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MINIATURIZATION OF STACKED WEARABLE ANTENNA FOR 5G APPLICATIONS

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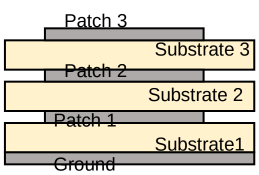
Graphical abstract



Abstract

Wearable antennas have significantly expanded the capabilities of electronic devices, as they can now be seamlessly integrated into clothing for user convenience. The advent of 5G has opened up possibilities for enhanced functionality, necessitating compact antennas with high gain for efficient data transmission. In this paper, a sub-6GHz 5G stacked wearable antenna is proposed. The choice of a rectangular patch structure was made for its simplicity and ease of fabrication. A comprehensive analysis of antenna design, progressing from a single layer to a multilayer configuration is explained. The antenna was designed using 1mm *felt* and *Shieldit Super* conductor, with a 50 Ω coaxial feed. The proposed stacked three-layer antenna, with substrate dimensions of 44 x 44 mm², achieves a gain of 2.7 dBi. Stacking the substrate and patch layer improves the antennas' performance, especially the impedance bandwidth and gain. On top of that, the antenna dimensions were reduced to 57% while maintaining its performance. Bending tests conducted in both X- and Y-axes demonstrate that the antenna's performance remains within an acceptable range. Although the resonating frequency shifted to 3.4 GHz in 3 layers during bending in Y-axis, the gain was kept to 1.8dBi. Both measured and simulated results exhibit good consistency, with a slight shift observed in the case of the three-layer structure.

Keywords: 5G application, bending assessment, stacked antenna and Wearable antenna

Abstrak

Antena boleh pakai telah membolehkan perkembangkan peranti-peranti elektronik dengan ketara, ia kini boleh disepadukan dengan pakaian bagi kesenangan pengguna. Kemunculan 5G telah membuka peluang kepada lebih banyak fungsi, yang mana perlunya kepda antena yang kompak dan gandaan yang tinggi bagi penghantaran data yang efisien. Dalam kertas kerja ini, sub-6GHz 5G antena boleh pakai bertindan dicadangkan. Struktur segiempat tepat dipilih berdasarkan bentuk yang sederhana dan memudahkan fabrikasi. Analisis secara komprehensif bagi rekabentuk antena daripada layer pertama kepada konfigurasi beberapa layer diteranglan. Antena direkabentuk dengan menggunakan 1 mm *Felt* dan konduktor *Shieldit Super*, dengan suapan sepaksi 50 Ω. Antenna boleh pakai bertindan yang dicadangkan mempunyai keluasan substratum 44 x 44 mm2, mencapai gandaan 2.7dBi. Susunan secara bertindan lapisan substratum dan tampalan meningkatkan prestasi antenna tertutamanya lebarjalur galangan dan gandaan antena. Tambahan pula, saiz antena berjaya dikurangkan kepada 57% disamping mengekalkan prestasi asal. Ujian pelenturan dibuat untuk kedua-dua paksi-X dan paksi-Y menunjukkan prestasi antenna kekal dalam julat yang boleh diterima. Walaupun terdapat perubahan frekuensi kepada 3.4 GHz bagi antenna 3 lapis semasa lenturan paksi-Y, gandaan kekal pada 1.8 dBi. Kedua-dua hasil pengukuran dan simulasi menunjukkan konsistensi yang baik, dengan sedikit perubahan bagi struktur antena 3-lapis.

Kata kunci: Aplikasi 5G, kajian pelenturan, antena bertindan dan antena boleh pakai

1.0 INTRODUCTION

Microstrip patch antenna (MPA) is the most common types of antennas used in modern wireless system. This is due the antenna is low profile, light weight, cost effective, polarization flexibility and it compatible with integrated circuit. As the technology growth, the demand for seamless wireless communication has create huge opportunities to wearable devices, specifically wearable antenna. The design of antennas for wearable applications faces atypical challenges compared to traditional antenna [1], where these antennas must not only be compact, lightweight, and unobtrusive, but they must also adapt to the dynamic conditions of the human body and its surrounding environment [2]–[4]. The researchers need to consider not only the characteristics of the antenna by itself but also how its performance changes due to electromagnetic interactions with the wearer and objects in close proximity to the antenna.

Antenna miniaturization is one of the most challenging aspects of wearable antennas, particularly when the textile permittivity (ε) is typically low. Arrangement of the antenna in planar or one plane leads to poor efficiency, and it consumes a large area. To address these issues, a stacked antenna, by utilizing multiple radiating elements in a vertically aligned configuration is proposed. This emerged as a viable solution to address the challenges posed by limited space while aiming for improved performance in terms of bandwidth, gain, and radiation efficiency.

Researchers in recent years have proposed various designs for wearable antennas [2], [5]–[14], employing diverse stacking methods and objectives. Bandwidth enhancement is obtained in [6] by stacking parasitic patch to their design. Reported in [7], the antenna matching was enhanced by the arrangement of stacked circular patches, resulting in a reduction of S_{11} from -8 dB to -36 dB at 2.45 GHz. Notably, [9] enhanced the stability of the resonance frequency for a strip antenna when subjected to curvature, while [11] and [12] achieved a multiband antenna by implementing a stacked design. Additionally, [8] and [10] applied the concept of a Yagi antenna to improve the impedance bandwidth and gain of their stackable antenna design. Antenna miniaturization are obtained in [15]–[17] where suppression of backward radiation are achieved by sandwiching the AMC layer in between substrate [15]. Plus, higher BW and gain were also obtained [15], [17]. Further achievement in [16] where a dual band with independent matching at millimeter wave frequency was reported. Instead of arranging the array in planar, stacking four radiating element with individual port reduce the overall antenna dimension with better dynamic directional modulation [18].

In this paper, a sub-6GHz 5G stacked wearable antenna is proposed. A details methodology on designing a patch wearable from single layer to 3 layers antenna were discuss in section II. To demonstrate the benefits of a stackable configuration, we first added layers one by one without reducing the antenna's size, and then reduced the antenna size while maintaining its gain. Subsequently, we examined the antenna's performance to verify its functionality and the robustness of the design when it was bent in section III. Simulated and measured results for anticipated antenna are conferred in section IV. Conclusion of the paper is presented in Section V.

2.0 METHODOLOGY

This section describes the methodology related to the development of wearable and stackable antenna design. The aim of this work is to design a stackable wearable antenna and explore the benefit of having multilayer structure in the basic rectangular patch antenna. Researchers have proposed various methods to enhance antenna gain [19], including the use of arrays, introducing (AMC) [20], and employing Frequency Selective Surface (FSS) [21] structures, which the proposed structures were added on top of the antenna. However, textile antennas often face exposure to diverse environmental conditions, making smaller size and simpler designs preferable. When considering array arrangements in a horizontal position, challenges may arise in maintaining optimal performance. Considering this, inspired by the Yagi-Uda structure, the exploration of arranging patches in a vertical position is proposed. The process and techniques used in designing the antenna will be explained in detail. The antenna design and simulation were done using both time and frequency domain solver in CST Microwave Studio™.

A. Single Patch Antenna

The proposed antenna is designed for sub-6-GHz 5G applications which operates at 3.5GHz. The geometry of the proposed microstrip patch antenna is as shown in Figure 1. The designed antenna is realized using *Shieldit Super* conductive textile on a 1 mm thick Felt dielectric substrate with dimensions of 77.54 x 69.6 x 1 mm^3 and fed by coaxial feed of 50 Ω. The antenna is designed with full ground having dimensions same as substrate. The relative permittivity and loss tangent of the substrate is 1.44 and 0.02 respectively.

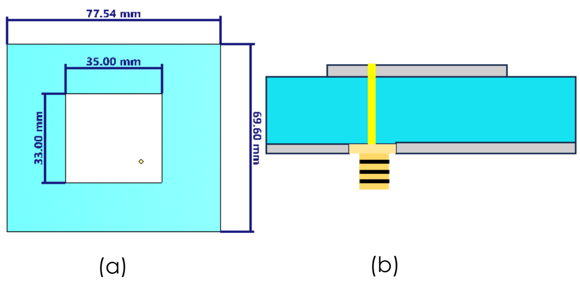


Figure 1 A single patch antenna (a) front view and (b) side view

B. Feed Location

The most common feeding method for microstrip patch antenna are microstrip feed and coaxial feed. The coaxial feeding method is used in the proposed design as it reduces the space need for feeding and better impedance matching plus reducing the loss. In this method, the outer conductor is connected to the ground plane, while the inner conductor is extended through the dielectric and is soldered to the radiating patch.

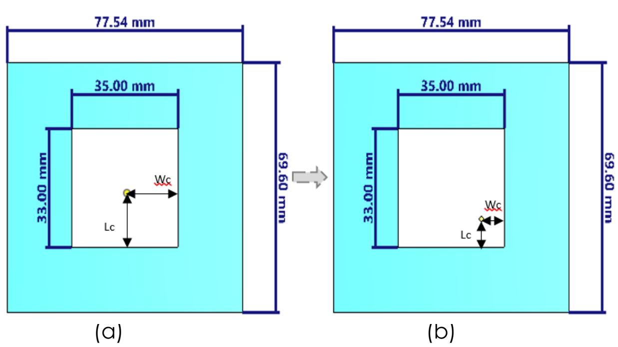


Figure 2 (a) original position of the feed and (b) optimized feed location

The location of the feed on the patch will affect the operating and matching of the antenna, practically the location should lie in one of the quarters of the rectangular patch. Figure 2 shows the location of the feed from the front view of the antenna. The analysis on feeding location with a step of 2 mm from center patch is carried out.

Wc and *Lc* are the distance from edge of the patch to the feed location. Shown in Figure 3(a), the *Wc* is kept at 14.75 mm from edge, while the *Lc* is swept from 12.25 to 6.25mm. Noted that the operating frequency is maintained in the range of 3.5 GHz, while the matching is improved as the *Lc* is reduced. *Lc* of 8.25 mm is chosen as it resonates at 3.54 GHz with 2.63 dB gain compared to *Lc* of 6.25mm which center 3.56 GHz with a gain of 2.6 dB. Figure 3(b) showed the result when *Wc* is swept from 12.75 to 6.75 mm with a fix Lc at 8.25 mm. Moving Wc towards the edge of the patch produced a second resonant to the antenna, however since the focus frequency is 3.5GHz, the *Wc* of 8.75 mm from patch edge is selected. The antenna S_{11} centre at 3.502 GHz with a gain of 2.61 dB. When the feed is located at 6.75, 8.25 (x,y), the antenna resonates at 3.5 GHz and 5 GHz, however the 3.5 GHz gain is reduced to 2.5 dBi with only 1 dBi gain at 5GHz.

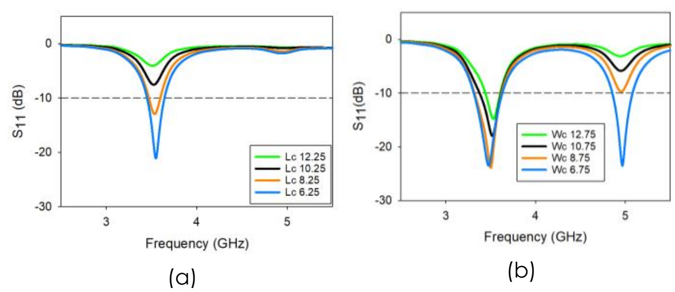


Figure 3 S_{11} Result with variation in Feed location (a) Lc and (b) Wc

C. Multilayer Structure

The performance of wearable antennas was limited by the low permittivity of the textile material. A common method for increasing antenna performance is to introduce an array structure, which creates a larger antenna size. Since textile materials have a thin layer, proposing a stacking structure in the design will not consume much space. However, it must not be too thick to ensure the wearer feels comfortable.

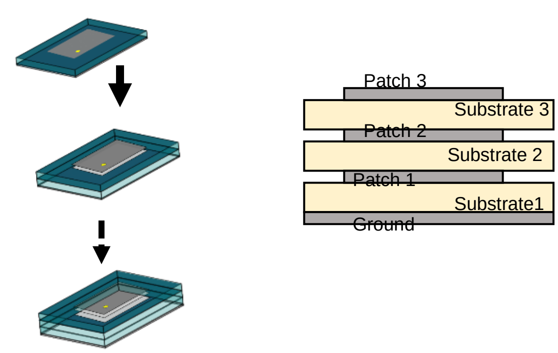


Figure 4 Antenna structure from single to 3 layers

In this work, a design with three layers of antenna is proposed. It has a total height of 3.68 mm from the upper radiating patch to the ground layer. The transformation from a single layer to three layers is illustrated in Figure 4. Adding layers to the structure increases the antenna gain while maintaining the resonating frequency within the 3.5 GHz range. This effect arises from the consecutive patches acting as driven elements, effectively directing the electromagnetic wave in a specific direction. Reflection coefficient results shown in Figure 5. Table 1 presents the antenna performance, comparing a single layer configuration to the three-layer configuration. The antenna gains increase by 31% and 62% when layer 2 and layer 3 are added to the proposed single layer, without any modification to the substrate size. However, to make the 3 Layers antenna resonates at 3.5 GHz, the patch size is reduced to 33 x 31 mm^2.

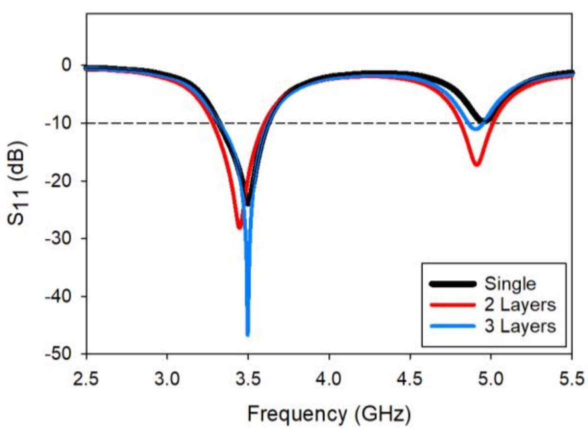


Figure 5 Reflection coefficient of the antenna from single

Table 1 Performance comparison for multilayer antenna with same substrate size

Layer	S11 (GHz)	S11(dB)	BW (GHz)	Gain(dBi)
Single	3.502	-24	3.62-3.31 (0.31GHz)	2.61
Double	3.46	-28	3.60-3.28 (0.32GHz)	3.43
triple	3.5	-46	3.62-3.32 (0.30GHz)	4.23

D. Size Reduction in Multilayer Structure

Arranging multilayer structure will increase the antenna performance, particularly the directivity and antenna's gain. In addition, the antenna dimensions can be reduced while keeping the same antenna performance. The substrate and the ground dimensions of the antenna are reduced from 77.54 x 69.6 mm^2 to 44 x 44 mm^2 when 2 layers is added to the single structure. The patch size is also minimized to 30 x 28 mm^2. The modification of the design is depicted in Figure 6. Table 2 tabulates the findings from single to 3 layers structure with size reduction.

The impedance bandwidth (BW) reduced to 70% for 2 layers structure, while in 3 layers structure, the BW remains unchanged. The gains were maintained in the range of 2.6 dBi with slight shift in the resonant frequency. Noticeably the matching of the antenna is improved from -24 dB to -41 dB as the layer increases.

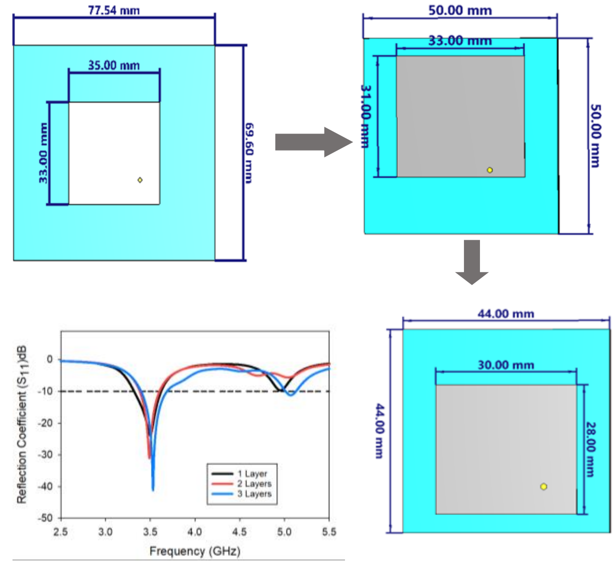


Figure 6 The modification of the proposed antenna, (a) single, (b) 2 layers, (c) 3 layers and (d) the reflection coefficient result

Table 2 The antenna performance with different layer and substrate size

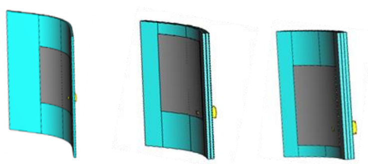
Layer	*Substrate (W x L) mm^2*	*S11 (GHz)*	*S11(dB)*	*BW (GHz)*	*Gain(dBi)*
Single	*77.54 x69.6*	*3.502*	*-24*	*3.62-3.31 (0.31GHz)*	*2.61*
Double	*50 x 50*	*3.49*	*-31*	*3.60-3.38 (0.22GHz)*	*2.68*
triple	*44 x 44*	*3.53*	*-41*	*3.70-3.39 (0.31GHz)*	*2.70*

3.0 RESULTS AND DISCUSSION

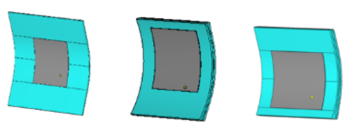
The findings of the propsed structure is discussed in this section. Bending and specific absorption rate (SAR) analysis is carried out to verify the robustness of the antenna and the suitability to using in Wireless Body Area Network (WBAN) applications.

A. Bending Experiment

The robustness of the antenna was tested through a bending experiment, involving both X- and Y-axis plane bending with a 45 mm radius. Figure 7 illustrates the bent antenna. Bending the antenna structure resulted in a leftward shift in the resonant frequency and a reduction in bandwidth for all proposed antennas. The results shown in Figure 8. The 2-layer antenna structure exhibited the most significant changes during X-axis bending, with the resonant frequency was brings down by 140MHz to 3.35 GHz and a bandwidth reduction to 160 MHz. Despite this, the S_{11} at 3.5 GHz remained at -6.3 dB, falling within an acceptable practical S_{11} range. While, both single- and 3-layer antennas resonated at 3.48 and 3.5 GHz, respectively, with a slight reduction in depth and more than 80% bandwidth retention. The antenna gain values were lowered but still maintained above 2 dBi for all antennas.



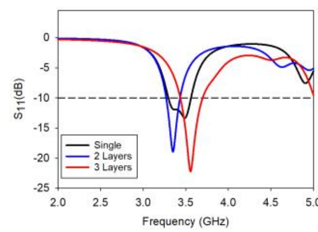
(a)X-axis bending.



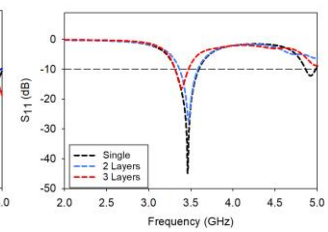
(b)Y-axis bending.

Figure 7 The antenna bending in X- and Y-axes

In the case of Y-axis bending, the 3-layer antenna experienced the most significant changes, with the S_{11} shifting to 3.4 GHz and an impedance bandwidth cover of -10 dB from 3.31 to 3.47 GHz. Consequently, the realized gain of the antenna decreased to 1.9 dBi. Conversely, no significant changes were observed for the single- and 2-layer antennas, with the impedance bandwidth falling within 3.5 GHz and a slight decrease in antenna gain to 2.1 dBi. The bending results are presented in Table 3.



(a)

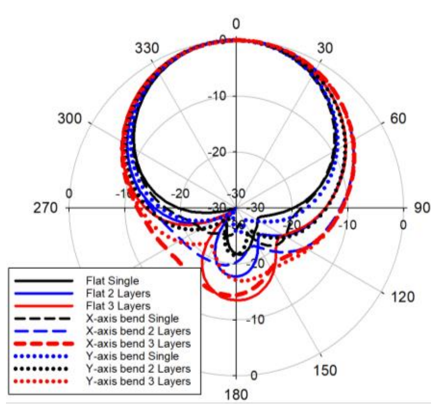


(b)

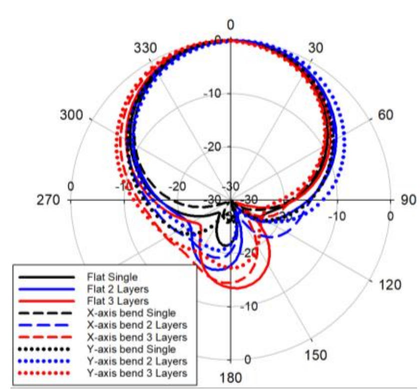
Figure 8 Reflection coefficient of the antenna during (a) X-axis and (b) Y-axis bending

Table 3 Bending performance of the proposed antenna

Layer	*Substrate (W x L) mm²*	*Bending Plane*	*S_{11} (GHz)*	*S_{11}(dB)*	*BW (GHz)*	*Gain(dBi)*
Single	*77.54 x69.6*	*X-axis*	*3.48*	*-13*	*3.56 – 3.29 (0.27 GHz)*	*2.03*
		Y-axis	*3.46*	*-44*	*3.6-3.31 (0.29 GHz)*	*2.13*
2 Layers	*50 x 50*	*X-axis*	*3.35*	*-19*	*3.43- 3.27 (0.16 GHz)*	*2.183*
		Y-axis	*3.47*	*-27*	*3.58 – 3.36 (0.22 GHz)*	*2.183*
3 Layers	*44 x 44*	*X-axis*	*3.5*	*-13*	*3.63 – 3.38 (0.25 GHz)*	*2.168*
		Y-axis	*3.4*	*-16*	*3.47 – 3.31 (0.16 GHz)*	*1.90*



(a) E-plane



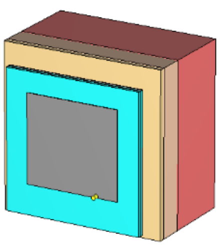
(b) H-plane

Figure 9 Polar plot of radiation pattern for the proposed antenna

Figure 9 shows a comparison of radiation pattern of the proposed antenna in flat and bending to X- and Y-axes. Layering the antenna produce extra back lobe to the antenna radiation pattern. Act of bending wider the back lobe for all antenna, however the main beam is maintained at 0 degrees. On the whole, no significant changes can be observed in radiation patterns in this bending analysis.

B. SAR Analysis

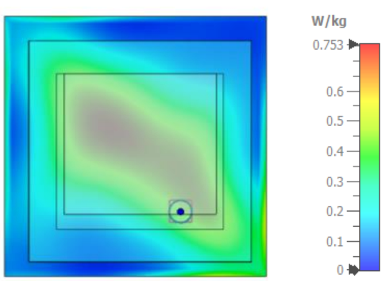
As antenna radiates, there will be electromagnetic wave around the antenna. As the proposed antenna aims to be wear, SAR assesment is required so that it will not give harm to the wearer. SAR described the portion of energy absorbed by human tissue. In this assessment, the single and 3 Layers antenna are placed on human tissue shown in Figure 10(a) and the details parameter were described by the Figure 10(b). Simulated SAR show result of 0.0574W/kg and 0.753W/kg for both single and 3 Layers, which are less than the allowable level of RF field exposure. According to standard guideline issue by IEEE C95-1-2005 the upper bound limit of SAR 1g of the tissue sample volume has a peak value of SAR is 1.6W/Kg [22], [23].



(a)

Type	εr	δ
Skin	38.06	0.2535
Fat	5.28	0.1938
Muscle	52.79	0.2419

(b)

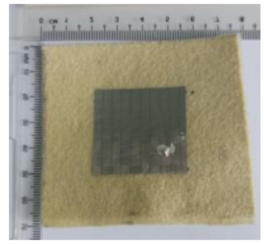


(c)

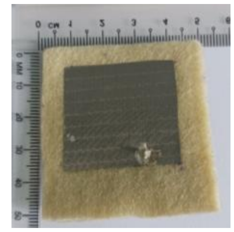
Figure 10 (a) antena with human tissue, (b) human tissue parameter and (c) SAR result for 3 Layers antenna

C. Simulated and Measured Result

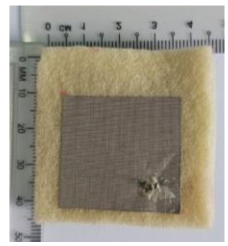
Figure 11 shows the fabricated antenna using 1mm thick felt as a substrate. The antenna is stacked into multilayer where the substrate size is reduced from 77.54 x 69.6 mm^2 to 44 x 44 mm^2. The antenna then is measured using ENA E55071C for the reflection coefficient and impedance bandwidth as shown in Figure 12.



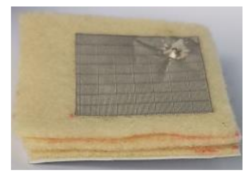
(a) Single layer



(b) 2 layers



(c) 3 layers



(d) 3 Layers (sideview)

Figure 11 The fabricated of the proposed antenna

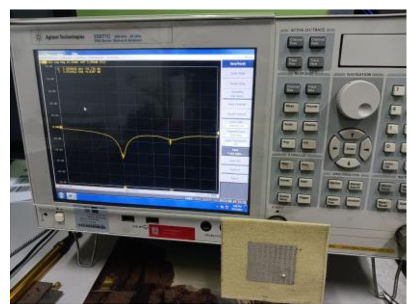


Figure 12 The proposed antenna is tested using ENA Vector Network Analyzer

Comparison of reflection coefficient is presented by graph shown in Figure 13. The measured results are generally consistent with the simulated results, despite some slights deviation of about 100MHz for 3 Layers antenna, where the S_{11} shifted to 3.4 GHz. The variation in the S11 results may be attributed to the air gap between layers in the fabricated antenna, which alters the overall antenna dielectric constant [24].

There are also deviations in the impedance BW which would be due to manual fabrication of the antenna. Measured S_{11} for single layer and 2 Layers antenna show a good match at 3.5 GHz with -30dB and -24.7 dB respectively. Noted a slightly wider BW for single layer for about 38% wider than simulated while 41% narrower BW for 2 Layers antenna. On the other hand, the measured S_{11} for the 3 Layers antenna show a shifted to 3.4 GHz , where the antenna operates from 3.25 to 3.57 GHz with about 3 % wider BW compared to simulated antenna.

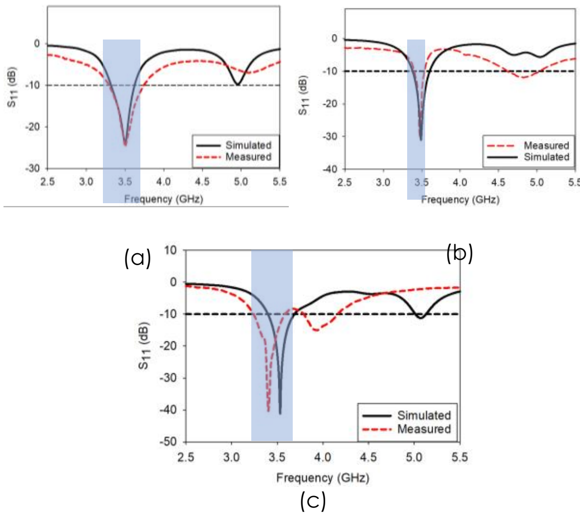


Figure 13 Simulated and measured S11 for the proposed antenna (a)single, (b) 2layers and (c) 3layers

4.0 CONCLUSION

The design and analysis for the stacked wearable antenna have been successfully discussed. Based on this proposed design, the antenna operated well at 3.5 GHz with a good gain of 2.7 dBi. Steps and analysis from single layer to 3 layers structure were explained in methodology section, where the antenna dimension of 3 layers structure is reduced to 57 % from the single layer. The robustness of the antenna is good as it performs well during bending analysis. Additionally, the simulated SAR result of below 1.6 W/kg for 1g tissue proves that the antenna is suitable to be used in close proximity to human body. The measurement result is also promising where the reflection coefficient (S_{11}) agreed well with the simulation result.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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