to be worn on the body, a numerical phantom model as illustrated in Figure 4 has been developed in CST MWS® software to compute the SAR value. Therefore, the information of human tissues such as the dielectric constants, densities and conductivities at 2.45 GHz are necessary in the design stage [25]. The phantom model consists of four layers of human tissues which are skin, fat, muscle and bone. Table 2 lists the important parameters of each human tissue layer.



(a) (b)

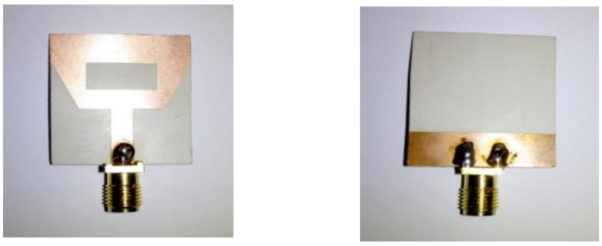
Figure 4. Numerical human phantom model; (a) Human tissue layers (b) Front and side view

Table 2. Important parameters of human tissue layers at 2.45 GHz

Tissue layers	Dielectric constants, ε_r	Densities, ρ (kg/m^3)	Conductivities, σ (Ωm)$^{-1}$	Thickness (mm)
Skin	44	1100	1.85	2
Fat	12	910	0.82	5
Muscle	49.6	1041	2.26	20
Bone	4.8	1850	0.21	13

2.4. Antenna Fabrication and Measurement

The fabrication process is conducted at the Advanced Printed Circuit Board (PCB) Design Laboratory. The outcomes of the fabrication process can be viewed in Figure 5. The antenna is fabricated on a semi-flexible, Rogers Duroid RO3003™ substrate with a relative permittivity, εr of 3, loss tangent, tan δ of 0.0010 and thickness, h of 1.52 mm. The antenna is then measured by using the ZVB14 Rohde & Schwarz Vector Network Analyser. Figure 6 shows the coaxial cable and the PVC pipes that have been used in bending measurement. The experimental setup of the wearable antenna in bending condition can be seen in Figure 7.



(a) (b)

Figure 5.The final prototype of the semi-flexible wearable antenna; (a) Front view (b) Back view

(a) (b)

Figure 6. Bending measurement apparatus; (a) Coaxial cable (b) PVC pipes with varying diameters

(a) (b) (c)

Figure 7. Experimental setup for bending measurement over various diameters of PVC pipes; (a) d = 70 mm (b) d = 80 mm (c) d = 100 mm

3. RESULTS AND ANALYSIS

In this section, the linear characteristics of the antenna, its performance in the bending condition and also the SAR level are discussed and analysed.

3.1. Reflection Coefficient

The simulation result of reflection coefficient, S11 and the comparison with the measurement result are shown in Figure 8. From the simulation result, the semi-flexible wearable antenna operates at 2.45 GHz with S11 of -47.29 dB. The measurement result, on the other hand, shows that the S11 also falls at 2.45 GHz but with -34.13 dB. Thus, a good agreement has been achieved.

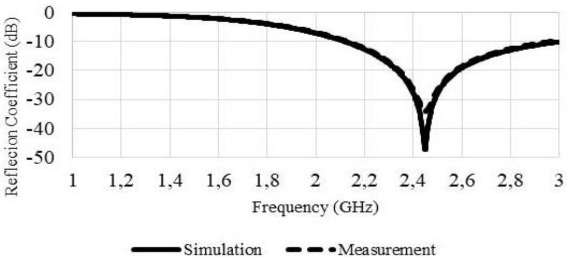
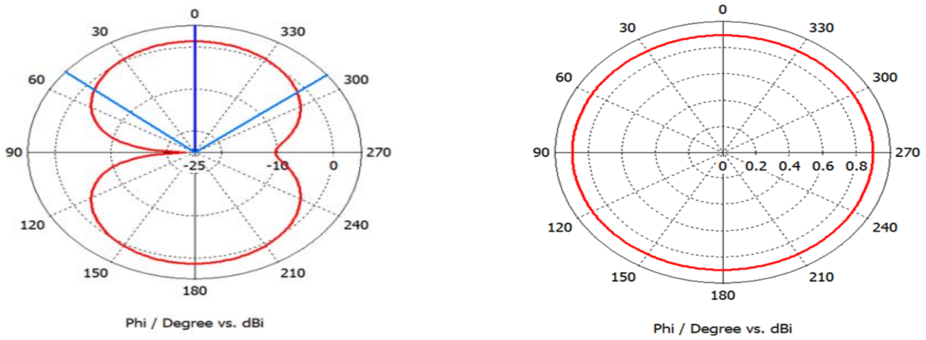


Figure 8. Simulated and measured reflection coefficient of the semi-flexible wearable antenna

3.2. Radiation Pattern

Figure 9 shows the radiation patterns of the semi-flexible wearable microstrip patch antenna in the E-plane and H-plane. From the figure, it can be seen that the radiation pattern in the E-plane is bidirectional with a doughnut-shaped pattern while in the H-plane, an omnidirectional pattern is observed.



(a) (b)

Figure 9. Simulated radiation patterns of the wearable antenna in the; (a) E-plane (b) H-plane

3.3. Surface Current Distribution

Figure 10 shows the surface current of the antenna. From the figure, the maximum surface current is seen to be concentrated around the edges of the feedline.

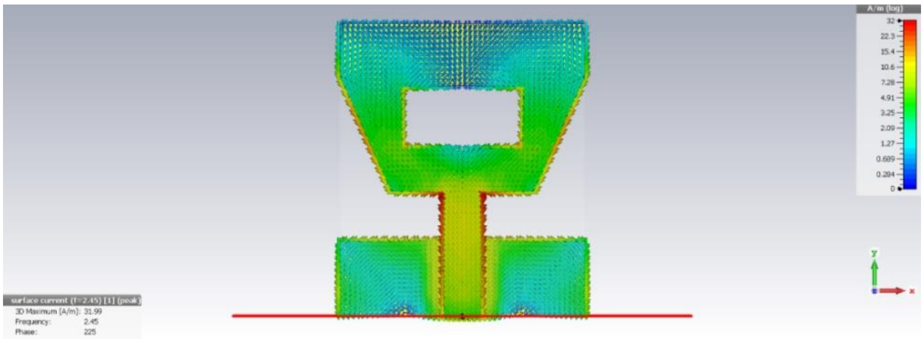


Figure 10. Simulated surface current of the wearable antenna at 2.45 GHz

3.4. Bending Investigation

The simulated reflection coefficients, S11 for different bending diameters are shown in Figure 11. From the figure, it can be observed that there is a slight shift in the resonant frequency of each diameter as compared to the antenna in a flat case (Figure 8). In this case, the antenna is shifted to 2.3 GHz. However, the S11 at 2.45 GHz is still reasonable which is at -17 dB. Therefore, the antenna is still functional at 2.45 GHz under bending condition.

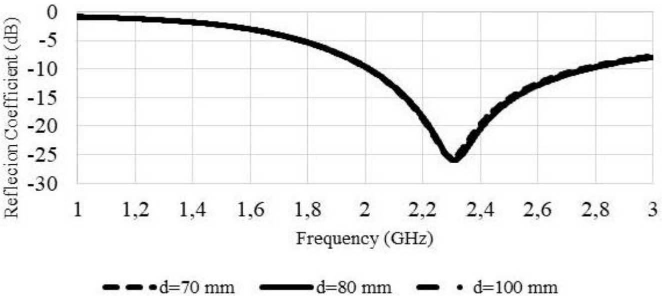


Figure 11. Simulated reflection coefficient for different bending diameters at y-axis

Figure 12 shows the measured S11 for different bending diameters of the antenna along the y-axis. From the figure, a backward shift is observed in the resonant frequency of each corresponding diameter. The contradiction between the simulation and measurement results can be attributed to the antenna misalignment.

Table 3 lists the comparison between the simulated and measured resonant frequencies in bending condition. From the table, a fair agreement is observed between the measured and simulated results.

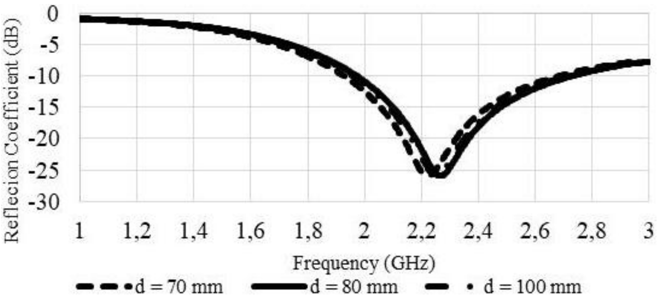


Figure 12. Measured reflection coefficient for different bending diameters at y axis

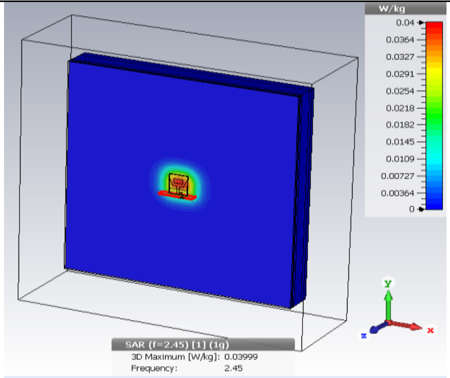
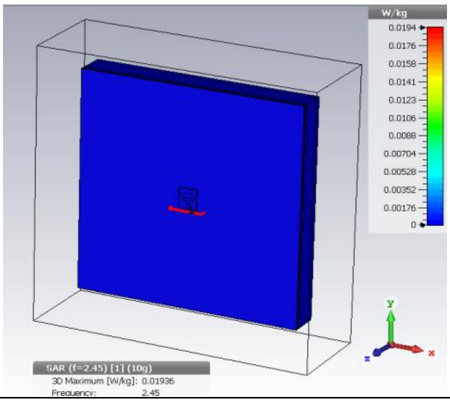
Table 3. Comparison of resonant frequencies between the simulated and measured results of the antenna in bending condition

Diameter, d (mm)	Simulated Resonant Frequency (GHz)	Measured Resonant Frequency (GHz)
70	2.3	2.25
80	2.308	2.298
100	2.308	2.3

3.5. Specific Absorption Rate (SAR)

Table 4 shows the simulated SAR values for the antenna at 2 mm away from the tissue model with 1 mW input power. From the table, it can be seen that the SAR value for 1g is calculated at 0.03999 W/kg (FCC standard: 1.6 W/kg) while for 10g is at 0.01936 W/kg (CNIRP standard: 2 W/kg). Thus, the SAR values of the antenna for 1 mW input power is used because it is applicable and obeys the FCC and CNIRP guidelines.

Table 4. Simulated SAR Values at 2 mm AWAY from the Tissue Model for 1 mW Input Power

Human tissue weight (g)	SAR (W/kg)
1	
10	

4. CONCLUSION

A wearable microstrip patch antenna with asemi-flexible Rogers Duroid RO3003 has been designed, simulated and fabricated in this work. The linear characteristics of the antenna is measured by using the ZVB14 Rohde & Schwarz Vector Network Analyzer (VNA). However, due to the lack of facilities, only the reflection coefficient of the antenna can be measured. The antenna bending on the approximate human arm diameters (d = 70 mm, 80 mm and 100 mm) have been modelled and simulated in CST MWS® software to investigate the on-body performance. The bending investigation shows that the initial resonant frequency of 2.45 GHz is shifted to 2.3 GHz. However, the reflection coefficient of the antenna in each diameter at 2.45 GHz is -17 dB which indicates that the antenna can still operate at that particular frequency. Specific Absorption Rate (SAR) values on 1g and 10g of human tissue have also been simulated by using CST MWS® software to ensure that the SAR limits on each weight obey the required standard by the FCC and CNIRP. The obtained SAR values show that the input power of 1 mW obeys the guidelines with the SAR value for 1g is calculated at 0.03999 W/kg (FCC standard: 1.6 W/kg) and for 10g is at 0.01936 W/kg (CNIRP standard: 2 W/kg). From the overall results, it can be concluded that the simulation and measurement results fairly agree with each other and implies that the semi-flexible Rogers Duroid RO3003™ substrate is acceptable for wearable applications.

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