

Bending Effects on Polyvinyl Alcohol Thin Film for Flexible Wearable Antenna Substrate

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ABSTRACT

Polyvinyl Alcohol (PVA) has been used in various applications, including the medical health industry and electronics. It is a synthetic polymer with advantages such as being transparent, flexible, biocompatible, biodegradable, and a simpler synthesis process. These advantages make PVA a very promising material for human wearable antennae. In this research, the bending effect of an antenna using a PVA substrate is studied to analyze its durability in the wearable application. Firstly, the thin film substrate synthesis is performed using PVA 2488 with the measured average dielectric constant and tangent loss of 1.24 and 0.066, respectively, across S-Band frequency. Later, a 5G antenna is designed and fabricated using the PVA substrate. Finally, the bending effects of the fabricated antenna are measured at different bending radii. Four different antenna-bending radii are selected to represent different curvatures of human body parts. Results show that bending does not have a significant effect on the reflection coefficient of the antenna, where the frequency shifts from 2.2% up to 7.4% only for all bending conditions. Hence, in that aspect of finding, the PVA thin film is a potential candidate for flexible and wearable antenna material in various human body parts in biomedical applications.

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INTRODUCTION

A polymer is a large molecule composed of repeating structural monomer units connected by covalent bonds. Polymers such as proteins, cellulose, and starch can be

naturally occurring or synthetic, such as plastics, synthetic fibers, and rubber. Polymers are versatile materials with a wide range of properties and applications. For example, some polymers are rigid and stiff, while others are flexible and resilient. Some are transparent, and others are opaque. Some are thermoplastic, meaning they can be melted and reshaped, while others set into a permanent shape when heat and pressure are applied. The properties of a polymer can be tailored by adjusting its composition and molecular structure. It can be achieved through copolymerization, blending, and cross-linking. Polymers have numerous practical applications, including in packaging, construction, textiles, electronics, and medicine (Rhazi et al., 2018; Turek et al., 2020; Wu et al., 2021; Zhang, Biesold et al., 2022; Zhong et al., 2020). For example, polyethylene is commonly used to make plastic bags, while polyvinyl chloride (PVC) is used in pipes and upholstery. Polyurethane is used in foam insulation, cushions, and adhesives; nylon is used in clothing and ropes. On the other hand, in recent years, there has been a growing concern about the environmental impact of synthetic polymers, particularly plastic. It has led to increased research into biodegradable and renewable polymer alternatives, as well as recycling and waste management strategies for conventional polymers.

Wireless on the body refers to wireless communications around the human body area to transmit data between wearable devices attached to the human body. This purpose includes medical sensors, fitness trackers and smartwatches. Hence, those technologies allow the collection of real-time data and monitoring of various physiological and environmental parameters, allowing for personalized and adaptive applications in healthcare, sports, and other fields. Therefore, a special flexible material needs to be used for a flexible, robust, biocompatible, and environmentally friendly antenna. Polymer materials such as Polyimide (PI), Polyethylene terephthalate (PET/PETE), Polydimethylsiloxane (PDMS) and Liquid Crystal Polymer (LCP) have been widely used as antenna substrates because those materials are highly flexible, and some are not biocompatible and biodegradable. Previous work on antennae using those materials is summarized in Table 1.

Interestingly, physical hydrogels based on poly (vinyl alcohol) (PVA), which contains a significant number of reactive groups (-OH groups), are notable for their remarkable biocompatibility, superior mechanical properties, and chemical stability (Xu et al., 2023). PVA is a more human-friendly wearable material than others because it is biocompatible and biodegradable, easy to synthesize and transparent (Ibrahim et al., 2022).

In addition, it is also a synthetic and water-soluble polymer that has been widely used in pharmaceutical, food packaging and electronics sensors. However, researchers have overlooked using PVA as a flexible material for wearable antennae. Most work that uses PVA as potential wearable sensors and other electronics applications has only been applied at frequencies lower than 1 GHz, such as work by Reddy et al. (2019), Mousa & Taha (2022), Ambrosio et al. (2018) and Hamad and Hashim (2022). With the potential, there is a need to

Table 1
Previous flexible material in antenna design

Flexible material	Author	Technique	Antenna operating frequency (GHz)	Dielectric constant (ϵ_r)	Tangent loss ($\tan\delta$)
PDMS	Shakirul et al., 2021b	Patch antenna	3.5	3.0	0.008
PTFE	Fujiwara et al., 2014	Patch antenna	2.4	2.1	0.002
LCP	Paul et al., 2013	Patch antenna	2.45 & 5.8	2.6	0.0025
PI Kapton	Khaleel, 2014	Patch antenna	3.1–10.6	3.5	0.02
Jeans	Gil & Fernández-García, 2016	Patch antenna	1.575	1.7	0.025
PVA/CaCO ₃	Appusamy et al., 2020	Patch antenna	2.4	1.67	0.039
Polyimide PI	Zhang, Huang et al., 2022	Patch antenna	5.8	3.6	0.02
PET	Hassan et al., 2017	Patch antenna	26–40	3.2	0.022
PDMS	Salleh et al., 2022	Patch antenna	3.5	2.54	0.05
Proposed work		Patch antenna	3.5	1.24	0.066

study several robustness elements of the material as part of wearable antennae, specifically the bending effects. Table 1 shows the previous flexible materials used in antenna design.

METHODOLOGY

A PVA thin film substrate was prepared using a simple synthesis process. This process involved several stages, starting with the preparation of the PVA substrate material.

Preparation of Antenna Substrate

The antenna substrate was prepared using a simple synthesis process. The formulation of the mixture was adopted from Appusamy et al. (2020) but modified. The PVA used in this project was PVA 2488, and in the modification, it was used with an 88% degree of hydrolysis. Normally, this material is applied to adhesion, coating, film packaging, the textile industry, personal care, and cosmetics (Achutha et al., 2023; Haque et al., 2021).

The synthesis started by measuring 4.3g of PVA 2488 powder and diluting it in 100 ml of double-distilled water. The solution was constantly stirred using a magnetic stirrer and heated at 80°C for



Figure 1. Fabricated PVA thin film substrate

2 hours until the PVA powder was completely dissolved and a homogenous solution was produced.

After that, the solution was poured into a petri dish and dried using Universal Oven for 12 hours. Then, the PVA thin film was peeled off from the cast, as in Figure 1, before its dielectric properties were measured.

Substrate Measurement

The PVA thin film substrate’s dielectric constant and tangent loss were measured using coaxial probe N1501A from Keysight Technologies and Vector Network Analyzer (VNA) from Agilent. A thin film PVA sample with a minimum thickness of 3 mm was used, as in Figure 2. Moreover, the thickness of the substrate sample plays an important role in determining the accurate dielectric and tangent loss value. The dielectric constant and tangent loss were measured and averaged in the S-Band range from 2 GHz to 4 GHz. The measurement result is as in Figure 3.

The average measured values for dielectric constant and tangent loss across S-Band frequency for pure PVA thin film are 1.24 and 0.066, respectively. The dielectric and tangent loss at 3.5 GHz is 1.27 and 0.066, respectively. These two values are not much different from the average value across the S-Band frequency range. The proposed PVA dielectric and tangent loss is compared with other wearable, flexible materials, as in Table 1.

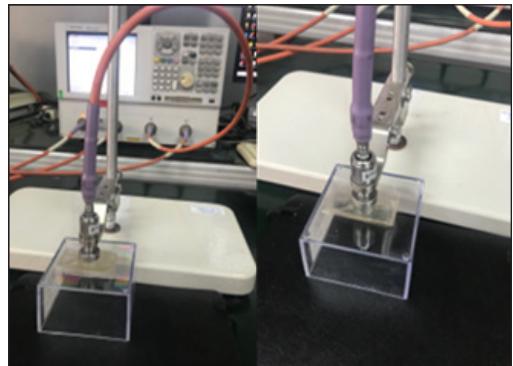


Figure 2. PVA thin film measurement technique using Keysight N1501 and Vector Network Analyzer

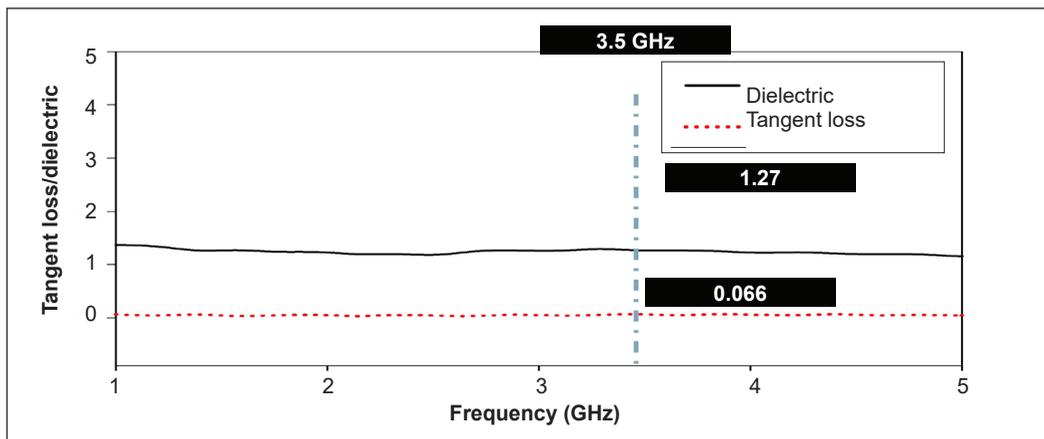


Figure 3. Result for PVA thin film (3 mm) substrate measurement using Keysight N1501 and Vector Network Analyzer

Antenna Design and Fabrication

The antenna design substrate used the average dielectric and tangent loss values. The microstrip patch antenna was designed with a resonance frequency of 3.5 GHz, located in the sub-6 5G band, which is the most popular 5G frequency.

The antenna dimensions of the microstrip patch were calculated using Equations 1 to 4 (Dewan et al., 2021). The patch width (W_p) was calculated using Equation 1. The dielectric constant (ϵ_r) of the substrate and desired resonance frequency (f_r).

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

After that, the effective dielectric constant (ϵ_{reff}) is determined as a function of W_p and substrate high (h), considering edge effects and the propagation speed of the field waves in the antenna provided by Equation 2.

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

Then, the length extension is calculated using Equation 3.

$$\Delta L = 0.412 \times h \times \left[\frac{(\epsilon_{reff} + 0.3) \left(\frac{W_p}{h} + 0.264 \right)}{(\epsilon_{reff} - 0.258) \left(\frac{W_p}{h} + 0.813 \right)} \right] \quad (3)$$

Finally, the length of the patch (L_p) is calculated by substituting the effective dielectric constant ϵ_{reff} and length extension ΔL values in Equation 4.

$$L_p = \frac{c}{2 \times f_r \sqrt{\epsilon_{reff}}} \times 2 \times \Delta L \quad (4)$$

The calculated formula used the starting parameters dimensions to design, simulate, and improve the rectangular patch antenna using Computer Simulation Technology (CST) software. The calculated values for $W_p = 40.47$ mm, $\epsilon_{reff} = 1.228$, $\Delta L = 0.514$ mm and $L_p = 37.62$ mm were used as the dimension references in antenna simulation in CST Software. This calculation and simulation process was completed before the antenna was constructed as a prototype.

Copper tape with a thickness of 0.025 mm was used as the conductive patch radiator and ground. The design structures are listed in Table 2, where these values are based on calculations. Besides, some optimization modification was done, and the optimal structures of the antenna substrate were 50×50 mm² with a thickness of 0.8 mm.

Antenna Bending Analysis

The intended design and functional PVA wearable antenna must have good mechanical characteristics; thus, the bending effect on the designed antenna is investigated. Both simulation and measurement were carried out, and the results were compared.

Normally, antenna bending is used to investigate the robustness performance of a wearable antenna. The bending also represents the curve of human body parts, such as the head, arm, leg and chest, where it is normally attached.

The simulation has been done in CST Microwave Studio, and the bending effect was simulated on XZ-plane, and TE mode will be contributed to the frequency resonant shift. A cylinder structure was used in the simulation to bend the antenna, hence representing several body parts (Shakhirul et al., 2021a; Zaidi et al., 2022; Zhang, Huang et al., 2022).

In the simulation process, four bending radii were chosen, which are $R = 18$ mm, $R = 25$ mm, $R = 38$ mm and $R = 50$ mm (Figure 4). The radius represents the several body part curvature conditions and shapes as in practical conditions explained by Zaidi et al. (2022), Salleh et al. (2022), and Zhang, Huang et al. (2022). The performance in reflection coefficients S_{11} , gain and directivity are compared on those works with different wearable substrates and operating frequency.

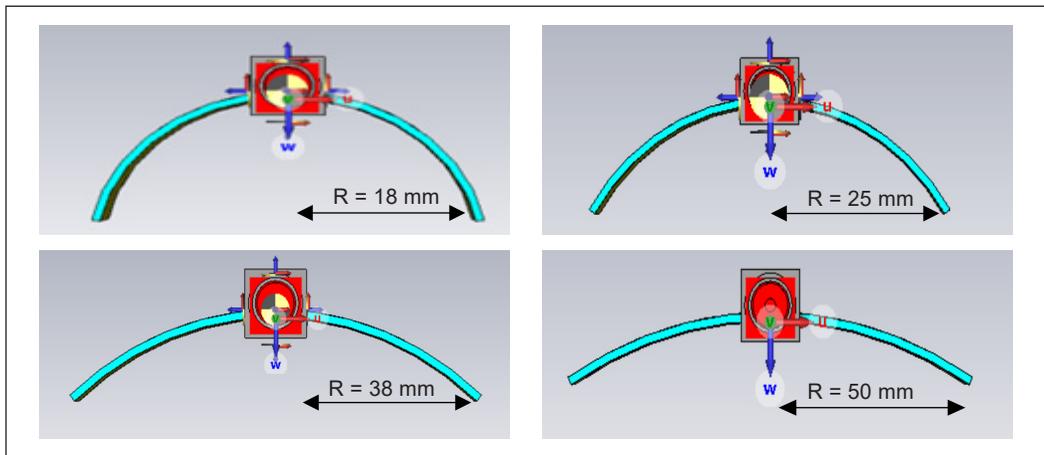


Figure 4. Antenna bending for radius $R = 18$ mm, 25 mm, 38 mm and 50 mm in CST Simulation Software

RESULTS AND DISCUSSION

This project starts with simulation, fabrication, and measurement processes to achieve the research aim of PVA antenna bending effects. Typically, the initial step involves conducting the substrate synthesis process to obtain the dielectric and tangent loss values. Subsequently, the focus shifts to simulating the prototype and proceeding with the fabrication and measurement of the antenna. The final design is finally subjected to the study of its bending characteristics.

Antenna Simulation and Prototype

Equations 1 to 4 were used as the reference dimension for the antenna design. However, some modifications and optimizations were done to produce good antenna performance, such as S_{11} , radiation pattern, bandwidth, directivity, and gain.

The antenna has been designed and simulated in Computer Simulation Technology (CST) Studio Suite, as in Figure 5, using the optimized values from Table 2. In contrast, the fabricated prototype antenna is shown in Figure 6.

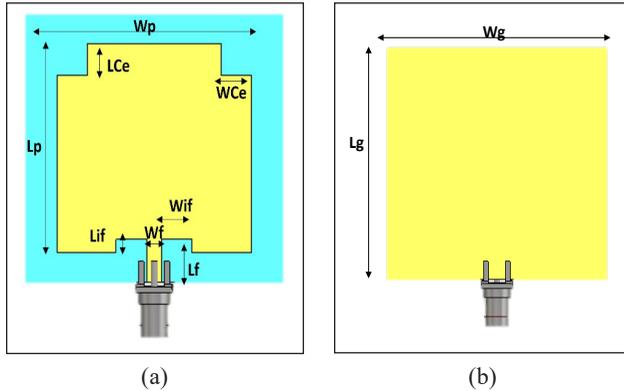


Figure 5. View of antenna in CST simulation: (a) Front; and (b) back

Table 2
Dimension for antenna structure

Antenna structure	Dimension (mm)
Width substrate	50.0
Length substrate	50.0
Thickness substrate	0.80
Feedline (Lf)	9.97
Feedline width (Wf)	2.90
Patch width (Wp)	38.00
Patch length (Lp)	38.99
Length edge cut (Lce)	5.98
Width edge cut (Wce)	5.98
Width inset feed (Wif)	5.97
Length inset feed (Lif)	2.48
Ground width (Wg)	50.0
Ground length (Lg)	50.0
Copper thickness	0.025

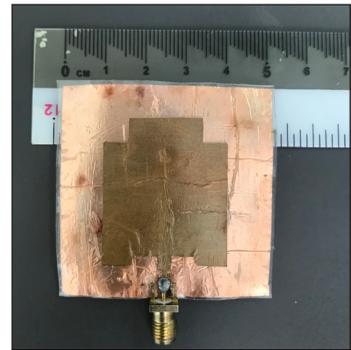
Flat Condition Test

Basically, wearable antennae will be designed and simulated under two major conditions: flat and bending. Table 3 compares the simulation and measurement of the designed antenna under flat conditions. It will ensure that the fabricated antenna’s practicality is suitable for flexible wearable conditions.

Table 3 compares the simulation and measurement results. The reflection coefficient S11 for the flat condition shows a good correlation between the simulation and measurement. The simulation S11 is -22.627 dB at 3.5 GHz, while the measurement S11 is -20.966 dB at 3.42 GHz, as shown in Figure 7. The operating frequency shift is about 2.2% from the 3.5 GHz resonant frequency.

Table 3
Antenna performance comparison

Parameter	Simulation	Measurement
S11 (dB)	-22.627	-20.966
Bandwidth (MHz)	143	400
VSWR	1.08	1.20
Impedance Matching (Ω)	50	41



(a)



(b)

Figure 6. View of the fabricated antenna: (a) Front; and (b) back

Bending Condition Test

The fabricated antenna has been tested under different bending conditions for simulation and measurement analyses. For measurement, it has been tested on polystyrene foam with a different radius, R , as in Figure 8. The antenna will be placed on top of the polystyrene foam and taped to produce some bending conditions.

Based on the bending simulation result in Figure 9, the resonant frequencies were shifted to the lower frequency, around 3.42 GHz. It represents the shifted frequency of 2.2% at the maximum shift. The reflection coefficient for all bending radiuses, R , was below -10 dB. This result significantly proves that the bending condition is less affected by the radius. However, the smaller the antenna bending radius, the higher the shift, as seen in the results.

Similarly to the antenna bending measurements in Figure 10, the resonant frequencies were shifted from the original

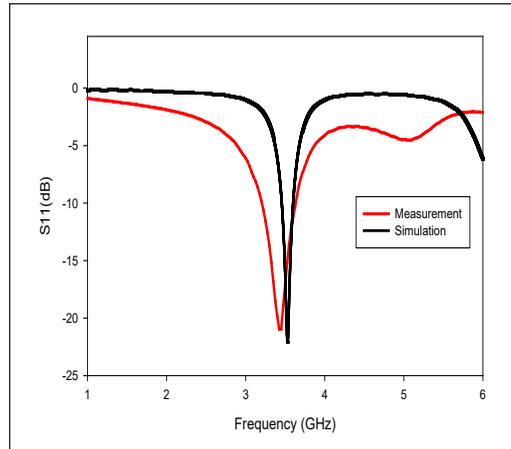


Figure 7. S11 for simulation and measurement under flat condition

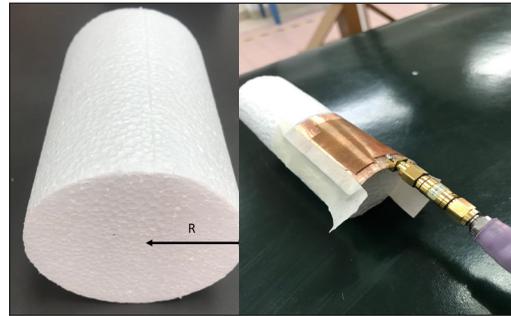


Figure 8. Antenna bending setup on polystyrene foam with different radius R

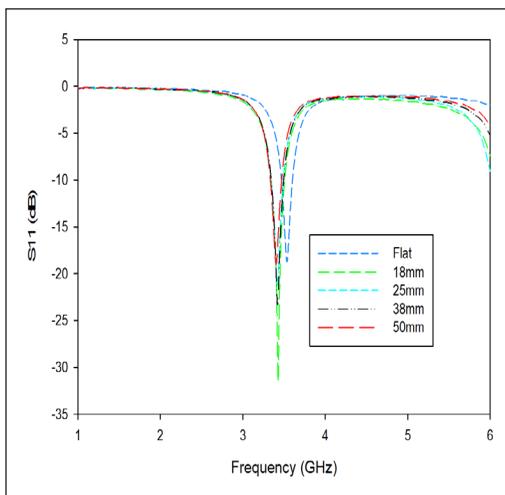


Figure 9. Antenna bending simulation with different radii R

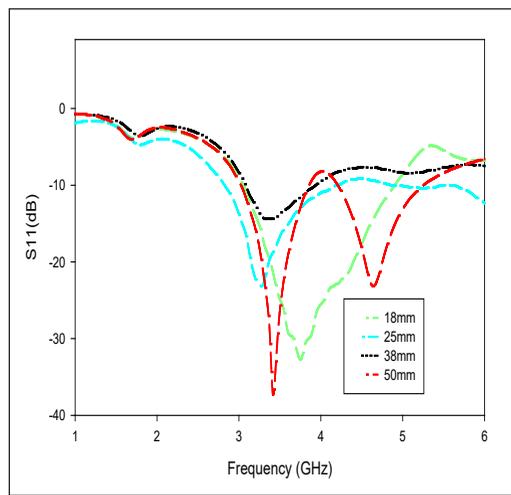


Figure 10. Antenna bending measurement on polystyrene foam with different radii R

flat position (without bending) resonant frequency. Most resonant frequencies were shifted to a maximum of 7.7%, as recorded in the results. Overall, there are weak correlations between simulation and measurement results due to human and equipment errors during the fabrication and measurement process. However, it can be concluded that the antenna's performance is still in the range of 3.4 GHz to 3.6 GHz, which is allocated bandwidth for the 3.5GHz sub-6 band.

The radiation patterns for E and H-Plane were evaluated for flat and four different bending radii. The radiation pattern for flat and four different bending radiuses shows an almost similar pattern, a monopole directional pattern, as in Figure 11. However, this pattern is desired, especially when the antenna is designed for wearable applications, because it minimizes radiation from the back lobe to the human body.

Apart from radiation, the performance of the antenna, such as S11, realized gain, directivity, efficiency, and bandwidth, were evaluated and summarized in Table 4. The bending radius has a significant impact on the antenna, particularly on its gain performance.

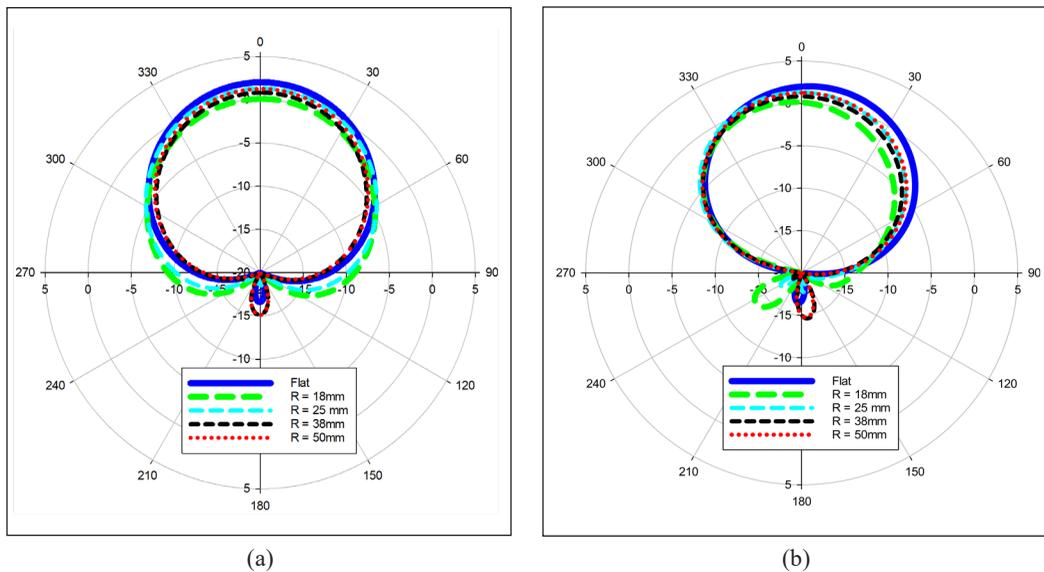


Figure 11. Radiation pattern for flat and bending conditions: (a) E-plane; and (b) H-plane

Table 4
Antenna bending performance under various bending conditions

Parameter/ Radius	18 mm	25 mm	38 mm	50 mm
S11 (dB)	-17.497	-17.676	-19.471	-18.543
Gain (dBi)	0.212	1.32	0.825	1.26
Directivity (dBi)	6.106	7.248	7.184	5.75
Efficiency	25.75%	25.54%	23.13%	23.24%
Bandwidth (MHz)	130	133	137	135

The gain performance of an antenna is reduced when it has a smaller radius bending angle because more energy is trapped inside the antenna as it is bent on the small bending radius. Therefore, the shorter the bending radius, the lower the gain.

Figure 12 shows the relationship between the antenna bending radius with realized gain and directivity. The gain and directivity were increased when the bending radius varied from the lower to the higher bending radius. It shows $R = 18$ mm having the lowest gain and directivity, while $R = 50$ mm shows the best performance.

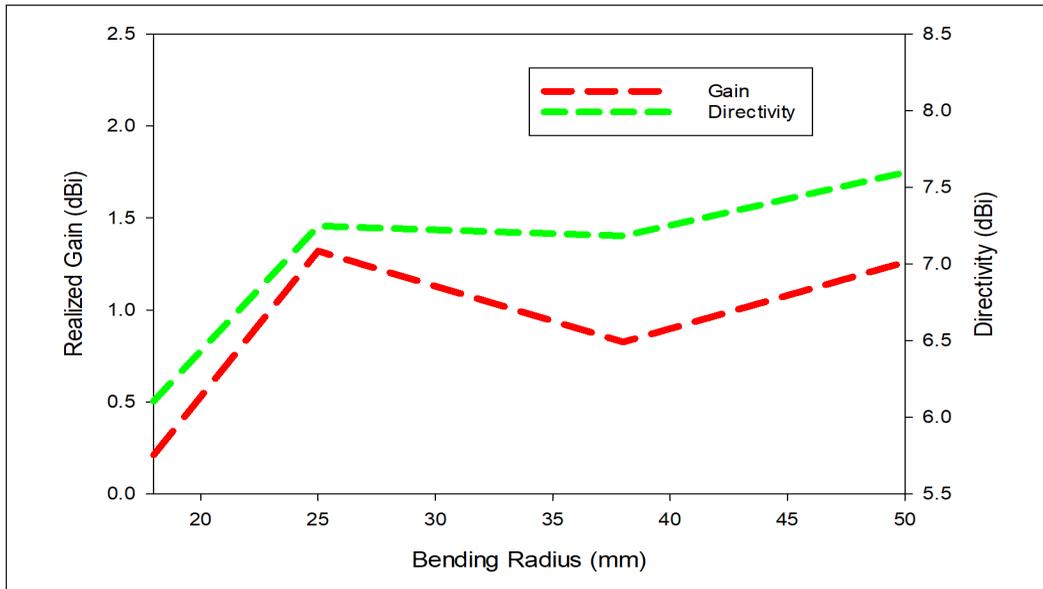


Figure 12. Gain and directivity of the antenna under various bending radius

CONCLUSION

In conclusion, an analysis of the bending effects on the PVA antenna substrate has been carried out. When the antenna is in flat condition, the return loss S_{11} is resonated at 3.5 GHz while under the bending condition from 18 mm to 50 mm, the return loss S_{11} was shifted to the lower frequency band by 269MHz shift, which is still acceptable under the 3.5GHz bandwidth allocation. In the study, it is found that at the bending conditions, the resonant frequency did not severely affect the original return loss due to the lower dielectric constant value of the PVA thin film substrate, which is around 1.24 on average across the S-Band and closer to the dielectric constant of the air. The obtained resonant frequency shifts are around 2.2% to 7.7% from the desired resonant frequency at S_{11} less than -10 dB.

This finding indicates that apart from its human-wearable-friendly material properties, PVA thin film holds substantial promise as a flexible material in the design of wearable antennas for wireless on-body monitoring, showcasing its significant potential in the robustness of flexible wearable antennas in biomedical applications.

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