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Effect of Bending Condition towards the Performance of Pac-Man Textile Antenna

A. A. Samat[1], D.N.A. Zaidel[1,*], R. Anwar[2], M. M. M Sahidi[1], D. A. A. Mat[1], M. R. M. Sharip[3]

[1] Department of Electrical and Electronics Engineering, Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), Kota Samarahan, Sarawak, Malaysia
[2] School of Applied Science, Telkom University, Bandung, Indonesia
[3] Institute of High Voltage and High Current, School of Electrical Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia

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ABSTRACT

This paper aims to design a sectorial slot Pac-Man textile patch antenna designed specifically for the 2.45 GHz ISM band (WLAN), catering to the needs of smart wearable devices. The antenna's performance was thoroughly evaluated in terms of resonance frequency, return loss, and voltage standing wave ratio (VSWR) while subjected to bending conditions with four different cylinder radii. Leveraging jeans as the substrate material, with a dielectric constant, $\boldsymbol{\varepsilon r}$ of 1.7 and 1mm thickness, the design demonstrates exceptional promise where jeans proven its suitability as a textile antenna substrate. Based on the simulation results by using CST Microwave Studio software, it is shown that using jeans as a substrate material and maintaining the design with the previous research have resulted in an acceptable return loss of -15.33 dB with a VSWR of 1.42. Also, by comparing to the conventional circular microstrip patch antenna, the improvement can be seen in the antenna bandwidth by 10.79%, from 39.7 MHz to 44.5 MHz. While the proposed antenna exhibits a narrow bandwidth of 1.81%, it also holds significant potential for mobile applications and government security systems emphasizing privacy protection.

1. Introduction

In recent years, our everyday lives have become even more connected. Exciting breakthroughs in wireless technology have sparked a surge of research in wearable communication systems. Wearable antennas have garnered significant attention due to their potential in enabling lightweight, flexible, low-cost, and portable wireless communication and sensing [1]. The development of wearable antennas made from various fabrics has been a notable advancement in the field of wireless technology, allowing for enhanced integration of antennas into everyday clothing items [2]. This integration of antennas into textiles opens up new possibilities for seamless communication and sensing capabilities in wearable devices.

* *Corresponding author.*
E-mail address: azdnorkhairunnisa@unimas.my

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Metamaterial-based antennas have emerged as a promising avenue for wearable applications, with studies highlighting the use of composite right/left-handed transmission lines (CRLH TLs), metasurfaces, and tunable metamaterials in wearable antenna designs [3]. These metamaterial-based antennas offer unique properties that can enhance the performance of wearable devices in wireless body area networks (WBANs).

Flexible and transparent antenna technologies have also been a focus of recent research efforts, with a particular emphasis on fabric or textile-based antennas [4]. The design considerations and recent developments in flexible, transparent, and wearable antenna technology have paved the way for innovative applications in various fields, including biomedical applications. Furthermore, the use of clothing components in the development of wearable textile antennas has been explored, highlighting the design and experimental procedures involved in creating functional and practical wearable antenna systems [5].

The integration of metamaterial structures into wearable antennas has been a key area of interest, with a focus on single and dual-band antenna designs that leverage flexible and wearable substrate materials [6]. This integration allows for the creation of antennas that can adapt to different operating frequencies and communication requirements. Moreover, the research and development of miniature wearable antennas have seen significant growth alongside the expansion of the Internet of Things (IoT) and wearable technologies [7]. These miniature antennas are essential for enabling seamless connectivity in various wearable devices and IoT applications.

Reconfigurable antenna technologies have also been a subject of recent research, with a focus on developing antennas that can operate at multiple resonant frequencies, radiation patterns, and polarizations using active switching devices [8]. This reconfigurability enhances the versatility and adaptability of wearable antennas for different communication scenarios. Additionally, advancements in 5G technology and applications in the ISM band and IoT have driven research efforts towards enhancing the performance of wearable antennas for biomedical applications [9]. These advancements include features like SAR reduction, gain enhancement, and bandwidth improvement to meet the specific requirements of healthcare monitoring and biotelemetry.

The design and performance analysis of flexible planar monopole ultra-wideband antennas for wearable wireless applications have been explored in recent studies, emphasizing the importance of creating low-profile antennas that can operate effectively in wearable scenarios [10]. The development of wearable textile antennas on various fabric substrates has also been a focus, with researchers aiming to overcome challenges related to antenna design and human exposure assessment [11]. By utilizing fully fabric materials or partially integrating fabric into antenna designs, researchers have been able to create wearable antennas that are lightweight, flexible, and comfortable for long-term wear.

“Smart clothing”, also known as smart textiles or e-textiles, refers to clothing items that incorporate advanced technologies, such as sensors, actuators, and communication modules, to provide additional functionalities beyond traditional apparel. These technologies are seamlessly integrated into the fabric of the clothing, allowing for the collection of data from the wearer and the environment, as well as enabling intelligent responses based on this information [12]. The primary goal of smart clothing is to enhance the user's experience by offering features like health monitoring, environmental sensing, communication capabilities, and even adaptive responses to stimuli [13].

One of the key aspects of smart clothing is the integration of wearable microelectronic technologies into garments that cover a significant portion of the human body, such as coats, pants, shirts, and leggings [13]. By embedding these technologies into everyday clothing items, smart clothing can continuously monitor the wearer's health conditions, detect anomalies that may require medical intervention, or even help improve physical fitness levels. This integration of electronics into textiles represents a significant advancement in the field of wearable technology, enabling a seamless fusion of functionality and fashion.

Smart clothing systems are designed to be "smart systems" capable of sensing and communicating with both the wearer's conditions and the surrounding environment [14]. Using Bluetooth or Wi-Fi, many smart garments can connect with an app or programme running on a second device. However, the success of this intelligent clothing is entirely dependent on the antenna's ability to receive, share data and interact with one another as if they were live organisms. In terms of visibility, health advantages, comfort, and aesthetics, smart clothing is expected to be a huge industry in the near future [15]. Consequently, the widespread use of microstrip antennas is well-known across several industries due to its low-cost substrate material and simple manufacturing.

Earlier study on the creation of a circular patch antenna for Pac-Man [16] utilized a bio-composite Leucaena Leucochephala substrate with a dielectric constant of 4.4, loss tangent of 0.0082, and with 1.6 mm thickness. It is made from plants and is used to make new parts and antenna substrates for green technology that uses polymer materials. There are two operational frequencies at which the microstrip patch antenna can operate which is 1.6 GHz and 2.4GHz. The antenna reported that 1.63GHz as the resonance frequency for the first band of 1.16 GHz, with a return loss value of -19.3dB on simulation. However, the measured value was displaced around 0.003GHz to the upper frequency and was completed at 1.66 GHz with a return loss value of -28.6dB. Meanwhile in the simulation for the second band of the antenna, it resonates at 2.45GHz with return loss value of -43.3dB. Likewise, for the measured data, it was moved to a higher frequency by approximately 0.11 GHz, which was operated at a frequency of 2.56 GHz and a -37.54dB for the return loss' result.

A concern in antenna design was the choice of substrate material. Thus, it is essential to understand the electrical performance of the material to select an appropriate substrate Since this material data is not available, therefore, it is necessary to conduct electrical tests on different textile materials. It is not considered as direct operation, and various measuring techniques must be utilized to analyze the component such as dielectric permittivity. Second issue concerning on the antenna's performance under bending conditions. Whenever the antenna is patched to clothing, it is subjected to a various of bending occurrences. The critical challenge is keeping the antenna's characteristics at an allowable level in all settings considered normal operation conditions. These parameters are a bend resistance, operating frequency (bend stability), and efficiency (prevent human tissue from degrading efficiency) [17].

In this paper, instead of by using bio-composite Leucaena Leucochephala as the substrate, jeans will be used due to substrate factors, such as dielectric constant, homogeneity, and loss tangent, influence the performance of a microstrip patch antenna [18]. A study by Salvado et al. [19] on an X-band microstrip antenna operating at 9.2 GHz, there is a superior bandwidth performance of comparatively thick substrates. As reported in [20], the authors also demonstrate the same result in their investigation on comparing the antenna bandwidth and reflection loss of various substrates. For substrates, data reveal that those with lower dielectric constant and lower loss tangent values perform better.

Thus, lower dielectric constants and thicker substrates tend to produce greater bandwidth performance. Therefore, jeans were chosen as the substrate compared to bio-composite Leucaena Leucochephala which has higher dielectric constant. The dielectric constant of jeans textiles is extremely low, which minimises surface wave losses and boosts the antenna's impedance bandwidth [21].

Therefore, this paper will describe the design process for a single band sectorial slot Pac-Man textile patch antenna for smart wearable applications that adheres to IEEE 802.11 standards and operates at 2.45 GHz. As mentioned, jeans are chosen as the substrate material. This investigation will focus on the antenna's performance under various bending conditions. In order to evaluate the antenna's performance and dependability, the graph of return loss, resonance frequency, and gain will be provided in the results and discussion section.

2. Proposed Design Work

Traditional sectorial slot Pac-Man patch antenna [16] is used as a basis for this antenna's design by using a transmission line feeding mechanism instead of the coaxial feed used in prior arrangements. Even though the circular patch design has been a success utilizing various feeding and matching techniques, the transmission line feed technique type was selected since the feed line impedance matches that of the patch, obviating the requirement for an additional matching component. As a result, other physical parameters such as the thickness of the substrate can be used to alter the resonant frequency. Additionally, microstrip line feed is one of the simplest methods to construct since it consists of a conducting strip connected to the patch and can be considered an extension of the patch.

By substituting the sector slotted circular patch with two equal circular patches of circumferences $C1$and $C2$, the notion of modelling the sectorial slot section was conceived. A circumference of $C1$ equal to the complete perimeter of the sector slot. Meanwhile, a circular patch with sector slots has a circumference of $C2$is corresponds to its main arc length. The sectorial antenna stayed true to the physical design of a traditional Pac-Man circular patch antenna [16]. The purpose was to explore whether employing a transmission line feed and utilizing jeans as a substrate could enhance bandwidth, gain, and reduce return loss. Aside from that, a small circular slot, $R1$ was meant to adjust the frequency of shifting up and down depending on the radius. It is necessary to reduce the size of $R1$ to shift the operating frequency down and the other way around. Due to the patch's decreasing surface area, each 0.5 mm increase in size $R1$ raises the operating frequency by around 200 MHz. As seen in Figure 1, the proposed Pac-Man antenna, R1 is in the centre of the circular patch. The antenna design specification is a critical part of the process. Several factors must be taken into consideration to attain optimal results.

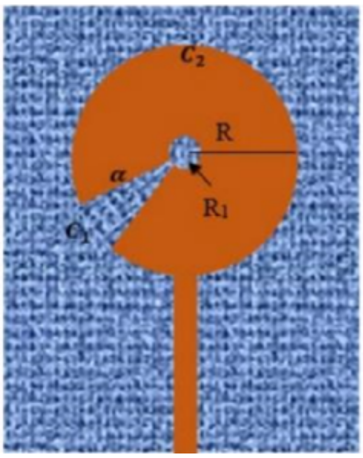


Fig. 1. Proposed Design of Pac-Man Antenna

2.1 Design Methodology

The intended resonance frequency, substrate thickness, and dielectric constant are all predetermined before the designing process. The radius of the patch can be calculated using Eq. (1):

$$R = \frac{F}{\sqrt{1+\frac{2h}{\pi\varepsilon_r}\left[ln\left(\frac{\pi F}{2h}\right)+1.7726\right]}} \tag{1}$$

The circular patch antenna can be represented as a square shape design to acquire its diameter in the second method. The width of imaginary square design can be calculated using Eq. (2), meanwhile the length can be calculated using Eq. (3) and Eq. (4) [22];

$$Width, w = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{2}$$

$$\Delta L = 0.412h\left[\frac{\varepsilon_{eff}+0.3}{\varepsilon_{eff}-0.258}\right]\left[\frac{\frac{w}{h}+0.264}{\frac{w}{h}+0.8}\right] \tag{3}$$

$$L = \left[\frac{c}{2f_r\sqrt{\varepsilon_{eff}}}\right] - 2\Delta L \tag{4}$$

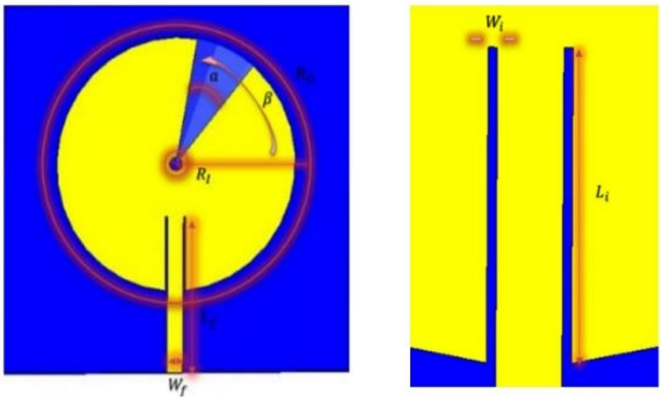
In the optimization process, inset feed was implemented into the design to maximize the value of return loss. The feed is inserted deep into the circular radiating element for the proper impedance matching. This arrangement for the feeding a microstrip antenna is known as the “inset feed”. The value of inset feed length can be calculated using Eq. (5) [18]. The computation of inset length was done by MATLAB software to achieve precision.

$$L_i = \frac{cos^{-1}\sqrt{\frac{Z^0}{R_{in}}}}{\frac{\pi}{L}} \tag{5}$$

2.2 Optimization Process

All parameters calculated such as substrate width, substrate length, patch outer radius, patch inner radius, fed width, fed length, inset gap width, inset length, sector angle, and sector angle position will be included in the initial design. These parameters were calculated based on the dielectric permittivity, the thickness of the jeans substrate, and the antenna’s operating frequency, which is 2.45 GHz.

Figure 2 shows the geometric dimensioning of all elements implemented in the optimized Pac-Man patch antenna. The previous design was introduced with inset feed along the transmission line with the purpose of improving the return loss value. Furthermore, the value of sector angle position (β) and inner radius, $R1$ were also being altered in the position and size. Meanwhile, Table 1 show a comparison table of the calculated value from the theoretical formula, with the optimized parameters.



(a) (b)

Fig. 2. Dimension of optimized proposed Pac-Man antenna (a) whole top view (b) inset feed area

Table 1
Comparison on the calculated and optimized value

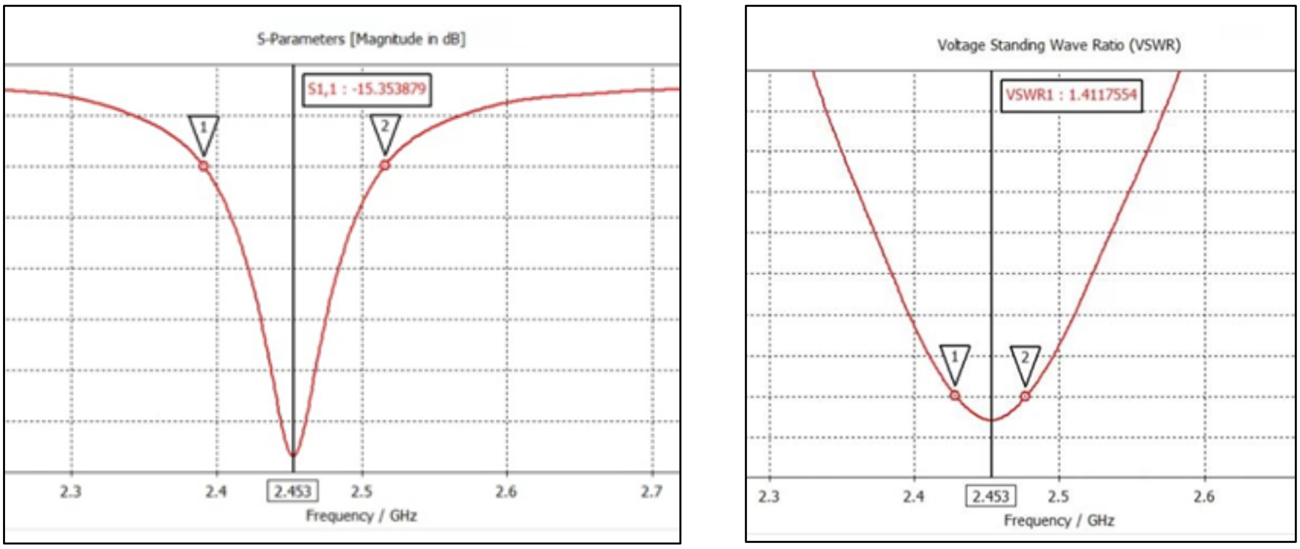
Parameter	Calculated Value	Optimized Value
Substrate Width, *Ws*	66 mm	80 mm
Substrate Length, *Ls*	66 mm	80 mm
Sector Angle position, *β*	220°	80°
Sector Angle, *α*	15°	30°
Patch Outer Radius, *Ro*	25.04 mm	27.5 mm
Patch Inner Radius, *Ri*	2.5 mm	2.5 mm
Fed line Width, *Wf*	3.61 mm	3.61 mm
Fed line Lecth, *Lf*	24.84 mm	30 mm
Inset Width, *Wi*	0.31 mm	0.51 mm
Inset Length, *Li*	16.14 mm	16.14 mm

3. Results and Discussions

Once the optimization is done, simulation of the proposed Pac-Man antenna is done by using CST Microwave Studio software. Figure 3(a) shows the simulation result of the proposed antenna where the resonance frequency at 2.45 GHz and the value of the return loss is -15.33 dB. Meanwhile for Figure 3(b), VSWR result shows that the proposed antenna exhibits the VSWR of 1.42 which is almost to ideal value or VSWR. Both of these results show that jeans are acceptable and reliable to be used as the material to design the antenna.

Then, analysis of four cylindrical objects with 30 mm, 50 mm, 70 mm, and 100 mm, each with a different radius, were employed in this simulation study. The radius of each object corresponds to a distinct component of the human body, such as an arm, leg, or shoulder. It was also previously noticed that the antenna's electromagnetic radiation pattern had high radiation on its front face. The antenna patch was thus positioned so that it faced outwards during the bending simulation. Table 2 shows a simulation photograph of the wearable antenna structures wrapped around the cylindrical object for this simulation study. As the cylinder radius decreases, the antenna experiences greater bending.

The resonance frequency under bending condition were extracted from the simulation in the CST software. Table 3 summarized the findings on resonance frequency according to cylinder radius when the Pac-Man patch antenna were simulated under bending condition. As depicts in the table, with the decrement of cylinder radii, the operating frequency tends to resonate to a higher frequency. This can be seen from the comparison of cylinder radius of 130 mm has a resonance of 2.26 GHz, while the cylinder of 30 mm radius resonates at 2.74 GHz.



(a) (b)

Fig. 3. Simulation results for the optimized proposed Pac-Man antenna (a) Return Loss (b) VSWR

Table 2
Simulation photograph of Pac-Man antenna wrapped around cylindrical object

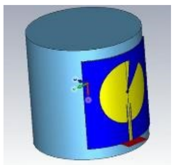
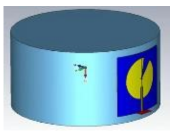
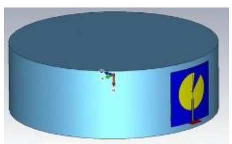
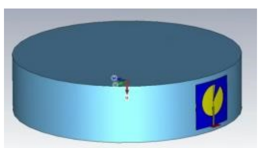
Cylinder radius (mm)	Position of the Patch
30	
50	
70	
130	

Table 3
Simulation results of resonance frequency and VSWR obtained on bending condition

Cylinder radius (mm)	Resonance Frequency	Return Loss Value [dB]	VSWR Value
0	2.45 GHz	-15.33	1.42
30	2.74 GHz	-10.52	1.84
50	2.70 GHz	-16.75	1.34
70	2.25 GHz	-27.28	1.09
130	2.26 GHz	-27.29	1.09

The current path, particularly for the fundamental mode of resonance, is affected by E-plane bending, which explains this occurrence. Concurrently, the curved patch also modifies the fringe field of the radiating edge, which in turn influences the effective dielectric constant of the antenna [23]. The phenomenon of fringing causes a microstrip patch antenna to appear electrically broader than its actual dimensions, even though it has a smaller footprint. Waves can propagate in both the substrate and the air. As a result, a new dielectric constant will be introduced.

Also, based on Table 3, the value of VSWR for the simulated antenna was increasing from 1.09 with a bending radius of 130 mm to 1.84 with a bending radius of 30 mm. The increasement can be attributed to the impact of bending on the antenna's performance. When an antenna is bent, especially with a smaller bending radius, it can lead to changes in its electrical characteristics, such as impedance matching and radiation pattern, which in turn affect the VSWR [24]. The bending of the antenna alters the electromagnetic field distribution around the antenna structure, causing deviations in its resonant frequency and impedance matching properties.

A higher VSWR indicates more reflected power occurs while it reducing the power delivered efficiency. On the other hand, in real-world RF components, a VSWR of less than 1.5:1 is considered good. This phenomenon was due to the impedance mismatch with the transmission line and the creation of the surface waves. From the table, it also can be seen that as the radius of cylinder was reduced, a higher value of VSWR was obtained. This shows with a higher degree of bending on wearable devices, more reflected power would occur. Therefore, a suitable position for the antenna to be patch is considered as crucial to minimize the impedance mismatched.

As seen in all the results, it is shown that the bending of the antenna has resulted in a decrement in performance. Specifically, when bent up to 50 degrees, the frequency has shifted to the right, changing from 2.45 GHz to 2.7 GHz. As the bending angle increases, the frequency shifts to the left, ranging from 2.45 GHz to 2.25 GHz. This phenomenon is attributed to a change in the antenna's shape, causing alterations in radiation patterns. The decrement in performance is not due to the material used however it is the nature of the antenna itself where any alterations or variations in the antenna's shape or construction will inevitably lead to different performance outcomes.

As known, VSWR has a close relationship with the value of return loss, where less losses (more negative) result in a better VSWR. As seen in Table 3, the value of VSWR tends to approach its ideal value (which is equal to 1) when the antenna bent at 70 and 130 degrees compared to the antennas bent at 30 and 50 degrees due to the return loss value.

Furthermore, the bending of antennas can introduce structural deformations that affect the antenna's resonance frequency and impedance bandwidth, leading to variations in the VSWR [25]. The bending-induced changes in the antenna's geometry and electromagnetic properties can result in impedance mismatches between the antenna and the feeding network, causing the VSWR to deviate from its optimal value. As the bending radius decreases, the mechanical stress on the antenna structure increases, potentially altering its electrical performance and leading to higher VSWR values.

4. Conclusions

In this paper, a sectorial slot Pac-Man antenna with a single band operation at 2.45 GHz using jeans substrate was simulated with CST Microwave studio software. Based on the simulation results, it is shown that using jeans as a substrate material and maintaining the design with the previous research have resulted in an acceptable return loss of -15.33 dB with a VSWR of 1.42. However, by comparing to the conventional circular microstrip patch antenna, the improvement can be seen in the antenna bandwidth by 10.79 %, from 39.7 MHz to 44.5 MHz. The bandwidth was calculated to be 1.81%, indicating the PacMan patch antenna has a narrow bandwidth and is suitable for mobile or government security systems that focus on privacy protection. Also, to observed on the performance under different bending condition, the antenna went through four different cylinder radii and it resulted in performance degradation of return loss and shifted the resonance frequency away from 2.45 GHz. Nevertheless, the value of return loss was still in an acceptable range of less than -10 dB, showing that the antenna is still in good impedance matching. Hence, the Pac-Man patch antenna using jeans as a substrate material can be considered a suitable antenna to be implemented as a smart wearable antenna application.

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