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5 GHz Microstrip Patch Antenna from Pineapple Leaf-Based Substrate for Environmentally Sustainable Wireless Communication

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ABSTRACT

Pineapples generate approximately 75% waste, each with its unique characteristics. Pineapple leaves have the potential to be utilized in the development of new fibres or raw materials. This study aims to present the design of a microstrip patch antenna that utilizes a pineapple leaf substrate to achieve a 5 GHz frequency resonant. The antenna design was simulated using CST software. The manufacturing process of the pineapple leaf substrate involves boiling, drying, blending, filtering, and mixing composite compositions. The dielectric permittivity at a frequency of G-band was determined using the waveguide technique, revealing an outstanding permittivity of 5.03 at 5 GHz. Subsequently, a microstrip patch antenna was fabricated and characterized to validate the concept. The results demonstrate an acceptable agreement between the simulation and the fabricated substrate at 5 GHz in term of return loss.

1. Introduction

Microstrip patch antenna substrate has a thin layer of dielectric material on which the antenna is printed or etched. It is made up of a thin metallic patch applied on a ground plane separated by a dielectric substrate. The substrate is often construct with low dielectric constant material such as Rogers or FR4 which is allow radio waves to pass through with minimum losses [1]. The patch usually creates a consistent and regulated dielectric environment for the antenna which influences its electrical attributes such as resonant frequency, bandwidth, and radiation pattern [2,3]. Microstrip patch antennas are widely used in various applications at 5 GHz, including wireless communication systems [4,5], medical applications [6-8], and radar systems [9].

Dielectric substrates are electrical insulators that can be polarised by an applied electric field, which means that instead of allowing electric charges to flow through them, they align their internal

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electric dipoles in the direction of the field. Substrates suited for high-frequency applications have dielectric constants that are reasonably constant throughout a large frequency range, ranging from a few hundred MHz to several GHz, and have low dielectric constants to minimize electric power loss [10]. Bandwidth, gain and frequency is an effect of performance that has been considered by previous research [11,12]. Dielectric substrate is used in construction of microstrip patch antennas. It is developed by selecting appropriate materials, dielectric constant, manufacturing procedures and design [13].

Raw materials are processed and manufactured to generate the dielectric substrate [14-16]. Composite materials, ceramic, and flexible polymer films are examples of raw material substrates [17,18]. Selection of raw material are providing the appropriate antenna performance parameters from size and dielectric constant of the substrate. In producing antenna, conductors serve an important role in dielectric substrates. The interaction between conductive elements and the dielectric substrate is fundamental to the operation of many electronic components. The function of conductor is as a ground plane that allows current to flow through and can change the radiation pattern of the antenna [13]. Copper, aluminium, gold, and silver are the example of conductor that has good electrical conductivity [19]. Pineapple leaf have been investigated as a potential dielectric material for antennas, as they have a high cellulose content that can contribute to sustainable resources and used in a variety of applications and have a good dielectric property [20]. Composite materials are used as substrate materials in antenna manufacturing because their properties can be tailored to low loss and high permittivity which helps to improve antenna performance [21].

In designing antenna, the size of patch and dielectric constant of the substrate are significant characteristics that influence aerial performance. There were several types of antennas with various substrates and forms on the market. A substrate with a greater dielectric constant will decrease antenna size but also bandwidth. In this work, the design of microstrip patch antenna from pineapple leaf is intended to indicate the reflection coefficient, S_{11} bandwidth of the antenna at 5 GHz of frequency.

2. Composite Dielectric Substrate Development

2.1 Pineapple Leaf Substrate Development

The manufacturing process of pineapple leaf substrate starts by alkali treatment with distilled water to reduce lignin of leaves [22]. Figure 1 shows the process of pineapple leaf development. The pineapple leaf was treated with a 3% sodium hydroxide concentration solution with constant boiling temperature. Then, the leaves are dried under the sun for 24 hours to remove water content in the leaves until it gets constant water mass. To obtain the filler, pineapple leaves are ground and filtered to get the suitable mass. To fabricate the substrate, epoxy resin is employed as the base material. The choice of epoxy as the substrate material stems from its well-established use due to its chemical and mechanical properties, akin to the widely used substrate FR4, which is also composed of epoxy resin as the base material. In this work, a mixture of epoxy resin and hardener is utilized at a ratio of 3:1. Lastly, 15 g of pineapple leaf was mixed with the 19.5 g of resin and 5.5 g of hardener. For bonding the pineapple leaf filler, resin is employed as a glue to any adjacent material layer [23]. Moreover, hardener agent must be added to the mixture to ensure that the sample became solid.

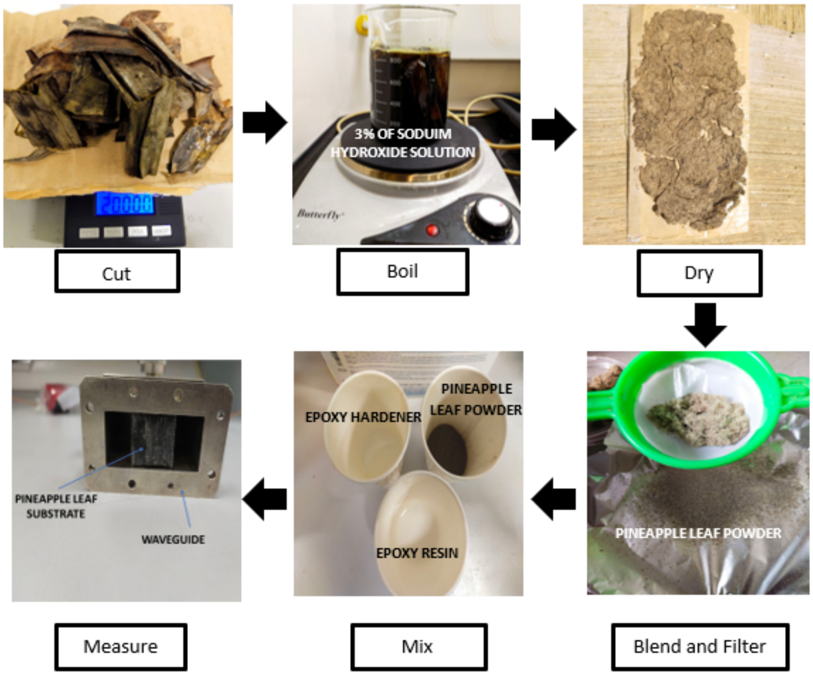


Fig. 1. Process of Pineapple Substrate development

Since pineapple leaf substrate is a new substrate in antenna application, material characterization was performed to measure the dielectric constant. These values of dielectric constant were measured by using Vector Network Analyzer (VNA) at 5 GHz [24] with the frequency between 4 GHz to 6 GHz and the measurement setup is as shown in Figure 2. The substrates were prepared considering the height of the G-band waveguide with 22.15 mm. The dielectric constant parameter value of pineapple leaf substrate was determined by using waveguide technique [25,26].

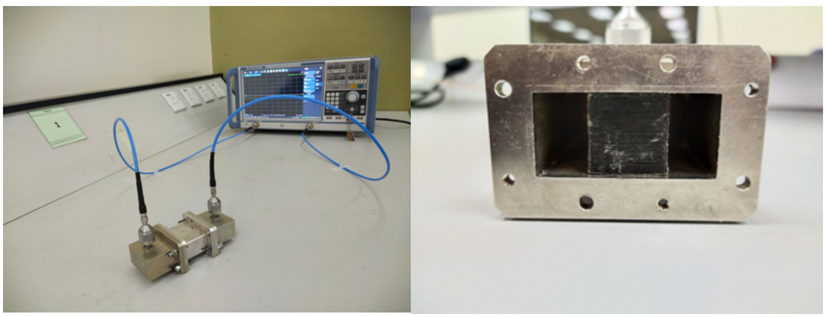
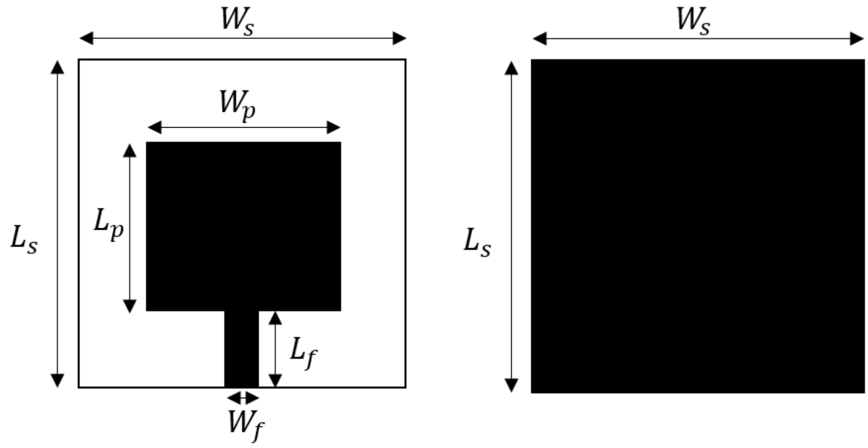


Fig. 2. Measurement setup of material characterization

2.2 Antenna Design

Microstrip patch antenna are basically an open resonator's structure. The antenna is positioned above a ground plane, and the field confinement between the patch antenna and the ground plane specifies characterization in which the antenna may function [27]. A rectangular patch and 50 Ω feed lines were included in the design. Feeding techniques for the microstrip patch antenna include coaxial probe, proximity, and aperture coupling [28,29]. The design is obtained through the utilization of the microstrip line feeding technique. A microstrip patch antenna has been simulated by using Computer Simulation Technology (CST) Studio Suite Software. The antenna design is characterized by linear polarization.

The microstrip patch antenna is composed of three layers, which include a copper patch, a pineapple leaf substrate layer, and a copper ground as shown in Figure 3. In this work, the conductive material and ground plane are constructed from 0.06 mm thin copper which has a good conductor of electrical energy. Pineapple leaves are used as a dielectric substrate material of the microstrip patch antenna.



(a) (b)

Fig. 3. (a) Top view of microstrip patch antenna with pineapple leaf substrate, (b) bottom view of antenna with pineapple leaf substrate

Designing a microstrip patch antenna involves calculating the physical dimensions of the patch needed to resonate at a specified frequency and efficiently transmit or receive electromagnetic waves. The patch size is determined by operating frequency and properties of substate. Eq. (1) is used to determine the optimal width of the patch based on the resonant frequency and the dielectric constant (ε_r) of pineapple leaf substrate. Furthermore, length Eq. (2) takes into account the effective dielectric constant (ε_{eff}) of pineapple leaf substrate. Both the length and width can be adjusted to fine-tune the resonance frequency and radiation pattern of antenna.

$$Width = \frac{c}{2f_o\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{1}$$

$$Length = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} \tag{2}$$

The top of microstrip patch antenna has conducting patch by using copper material with dimension of width, $W_p = 29.5$ mm and length, $L_p = 25.6$ mm of copper sheet. Feedline dimension of width, $W_f = 5$ mm and length, $L_f = 11.8$ mm also a group of front view conducting patch of the antenna. The dimension of pineapple leaf substrate was located at the middle of the antenna with width, $W_s = 50$ mm and length, $L_s = 50$ mm. The bottom of antenna is a ground plane using copper material with same dimension as the pineapple leaf substrate material. All the parameters used are shown in Table 1.

Table 1
Parameter of pineapple leaf substrate antenna design

Parameter	Values (mm)
Length of substrate, L_s	50.0
Width of substrate, W_s	50.0
Height of substrate, h_s	1.8
Width of feedline, W_f	5.0
Length of feedline, L_f	11.8
Width of patch, W_p	29.5
Length of patch, L_p	25.6

3. Result and Discussion

3.1 Dielectric Properties

The dielectric constant curve and loss tangent of pineapple leaf material during the process of substrate development is shown in Figure 4. The measurements were conducted by using Vector Network Analyzer (VNA) and rectangular waveguide. Dielectric constants and loss tangent were measured at frequency of 4 GHz to 6 GHz. It has been found that when the frequency increases, the value of dielectric constant and loss tangent decreases. The dielectric constant and loss tangent values at lower frequencies were greater than those at higher frequencies. It can be observed that the dielectric constant value of pineapple leaf at 5 GHz is 5.03 and the value of loss tangent is 0.19.

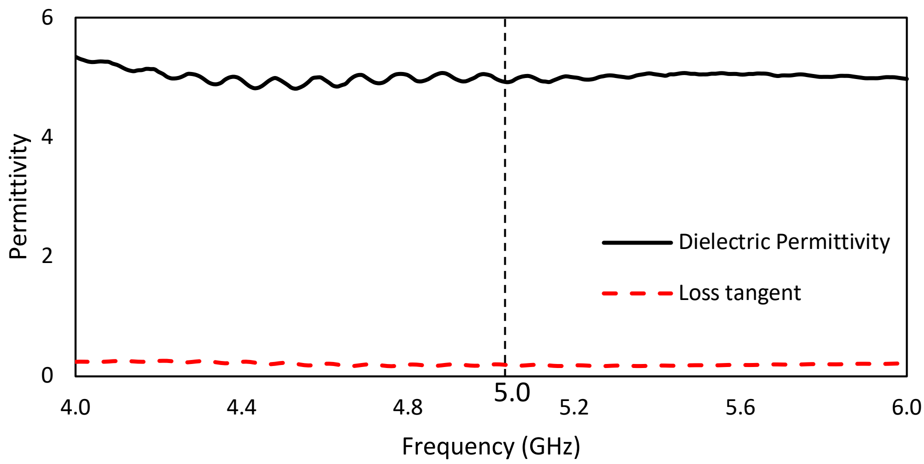
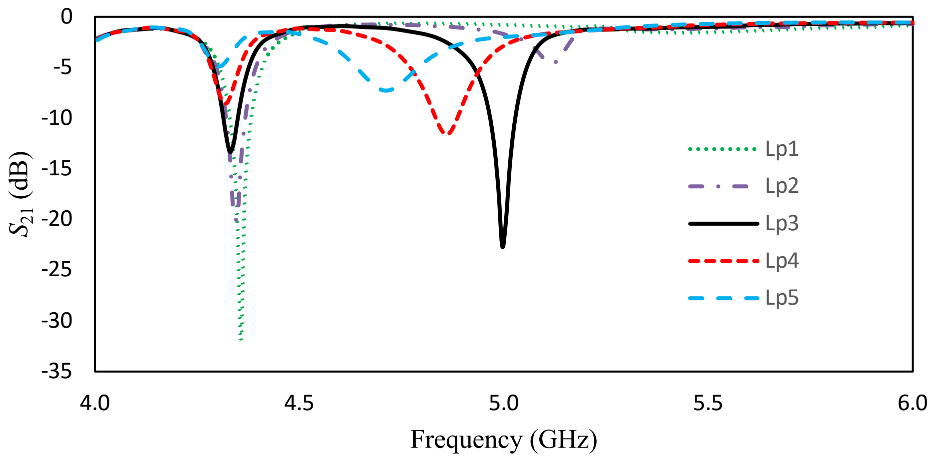


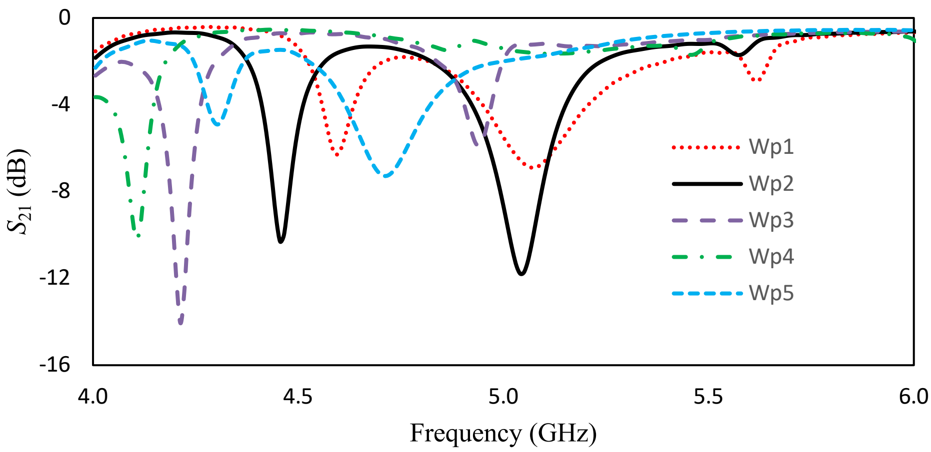
Fig. 4. Dielectric permittivity and loss tangent of pineapple leaf

3.2 Parametric Analysis of Antenna

The results derived from equations Eq. (1) and Eq. (2) are applied in the formulation of the design for the microstrip patch antenna. Subsequently, a parametric sweep analysis is executed incrementally in intervals of 1 mm for width and inset length. This iterative process aims to achieve resonance at 5 GHz and optimize the reflection coefficient parameter for superior performance. The effect length of patch, L_p with different parameter are shown in Figure 5(a). It can be observed that the length dimension of the patch at 5 GHz is L_{p3} = 25.6 mm, yielding a coefficient reflection of -20.12 dB. Meanwhile, the effect width of patch, W_p is shown in Figure 5(b). It can be discussed that the acceptable width dimension of the patch at frequency of 5.02 GHz is W_{p2} =28.5 mm.



(a)

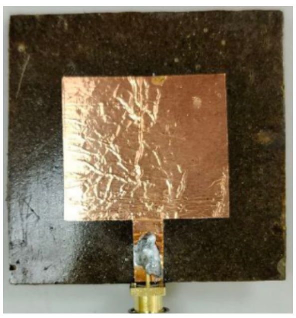


(b)

Fig. 5. (a) L_p parametric analysis between L_{p1} = 23.6 mm, L_{p2} = 24.6 mm, L_{p3} = 25.6 mm, L_{p4} = 26.6 mm, L_{p5} = 27.6 mm (b) W_p parametric analysis between W_{p1} = 27.5 mm, W_{p2} = 28.5 mm, W_{p3} = 30.5 mm, W_{p4} = 31.5 mm, W_{p5} = 29.5 mm

3.3 Antenna Performance

Figure 6 shows microstrip patch antenna fabricated by using pineapple leaf substrate. The size and thickness are followed the CST design simulation based on Table 1. The composition of the layers remains consistent with the simulation setup. The size of patch antenna is 29.5 mm × 25.6 mm.


(a)

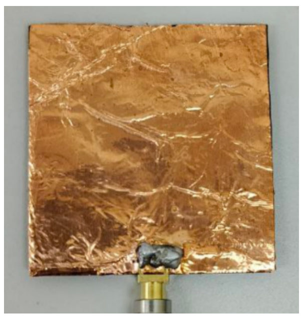

(b)

Fig. 6. (a) Top view and (b) bottom view of fabricated microstrip patch antenna

Figure 7 shows the comparison between simulation and measurement of return loss for the microstrip patch antenna using fabricated pineapple leaf substrate. The bandwidth can be calculated by reflecting the reflection coefficient curve onto the -10 dB line, as shown in Figure 7. It can be observed that the return loss of simulation bandwidth range at 5 GHz is -21.524 dB, meanwhile the measured return loss is -32.76 dB. Observably, the reflection coefficient values obtained from both the simulation and measurement are deemed acceptable. It is attributed to potential factors such as errors introduced during fabrication and imperfections in the substrate's dielectric constant. The accurately determined reflection coefficient parameter signifies the suitability of the simulated antenna for radiation, further highlighting its capacity to efficiently convert more than 90% of the input power into antenna radiation.

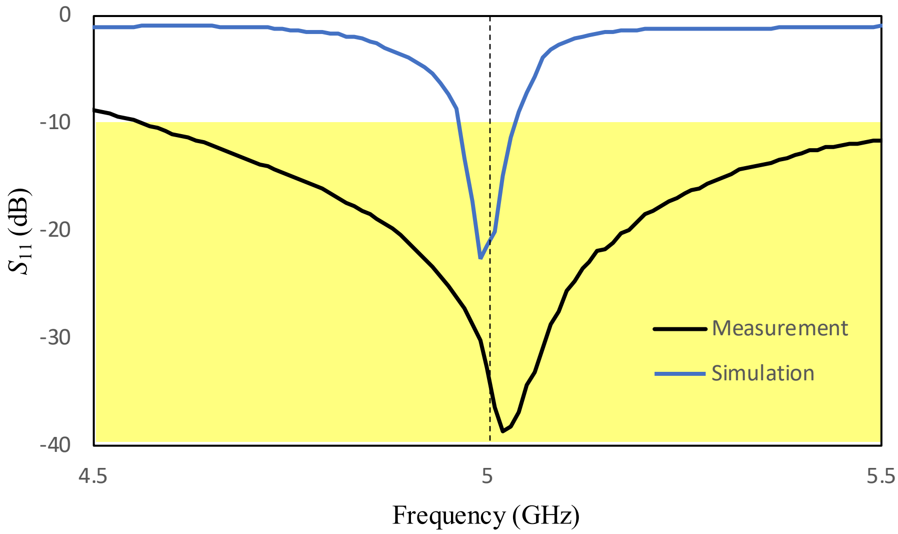


Fig. 7. Comparison of the S_{11} parameter for simulation and measurement of microstrip patch antenna

The voltage standing wave ratio (VSWR) is a crucial characteristic for communication devices. It indicates how well the antenna is matched to the SMA port without reflection. Figure 8 depicts the relationship between the simulated VSWR and frequency. The VSWR is 1.18 at 5 GHz of frequency, which falls comfortably below the threshold of 2. This indicates a well-matched transmission signal with a low attenuation.

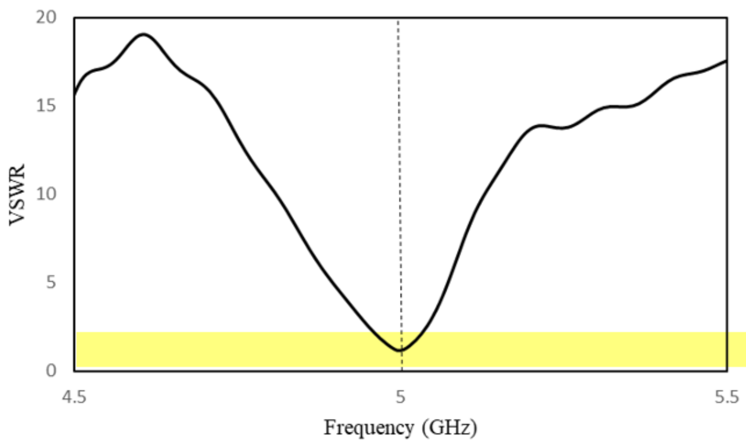


Fig. 8. VSWR parameter of microstrip patch antenna

The simulated 3D pattern of microstrip patch antenna is plotted in Figure 9. The result shows maximum radiation values were in red colour and the minimum radiation value were in blue colour. The value of directivity is 7.468 dB at 5 GHz according to isotropic antenna with 6.315 dB of gain.

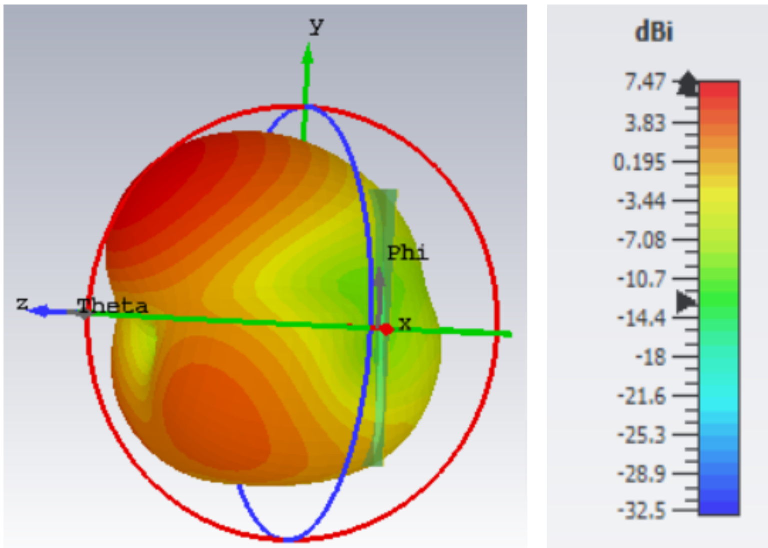
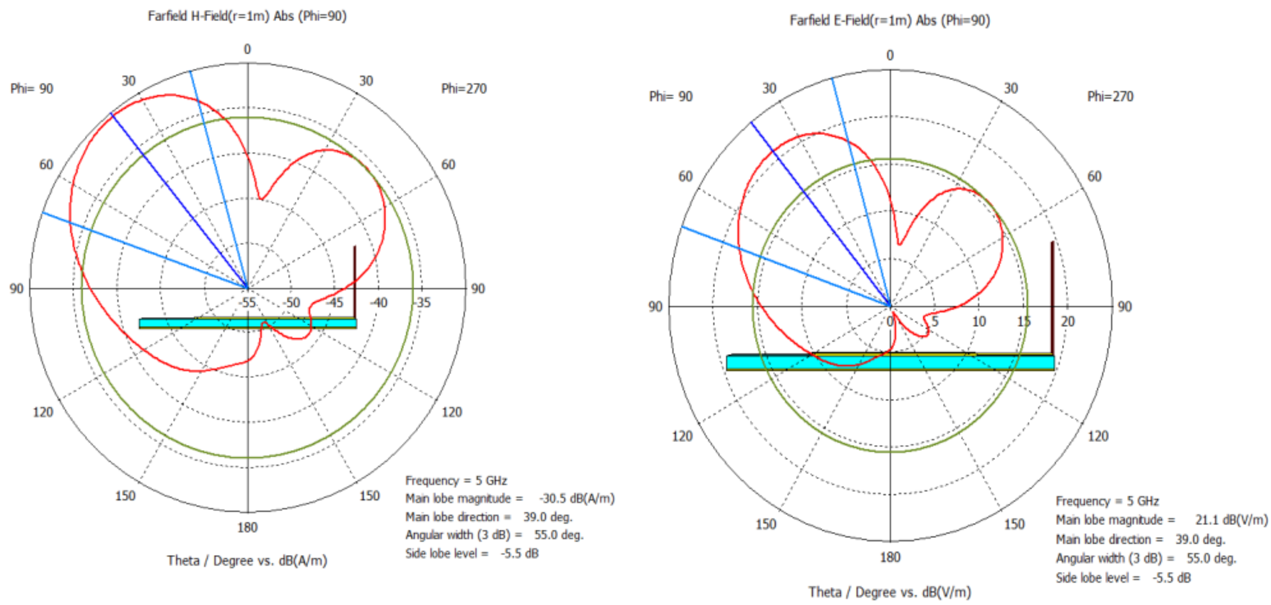


Fig. 9. 3D radiation pattern of microstrip patch antenna at 5 GHz

Figure 10(a) and Figure 10(b) show simulated of far field radiation patterns in H-plane and E-plane at 5 GHz of frequency. Both the co-polarization and cross-polarization for Ludwig are determined in the H-plane and E-plane. The simulated radiation pattern, often referred to as the far-field pattern. It is used to identify the region farthest from the antenna, regardless of the actual distance. The pattern is influenced by directing the majority of the generated power towards the direction. It characterizes the distribution of field and power without being affected by the distance.



(a) (b)

Fig. 10. Radiation pattern of (a) H-plane (b) E-plane at 5 GHz

Table 2 compares the performance of several antennas using different materials. At the same operating frequency of 5 GHz, both substrates produce nearly comparable return loss. This comparison demonstrates the feasibility of pineapple leaf as a substrate. It can be concluded that pineapple leaf substrate can be utilized as antenna substrate with some improvement and able to be a good alternative material for the existing substrate.

Table 2
Comparison of microstrip patch antenna using different substrate

Substrate	Frequency (GHz)	Permittivity	S_{11} (dB)	Gain
FR4 Epoxy [30]	5.00	3.38	-11.70	Not available
FR4 [31]	5.19	4.4	-29.28	5.62 dB
Roger RT/duroid 5880 [32]	5.80	2.2	-38.00	7.48 dB
FR4 Glass Epoxy [33]	6.00	4.3	-31.32	5.70 dB
RT duroid 5880 [33]	6.00	2.2	-21.97	3.74 dB
FR4 [34]	60.0	4.3	-15.00	7.05 dB
Rogers RO4350B [34]	60.0	3.66	-27.20	8.22 dB
RT/duroid 5880 [35]	35.0	2.2	-49.00	7.39 dB
Pineapple leaf (This study)	5.00	5.03	-32.76	6.31 dB

4. Conclusions

In this paper, the performance of microstrip antenna using pineapple leaf substrate is investigated at 5 GHz. The microstrip antenna using fabricated substrate is designed at 5 GHz, which is suitable for communication application. It is essential to achieve an acceptable compromise between simulation and measurement. The result shows that the fabricated antenna from pineapple leaf substrates can produce an excellent return loss performance. It can be concluded that the antenna from pineapple leaf substrate can be utilized to replace the antenna from conventional substrate. In addition, the dielectric properties of developed materials can be further explored by measuring at higher frequency such as at X-band frequency and the materials could be used for next generation applications. The pattern from the measured data showed that it has no drastic changes of dielectric properties which suitable for communication applications.

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