

Performance Comparison of Cotton and Silk Substrates on 1.575 GHz Frequency Textile Antenna

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Abstract—Textile antennas are currently being researched and developed so that they can be integrated into clothing. In this paper, two textile antennas with cotton and silk substrate are presented. The antennas operate at GPS L1 frequency, which is 1.575 GHz. This paper discusses the effect of antenna parameters on free space and on-body conditions, and the effect of antenna bending. Based on simulation and measurement results, the parameter values obtained indicate that the antenna can operate properly at a frequency of 1.575 GHz and is safe to use on the body.

Index Terms—Antenna bending; Cotton substrate; GPS L1; Silk substrate; Textile antenna.

I. INTRODUCTION

Textile antenna is one type of wearable antenna that uses textile material as a substrate. Textile antenna must have flexibility property and must be able to operate well when bent or placed on-body parts. The antennas must also have a Specific Absorption Rate (SAR) value below 1.6 W/kg [1], which states that the antenna is safe to use when placed on a body part. Some papers revealed that this type of antenna can be applied to defence [2], health monitoring [3], and smart clothing [4]. The type of textile used also varies, such as jeans [2], cotton, polyester, corduroy [5], and jute [6].

The discussion about wearable antennas is interesting so that there are several studies that discuss this matter. In [7], it was explained that the study used an antenna with a silk, nylon, and leather substrate with size dimensions of about 215.5 mm × 115 mm and working at MICS and ISM frequencies, whereas the gain on a silk antenna at a frequency of 1.49 GHz was 1.82 dBi. There is also a study [8] that uses a textile electrode in a device designed to measure the impedance of the human body through breathing and heart rate with a frequency range of 2 MHz–20 MHz, while in the paper in [9], the use of flexible electronic measuring (70 mm × 43 mm) in an antenna

connected to a microcontroller and functions to monitor biological variables are described. The two papers describe the applications for near field communication. In addition, the paper in [10] describes the use of a wearable antenna at a frequency of GPS L1 in 1.575 GHz which is indicated on the front of the cap. For the patch and ground plane, the copper sheets with fractal patches are used, while flannel and polyester are used as substrate materials. Based on the measurement results, a gain of 2.1 dBi was obtained. On the other hand, the proposed antenna uses 2 types of substrates with aluminium foil tape for the patch and groundplane. The cotton substrate antenna obtained a gain value of about 1,206 dBi, while the silk substrate antenna obtained a gain value of about 6.104 dBi in free space condition.

This paper explains the parameter values produced by antennas that use cotton and silk as substrates. These two materials are a part of the study on three types of substrates that are commonly used as clothing materials, where the result of nylon material has been published in other papers. The novelty of this proposed research is the use of aluminium foil tape as a patch and ground plane material, which is different from some papers in [1], [6], [7], [10] which use copper or copper tape for the patch and groundplane. In addition, the proposed antenna using the L1 GPS frequency has not been widely used in current research and can be integrated into a person's position detection application. This paper presents the simulation results in free space and on-body conditions, along with the results of the antenna measurements that have been fabricated. In addition, the SAR value and the effect of bending on the proposed antenna will also be discussed.

II. RELATED WORKS

To design the shape and dimensions of the antenna, manual calculations are performed based on [11]. Then, based on the calculation results, a simulation was carried out in the CST Studio Suite 2018 software and it turned out that the results of the parameters are not optimum. Therefore, the

antenna optimization is performed so that the desired parameter values can be reached. Furthermore, the fabrication stage is done entirely manually without a printing process, and then a female SMA connector is attached to the feed line reinforced with hot glue because basically aluminium cannot be soldered. To make sure the connector and antenna are connected, the measurements are taken using a multimeter.

At the time of measurement, measurements were made for the near field and far field. Specifically, a measurement of the far field was carried out in the Anechoic Chamber room so that the data obtained were more valid.

III. METHODOLOGY

In this paper, the textile antennas use a microstrip antenna model. Two types of textile antennas were designed to operate at a frequency of 1.575 GHz. The antennas' material used as a substrate are cotton fabric and silk fabric, whereas the patch and ground plane parts used aluminium foil tape because it is flexible and easy to fabricate. Both of antennas use rectangular patches with different dimension sizes and full groundplane. The first antenna used a cotton substrate with a relative permittivity of $\epsilon_r = 1.6$, tangent loss of 0.04 [5], and textile thickness of $h = 0.125$ mm. In the second antenna, silk fabric as a substrate has a relative permittivity of $\epsilon_r = 1.75$, tangent loss of 0.012 [4], and thickness of $h = 0.178$ mm. For patches and groundplanes, the aluminium foil tape with a thickness of $t = 0.033$ mm was used. To design the two purpose antennas, the equation from Balanis [11] is used. Equation (1) below is used to define the patch width

$$W_p = \frac{v_o}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}}, \quad (1)$$

where v_o is the velocity of light, ϵ_r is the relative permittivity of antenna substrate, and f_r is the working frequency of antenna.

Then to determine the length of the microstrip antenna patch, (2), (3), and (4) are used:

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W}\right)^{-\frac{1}{2}}, \quad (2)$$

$$\Delta L = 0.412h \frac{(\epsilon_{reff} + 0.3) \left(\frac{W}{h} + 0.264\right)}{(\epsilon_{reff} - 0.258) \left(\frac{W}{h} + 0.8\right)}, \quad (3)$$

$$L = \frac{v_o}{2f\sqrt{\epsilon_{reff}}} - 2\Delta L, \quad (4)$$

where ϵ_{reff} is the ϵ_r effective, ΔL is the length increased due to the fringing effect, and L is the length of patch.

In the feed line, it can be calculated with equations from (5) to (7) below:

$$B = \frac{20\pi^2}{Z_o\sqrt{\epsilon_r}}, \quad (5)$$

$$W_f = \frac{2h}{\pi} \left\{ B - 1 - \ln(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r} \left(\ln(B - 1) + 0.39 - \frac{0.61}{\epsilon_r} \right) \right\}, \quad (6)$$

$$L_f = \frac{v_o}{4f\sqrt{\epsilon_{eff}}}, \quad (7)$$

where Z_o is characteristic impedance with value of 50 ohm, W_f is width of feed line, an L_f is length of feed line.

In Fig. 1, the overall antenna geometry is shown.

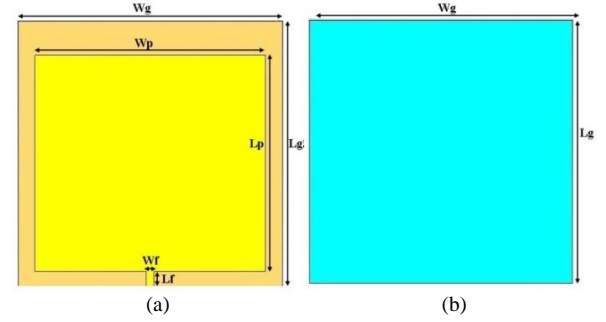


Fig. 1. Antenna geometry: (a) front section, and (b) back section.

Figure 1 shows the geometry model used in the purpose antenna. The geometry design is obtained from the calculation results based on the theory and optimized. Whereas Table I explains each antenna parameter symbol used in Fig. 1.

TABLE I. ANTENNA PARAMETER.

Antenna Parameter	Symbol
Patch length	L_p
Patch width	W_p
Groundplane length	L_g
Groundplane width	W_g
Feed length	L_f
Feed width	W_f
Substrate thickness	h
Aluminium foil tape thickness	t

IV. SIMULATION RESULTS

The simulations are needed to ensure that the geometry of the designed antenna can produce the required characteristics. After the desired characteristics are achieved, the antenna can be realized. Table II details each antenna parameter value of the two antennas with different substrates based on mathematical calculation result using the equation from the textbook [11] and after optimization.

TABLE II. ANTENNA PARAMETER VALUE.

Par. Symbol	Antenna Value (mm)			
	Cotton Substrate		Silk Substrate	
	Calculation Results	Optimization Results	Calculation Results	Optimization Results
L_p	75.36	73.36	72	70
W_p	83.5	88.50	81.2	95
L_g	85	110	73.068	90
W_g	76.86	100	82.268	100
L_f	3.8	7	3.6	7
W_f	3.47	4	3.27	2
h	0.125	0.79	0.178	0.99
t	0.033	0.033	0.033	0.033

In the optimization process, the size of the patch, feedline, and substrate are changed. While the thickness of the aluminium foil tape is not changed. In addition, the thickness of the substrate is also optimized. Therefore, each antenna is added to the thickness of the substrate into 5 layers. The addition of substrate thickness aims to increase the value of the gain.

A. Free Space Condition

In the free space condition, the antenna is simulated without involving phantom. In Fig. 2, the simulation near field results of silk and cotton substrate are compared. Based on this simulation, the antenna with cotton substrate has a Voltage Standing Wave Ratio (VSWR) value of about 1.124 with a bandwidth of about 58 MHz, whereas for antenna with silk substrate, it has a VSWR value of about 1.379 with a bandwidth of about 30 MHz. From here, the VSWR and bandwidth of cotton substrate is better than of silk substrate. This can be affected because the permittivity value of the cotton substrate is smaller than of the silk substrate.

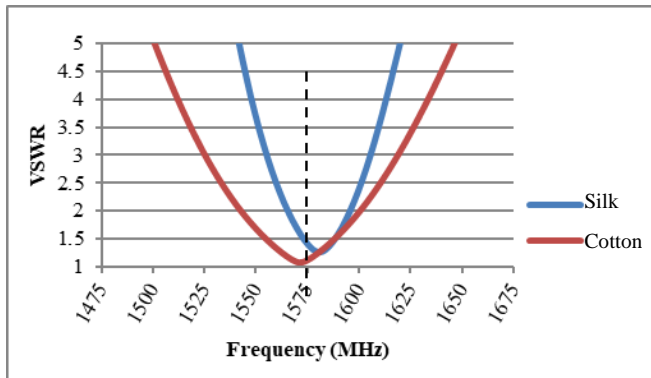


Fig. 2. Simulated VSWR comparison of the proposed antennas on free space condition.

Besides, a far-field simulation of the antenna is also performed to see the direction of the radiation pattern and the gain value obtained. Based on Fig. 3 and Fig. 4, it can be seen that the antenna with silk substrate has a higher gain value than the antenna with cotton substrate and both of them have unidirectional radiation pattern. The simulation results have met the specifications, so the antenna can be fabricated.

B. On-Body Condition

In this simulation, the forearm phantom is used as a small part of the actual arm structure. The use of phantom in simulations aims to determine changes in the characteristic value of the antenna that has been designed. The simulation using phantom also functions to find out the SAR value of an antenna so that it can be determined whether the antenna is safe to use or not. The simulated phantoms consisted of skin with a thickness of 2 mm, fat with a thickness of 2 mm, muscle with a thickness of 20 mm, and bone with a diameter of 14 mm. Each part of the phantom has a different permittivity value, such as skin with permittivity value of 37.95, fat with permittivity of 5.27, muscles with permittivity of 52.67, and bones with permittivity of 18.49 [12]. Figure 5 presents the antenna simulation on the phantom.

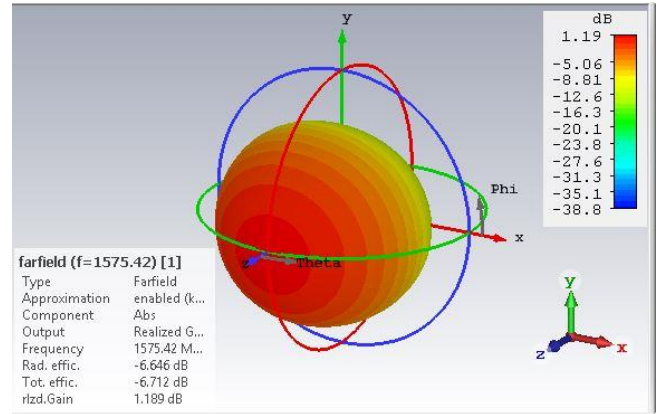


Fig. 3. Simulated gain of the cotton substrate antenna.

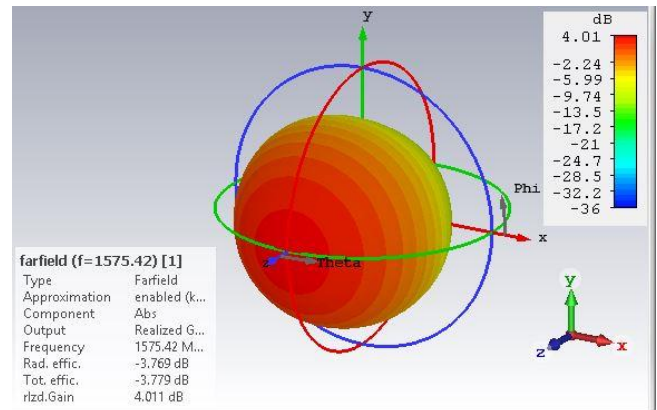


Fig. 4. Simulated gain of the silk substrate antenna.

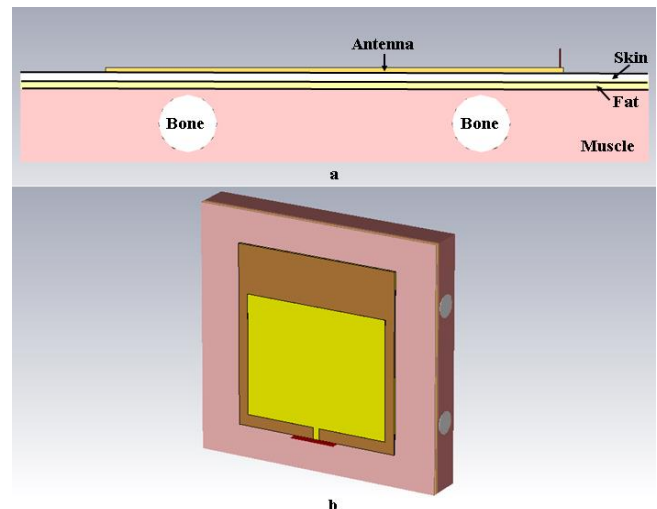


Fig. 5. (a) Side view of phantom; (b) front view of the phantom.

Figure 6 compares the VSWR results' simulation of the cotton and silk substrates, and in Table III, the results of the characteristic values after adding phantom are detailed. The antenna with cotton substrate has a bandwidth of about 56.8 MHz, whereas the antenna with silk substrate has a bandwidth of about 32 MHz. It can be seen that the antenna characteristic values have decreased the VSWR values and bandwidth of the cotton substrate, but increased the VSWR values and bandwidth of the silk substrate, and decreased the gain values for both of them. This is due to the impact of phantoms which disturbs the near field of the antenna so that it affects the antenna impedance value and causes an increase in the value of power loss.

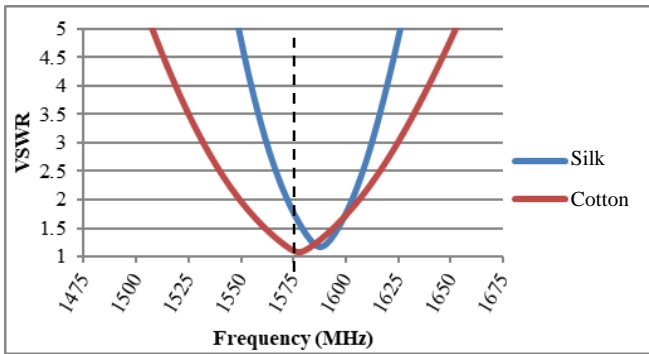


Fig. 6. Simulated VSWR comparison of the proposed antennas with phantom.

TABLE III. PHANTOM SIMULATION RESULTS.

Gap (mm)	Cotton Substrate Antenna			Silk Substrate Antenna		
	VSWR	Gain (dBi)	SAR (W/kg)	VSWR	Gain (dBi)	SAR (W/kg)
0	1.091	0.77	0.168	1.75	3.561	0.566
1	1.092	0.86	0.151	1.74	3.63	0.486
5	1.083	1.03	0.119	1.729	3.647	0.265
10	1.084	1.20	0.065	1.689	3.725	0.142
20	1.088	1.45	0.025	1.641	4.056	0.064

V. MEASUREMENT RESULTS

After the simulation, the antenna fabrication is done manually without Printed Circuit Board (PCB) printing process (Fig. 7 and Fig. 8).

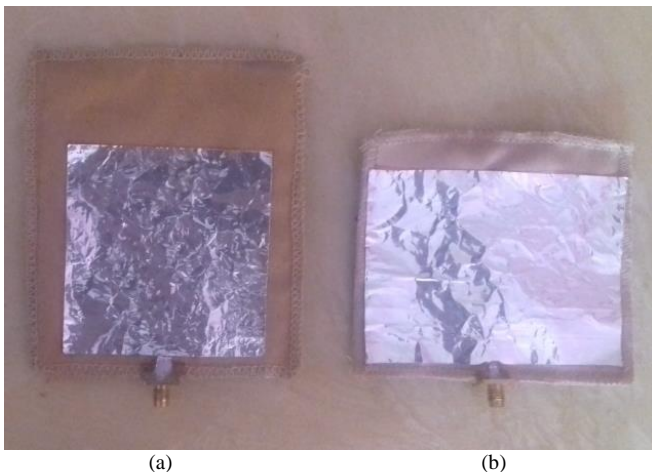


Fig. 7. Front view of (a) cotton substrate antenna, and (b) silk substrate antenna.

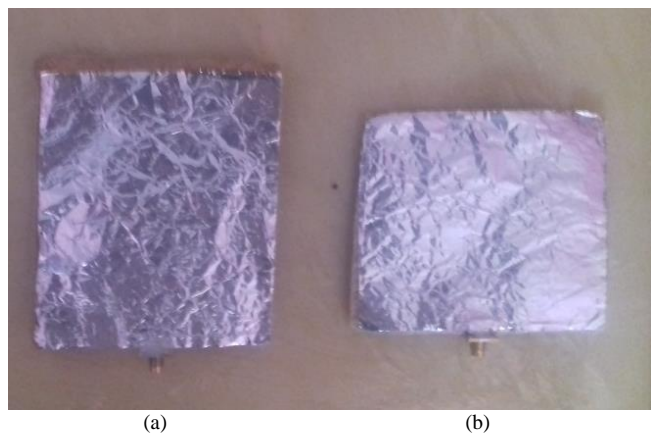


Fig. 8. Back view of (a) cotton substrate antenna, and (b) silk substrate antenna.

The cutting patch, ground plane, and substrate are done

manually. Both of these antennas used SMA connector. Because of the nature of aluminium that cannot be soldered, the connectors are installed using aluminium foil tape and reinforced using hot glue. Then the measurement phase, which aims to determine the real value of the antenna characteristics and compares the results obtained with the simulation results, is carried out. In Fig. 7 and Fig. 8, the textile antenna results are shown.

A. Free Space Condition

In the free space condition measurement, the antennas are measured by placing the antenna in an upright condition in free air. The characteristics measured include return loss, VSWR, bandwidth, radiation patterns, and antenna gain.

Looking at the near field measurement results of the cotton substrate antenna compared to the silk substrate antenna as shown in Fig. 9, it can be concluded that the cotton substrate has a better VSWR value and wider bandwidth than the silk substrate. This can be due to the effect of the lower permittivity value of the cotton substrate than the silk substrate.

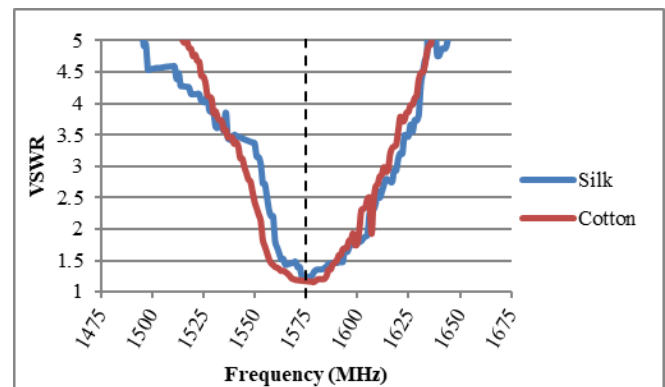


Fig. 9. Measured near field of the proposed antennas on free space condition.

Whereas in Fig. 10, the comparison results of radiation pattern measurement for the cotton and silk substrate antenna are displayed. It can be seen from the figure that the shape of the radiation pattern produced after every 10° measurements is a unidirectional radiation pattern.

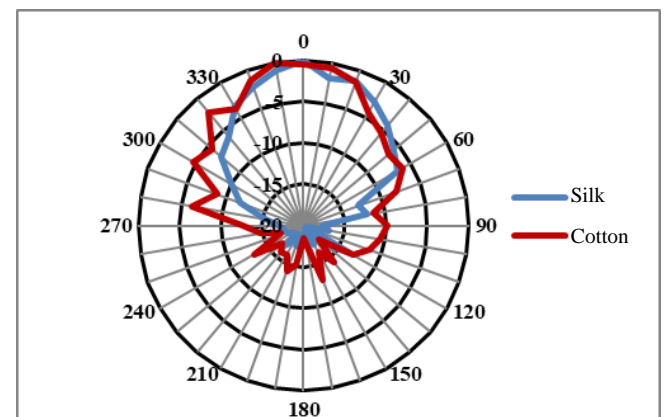


Fig. 10. Measured radiation pattern of the proposed antennas on free space condition.

The shape of the dominant main lobe in one direction only indicates this. For the cotton substrate, the highest power value is obtained when the antenna is at position 0° of the reference antenna with a power value of about -

32.7 dBm, while the lowest power value is obtained at position 180° from the reference antenna with a power value of about -50.7 dBm. Meanwhile, for the silk substrate, the highest power value generated is of about -27.9 dBm and the lowest power value generated is of about -47.6 dBm.

To calculate the gain value from the power level value, an equation from the textbook [7] can be used

$$\text{Gain(dBi)} = (P_{\text{AUT}} - P_{\text{REF}}) + 9.5\text{dBi}, \quad (8)$$

where P_{AUT} = Power level of purpose antenna and P_{REF} = Power level of reference antenna is -24.49 dBm.

The results of the antenna measurement with the gain of the cotton substrate are detailed in Table IV with the gain value from the measurement results obtained of around 1.206 dBi. Based on these results, it can be seen that there is an increase in the gain value of 0.017 dBi compared to the simulation results. It turned out that the difference was not significant.

TABLE IV. GAIN MEASUREMENT RESULT OF COTTON SUBSTRATE ANTENNA ON FREE SPACE CONDITION.

Measurement	Power Level (-dBm)
1	32.70
2	33.14
3	31.59
4	33.55
5	32.94
Average	32.78
Gain (dBi)	1.206

Table V shows the results of the measurement of the silk substrate antenna along with the results of the conversion to the actual gain value. From the table, the obtained gain value is of about 6.014 dBi. When compared with the simulation results, there is an increase in the gain of 2.093 dBi. This increase in gain can be due to the measurements made in the Anechoic Chamber.

TABLE V. GAIN MEASUREMENT RESULT OF SILK SUBSTRATE ANTENNA ON FREE SPACE CONDITION.

Measurement	Power Level (-dBm)
1	27.90
2	28.01
3	27.81
4	28.15
5	27.56
Average	27.886
Gain (dBi)	6.104

The high gain value is due to the larger dimensions of the antenna so that the received power is more optimal. In addition, because silk fabric has a fairly low permittivity value of 1.75, the gain value obtained is also higher. This is because the permittivity value is inversely proportional to the gain value, so the lower the permittivity value, the greater the gain value obtained [13]. Another factor affecting the high-value gain is the thickness of the substrate, where a silk substrate has a higher thickness than cotton. Because the increase in the thickness of the substrate is directly proportional to the increase in the value of the gain, it can be ascertained that the value of the obtained gain is also higher [12], [13].

B. On-Body Condition

In the on-body condition, the antenna placed on the forearm and the characteristic was measured. Figure 11 shows the configuration of the measurements made.

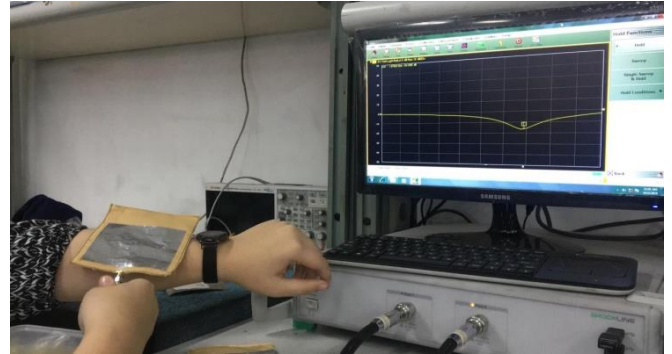


Fig. 11. Near field measurement on-body condition.

When the results of the near field measurements of the cotton antenna and the silk antenna are compared, it can be seen in Fig. 12 that the VSWR values of the two antennas are almost the same, but the bandwidth on the silk antenna is wider than on the cotton antenna. Based on these results, it can be seen that the silk substrate antenna has better performance in on-body conditions.

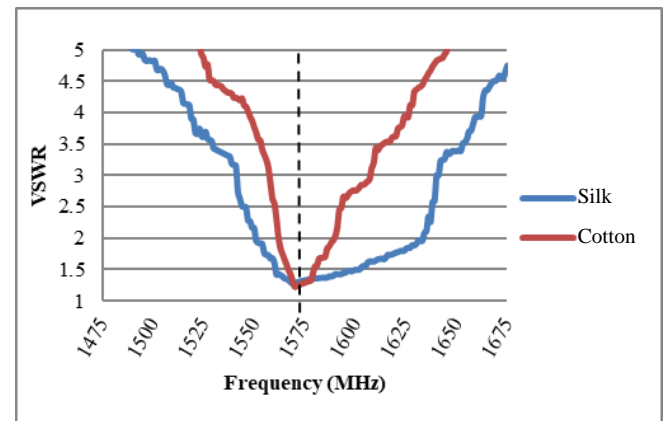


Fig. 12. Measured near field of proposed antennas when on-body condition.

Table VI lists the values of the gain generated when the on-body condition is of about 0.768 dBi. The measurement results have decreased by 0.438 dBi from the gain value in normal conditions. Placing the antenna close to the body causes the field near the antenna to be disturbed, thereby increasing the reflected power. This causes the power received by the antenna to decrease so that the gain obtained by the antenna also decreases.

TABLE VI. GAIN MEASUREMENT RESULT OF COTTON SUBSTRATE ANTENNA ON-BODY CONDITION.

Measurement	Power Level (-dBm)
1	33.71
2	33.29
3	33.15
4	33.04
5	32.92
Average	33.22
Gain (dBi)	0.768

When compared with the simulation results, the gain

value of the measurement has decreased by 0.002 dBi from the simulation results using phantom, which has a gain value of 0.77 dBi. This is due to the fabrication done manually and the occurrence of mismatch due to antenna connectors that are not firmly attached so that it affects the input impedance. In addition, the increase in the value of return loss and VSWR can be caused by differences in body surface conditions during simulation and measurement. In the simulation, phantom is used, which has a flat surface, while the measurement of the forearm is used with uneven and curved surfaces.

Table VII shows the results of the measurement of silk substrate gain antenna on-body condition. From the table, it can be seen that the gain value is of about 4.236 dBi and it has decreased by 1.868 dBi when compared to measurements on the free space condition. In addition, when compared with the simulation results, the gain value from the measurement results is 0.675 dBi higher than from the simulation results.

TABLE VII. GAIN MEASUREMENT RESULT OF SILK SUBSTRATE ANTENNA ON-BODY CONDITION.

Measurement	Power Level (-dBm)
1	30.01
2	29.53
3	31.27
4	28.43
5	29.53
Average	29.75
Gain (dBi)	4.236

VI. BENDING EFFECT MEASUREMENT

The measurement of bending effect is done to determine the performance of the antenna when experiencing bending. This needs to be done because textile antennas are prone to bending if applied to clothing or the body. The measurements were made using cardboard tubes with diameters of each tube being 5 cm, 7 cm, and 9 cm. The data from the measurements of the two antennas are shown in Table VIII. Based on these data, it can be seen that the characteristic values tend to decrease due to the narrowing of the feed line and patch areas during bending.

TABLE VIII. BENDING EFFECT MEASUREMENT.

Parameter	Cotton Substrate Antenna (cm)			Silk Substrate Antenna (cm)		
	5	7	9	5	7	9
Return Loss (dB)	-12.5	-12.5	-15.0	-21	-20	-24.4
VSWR	1.61	1.688	1.432	1.31	1.35	1.129
Gain (dBi)	0.72	1.04	1.17	3.74	4.31	5.05

VII. DISCUSSION

In this section, a comparison between the simulation results and measurements of the two proposed antennas is presented. The parameters compared are VSWR and radiation pattern of each antenna in free space condition and on-body condition. This aims to determine whether the measurement results match the simulation or not.

In free space condition, Fig. 13 shows comparison simulation and measurement of VSWR, where the measurement obtained a VSWR value of about 1.162, and

bandwidth is of about 56 MHz. When compared with the simulation result, there was an increase in the VSWR value of 0.038 and a narrowing of the bandwidth by 2 MHz. The fabrication process carried out manually and the effect of installing a connector that is not too strong can cause this. Both of these reasons can cause differences in the value of the antenna characteristic simulation results and measurement results. However, the difference in value is not too significant, so the results can still be accepted and meet the required antenna specifications.

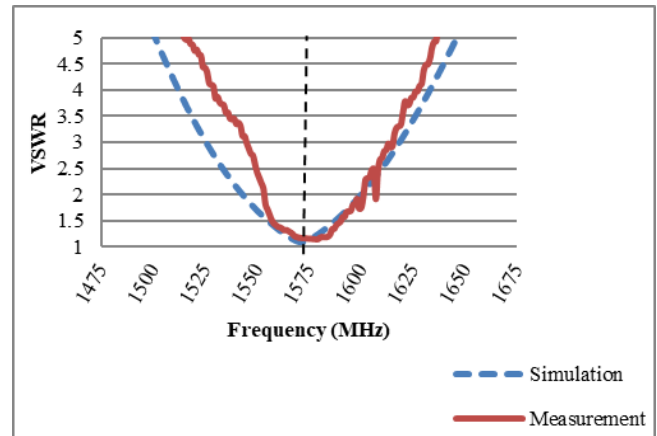


Fig. 13. Simulated and measured near field of the cotton antenna on free space condition.

Meanwhile, the comparison of the simulation and measurement results for near field on silk substrate antenna can be seen in Fig. 14. According to this, the measurement obtained a VSWR value of 1.22 with a bandwidth of 45 MHz. From these results, it can be seen that the antenna characteristic values tend to be higher than the simulation results. This can be caused by the difference in the permittivity value of the fabric used for fabrication with the permittivity value obtained from previous studies.

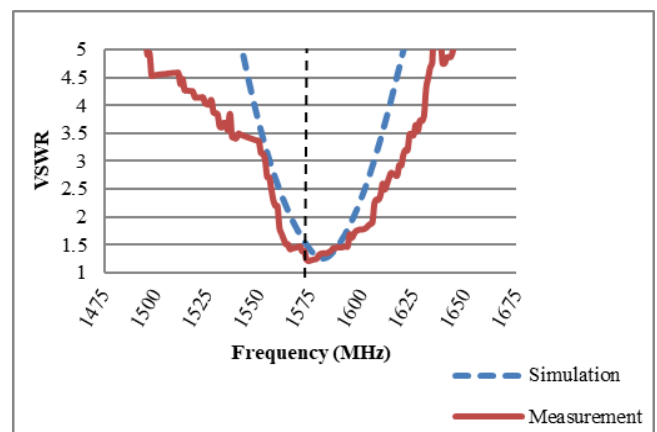


Fig. 14. Simulated and measured near field of the silk antenna on free space condition.

Figure 15 below shows the comparison of simulated and measured results of antenna with cotton substrate. Simulation and measurement results show that the radiation pattern of antennas is pointing strongly in one direction, whereas in Fig. 16, the comparison of simulation results and measurements on the antenna with a silk substrate is shown.

The antenna measurement results when on-body condition can be seen in Fig. 17. Based on the figure, the antenna with cotton substrate has the VSWR value of about

1.3, and the bandwidth is of about 28 MHz. From the measurement results, it can be seen that the VSWR measurement value is higher than the simulation result with an increase of 0.209. This is caused because the placement of the antenna on the arm interferes with the field near the antenna, thus affecting the antenna input impedance. Inadequate input impedance values cause the transmission line impedance is not matching, so it will cause increased VSWR values.

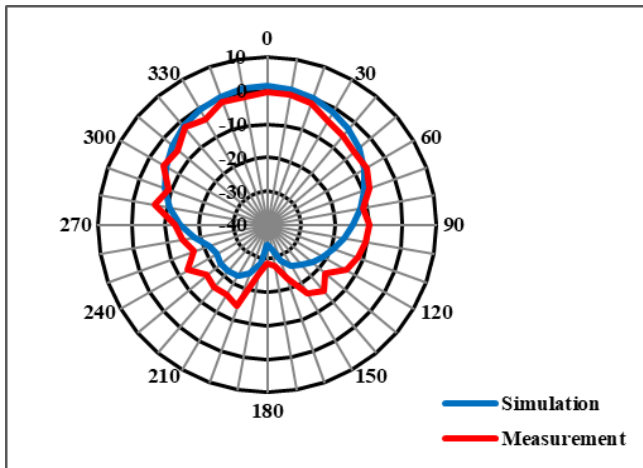


Fig. 15. Comparison of radiation pattern of the cotton antenna on free space condition.

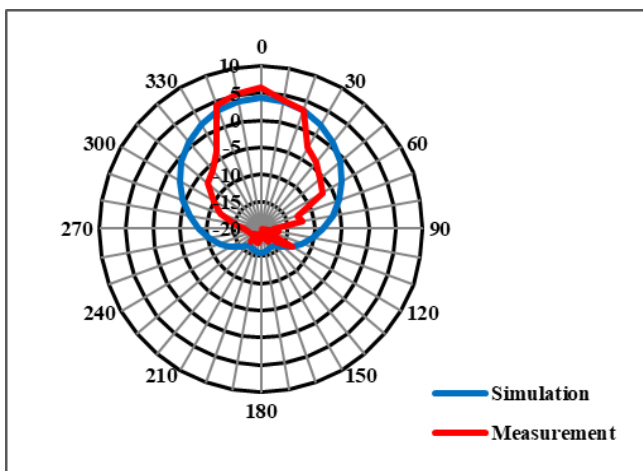


Fig. 16. Comparison of radiation pattern of the cotton antenna on free space condition.

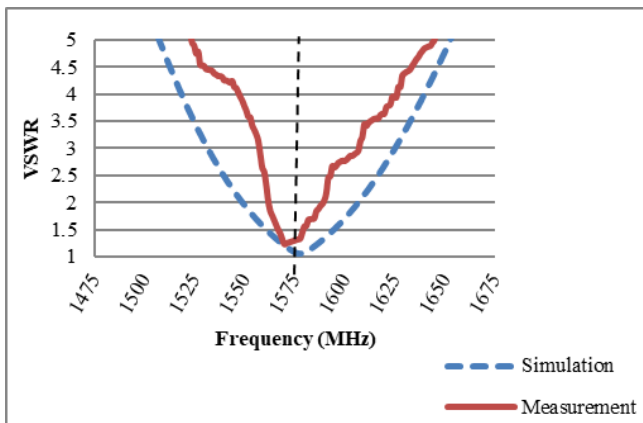


Fig. 17. Simulated and measured near field of the cotton antenna on-body condition.

The measured VSWR value of silk substrate is of about 1.327, and the bandwidth is of about 82 MHz. Figure 18

shows the comparison of the measurement and simulation values of the silk substrate antenna with the body condition. It can be seen that the measured VSWR is lower than the simulated one. While in terms on bandwidth, the measurement result is wider (of about 50 MHz) than the simulation result. The difference between the measurement and simulation results can be caused by the influence of the antenna placement on the arm and also by the lack of strength of the connector attached to the antenna.

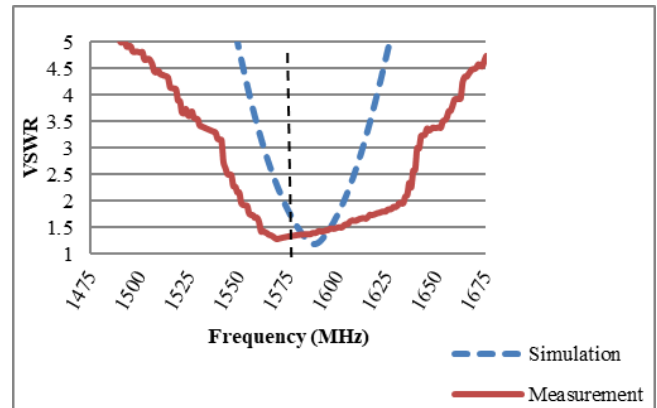


Fig. 18. Simulated and measured near field of the silk antenna on-body condition.

In the paper in [14], the antenna uses a jeans substrate operating at a frequency of 1.575 GHz. The reference antenna uses a copper tape for patch and groundplane. The gain value obtained in the free space condition is 1.7 dBi, while the on-body condition has a gain value of 1.2 dBi. When compared with the antenna, the proposed antenna has a better gain value with a gain value of 4.011 dBi for silk antennas in free space conditions, and on-body conditions, the gain value obtained is 3.561 dBi.

In another paper in [10], the SAR value generated by the antenna during on-body condition is described. The SAR value obtained for the flannel substrate was 0.303 W/kg, and for the polyester substrate, it was 0.295 W/kg. Meanwhile, the proposed antenna has a SAR value of 0.168 W/kg for cotton substrate and 0.566 W/kg for silk substrate.

VIII. CONCLUSIONS

From the simulation and measurement results, it can be concluded that the two textile antennas can operate well at a frequency of 1.575 GHz with unidirectional radiation pattern in free space and on-body conditions. The substrate permittivity value and its thickness affect the proposed antenna characteristic values. In addition, based on the simulation results, the two antennas have a Specific Absorption Rate (SAR) value which still meets specifications so that the antennas are safe to use on the body. In free space conditions, the VSWR value of cotton antenna is better than of silk antenna, but the gain value tends to be lower. Whereas in the on-body condition, an antenna with a silk substrate has a better performance because it has a high gain value and a wider bandwidth. From this research, it can be concluded that the silk antenna has a better performance value than the cotton antenna for both conditions. Therefore, an antenna with a silk substrate can be used in position detection applications because it has a high gain value and better performance.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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