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Original Article

Design of a Polyester Substrate Based Microstrip Patch Antenna for WBAN Applications

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Abstract *- Nowadays, the development of wireless communication systems requires thin, lightweight and inexpensive antennas. This paper presents a wearable microstrip patch antenna designed on a polyester-based flexible substrate and recommended for Wireless Body Area Network (WBAN) applications. The designed antenna operates in the Industrial Scientific and Medical (ISM) band. Its operating frequency ranges from 2.4202-2.4784 GHz with a 10 dB impedance bandwidth of 58.3 MHz. It has low return loss and high gain value of -23.64 dB and 8.38 dB, respectively. The maximum radiation efficiency of the antenna is 88% at 2.45 GHz. Specific Absorption Rate (SAR) measurement satisfies the safety guidelines defined by the IEEE standards.*

Keywords *- Microstrip patch, WBAN, Polyester, On body applications, SAR.*

1. Introduction

Nowadays, wearable textile-based antennas have become an interesting research topic to the researcher for body-centric communications [1]. In recent years, there has been a huge increase in demand for wearable devices and related (WBAN) technology since these devices are highly attractive to providing healthcare at a distance [2], [3], [4]. These antennas have a wide domain of applications such as GPS navigation [5], [6], military use [7], [8], digital watches [9], [10], RFID [11], athlete fitness tracking [12], [13], telemedicine [14], [15], [16], particularly for the many real-time health monitoring applications [17], [18], [19], [20]. Antennas used in these devices are known as wearable antennas. Antennas are the key and front-end components of these devices. A good design of the antenna can improve overall system performance and reduce system size [21].

The design of wearable antennas is a challenging task because these antennas are designed to function in the proximity of the human body [22], [24], [38]. Therefore, some important factors need to be considered, such as lightweight, conformable, biocompatible, low cost, and compact size [25], [26]. Recently, many research works have been carried out to design microstrip patch antennae on flexible textile substrates for WBAN applications. The textile materials are readily available, environment friendly and easy to deploy [27], [28].

In [39], a wearable patch antenna having a low profile is designed for biomedical applications using WBAN technology. Its total size is 90×90×2.85 $mm^{3,}$ and its operating frequency is 2.36-2.45 GHz (10 dB impedance BW 90 MHz). It has a peak gain value of 7.81 dB at 2.45 GHz. Human safety should be considered since this antenna is designed for wearable applications. For this purpose, a 3-layered tissue model is considered, and the SAR value is measured. The referenced antenna satisfies the safety guidelines defined by IEEE standards. Likewise, flexible and non-flexible substrate-based patch antennas are designed in [30]. Here, FR4 material is used for the non-flexible substrate, and Kapton polyimide film is used for the flexible substrate. In the case of the Kapton polyimide film substrate, 's total antenna size is 70×70×0.85 mm^3. It covers frequencies ranging from 2.25-2.35 GHz with a 10 dB impedance bandwidth of 100 MHz. However, the gain of the antenna is negative (-3.249 dB).

Similarly, a wearable patch antenna based on jeans substrate is designed in [31]. It has a good return loss value (-32.57 dB) at the resonant frequency of 2.45 GHz and a high gain value of 7.26 dB. But the antenna size is large, which is 120×120×3.5 mm^3. Besides, SAR analysis important for wearable applications has not been done here. Further, a polyester-based wearable antenna is designed for WBAN applications [32]. The total dimensions of the antenna are 90×90×2.85 mm^3. It operates at 2.45 GHz with return loss and gains values of -10.52 dB and 7.81 dB, respectively. SAR analysis has also been done for safety considerations. Here, a 3-layer tissue model has been used for the SAR analysis. The designed antenna satisfies the safety guidelines defined by the IEEE standards.

However, almost all the recently proposed works discussed above [30], [32], [39] have moderate gain with high return loss value, i.e., the loss of the signal power due to higher reflection. In [31], the return loss value is lower, but the total antenna is larger. Therefore, the objective of this research work is to design a polyester substrate-based flexible wearable patch antenna for WBAN applications having a compact size, low return loss, and high gain.

2. Proposed Antenna Design Methodology

In general, design parameters such as length, width, and thickness of the radiator, ground plane, and substrate are crucial for properly designing any antenna. However, designing wearable antennas for WBAN applications is more challenging than conventional antennas like mobile phone antennas and others. The wearable antennas are designed on fabrics, and each fabric's dielectric constant is different in nature.

In the proposed antenna design, polyester fabrics are used as a substrate material (thickness, $h = 2.85\,mm$, and dielectric constant, $\epsilon_r = 1.44$) that is readily available in daily life. At first, a conventional rectangular microstrip patch antenna is designed. Considering the ISM frequency band, the resonance frequency (f_r) is selected at 2.45 GHz. After picking the thickness (h) and dielectric constant (ϵ_r) of the substrate and the resonant frequency (f_r), the dimensions of the patch and ground plane are determined by the following equations [33], [34]. The following formulas can be used to determine the length and width of the microstrip patch antenna.

$$W_p = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r+1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}} \qquad (1)$$

where light velocity, $v_0 = 3 \times 10^8\,ms^{-1}$, and resonant frequency, $f_r = 2.45\,GHz$.

The expression for the effective refractive index (ϵ_{eff}) is given by:

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[1 + 12\frac{h}{W_p}\right]^{-\frac{1}{2}} \qquad (2)$$

where relative dielectric strength of the substrate, $\epsilon_r = 1.44$, substrate height, $h = 2.85\,mm$, and patch width, W_p computed by using equation (1).

Now, the effective length (L_{eff}) and fringing length (Δl) may be calculated for the microstrip patch antenna. as follows.

$$L_{eff} = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}\sqrt{\epsilon_{eff}}} = \frac{v_0}{2f_r\sqrt{\epsilon_{eff}}} \qquad (3)$$

$$\Delta l = 0.412 \times h \times \frac{\epsilon_r + 0.300\left(\frac{W_p}{h}\right) + 0.262}{\epsilon_r + 0.258\left(\frac{W_p}{h}\right) - 0.813} \qquad (4)$$

Therefore, the accurate length of the patch is given by:

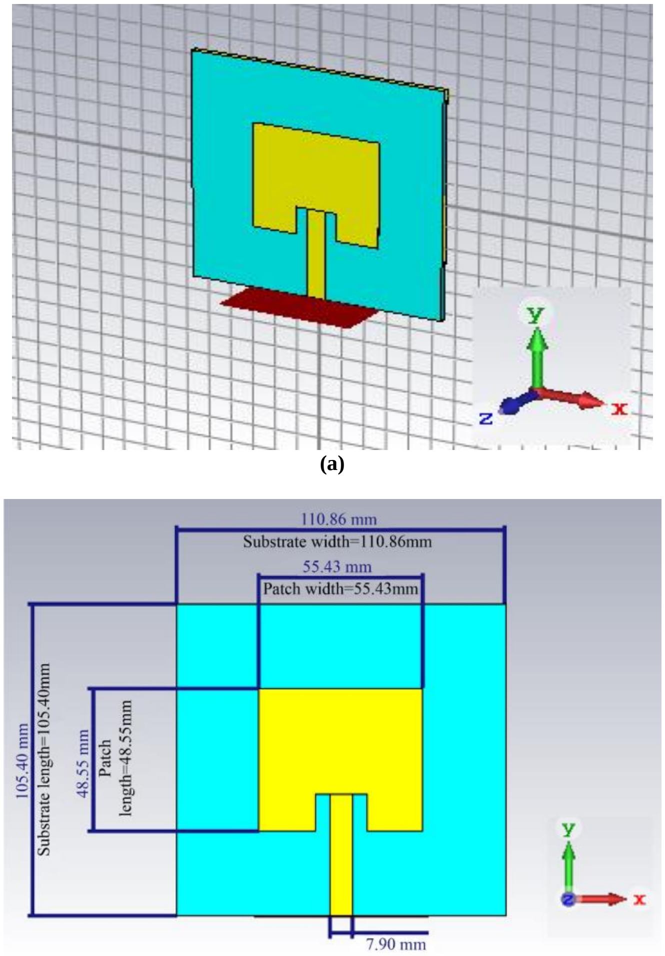
$$L_p = L_{eff} - 2\Delta l \qquad (5)$$

The following equations are used to compute the sizes of the ground plane.

$$L_g = 2L_p \qquad (6)$$

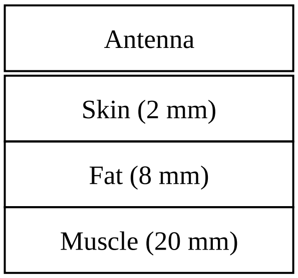
$$W_g = 2W_p \qquad (7)$$

Finally, the proposed patch antenna is placed to the conclusion proximity of human bodily tissue, as illustrated in Figure 1(c). The antenna fat (8 mm), skin (2 mm), and muscle (20 mm) are used for conducting the simulation. The different body tissues have different dielectric properties listed in Table 2.



(a)

(b)



(c)

Fig. 1 Proposed antenna (a) Perspective view, (b) Front view, and (c) On human body tissue

Conducting copper is used as a component for both patch radiators and the ground plane. The optimized measurement of the patch and partial ground plane is $L_p \times W_p$ and $L_g \times W_g$ respectively. Here, the main reason for using partial ground is the increasing impedance bandwidth. An inset gap (G_{pf}) is used to improve the matching of impedance, and so on, improve the overall radiation performance of the proposed antenna. A 50Ω microstrip transmission line with a feed width of W_f is used to feed the proposed antenna system. The suggested antenna model design, optimization, and analysis are carried out using the CST simulator software.

Table 1. List of the optimized antenna parameters

Parameter List	Value
Operating frequency (f_r)	2.45 GHz
Patch Width (W_p)	55.43 mm
Patch length (L_p)	48.55 mm
Substrate Dielectric constant (ϵ_r)	1.44
Substrate depth (h)	2.85 mm
Ground Width (W_g)	110.86 mm
Ground length (L_g)	105.4 mm
Substrate width (W_s)	110.86 mm
Substrate length (L_s)	105.4 mm
Feed width (W_f)	7.9 mm
Inset gap (G_{pf})	4.7 mm
Feed insertion (F_i)	12.7 mm

Table 2. The dielectric properties of the human bodily tissues

Tissue	Permittivity (ϵ_r)	Conductivity (S/m)	Loss Tangent	Density (Kg/ m^3)
Skin	31.29	5.0138	0.2835	1100
Fat	5.28	0.1	0.19382	1100
Muscle	52.79	1.705	0.24191	1060

3. Results and Discussion

Inside this section, some important performance metrics within the antenna, such as return loss, VSWR, gain, directivity, radiation pattern, and efficiency, are studied and analyzed to demonstrate the working of the proposed antenna in the ISM band. Since the antenna is recommended for wearable WBAN applications, energy absorption by the human body should be evaluated using a parameter named SAR (Specific Absorption Rate), discussed below in detail.

3.1. Return Loss

The return loss parameter determines the level of impedance matching between the source and the load. To minimize the reflected power and maximize the transferred power to the load (antenna), the return loss value should be as low as possible. For effective wireless communications, the return loss value should be less than -10 dB. Here, a lower return loss value indicates less wasted power and implies better antenna performance. At the $f_r = 2.45$ GHz, the attained return loss value is -23.6407 dB that, ensures excellent impedance matching from the patch to the feed line as depicted in Figure 2. The lower cut-off and upper cut-off frequencies are 2.4202 GHz and 2.4784 GHz, respectively. Therefore, the 10-dB impedance bandwidth of the suggested antenna is 0.0582 GHz or 58.2 MHz, which is sufficient for WBAN applications.

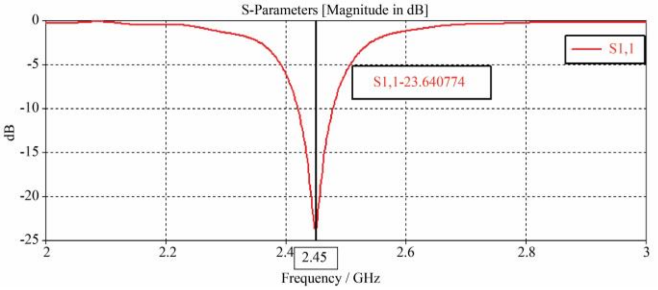


Fig. 2 Simulated return loss curve of the designed antenna

3.2. Voltage Standing Wave Ratio (VSWR)

Figure 3 shows the predicted VSWR curve of the recommended antenna. It represents the quantity of power reflection by the designed antenna due to impedance mismatch. The lower value of VSWR means higher power is transmitted to the antenna. In practice, its value varies from 1 to 2 and should be less than 2 $(VSWR \le 2)$ over the operating frequency range for effective communication.

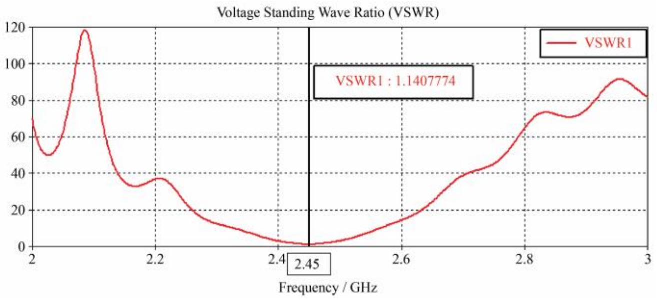


Fig. 3 Simulated VSWR curve of the designed antenna

It is clearly noted that the VSWR value of the designed antenna is less than 2 over the entire operating band and is 1.1407 at 2.45 GHz resonant frequency. It ensures that the designed antenna perfectly matches the transmission line for effective transmission and reception.

3.3. Gain

Antenna gain is the term used to describe the direction of the strongest radiation, normally expressed as dB. It indicates how much power is radiated or received in a particular direction. Generally, low-gain antennas are preferred for short-range wireless communications, and high-gain antennas are preferred for long-distance wireless communications. Therefore, as the antenna's gain increases, it becomes directional in nature. Figure 4 shows the simulated 3D far field gain of the designed antenna. At 2.45 GHz, the maximum gain from the proposed antenna is 8.384 dB, confirming the designed antenna's capability to transmit and receive data at a distance.

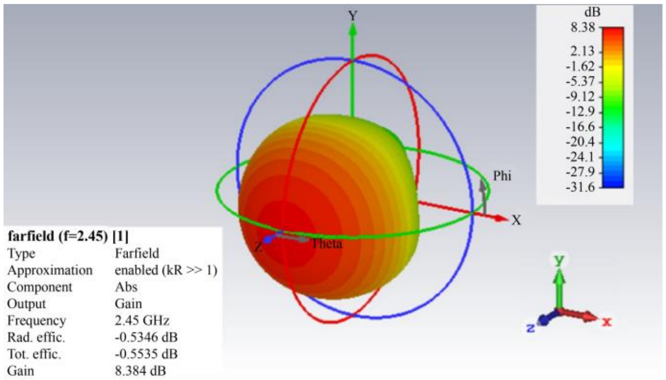
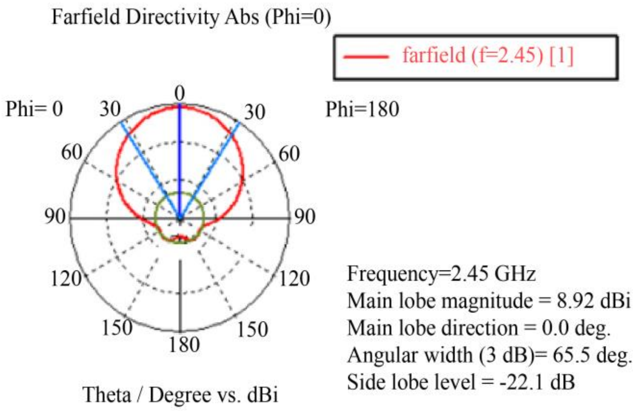


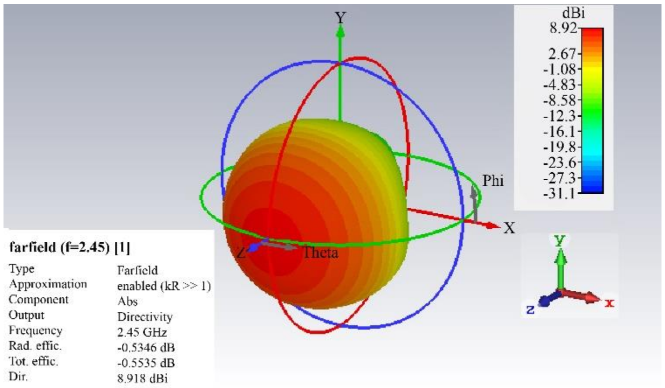
Fig. 4 Simulated 3D Far-field gain of the proposed antenna

3.4. Directivity

The proportion between maximum power density and the sphere's average value detected in the far field, which measures how strongly the antenna radiates in its favored direction, is known as directivity. The achieved directivity of the designed antenna is 8.93 dB at 2.45 GHz, displayed in Figure 5. The magnitude of the main lobe is 8.92 dB, and the angular width is 65.5 deg.



(a)



(b)

Fig. 5 Directivity of the designed antenna (a) Polar plot (b) 3D view.

3.5. Radiation Efficiency

The radiation efficiency of the designed antenna with respect to frequency is shown in Figure 6. It fluctuates from 80% to 88.41% over the operating band. The highest efficiency of 88.41% is obtained at the resonant frequency of 2.45 GHz. The higher efficiency value of the desired antenna indicates that it can radiate or receive power into or from free space effectively.

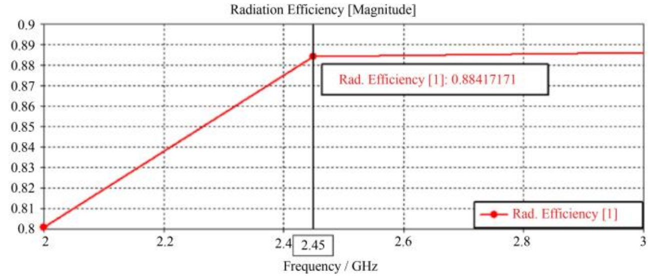


Fig. 6 Radiation efficiency of the designed antenna

3.6. Specific Absorption Rate (SAR)

The SAR parameter determines the energy absorption per unit mass of the human bodily tissues. Watt per kilogram (W/kg) is the common unit. To guarantee patient security, the maximum value of SAR must be less than 1.6 W/kg for 1 g of cubic tissue and 2 W/kg for every 10 g of cubic tissue

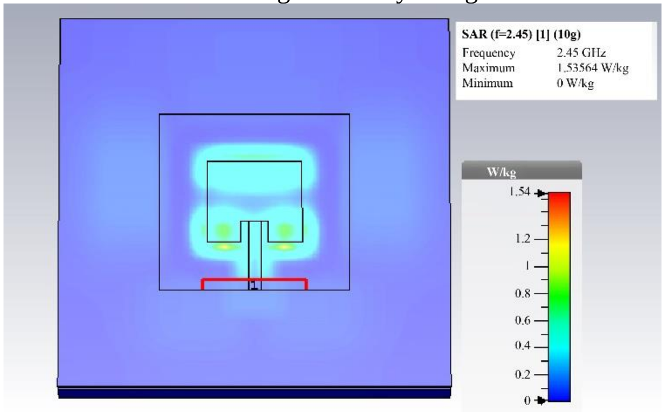


Fig. 7 Predicted SAR value of the designed antenna at 2.45 GHz

according to IEEE C95.1-1999 standard [35] and IEEE C95.1-2005 standard [36] respectively. The SAR value is measured based on the IEEE mentioned above standards. Figure 7 shows that the maximum SAR value at 2.45 GHz is 1.53564 W/kg which satisfies the safety limit of both the IEEE standards. The proposed polyester-based flexible antenna's overall simulated results are summarised in Table 3.

4. Performance Comparison

The performance comparison of the polyester-based flexible patch antenna with some recently proposed work is given in Table 4. Here, almost all the antennas operate around the same resonant frequency at 2.45 GHz with different gain, efficiency, BW, etc. It is apparent that the suggested antenna has low return loss (-23.64 dB) and high gain (8.38 dB) with moderate antenna size. It has a considerable bandwidth of 58.2 MHz as well as high efficiency of 88%. Therefore, in terms of antenna performances, the designed polyester-based flexible wearable patch antenna is comparable to others listed in Table 4.

Table 3. Overall simulated results of the proposed antenna at 2.45 GHz

Parameters	Values
Operating Frequency	2.4202-2.4784 GHz
Bandwidth	58.2 MHz (2.37 %)
Return Loss	-23.6407dB
VSWR	1.1407
Gain	8.384 dB
Directivity	8.93 dB
Radiation Efficiency	88.41 %
SAR (Maximum)	1.53564 W/kg

Table 4. Performance comparison of the proposed antenna

Ref.	Material	Antenna Size (mm^3)	Operating Frequency (GHz)	Gain (dB)	Total Efficiency (%)
[39]	Natural Rubber, Denim, Cotton	90×90×2.85	2.45	7.81	-
[30]	Kapton Polymide Film	70×70×0.85	2.30	-3.249	47
[31]	Jeans	120×120×3.5	2.45	7.26	-
[32]	Polyester	90×90×2.85	2.45	7.81	-
This Work	Polyester	105.4×110.86×2.85	2.45	8.384	88

5. Conclusion

In this paper, a polyester substrate-based wearable microstrip patch antenna is created and recommended for WBAN applications. The designed antenna covers the ISM band (2.4 GHz) with a low return loss value of -23.64 dB and 10-dB impedance bandwidth of 58.2 MHz. At the resonant frequency of 2.45 GHz, the maximum peak gain, directivity, and radiation efficiency of the designed antenna are 8.384 dB, 8.93 dB, and 88%, respectively. Considering wearable applications, SAR analysis addresses the effect of EM waves on human body tissues. The maximum calculated SAR value is 1.53564 W/kg at 2.45 GHz, within the safety limit defined by the IEEE standards. Due to the satisfactory antenna performances and features, the proposed polyester substrate-based flexible patch antenna would be a promising candidate for WBAN applications.

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