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Serial Rectifier Antenna (Rectenna) Circular Microstrip Patch 2.4 GHz for RF Energy Harvesting

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ABSTRACT

The rapid development of Radio Frequency (RF) usage at this time causes the abundance and waste of radio frequency (RF) electromagnetic wave energy sources in the air. This RF energy source can be used as an environmentally friendly alternative by harvesting energy using the rectenna system .

The rectifier antenna (rectenna) system is designed using the serial rectenna system , this system is used to improve the performance of the rectenna in converting electromagnetic waves into a direct voltage (DC) source. To design a serial rectenna system, use 3 antennas and 3 series of rectifiers . The antenna used in the serial rectenna system is a 2.4 GHz circular microstrip patch antenna for WiFi signal reception. Meanwhile, the rectifier circuit uses a 6-stage voltage doubler using a Schottky 2860 diode and a 1nF smd capacitor.

From testing and measuring the *serial rectenna* system , the circular patch microstrip antenna is able to capture and rectify the voltage to DC. Antenna system has return loss values of -26.29 dB, -21.75 dB, and -28.57dB, VSWR 1.11, 1.16, and 1.07, impedances 51.1, 55.56, and 50.22, bandwidth 60 MHz, 60 MHz and 50MHz with resonant frequency 2.42 GHz, 2.36 GHz and 2.48 GHz. So that the voltage generated by a single *rectenna* system is 51.3 mV at a distance of 25 cm. Meanwhile, the *rectenna* serial system can convert direct voltage of 151.3 mV at a distance of 25 cm from the source of the *Access Point* transmitter.

INTRODUCTION

The increasing demand for wireless power transfer and energy harvesting technologies has spurred significant research into efficient and compact Radio Frequency energy harvesting systems. Traditional power sources like batteries have limitations in terms of lifespan, maintenance, and environmental impact. RF energy harvesting offers a promising alternative by scavenging ambient RF signals and converting them into usable electrical energy (Pan et al., 2017); (Moser, 2009). This approach is particularly attractive for low-power applications such as wireless sensor networks, wearable devices, and remote monitoring systems.

RF Energy Harvesting

RF energy harvesting involves capturing electromagnetic energy from various sources, including dedicated transmitters, ambient radio waves (e.g., Wi-Fi, cellular signals), and broadcast transmissions (Aisah et al., 2021). The key component in an RF energy harvesting system is the rectenna, which integrates an antenna for capturing RF signals and a rectifier circuit for converting the RF energy into DC power (Elsheakh, 2017). The efficiency of the rectenna is crucial for the overall performance of the energy harvesting system (Zhang et al., 2019).

Microstrip Patch Antennas in RF Energy Harvesting

Microstrip patch antennas are widely used in rectenna designs due to their low profile, lightweight, and ease of integration (Elsheakh, 2017). Circular patch antennas offer additional advantages such as simple structure and ease of impedance matching. At 2.4 GHz, the frequency band commonly used for Wi-Fi, Bluetooth, and other wireless communication, microstrip patch antennas can be designed to efficiently capture RF energy (Assogba et al., 2021). The design of the microstrip patch antenna, including the feeding technique and substrate material, significantly affects its performance (Islam et al., 2010).

Serial Rectenna Configuration

To enhance the voltage output and overall efficiency of the RF energy harvesting system, serial rectenna configurations are often employed. By connecting multiple rectenna elements in series, the DC voltage can be

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increased, making it suitable for powering various electronic devices (Kim et al., 2020). The design and optimization of the rectifier circuit are critical for maximizing the RF-to-DC conversion efficiency (Kundu et al., 2017).

Research Motivation and Objectives

This research focuses on the design and implementation of a serial rectenna using a microstrip circular patch antenna operating at 2.4 GHz for RF energy harvesting. The objective of this study is to develop an efficient and compact rectenna system capable of scavenging ambient RF energy and providing a stable DC power output. The specific objectives include:

- Designing a 2.4 GHz microstrip circular patch antenna with optimal gain and impedance matching.
- Developing a high-efficiency rectifier circuit for converting the RF signal to DC power.
- Integrating the antenna and rectifier circuit into a serial rectenna configuration.
- Evaluating the performance of the developed rectenna system in terms of RF-to-DC conversion efficiency and output voltage.

By achieving these objectives, this research aims to contribute to the advancement of RF energy harvesting technologies and enable the development of self-powered wireless devices.

LITERATURE REVIEW

RF Energy Harvesting: An Overview

RF energy harvesting is a rapidly growing field that focuses on capturing and converting ambient radio frequency energy into usable electrical power (Ibrahim et al., 2020). This technology offers a sustainable and maintenance-free power source for low-power electronic devices, reducing reliance on batteries and wired power connections (Pan et al., 2017). RF energy is available from various sources, including dedicated transmitters, mobile base stations, Wi-Fi routers, and broadcast signals (Aisah et al., 2021). The density of ambient RF energy varies depending on location and frequency, necessitating efficient energy harvesting techniques to capture and convert this energy effectively.

Rectenna Technology

The core component of an RF energy harvesting system is the rectenna, which combines an antenna and a rectifier circuit. The antenna captures the RF signal, and the rectifier converts it into DC power (Elsheakh, 2017). The design of both the antenna and the rectifier significantly impacts the overall efficiency of the rectenna system. The limited sensitivity of rectifiers is a key challenge, typically around -35 dBm to -25 dBm, which is much higher than the sensitivity of communication circuits (Alevizos et al., 2018).

Microstrip Patch Antennas for RF Energy Harvesting

Microstrip patch antennas are popular choices for rectenna designs due to their low profile, light weight, ease of fabrication, and compatibility with planar circuit boards (Elsheakh, 2017). Various shapes of patch antennas are used, including rectangular, square, and circular (Aisah et al., 2021). Circular microstrip patch antennas offer advantages such as simple structure, ease of impedance matching, and good radiation characteristics. The performance of a microstrip patch antenna depends on several factors, including the substrate material, patch dimensions, and feeding technique.

2.4 GHz RF Energy Harvesting

The 2.4 GHz frequency band is widely used for RF energy harvesting due to the prevalence of Wi-Fi, Bluetooth, and other ISM band devices. Several studies have investigated rectennas operating at 2.4 GHz for various applications. Microstrip antennas are often employed at this frequency to efficiently capture RF energy (Assogba et al., 2021).

Rectifier Circuit Design

The rectifier circuit is a critical component of the rectenna, responsible for converting the AC signal received by the antenna into DC power. Schottky diodes are commonly used in rectifier circuits due to their low turn-on voltage and fast switching speed (Diagarajan et al., 2018). Impedance matching between the antenna and the rectifier circuit is essential to maximize the power transfer. Various impedance matching techniques, such as L-section matching networks, are used to optimize the power transfer efficiency (Zhang et al., 2019).

Serial Rectenna Configurations

To increase the output voltage and overall efficiency of the RF energy harvesting system, multiple rectenna elements can be connected in series (Kim et al., 2020). This configuration allows for a higher DC voltage output

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compared to a single rectenna element. The design and optimization of serial rectenna configurations require careful consideration of the impedance matching and rectifier circuit parameters.

Challenges and Future Directions

Despite the advancements in RF energy harvesting, several challenges remain (Alevizos et al., 2018). These include improving the efficiency of rectennas, increasing the harvested power levels, and reducing the size and cost of the systems. Future research directions include exploring new antenna designs, advanced rectifier circuits, and efficient power management techniques (Ibrahim et al., 2020).

By addressing these challenges, RF energy harvesting technology can be further developed and deployed in a wide range of applications, contributing to a more sustainable and energy-efficient future.

METHOD

Design And Manufacture Of The Rectenna Series

This chapter explains how to design and manufacture a rectenna (antenna rectifier) that utilizes a 2.4 GHz frequency signal (access point frequency), starting from the design of the block diagram, namely the RF transmitter, receiving antenna, and rectifier. All parts in the block diagram have important roles in this final assignment. The design of the rectenna is carried out by simulation using software, which will then be fabricated to determine the output voltage that has been converted by the rectifier.

Design and Manufacturing Flow of Serial Rectenna

The flow of designing and manufacturing the rectenna in this final project has been shown in Figure 3.1. The initial step taken is to conduct a literature study on the Final Project. After that, determine the antenna specifications such as working frequency, type of substrate, and choose the dimensions of the patch and groundplane. Then the antenna is simulated using Ansoft HFSS 13.0 software. Furthermore, the rectifier is designed using the voltage doubler n-stage method, which requires several electronic components such as active components (diodes) and passive components (capacitors). The selection of these electronic components is based on the working frequency of the rectenna. The antenna and rectifier that have been fabricated are serialized to increase the DC output that has been converted by the rectifier and measured using an AVOmeter.

Antenna Design with Calculations

The first thing to do before designing an antenna is to determine the specifications of the antenna to be designed, such as working frequency, Return Loss, VSWR, and impedance. It can be seen as follows:

1. Working frequency: 2.35-2.45 GHz
2. Center Frequency: 2.4 GHz
3. Return Loss: <-10 dB
4. VSWR: $1 \leq VSWR \leq 2$
5. Impedance: 50 Ω

After that, the determination of the substrate material to be used is a PCB made of epoxy double layer fiber - FR4 which has a dielectric constant (ϵr) of 4.7 and a substrate thickness (h) of 1.6 mm. To start designing the antenna, it begins by calculating the antenna theoretically so that it can be simulated using HFSS 13.0 software. The following are the calculations carried out to determine the dimensions of the antenna.

Determine the radius of the radiating element of a microstrip antenna using equation 2.11.

$\alpha = \quad 2h \quad \pi F$ 1/2

$\{1 + \pi \varepsilon r F \; [ln \; 2h + 1{,}7726]\}$

First, the logarithmic function F is calculated.
With fr = 2400 MHz; (ϵr) = 4.7, then the value of the logarithmic function F can be calculated using equation 2.12.
8.791 × 109
$F = \quad fr\sqrt{\epsilon r}$

Where h is the thickness of the substrate and a is the radius of the antenna patch. and the dimensions of the antenna groundplane are 42.44 mm x 42.44 mm. So the dimensions of the antenna can be shown in table 1.

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Table 1. Antenna dimensions from calculations

NO	Dimensions	Dimensions	Dimensions
1	α	16.42	Antenna radius
2	Yo	9.852	Feed inset slot length
3	Wo	2.99	Transmission line width
4	Lo	14.41	Transmission line length
5	L	42.44	Groundplane length
6	W	42.44	Groundplane width

From table 1, we can see the results of the antenna design that has been calculated theoretically in figure 1.

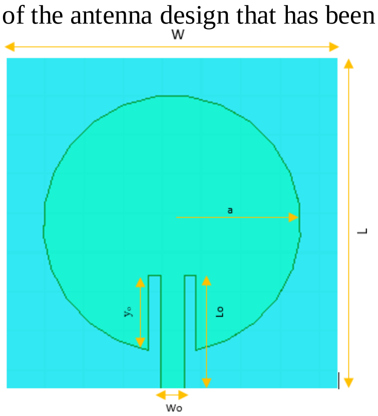

Figure 1. Antenna design results from calculations

Antenna Design with software

After calculating the antenna dimensions, the next step is to design it using software to obtain antenna parameters that meet the needs. The design of a circular microstrip patch antenna with HFSS software is carried out through several stages, starting with patch design, feeder channel design, substrate design, ground plane design, and feeder channel design. The steps to create this antenna model are.

1. Make sure the HFSS software is installed on the PC. After that, run the software and create a new project by:
   a. Click the file, then select New.
   b. After that, clickProjectt and select Insert HFSS Design
   For more details.
2. Next, create a substrate, which can be done by:
   a. Select the draw item, then click the draw box.
   b. Then click the attribute tab in the properties column then change the name to substrate and the material to FR4 Epoxy.
   c. After that, change the dimensions of the substrate by clicking createbox, and a column will appear.
3. Next, design the patch, which can be done by:
   a. Select the draw menu item, then select cylinder
   b. Click the attribute tab, then change the name to patch
   c. Click the material, and change it to copper
   d. Enter the coordinate values (direction and magnitude). In this case, you must be careful in entering these coordinate values, by changing the patch dimensions with position (8; 12; 1.6) and radius, height size (16.9; 0.035).
4. Next, designing the inset feed supply channel can be done by:
   a. Select the draw item, then select the box
   b. Click the attribute ta,b, then change the name to inset feed
   c. Change the material to copper
   d. Click create box and enter the coordinate values (direction and magnitude) with position (25; 17; 1,6), and X, Y, Z (10.5; 5.98; 0.035)
   e. Next, combine the patch with the inset feed channel by holding down the ctrl key and clicking the patch and inset feed sections then click unite on the toolbar.
5. Next, designing the subtraction on the patch can be done by:
   a. Select the draw item, then select the box
   b. Click the attribute tab and change the name to subtract
   c. Then change the material to Copper

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d. Click createbox and enter the coordinate values (direction and magnitude) with position (25; 18.6; 1,6), and X, Y, Z (15; 3; 0.035)
e. Then combine the patch with the subtract using the unite feature.

6. Next, design the ground plane
   a. Select the draw item, then select the box
   b. Click the attribute tab and change the name to ground
   c. Change the material to copper
   d. Click createbox and enter the coordinate values (direction and magnitude) with position (0;0;0), and X, Y, Z (40;40;-0.035)
7. Next, design the supply channel port, which can be done by:
   a. Select the draw item then select rectangle
   b. Change the axis to the Z axis
   c. Click the attribute tab and change the name to port
   d. Enter the coordinate values (direction and magnitude) with position (40; 18.5; 0), and Y, Z (3; 1.6)
8. Next, design the boundary, which can be done by:
   a. Select the draw item, then select the box
   b. Click the attribute tab and change the name to boundary
   c. Change the material to water (air)
   d. Enter the coordinate values (direction and magnitude) with position (-5;-5;- 5), and X, Y, Z (50;50;10)
   e. Then select the color according to your wishes, and then adjust the color transparency

After all the steps above are done, a circular microstrip patch antenna will be produced as in Figure 2.

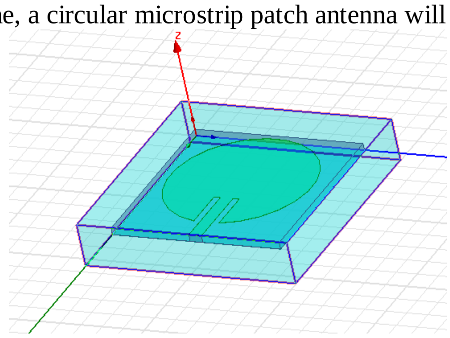

Figure 2. Antenna design in HFSS software simulation

The next step is to run the simulation. The steps are as follows.

1) Click the HFSS menu, then select analysis setup
2) Then select Add Solution Setup, then the solution setup window will appear. Then fill in the setup name, then the solution setup window will appear. Then fill in the setup name, just follow what is in the tab (eg, setup1, setup2, etc.)
3) Then enter the value of the solution frequency to 2.4 GHz. The solution frequency value is the same for each setup.
4) Next, fill in the maximum number of phases to 20 or as needed.
5) Then fill in the maximum delta S value of 0.0,2 then select OK.

After adding the analysis setup, set the frequency sweep by:

1) Click the HFSS menu, then click analysis setup, and select add frequency sweep
2) Select the solution setup 1, then click OK.
3) Then edit the sweep windows, set the sweep type to fast, and set the frequency setup type to linear step. Then put the start frequency to 2 GHz, the stop frequency to 3 GHz, and the stop size to 0.01 GHz. Next, check the save fields and click OK.

The next step is to check whether the model that has been created is feasible or can be run. The method is as follows.

1) Clicking the validation check symbol on the toolbar.
2) Next, a validation check window will appear.

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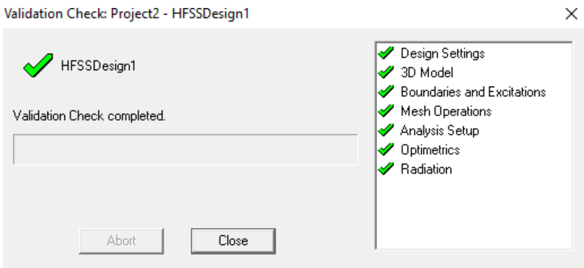

Figure 3. Validation check window

3) If the antenna design is correct, a green check mark will appear as in Figure 3. If it is incorrect or missing steps, it will be highlighted in red or marked with a red cross. This indicates an error in the designed antenna. And the simulation cannot be continued
4) After performing the validation check, the next step is to simulate by pressing the HFSS menu bar and then selecting "Analyze All." And wait for about ± 60 minutes.
5) After the analysis process is complete, antenna parameters such as return loss, VSWR, radiation pattern, and gain can be displayed.
6) If the antenna simulation design is not what is needed, then optimization needs to be carried out several times in order to obtain the antenna parameters as expected. The results of the antenna that has been optimized and gets the best parameters can be seen in Figure 4

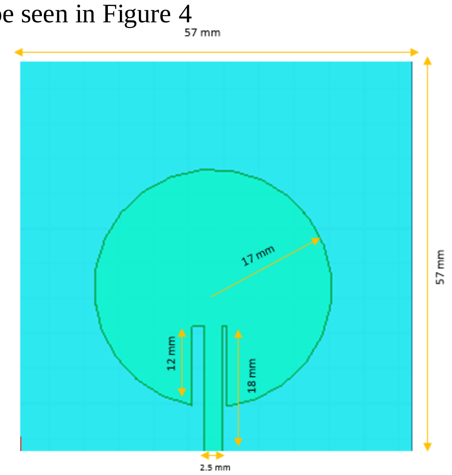

Figure 4. Optimized antenna design results

Antenna Fabrication

To fabricate the antenna, the following steps need to be taken.

1) Prepare the tools and materials used, such as a ruler, pencil, sticker, knife, container, solvent solution (H3, HCL, H2O2), solder, tin, double-layer PCB, and SMA 50Ω female connector.
2) Cut the double-layer PCB according to the final size of the antenna, and then clean the PCB with thinner.
3) Next, attach the printed sticker paper based on the size of the patch and groundplane that have been designed using CorelDRAW.
4) Then dissolve the double-layer PCB with H3, HCL, and H2O2 solutions. The dissolution process can be seen in Figure 5.

Figure 5. Antenna dissolving process

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5) Next, clean the PCB solution with water, and remove the sticker paper that covers the patch and groundplane on the double-layer PCB.
6) After that, connect the SMA female connector to the antenna port by soldering the patch. The port installation
7) After all the antenna manufacturing processes are complete, the next step is to measure the antenna in the antenna laboratory using a network analyzer measuring tool. This measurement aims to determine the parameters of the antenna that has been fabricated, as can be seen in Figure 6.

Figure 6. Antenna Measurement using Network Analyzer

8) The last step is to measure the antenna polarization manually using an RF generator, spectrum analyzer, and Antenna training system (main controller). The process of measuring the polarization can be seen in Figure 19.

Figure 7. Manual measurement of antenna polarization

RF Harvester Design

Are RF harvester consists of a series of rectifier voltage doublers consisting of several stages. The rectifier circuit acts as a rectifier and multiplies the alternating voltage (AC) received by the antenna from the RF transmitter (access point) into direct voltage (DC). Each stage of the rectifier circuit has active and passive electronic components that are designed and simulated in Multisim and Eagle software. To obtain a large output voltage, components are needed that can work on the characteristics of the RF waves to be harvested (wifi frequency) and have the smallest power losses (component power losses) so that they can multiply the small input voltage received by the antenna.

The rectifier circuit was designed several times by troubleshooting several types of rectifier circuits and electronic components. Troubleshooting carried out on the rectifier circuit is as follows.

1) Using a 2-stage Rectifier Circuit

This circuit is designed using a regular rectifier circuit using active components, namely 1N4148DO35-10 schottky diodes and 0.22uF and 100mF ceramic capacitors. This rectifier circuit can be seen in Figure 3.23. suggested to present their articles in the section structure:

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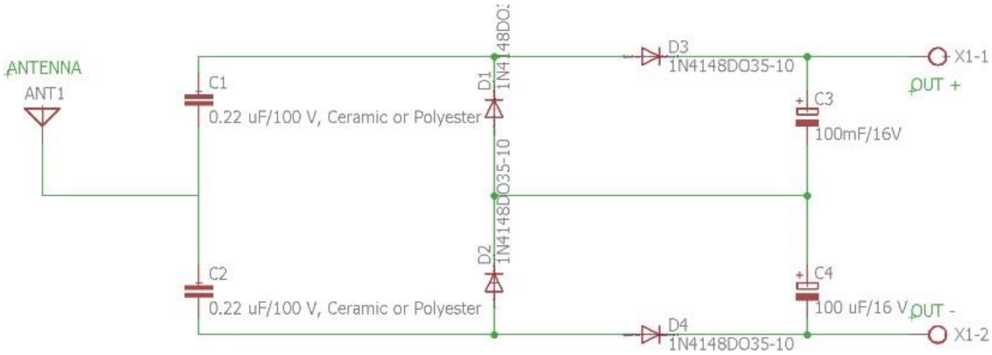

Figure 8. 2 Stage Rectifier Circuit

The highest output voltage produced when using this type of rectifier circuit is 20mV at a distance of 10 cm from the transmitter source. This voltage is not yet optimal because the electronic components used have large power losses and voltage drops, so that they do not match the energy characteristics captured by the receiving antenna (very small).

2) Using a 6-stage voltage doubler rectifier circuit

This circuit is designed using a 6-stage voltage doubler rectifier circuit. By using electronic components of HSMS 2860 Schottky diodes and 1 nF SMD capacitors. This voltage doubler circuit is arranged in series as many as 6 stages.

The circuit in Figure 3.24 produces an output voltage of 51.8 mV at a distance of 25 cm from the transmitter source. The resulting voltage is much better than the voltage designed in the previous rectifier. The components used have been replaced with components that match the characteristics of the energy to be harvested, namely the 2.4 GHz wifi frequency with very small captured power. By using electronic components, namely the HSMS 2860 diode and 1nF SMD capacitor, this rectifier circuit can work optimally and produce a voltage of 51.8 mV.

3) Using a series of 3 rectifier voltage doubler 6 stages

To improve the output performance of a rectenna, it is necessary to design a series rectifier circuit (3 series of 6-stage voltage doubler circuits) using components that are identical to the previous circuit, namely the HSMS 2860 type Schottky diode and 1nF SMD capacitor. RF Harvester circuit form

RF Harvester Fabrication

After troubleshooting the rectifier circuit design, the next step is to fabricate the RF Harvester. The steps are as follows.

1) Prepare the tools and materials needed for RF Harvester fabrication.
2) Cut the single-layer PCB as needed.
3) Create an RF Harvester circuit using Eagle software so that the layout can be arranged
4) Print the rectifier layout onto the PCB, then dissolve and install the components and solder the components used, so that the RF harvester circuit can be tested and used.

RESULT AND DISCUSSION

Antenna Measurement Results

Antenna measurements were conducted to determine and compare the parameters of the antenna obtained from the Ansoft HFSS 13.0 simulation with practical measurements. Antenna measurements were conducted in the G301 Antenna Laboratory by conducting direct measurements to obtain antenna parameters, namely return loss, VSWR, and radiation pattern.

1) Return Loss Measurement

The return loss of the fabricated antenna is measured using a network analyzer measuring instrument in the G301 antenna laboratory. Return loss is the reverse attenuation of the antenna. Return Loss is used to check the loss of transmitted power and to determine the power value received by the antenna. In return loss measurements, a good value is below -10 dB, which means that 90% of the signal can be absorbed and 10% is reflected. The results of the return loss measurement of the fabricated antenna

VSWR measurement is related to the reflection coefficient of an antenna. VSWR is measured using a network analyzer. In general, a good antenna VSWR parameter value is $1 \leq VSWR \leq 2$.

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2) Polarized Radiation Measurement

Polarization measurement is done to see the direction of wave radiation from the designed antenna. Antenna polar radiation measurement is done using a spectrum analyzer and signal generator in the G301 antenna laboratory. The results of the fabricated antenna's polar radiation measurement are unidirectional and bidirectional, meaning that the antenna signal radiation pattern is only focused in one direction.

Antenna Simulation Results Using HFSS 13.0 Software

The antenna to be fabricated was previously designed and simulated using Ansoft HFSS 13.0 software. Simulations were carried out to obtain a physical antenna design with antenna parameters that meet the desired specifications. The parameters viewed during the simulation were return loss, VSWR, and radiation pattern.

1) Return Loss Simulation

To obtain good return loss parameters during simulation, various methods are used. One of them is changing the antenna dimensions, such as patch, groundplane, and feeder channel. In order to obtain a frequency that matches the specifications, several patch size optimizations are carried out by enlarging its size. So that the best return loss is produced during simulation, which is -24.66 dB at a frequency of 2.4 GHz

2) VSWR Simulation

In addition to affecting the return loss value, antenna dimension optimization also affects the VSWR parameter. The VSWR value obtained during simulation has met the criteria for a good antenna, which is 1.01, which works at a frequency of 2.4 GHz.

3) Radiation Pattern Simulation

The antenna parameter determined during the next simulation is the radiation pattern. The results of the optimized simulated antenna radiation pattern form a unidirectional radiation pattern for a frequency of 2.4 GHz.

Antenna Analysis of Measurement Results with Antenna Simulation Results

The results of the antenna that has been simulated with the antenna that has been measured directly show differences. However, the differences that occur are still within the criteria of the desired antenna specifications with a working frequency of 2.35-2.45 GHz. The differences that occur in the antenna parameters of the measurement results with the simulation results will be analyzed to see how far the two results differ.

1. Return Loss Results Analysis

Return Loss is a parameter to determine the amount of power lost (reflected) and the power that can be received by an antenna. The minimum limit value of the return loss value is -10 dB. Comparison graph of return loss Based on Figure 4.7 and the tables in Appendices 1 and 4, there is a significant difference in the measurement results with the simulation. During the measurement, although there was a shift, the fabricated antenna was still within the desired antenna specifications. As in the measurement of antenna 1, a return loss value of -0.637 dB was obtained at a frequency of 2.05 GHz, -1.2979 dB at a frequency of 2.2 GHz, -15.98 GHz at a frequency of 2.41 GHz, -26.29 dB at a frequency of 2.425 GHz, -1.55 dB at a frequency of 2.605 GHz, -0.721 dB at a frequency of 2.8 GHz, and -0.62 dB at a frequency of 3 GHz. Furthermore, in the measurement of antenna 2, the return loss value was obtained as -0.47 dB at a frequency of 2.05 GHz, -1.23 dB at a frequency of 2.2 GHz, -21.75 dB at a frequency of 2.36 GHz, -5.59 dB at a frequency of 2.4 GHz, -0.78 dB at a frequency of 2.605 GHz, -0.60 dB at a frequency of 2.8 GHz and -0.58 dB at a frequency of 3 GHz. Then in the measurement of antenna 3, the return loss value is obtained at -0.63dB at a frequency of 2 GHz, -0.74 dB at a frequency of 2.2 GHz, -4.09 dB at a frequency of 2.41GHz, -28.57 dB at a frequency of 2.485 GHz, -2.18 dB at a frequency of 2.605 GHz, -0.81dB at a frequency of 2.8 GHz, and -0.90 dB at a frequency of 3 GHz. While for the return loss obtained from the simulation results from frequencies of 2 GHz, 2.2 GHz, 2.4 GHz, 2.6 GHz, to 3 GHz, each of which is -1.104 dB, -2.19 dB, -24.69 dB. -2.004 dB, -1.05 dB, and - 0.905 dB. So from the measurement results and simulations, the return loss obtained is below -10 dB, namely -26.29 dB, -21.75 dB, and -28.57 dB at a frequency of 2.42 GHz for antenna 1, 2.36 GHz for antenna 2, and 2.485 GHz for antenna 3. The simulated return loss value is -24.69 dB at a frequency of 2.4 GHz.

Overall, the antenna return loss value from the measurement results with the simulation is very good.

2. Volt Standing Wave Ratio (VSWR)

VSWR is a parameter that determines the matching between the antenna and the transmitter. The antenna impedance should match the receiving antenna; if it is different, it will cause reflected power, which is the power reflected from the receiver and causes interference along with the signal sent by the transmitter. A good VSWR value is 1, but the largest VSWR value is 2. This is because if the VSWR value is 2, the return loss is -10 dB. The VSWR value during measurement is close to the good VSWR value, which is 1.11, 1.16, and 1.07 at a frequency of 2.425 GHz for antenna 1, a frequency of 2.36 GHz for antenna 2, and a frequency of 2.485 GHz for antenna 3. During the simulation, it has a VSWR value of 1.01 at a frequency of 2.4GHz.

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So, from the measurement and simulation results, the VSWR value for the fabricated and simulated antennas is good, already in the range of good VSWR values, namely 1 ≤ VSWR ≤ 2. This means that at antenna frequencies 1, 2, and 3, namely 2.42 GHz, 2.36 GHz, and 2.485 GHz, the reflected power is almost non-existent, and the channel is in a state of almost perfect matching. Similar to the fabrication results, the simulated antenna at a frequency of 2.4 GHz has almost no reflected power (the VSWR value is close to 1).

3. **Impedance**

Impedance is a comparison of the power in the antenna supply line section, where the impedance of an antenna must match the impedance of its supply line. Based on the results of simulations and measurements, the impedance of the measurement and simulation results is almost close to the impedance condition of an antenna said to be matched with an impedance value of 50 Ω. In the measurement, the impedance of antenna 1 at a frequency of 2.42 GHz was obtained at 48.15 Ω, the impedance of antenna 2 at a frequency of 2.36 GHz was obtained at 55.56 Ω, and the impedance of antenna 3 at a frequency of 2.48 GHz was obtained at 50.22 Ω. For the simulation results, the impedance was obtained at 55.93 Ω at a frequency of 2.4 GHz, So that the impedance values obtained in the simulation and measurement of antennas 1, 2, and 3 are close to the value of the matched impedance condition, which is 50 Ω. Based on the theory, the antenna/load impedance value (ZL) can be calculated based on the equation.

Simulation Frequency 2.4 GHz ZL simulation = Zo x VSWR
= 50.21 x 1.01
= 50.31 Ω

Measurement frequency

- ZL measurement 2.425 GHz = Zo x VSWR
  = 51.142 x 1.11 = 58.45 Ω

- ZL measurement 2.365 GHz = Zo x VSWR
  = 55.175 x 1.167 = 64.38 Ω

- ZL measurement 2.485 GHz = Zo x VSWR
  = 50.64 x 1.07 = 54.1848 Ω

4. **Radiation Polarization**

Based on the measurement data and antenna radiation polarization simulation results in Figures 4.3 and 4.6, the measurement polarization form of antennas 1 and 2, namely at frequencies of 2.42 GHz and 2.36 GHz, is unidirectional, almost approaching the simulated polarization form of the antenna at a frequency of 2.4 GHz using Ansoft HFSS 13.0, while antenna 3 at a frequency of 2.48 GHz is bidirectional.

The difference in the shape of the antenna radiation polarization results from the measurement and simulation is due to the manual measurement process of the polarization in the antenna laboratory which is not empty, meaning that there is the influence of other signals in the room that cause the antenna performance to not be optimal at its working frequency. In addition, the transmitter source used to measure the antenna radiation polarization has a value of 2.5 GHz, causing the power received by antennas 1, 2, and 3 at frequencies of 2.42 GHz, 2.36 GHz, and 2.48 GHz not to be captured optimally at their respective working frequencies. This was done because of the limitations of the transmitter antenna in the antenna laboratory, so that an antenna with a frequency close to the working frequency used was made, namely 2.5 GHz. All data on the results of the radiation polarization can be seen in Appendices 4 and 8.

5. **Bandwidth**

Bandwidth is the frequency range at which an antenna can work optimally. From the measurement and simulation results, the measured bandwidth shows a significant difference. The antenna bandwidth from the measurement results to the simulation results can be calculated theoretically using the formula explained in the previous chapter, namely as follows.

- Antenna 1

BW = Fupper - FLower
= (2.45 - 2.39) GHz
= 60 MHz

- Antenna 2

BW = Fupper - FLower
= (2.39 - 2.33) GHz
= 60 MHz

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- Antenna 3

BW = Fupper - FLower
= (2.51 - 2.46) GHz
= 50 MHz

- Antenna simulation

BW = Fupper - FLower
= (2.444 – 2.353) GHz
= 91 MHz

From the calculation results of the antenna bandwidth that has been fabricated, the bandwidth for antennas 1 and 2 is 60 MHz, and for antenna 3, it has a bandwidth of 50MHz. While the simulation results have a bandwidth of 91 MHz. This means that there is a difference in the amount of bandwidth during measurement and simulation. The bandwidth of the simulation results is much larger than the measurement antenna. This occurs due to several factors such as human error, namely lack of accuracy when installing stickers to the PCB, the quality of connector soldering, and so on.

The results of the antenna that has been designed in this final assignment will be compared in terms of parameters and current flow distribution with the antenna that is usually used for the receiving antenna on the rectenna.

Rectenna Work Measurement

The main purpose of this measurement is to find out the results of the fabricated rectenna. This final project uses the concept of a serial rectenna to improve the performance of the DC output produced by the rectenna. In this rectenna work measurement, the author compares the output produced by a single rectenna with the output of a serial rectenna. Serial rectennas have characteristics, namely antennas and rectifier circuits, that are identical to each other.

Single rectenna measurement

This measurement is carried out to see the output voltage that has been successfully converted by the single rectenna system or the work produced from the combination of the antenna with the rectifier before being serialized. The rectifier used in this rectenna has 6 stages. Measurement of the work of a single rectenna by utilizing a WiFi transmitter source or Huawei ONT, which has a transmit power of +2 dBm and a frequency of 2.4 GHz. The output voltage of a single rectenna is measured using an AVO meter based on the distance range from the transmit source, namely 25cm, 50cm, 75cm, and 100cm.

CONCLUSION

In this final project, the design and testing of a serial rectifier microstrip patch circular antenna at a frequency of 2.4 GHz for RF energy harvesting has been carried out, so it can be concluded that:

1. The microstrip patch circular antenna has been designed at a frequency of 2.4 GHz with a patch radius of 17 mm and a ground size of 57x57mm.
2. The rectifier designed uses a 6-stage voltage doubler model with a voltage obtained of 50.1 mV in a single system at a distance of 25 cm and 151.8 mV for a serial rectenna at a distance of 25 cm from the transmitter source.
3. The measurement process of the fabricated antenna using a network analyzer, RF generator and spectrum analyzer with the measurement results of the circular patch antenna working at a frequency of 2.42 GHz, 2.36 GHz, and 2.48 GHz has a return loss value of -26.29 dB, -21.75 dB and -28.57 dB, VSWR values 1.11, 1.16 and 1.07, bandwidth 60 MHz, 60 MHz and 50 MHz, and unidirectional radiation patterns.
4. The rectenna that has been tested using a circular patch microstrip antenna and a 6-stage voltage doubler rectifier circuit works maximally on a serial rectenna system that produces an output voltage of 151.8 mV at a distance of 25 cm measured with an AVO meter.

Suggestion

To get better rectenna performance, in the future, it is necessary to pay attention to things like:

1. In the future, an integrated rectenna design is needed using a matching network in one substrate to reduce losses in the connector in order to obtain more optimal and more efficient output voltage results.
2. Selection of the best type of substrate is needed to ensure the dielectric constant used during the design and transfer of the antenna design that is carried out should be carried out with great care in order to obtain measurement results that are by the simulation.

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