

A 2x4 Element Rectangular H-Slot Array Microstrip Antenna Rectifier for Harvesting Electromagnetic Energy at 2.4 GHz Frequency

Hendro Darmono¹, Koesmarijanto², Nugroho Suharto³, Yani Ratnawati⁴, Agung Dwi Cahyono⁵

^{1,5} Digital Telecommunication Network Study Program, Department of Electronics Engineering, State Polytechnic of Malang, 65141, Indonesia

^{2,3,4} Telecommunication Engineering Study Program, Department of Electrical Engineering, State Polytechnic of Malang, 65141, Indonesia

¹hendro.darmono@polinema.ac.id, ²koesmarijanto@polinema.ac.id, ³nugroho.suharto@polinema.ac.id, ⁴yani.ratnawati@polinema.ac.id, ⁵agdwi.cahyono@gmail.com

Abstract—This research aims to develop an energy capture system, specifically an antenna rectifier. The chosen antenna for this purpose is a microstrip antenna operating at a frequency of 2.4 GHz, utilizing a 2x4 array configuration to enhance the collection of electromagnetic waves emitted by an Access Point. To enhance the rectifier's voltage-doubling capability, the design incorporates three distinct levels: level 8, level 12, and level 14. Experimental results from implementing the 2x4 rectangular H-Slot array microstrip antenna rectifier demonstrate its capacity to convert incoming AC waves from the antenna into DC voltage. During the implementation phase, the rectenna harvesting system exhibits notable outcomes. The most significant outcome is observed in the 14th-level rectifier circuit, yielding a conversion of 101.98 mV when positioned 50 cm away from the wireless source or access point. This voltage reading diminishes to 49.148 mV at 200 cm. In the 12th-level rectifier circuit, the values are 64.8 mV at 50 cm and 39.08 mV at 200 cm. Furthermore, the 8th level circuit generates 24.72 mV at 50 cm and 11.4 mV at 200 cm. Evidently, the proximity of the testing distance correlates with the magnitude of the produced voltage.

Keywords—Microstrip, Rectenna, Microstrip, Voltage Doubler

I. INTRODUCTION

Currently, technology is rapidly advancing, particularly within the realm of electronics, which is undergoing significant transformations. This holds true for both the components employed and the software integrated into these electronic devices. At present, most electronic devices utilize Direct Current (DC) voltage as their input power source due to its adaptability across a diverse range of electronic applications. Although batteries serve as an optimal source of DC voltage, not all electronic devices can rely on them as a power source due to the finite lifespan of batteries. To counteract the limitations associated with battery energy, researchers are actively developing a variety of energy harvesting devices. Energy harvesting involves the extraction of energy from external sources such as sunlight, heat, radio frequency (RF) waves, and other electromagnetic emissions that transmit signals.

One notable device used for harnessing these electromagnetic emissions is a rectifier integrated with an antenna, also known as an antenna rectifier (Rectenna). A Rectenna combines the functions of an antenna, responsible for receiving electromagnetic waves from the surrounding environment, and a rectifier, which converts the received electromagnetic waves into Direct Current (DC) voltage. This mechanism allows the Rectenna to operate without requiring an independent power supply. Subsequently, the rectified output is connected to a DC measuring device to facilitate voltage analysis.

This research aims to design and analyze an energy harvesting system using a rectangular H-slot microstrip rectenna. The proposed antenna design is intended to function within the 2.4 GHz frequency range, coinciding with the WLAN frequency band. Employing the 2x4 array methodology on the patch is anticipated to yield amplified gain. Enhanced gain significantly influences the antenna's efficiency in both signal reception and transmission. Meanwhile, the rectifier intended for this study is classified as a voltage doubler rectifier featuring 8, 12, and 14 levels, with the objective of doubling higher voltages and conducting in-depth analysis of the outcomes at each level. The rectifier employs a specialized diode, specifically the Schottky BAT 17 diode, capable of handling frequencies spanning from 3 MHz to 3000 MHz and is accompanied by a 1nF capacitor. In a prior study,[1] conducted a study involving the design of a 6-stage Microstrip Patch Rectifier Antenna to generate a maximum voltage output of 24.8mV at 10 meters. At 100 meters, the achieved voltage value was 14.9mV. Then, [2] subsequently carried out research by employing a 1x2 Rectangular array microstrip patch antenna configuration integrated with a 3-level voltage doubler rectifier. However, the obtained DC voltage outcomes from this study remained relatively low, necessitating further advancements to achieve heightened voltage levels. Further exploration by [3] entailed the creation of a rectenna utilizing a conventional antenna, as opposed to a microstrip antenna, for signal reception. Test results employing a function generator revealed an attainable rectenna voltage output of 1.19V. Subsequent

investigations, undertaken by [4], revolved around the development of a rectenna featuring a microstrip patch array antenna optimized for operation at a frequency of 1800 MHz.

The significance of this study lies in the design of a Rectangular H-Slot Array 2x4 Element antenna, positioned as an electromagnetic energy harvester operating at a frequency of 2.4 GHz. What distinguishes this contribution as a valuable reference for rectenna design is the incorporation of a unique feature. Unlike previous research, the design incorporates a 3-level voltage doubler experiment, featuring 8, 12, and 14 stages, respectively. This innovative approach significantly multiplies the voltage levels, ultimately leading to superior output performance. This not only contributes to the field of RF Energy Harvesting but also enriches the existing body of knowledge, especially in terms of voltage magnitude, making this research particularly notable.

II. METHODOLOGY

This type of research is manufacturing research, this research will examine antennas that will be combined with rectifiers as electromagnetic energy harvesters. The block diagram that will be used as an electromagnetic energy harvester is shown in Figure 1. The research work can be summarized as follows:

Step 1: Block Diagram System

The first step involves describing the block diagram of the rectenna system and outlining the parameters that need to undergo testing.

Step 2: Antenna Design

This step entails designing the antenna using CST Studio Suite 2018 software.

Step 3: Antenna Parameter Calculation

This phase involves calculating antenna parameters using established formulas.

Step 4: Antenna Simulation and Design Optimization

Antenna designs are then simulated based on the calculated parameters. In cases where simulation results deviate from expected parameters, design optimization is conducted to align with calculations.

Step 5: Rectifier Circuit Design

Once desired parameters are achieved, the next step involves designing a rectifier circuit for rectification and voltage gain. This design phase utilizes NI Multisim 14.2 software.

Step 6: PCB Layout

Subsequently, the PCB layout is created to match the rectifier circuit design.

Step 7: Fabrication Process

Fabrication becomes the subsequent imperative, encompassing the physical realization of both the antenna and rectifier.

Step 8: Measurement and Analysis

Following fabrication, measurements are taken of both the antenna and rectifier. The acquired data is meticulously analyzed and conclusions are drawn

A. Block Diagram System

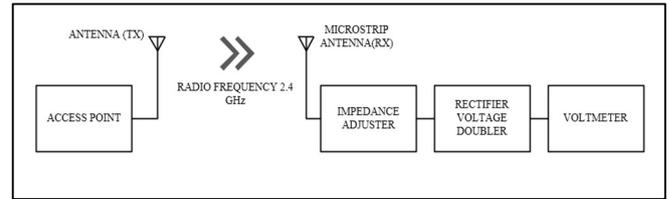


Figure 1. Rectenna block diagram

Figure 1 depicts a general overview of the rectenna that will be created. Access Point emits electromagnetic waves with a frequency of 2.4 GHz [5]-[7]. The wave is received by a 2x4 element rectangular h-slot array microstrip antenna then forwarded to the voltage doubler rectifier [8]. In the voltage doubler rectifier circuit, there is an impedance adjuster circuit which aims to match the antenna impedance with the rectifier impedance so that it is maximal in transferring power to the rectifier which will later convert the electromagnetic waves received by the antenna into a DC voltage [9] – [11]. The energy that has been generated and converted will be measured to determine the amount of DC voltage generated by the energy harvesting system. The expected design of this research is to produce a rectenna that can harvest electromagnetic energy from the Access Point beam and then convert it into a DC voltage.

The parameters that will be analysed in testing the rectenna that has been made are Gain, Return Loss, VSWR, Radiation Pattern. Meanwhile, the test variable that will be measured in the test is the DC voltage output at the rectenna measuring point.

B. Antenna Design

This step involves the creation of a 2x4 array rectangular h-slot microstrip antenna. This encompasses a series of tasks, which include establishing material specifications, computing the antenna's frame dimensions, determining the parameters of the H slot, calculating the channel width, as well as the dimensions of the $\frac{1}{4}$ transformer channel. Subsequently, the antenna is fashioned utilizing the CST application, where each calculated value is integrated into the CST Studio simulation program. Meanwhile, the formulation of the voltage doubler rectifier and impedance adjuster necessitates the utilization of the Multisim application.

The type of material used in the manufacture of microstrip antennas is fr4 type substrate which has a dielectric permittivity constant of 4.56 and has a substrate thickness of 1.56 mm. The material specifications intended for utilization are detailed in Table 1.

The design of the 2x4 rectangular Microstrip Array Antenna and rectifier design using 8, 12 and 14-level voltage doubler circuits can be seen in Figure 2 - Figure 4. An overview of the 2x4 microstrip rectangular array antenna that will be designed is depicted in the Figure 5. W = Patch Width, L = Patch Length, $Wf1$ = Width of Pickpocket 1, $Wf2$ = Width of Pickpocket 2, $Wf3$ = Width of Pickpocket 3, $Wf4$ = Width of Pickpocket 4,

Calculating the W of the antenna can be calculated using equation (1):

$$W = \frac{c}{2f\sqrt{\frac{\epsilon_r+1}{2}}} \quad (1)$$

$$W = \frac{3 \times 10^{-8}}{2(2,448 \times 10^9)\sqrt{\frac{4,58+1}{2}}}$$

$$W = 36,686 \text{ mm}$$

Before calculating L, first find the value of $\epsilon_{r\text{eff}}$ (Dielectric Constant) as Equation (2) and ΔL as Equation (3), then L can be calculated by using Equation (4) below.

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

$$\epsilon_{\text{eff}} = \frac{4,58 + 1}{2} + \frac{4,58 - 1}{2} \left(1 + 12 \frac{1,6}{36,684}\right)^{-\frac{1}{2}}$$

$$\epsilon_{\text{eff}} = 4,246$$

$$\Delta L = 0,412h \left(\frac{\epsilon_{\text{eff}} + 0,3}{\epsilon_{\text{eff}} - 0,258} \right) + \left(\frac{\frac{W}{h} + 0,264}{\frac{W}{h} - 0,8} \right) \quad (3)$$

$$\Delta L = 0,412 \times 1,6 \left(\frac{4,246 + 0,3}{4,246 - 0,258} \right) + \left(\frac{\frac{36,684}{1,6} + 0,264}{\frac{36,684}{1,6} - 0,8} \right)$$

$$\Delta L = 0,716$$

$$L = L_{\text{eff}} - 2\Delta L \text{ where } L_{\text{eff}} = \frac{c}{2f\sqrt{\epsilon_{\text{eff}}}} \quad (4)$$

$$L = \frac{3 \times 10^{-8}}{2(2,448 \times 10^9)\sqrt{4,246}} - 2\Delta L$$

$$L = 29,73 \text{ mm} - 1,432 \text{ mm} = 28,298 \text{ mm}$$

After calculating the dimensions of the patch, the next step is to provide a slot in the H-shaped patch, for calculations we can use Equations (5) to (8).

$$E = \frac{\lambda}{60} \text{ where } \lambda = \frac{c}{f\sqrt{\epsilon_r}} \quad (5)$$

$$\lambda = \frac{3 \times 10^{-8}}{2,448 \times 10^9 \sqrt{4,58}} = 57,26 \text{ mm}$$

$$E = \frac{57,26}{60} = 0,95 \text{ mm}$$

Furthermore, to calculate C (vertical length of the slot) the equation (6) can be used:

$$\frac{C}{W} \geq 0,3 \quad (6)$$

$$\frac{C}{36,684} \geq 0,3$$

$$C = 36,684 \times 0,3 = 11 \text{ mm}$$

Then to find D (horizontal length of the slot) the equation (7) can be applied:

$$D = \frac{c}{f_{\text{low}}\sqrt{\epsilon_{\text{eff}}}} - ((2L) - (2\Delta L - E)) \quad (7)$$

$$D = \frac{3 \times 10^{-8}}{2,448 \times 10^9 \sqrt{4,246}} - ((2 \times 28,298) - (2 \times 0,716 -))$$

$$D = 59,47 - 56,114 = 3,356 \text{ mm}$$

The patch impedance is calculated as a first step to determine the impedance on channel 1 to the end of the channel, which is 50Ω. We can use Equation (8) to calculating patch impedance.

$$Z_A = 90 \frac{\epsilon_r^2}{\epsilon_r - 1} \left(\frac{L}{W}\right)^2 \quad (8)$$

$$Z_A = 90 \frac{4,58^2}{4,58 - 1} \left(\frac{28,298}{36,684}\right)^2$$

$$Z_A = 313,796 \Omega$$

Figure 7 shows several feeder channels, from Z1 to Z6. In the supply line has a different impedance with the calculation. In Impedance on supply line 1 (Z1), the first channel (Z1) has the same impedance value as the patch impedance value of 313.796Ω. In impedance on Supply Line 2 (Z2) Channel 2 is formed from parallel supply channel 1 which has a patch impedance of 313.796Ω. To calculate the impedance of supply channel 2, the following Equation (9) can be applied.

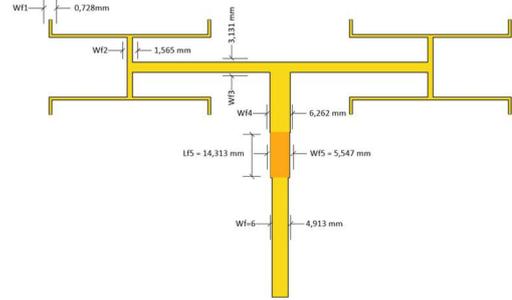


Figure 7. Feeder channel

$$\frac{1}{Z_p} = \frac{1}{Z_{in1}} + \frac{1}{Z_{in2}} \quad (9)$$

$$\frac{1}{Z_p} = \frac{1}{313,796} + \frac{1}{313,796} = 156,898 \Omega$$

In Impedance on supply line 3 (Z3), channel 3 is formed from parallel supply channel 2 which has a patch impedance of 156.898Ω. To calculate the impedance of supply line 3, the Equation (10) can be applied:

$$\frac{1}{Z_p} = \frac{1}{Z_{in1}} + \frac{1}{Z_{in}} \quad (10)$$

$$\frac{1}{Z_p} = \frac{1}{156,898} + \frac{1}{156,898} = 78,449 \Omega$$

In Impedance on supply line 4 (Z4), channel 4 is formed from parallel supply channel 3 which has a patch impedance of 78.449Ω. To calculate the impedance of supply channel 4, the following Equation (11) can be applied:

$$\frac{1}{Z_p} = \frac{1}{Z_{in1}} + \frac{1}{Z_{in}} \quad (10)$$

$$\frac{1}{Z_p} = \frac{1}{78,449} + \frac{1}{78,449} = 39,224 \Omega$$

In Impedance on supply line 5 (Z5), the supply channel 5 is a $\frac{1}{4} \lambda$ transformer, which functions as an impedance adjustment between Z4 and Z6, which is 50 Ω. To calculate the impedance of channel 5 can use Equation (11).

$$Z_T = \sqrt{Z_0 \times Z_{in}} \quad (11)$$

$$Z_T = \sqrt{50 \times 39,224} = 44,285 \Omega$$

In Impedance on supply line 5 (Z5), the supply channel 6 (Z6) is assigned an impedance of 50Ω as the impedance value in the 2x4 element Rectangular H-Slot Array microstrip antenna characteristics. To determining the width of each channel or the width of the supply line (Ws) can be calculated in Equation (12) as follows:

$$W = \frac{120 \cdot \pi \cdot h}{Z_p \cdot \sqrt{\epsilon_r}} \quad (12)$$

Width of channel 1 $W_{f1} = \frac{337 \times 1,6 \text{ mm}}{313,796 \times \sqrt{4,58}} = 0,782 \text{ mm}$
 Width of channel 2 $W_{f2} = \frac{337 \times 1,6 \text{ mm}}{156,898 \times \sqrt{4,58}} = 1,565 \text{ mm}$
 Width of channel 3 $W_{f3} = \frac{337 \times 1,6 \text{ mm}}{78,449 \times \sqrt{4,58}} = 3,131 \text{ mm}$
 Width of channel 4 $W_{f4} = \frac{337 \times 1,6 \text{ mm}}{39,224 \times \sqrt{4,58}} = 6,262 \text{ mm}$
 Width of channel 5 $W_{f5} = \frac{337 \times 1,6 \text{ mm}}{44,285 \times \sqrt{4,58}} = 5,547 \text{ mm}$
 Width of channel 6 $W_{f6} = \frac{337 \times 1,6 \text{ mm}}{50 \times \sqrt{4,58}} = 4,913 \text{ mm}$

To get the value of the transformer length $\frac{1}{4} \lambda$, Equation (13) can be used:

$$L_z = \frac{1}{4} \lambda_g \quad (13)$$

$$L_{S4} = \frac{1}{4} \times 57,263 \text{ mm} = 14,313 \text{ mm}$$

In this voltage doubler circuit, which can be seen in Figure 8, the BAT 17 diode type is used. It has a resistance value of 5,112 Ohm and uses a 1 nF capacitor. To get the total impedance value of the circuit is as follows:

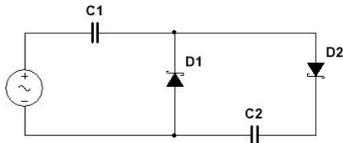


Figure 8. Rectifier voltage doubler circuit

- D2 and C2 are connected in series to get Z 1
- $Z1 = 5,112 - j \frac{1}{2\pi \times 2448 \times 10^6 \times 10^{-9}} = 5,112 - j (0,0650)$
- Z1 and D1 are connected in parallel to get Z2
- $Z2 = \frac{(5,112 - j(0,0650)) \times 5,112}{(5,112 - j(0,0650)) + 5,112} = 2,556 - j (0,016)$
- Z2 and C1 are connected in series to get the total impedance
- $Z \text{ total} = 2,556 - j (0,016) - j \frac{1}{2\pi \times 2448 \times 10^6 \times 10^{-9}} = 2,556 - j (0,0810)$

The next step is to calculate the L impedance adjusters. Figure 9 is a series of impedance adjusters L for rectifier level 8. To determine the value of C and L, the calculation to get the value of X_s must be calculated first and can be done by using Equation 14.

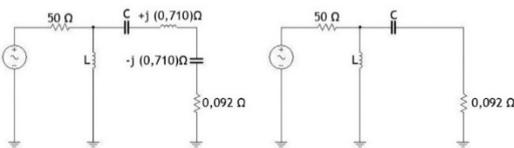


Figure 9. Circuit L impedance adjusting circuit

$$X_s = Q_s \times R_s \quad (14)$$

$$Q_s = Q_p = \sqrt{\frac{R_p}{R_s} - 1}$$

$$Q_s = Q_p = \sqrt{\frac{50}{0,092} - 1} = 23,91$$

$$23,91 = \frac{X_s}{0,092}$$

$$X_s = 23,91 \times 0,092 = 2,1 \Omega \text{ capacitive}$$

$$X_p = \frac{R_p}{Q_p} = \frac{50}{23,91} = 2,1 \Omega \text{ inductive}$$

The next step is determining the value of the Inductor (L) and the value of the Capacitor (C) by using the formula in Equation 15-16.

$$L = \frac{X_s}{\omega} \quad (15)$$

$$L = \frac{2,1}{2\pi (2448 \times 10^6)} = 8 \times 10^{-9} / 8 \text{ nH}$$

$$C = \frac{1}{\omega X_s} \quad (16)$$

$$C = \frac{1}{2\pi (2448 \times 10^6) \times 2,1} = 8 \times 10^{-9} / 8 \text{ nF}$$

Figure 10 is a series of impedance adjusters L for rectifier level 12, to determine the value of C and L used Equation 17 – Equation 19 below.

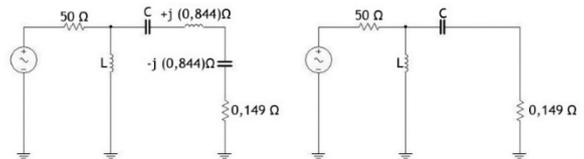


Figure 10. Impedance adjusting circuit L level 12.

$$Q_s = Q_p = \sqrt{\frac{R_p}{R_s} - 1} \quad (17)$$

$$Q_s = Q_p = \sqrt{\frac{50}{0,144} - 1} = 17,663$$

$$17,663 = \frac{X_s}{0,144}$$

$$X_s = 17,663 \times 0,144 = 2,5 \Omega \text{ capacitive}$$

$$X_p = \frac{R_p}{Q_p} = \frac{50}{17,663} = 2,8 \Omega \text{ inductive}$$

$$L = \frac{X_s}{\omega} \quad (18)$$

$$L = \frac{2,8}{2\pi (2448 \times 10^6)} = 10,7 \times 10^{-9} / 10,7 \text{ nH}$$

$$C = \frac{1}{\omega X_s} \quad (19)$$

$$C = \frac{1}{2\pi (2448 \times 10^6) \times 2,5} = 9,6 \times 10^{-9} / 9,6 \text{ nF}$$

Figure 11 is a series of impedance adjusters L for rectifier level 14. To determine the value of C and L used the same equation as Equation 14 – Equation 16 above.

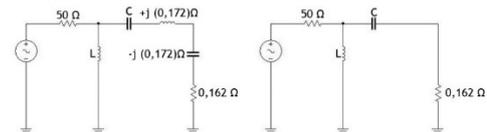


Figure 11. Impedance adjusting circuit L level 12

$$Q_s = Q_p = \sqrt{\frac{R_p}{R_s} - 1}$$

$$Q_s = Q_p = \sqrt{\frac{50}{0,162} - 1} = 16,568$$

$$16,568 = \frac{X_s}{0,162}$$

$$X_s = 16,568 \times 0,162 = 2,6 \Omega \text{ capacitive}$$

$$X_p = \frac{R_p}{Q_p} = \frac{50}{16,568} = 3,0 \Omega \text{ inductive}$$

$$L = \frac{X_s}{\omega}$$

$$L = \frac{3}{2\pi (2448 \times 10^6)} = 11,5 \times 10^{-9} / 11,5 \text{ nH}$$

$$C = \frac{1}{\omega X_s}$$

$$C = \frac{1}{2\pi (2448 \times 10^6) \times 2,6} = 9,9 \times 10^{-9} / 9,9 \text{ nF}$$

At the antenna simulation stage, CST 2018 software is used as a tool for designing and simulating antennas. Some of the parameters that can be displayed in the CST 2018 software are Return Loss, VSWR, Radiation pattern, Gain, and antenna characteristic impedance. Some of the parameters used to design microstrip antennas are explained in the Table 2. Multisim 14 software is used as a tool to design and simulate rectifier circuits along with impedance matching circuits. The selection of rectifier components in Multisim is referred to the original component data on the market, such as Schottky diodes, capacitors, and inductors. The variable to be observed in the simulation is the output voltage of the rectifier with an AC power supply.

TABLE II
SPESIFICATION OF RECTENNA

NAME	VALUE (MM)	DESCRIPTION
T	0,0325	Copper thickness
C	11	Vertical Length of H-Slot Gap
D	3,356	Horizontal Length of H-Slot Gap
E	0,95	H-Slot Gap Width
Lf1	50,5	Supplier Horizontal Length 1
Lf1a	5	Feeder Vertical Length 1
Lf2	19	Feeder Vertical Length 2
Lf3	92,5	Feeder Length 3
Lf4	19	Feeder Length 4
Lf5	14,313	Transformer Length 1/4
Lf6	37,75	Feeder Length 6
Wf1	0,782	Feeder Width 1
Wf2	1,565	Feeder Width 2
Wf3	3,131	Feeder Width 3
Wf4	6,262	Feeder Width 4
Wf5	5,8509	Transformer Width 1/4
Wf6	4,913	Feeder Width 6
Lg	140	Ground Length
Wg	200	Ground Width

At this fabrication stage, high precision is required because it will affect the results of the antenna to be tested. After carrying out simulations using CST Studio Suite 2018 software, the next step is fabrication. The dimensions of the antenna during fabrication must match the results of the simulation, with the following fabrication steps: Print the antenna design to be fabricated on 120-gram glossy paper, a laser printer is required for the printing process, so the results are precise. Then clean the FR-4 PCB which will be used for antenna fabrication using cleaning soap and tools that are not rough in texture so as not to damage the copper layer on the PCB and the print results can stick well to the PCB. Then paste the results of the antenna design that has been designed on the top surface of the PCB using an iron and smooth the surface of the paper so that it sticks perfectly. The next thing to do is to remove the paper slowly to minimize the printout not sticking. Then soak the PCB into the Ferrite Chloride ($FeCl_3$) solution. After the unnecessary copper parts have dissolved, clean the PCB again using a cleanser and soft tool until the design on the copper is visible. After that, install the SMA connector and install the antenna support with 5 mm thick acrylic material and PVC pipe with a diameter of $\frac{3}{4}$.

III. RESULTS AND DISCUSSION

A. Rectifier Circuit Design and PCB Layout

The results of this experiment are shown in Figure 12. After simulating the Multisim 14.0 application, the next process is fabrication as shown in Figures 13 to 17. Figure 13 shows the fabrication result of an 8-stage voltage doubler rectifier circuit with 16 BAT17 Schottky diodes, and 16 1nF capacitors. Figure 14 shows the fabrication result of a 12-stage voltage doubler rectifier circuit with 24 BAT17 Schottky diodes and 24 1nF capacitors. Figure 15 shows the fabrication result of a 14-stage voltage doubler rectifier circuit with 28 BAT17 Schottky diodes and 28 1nF capacitors.



Figure 12. Rectangular microstrip antenna H-Slot array 2x4 front view



Figure 13. Fabrication of 8-stage rectifier voltage doubler circuit

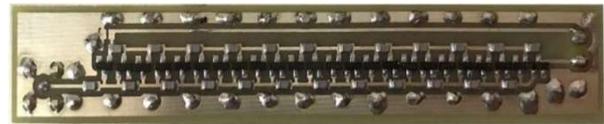


Figure 14. Fabrication of 12-stage rectifier voltage doubler circuit



Figure 15. Fabrication of 14-stage rectifier voltage doubler circuit

B. Measurement and Analysis

The simulation results of the return loss of the 2x4 rectangular microstrip antenna array with an H-slot designed at a working frequency of 2401-2495 MHz with a center frequency of 2448 Mhz. Marker 1 is the minimum frequency, which is located at 2401 MHz with a Return Loss result of -10,481 dB. Marker 2 is the maximum frequency, which is located at 2495 MHz with a Return Loss value of -10.655 dB. Marker 3 is located at the center frequency of 2448 MHz, which is the resonant frequency with a Return Loss value of -20.667 dB. This process can be seen in Figure 16. The simulation results using the CST Studio 2018 application

produce Return Loss at a center frequency of 2448 MHz, which is the resonant frequency, obtaining a Return Loss value of -20.667 dB. When compared with the minimum requirements for making an antenna, the Return Loss value must be ≤ 9.54 dB, it can be stated that the simulated antenna meets the minimum standards for antenna specifications.

Figure 17 shows the VSWR result from a simulation of a microstrip antenna designed at a working frequency of 2401-2495 MHz with a center frequency of 2448 MHz, and there is a marker with the following explanation: Marker 1 is the minimum frequency, which is located at 2401 MHz with a VSWR of 1.8541. Marker 2 is the maximum frequency, which is located at 2495 MHz with a VSWR of 1.8306.

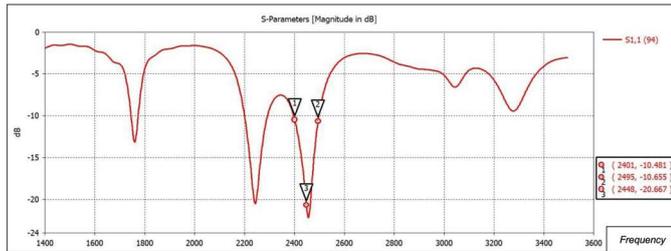


Figure 16. Return loss simulation results

Marker 3 is located at the center frequency of 2448 MHz, which is a resonant frequency with a VSWR value of 1.2041. From the simulation results using the CST Studio 2018 application, the VSWR at the center frequency 2448 is -1.2041. When compared with the minimum requirements for making an antenna, namely $VSWR \leq 2$, it can be stated that the simulated antenna meets the minimum standards for antenna specifications.

Figure 18 shows the results of bandwidth simulation using the CST Studio 2018 application, marker 1 and marker 2 are the working frequency of the antenna which is located below the horizontal measure line. The horizontal measurement line is the standard Return Loss of the antenna, namely ≤ 9.54 dB, meaning that the working frequency of 2401 - 2495 MHz has met the expected Return Loss standard so that it can be stated that the simulated antenna can work at a working frequency bandwidth of 94 MHz.

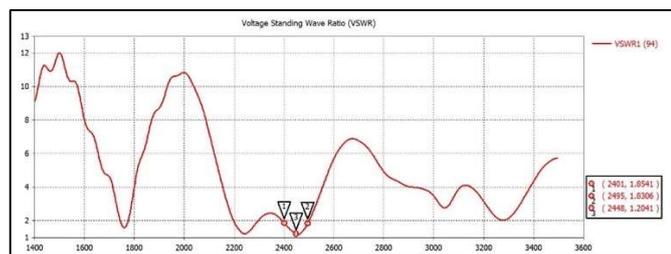


Figure 17. VSWR simulation results

Figure 19 shows a gain simulation result obtained in a simulation using CST Studio 2018. Based on the simulation results, the gain result is 7.767 dB. Compared with the minimum requirement for making an antenna, namely $Gain \geq 5$ dB, the simulation gain result of 7.767 dB shows that the

simulated antenna has met the minimum standard for making an antenna.

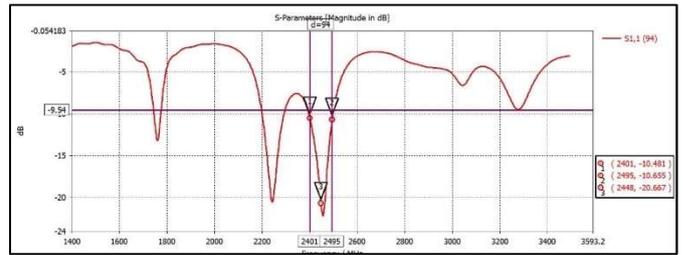


Figure 18. Bandwidth simulation results

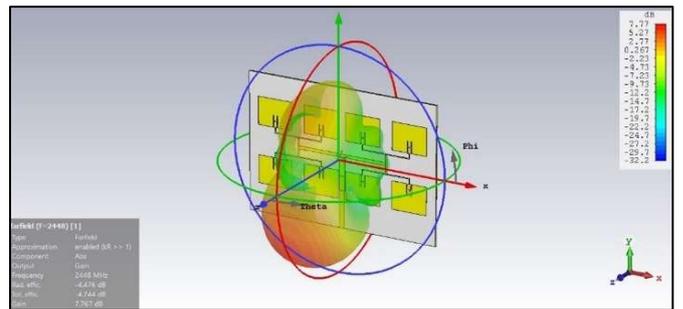


Figure 19. Gain simulation results

The results of the radiation pattern of the 2x4 Rectangular H-slot array microstrip antenna with a red line are shown in figure 20 when viewed at an elevation angle and in figure 21 viewed at an azimuth angle. The elevation angle can range from 0° to 90° while the azimuth angle ranges from 0° to 360° . The simulation results show a directional radiation pattern because the antenna has an effective radiation direction in a certain direction with a power value on the main lobe greater than the side lobe power value and HPBW of 30° .

In Figure 22, the polarization simulation results of the 2x4 rectangular microstrip antenna array with H-slot can be seen. The obtained polarization close to circular because the power received by the antenna is evenly distributed at each measuring angle.

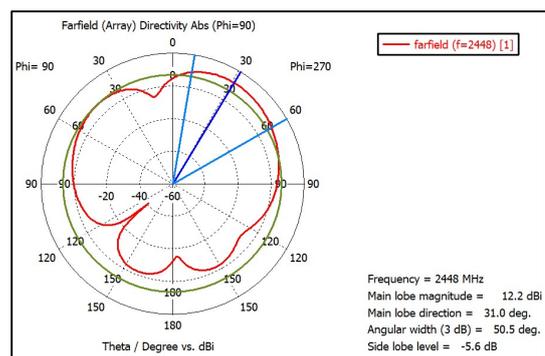


Figure 20. Radiation pattern simulation results

In the voltage doubler rectifier circuit, which has been combined with the L impedance adjuster circuit and based on the simulation results of the rectifier voltage doubler there are 3 types of levels, which is 8 levels, 12 levels and 14 levels, each

level will be tested with input power ranging from 0 dBm to 22 dBm with 5 dBm intervals. Table 3 shows the effect of the number of stages on the Schottky value in the circuit.

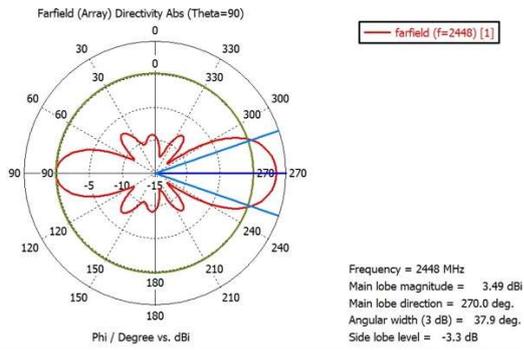


Figure 21. Azimuth pattern simulation results

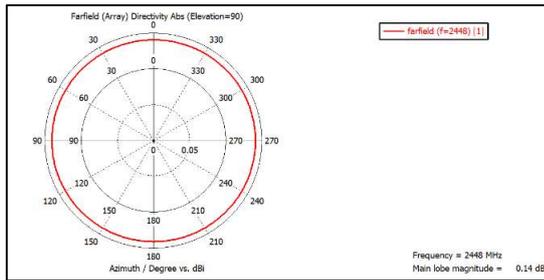


Figure 22. Polarization pattern simulation results

TABLE III
VOLTAGE DOUBLER CIRCUIT SIMULATION RESULTS

Input Power (dBm)	Rectifier Simulation Results (Volt)		
	Stage 1	Stage 2	Stage 3
0	1,24	2,34	2,57
5	4,9	6,29	8,61
10	11,03	17,40	19,78
15	22,46	33,98	38,87
20	44,12	64,07	75,65
22	24,29	81,28	94,67

Based on Table 3, every increase in rectifier stage, the voltage produced is also getting bigger. The biggest result in rectifier testing is on Rectifier Stage 14 with an input power of 22 dBm producing a DC voltage of 94.67 V. This proves that the simulation results have a good value and are in accordance with the concept of a voltage multiplier, how much input will be doubled according to the rectifier level.

Figure 23 and Figure 24 are the results of testing the reference value and return loss of the 2x4 rectangular array microstrip antenna with H-slot.

The bandwidth can be found through the return loss value which is close to -10 dB at $f_1 = 2250$ MHz and $f_2 = 2700$ MHz with a bandwidth value of 450 MHz. For the Wi-Fi working frequency of 2401-2495 MHz, the return loss value is >-10 dB so that the fabricated antenna is in accordance with

the antenna manufacturing plan. The detailed results can be seen in Table IV.

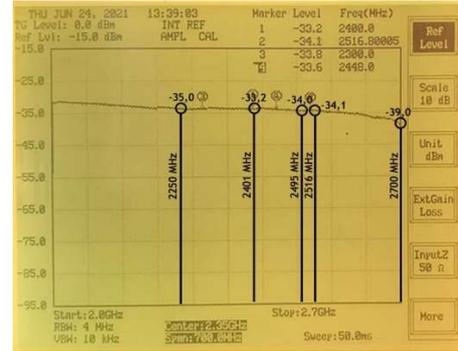


Figure 23. Reference level value on the spectrum analyser

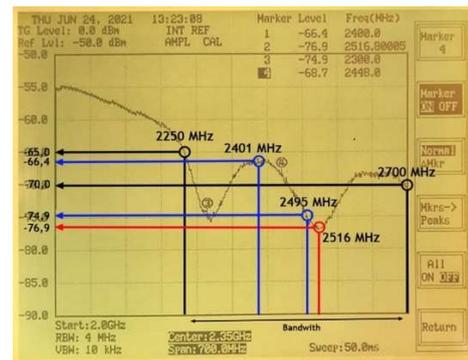


Figure 24. Return Loss Measurement Results

TABLE IV
RL AND VSWR TESTING OF 2X4 RECTANGULAR ARRAY MICROSTRIP ANTENNA WITH H-SLOT

Frequency (MHz)	Level (dBm)			RL (dB)	VSWR
	Read	Reference	Attenuation DC		
2250	-65	-35	-20	-10	1,925
2401	-66	-33,5	-20	-12,5	1,6
2495	-75	-33,6	-20	-21,4	1,15
2516	-76,9	-34,1	-20	-22,8	1,1
2700	-68,7	-33,6	-20	-14	1,4

The frequencies that have been marked show that the Return Loss obtained is still within the operational standards of the antenna, namely less than -10 dB. For the resonant frequency, it is found at a frequency of 2516 MHz. This is different from the simulation value that the resonant frequency is at a frequency of 2448 MHz. One of the factors that causes the difference in the resonant frequency obtained is the fabrication process that is less precise, giving rise to a shift in the Return Loss value. The resonant frequency is at 2516 MHz with a Return Loss result of -22.8 dB. Other parameters that can be known from the Return Loss test results are the Bandwidth and VSWR of the antenna. The VSWR results for the marked frequency still meet the minimum requirements for the antenna standard, namely less than 2 and the bandwidth obtained is $f_2 - f_1 = 2700$ MHz - 2250 MHz = 450 MHz.

The gain test of the 2x4 rectangular microstrip array antenna with H-slot can be seen in Table V. Based on Table V with an average gain value of 6.1 dBi so that these results are in

accordance with the antenna design planning parameters which are > 5 dBi.

TABLE V
GAIN TESTING RESULTS

Frequency (MHz)	Level (dBm)		Gain (dBi)
	Reference Antenna	Antenna Under Test	
2323	-59,4	-62,8	-1,15
2348	-58	-62,5	-2,35
2373	-59,4	-61,0	0,55
2398	-68,5	-59,0	11,15
2423	-74	-65,3	10,85
2448	-66,3	-61	7,45
2473	-65	-59,5	7,65
2498	-62,4	-57,2	7,35
2523	-65,7	-60,5	7,35
2548	-66,1	-62,9	5,35
2573	-73,8	-62,8	13,15
Average = (Gain Total)/11			6,1

Radiation pattern test results of 2x4 rectangular array microstrip antenna with H-slot can be seen in the following Table VI. Based on Table VI, the radiation pattern diagram can be drawn as shown in Figure 25. The measurement results in Figure 25 by rotating the antenna in azimuth of the horizontal axis show that it has a directional radiation pattern because the antenna has an effective radiation direction in a certain direction, namely between an angle of 329° and an angle of 20°.

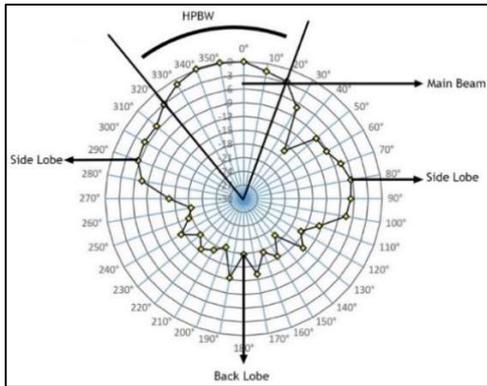


Figure 25. Radiation Pattern of 2x4 Element Rectangular H-Slot Array Microstrip Antenna

TABLE VI
RADIATION PATTERN TESTING RESULTS

Angle (°)	Frequency 2448 MHz	
	Polarization (dB)	Normalization (dB)
0	-57,2	0
10	-58,9	-1,7
20	-59,9	-2,7
...
...
340	-57	0,2
350	-57	0,2

TABLE VII
POLARIZATION PATTERN TESTING RESULTS

Angle (°)	Frequency 2448 MHz	
	Polarization (dB)	Normalization (dB)
0	-59,5	0
10	-60,2	-0,7
20	-62,5	-3
...
...
340	-62	-2,5
350	-63	-3,5

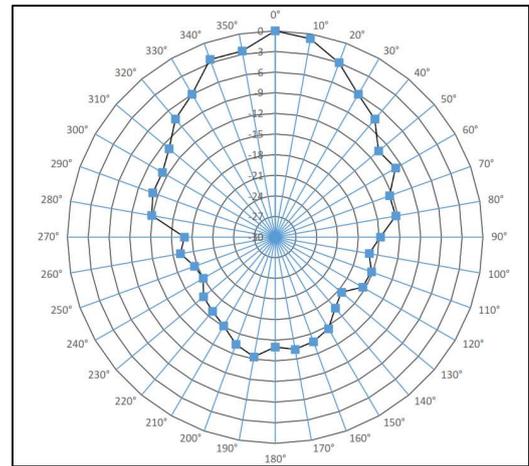


Figure 26. Polarization of 2x4 Element Rectangular H-Slot Array Microstrip Antenna

The Table 7 above shows the test result for the polarization of the 2x4 rectangular microstrip array antenna with H-slot. Based on Figure 26 of the polar diagram by rotating the antenna in elevation of the vertical axis for the polarization of the 2x4 rectangular array microstrip antenna with H-slot, a circular shape is seen because the power received by the antenna is almost evenly distributed at each measuring angle so that the polarization of this antenna is circular polarization.

Rectifier Voltage doubler testing is used to testing the Schottky power generated from the rectifier connected to the Signal Generator. The test results can be seen in Table 8 below. Based on the average results in Table 8, it can be proven that every increase in the rectifier level the converted voltage results is also getting bigger. This is in accordance with simulation and testing. The comparison graph of the rectifier voltage increase for each stage can be seen in Figure 27 below.

The test implementation includes the preparation of microstrip antennas integrated with rectifiers and measurement of the results of the rectenna system as energy harvesting can be seen in Table 9 below.

TABLE VIII
RECTIFIER TEST RESULTS

Input Power (dBm)	Rectifier Testing Results (Volt)		
	Level 8	Level 12	Level 14
0	3	4,48	6,43
5	3,81	4,98	8,34
10	8,72	7,31	10,71
15	10,88	13,58	14,95
20	14,17	17,21	43,7
25	16,77	21,14	49,1

Based on the average results in Table 9, it can be proven that every increase in the rectifier level the converted voltage results are also getting bigger. This is in accordance with simulation and testing, where the voltage output results are getting higher linearly with the increase in rectifier level. The largest voltage output result is obtained at rectifier voltage doubler level 14 with 50 cm from the Access Point, which is

101.98mV. However, in the implementation, the results obtained are not as great as during simulation and testing, because during implementation, it directly utilizes the power emitted by the Access Point with a maximum transmitting power of -23 dBm. The comparison graph of the rectenna voltage increase for each stage can be seen in Figure 28.

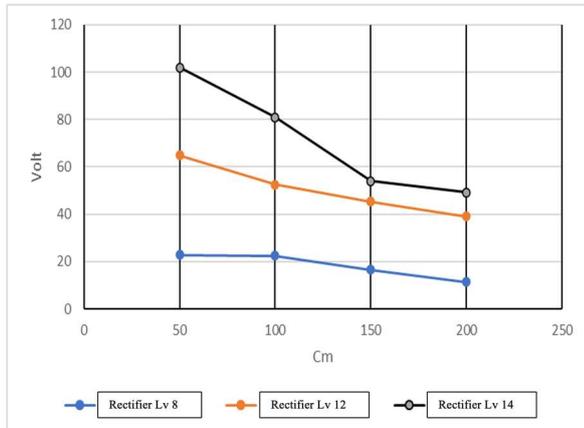


Figure 27. Graph of rectifier test results

TABLE IX
AVERAGE RESULTS OF RECTENNA VOLTAGE OUTPUT

Rectifier	Distance of Access Point to Rectenna (Cm)	Voltage Average Result (mV)
Level 8	50	24,72
	100	22,46
	150	16,52
	200	11,4
Level 12	50	64,8
	100	52,48
	150	45,34
	200	39,08
Level 14	50	101,98
	100	80,86
	150	54
	200	49,148

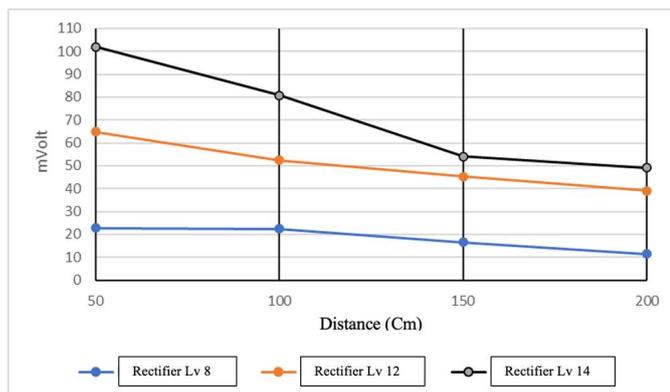


Figure 28. Graph of rectenna average voltage output test results

IV. CONCLUSION

Based on the research and testing that has been done, several conclusions can be obtained, In the simulation of the microstrip rectangular array H-Slot 2x4 element antenna, the resonant

frequency results are obtained in accordance with the expected specifications of 2448 MHz, with a Return Loss of -20.667 dB and a VSWR of 1.4. In addition, the simulation obtained a gain of 7.767 dB, this value is in accordance with the minimum requirements for antenna design. However, in antenna testing, a resonant frequency shift was obtained at 2516 MHz with a Return Loss of -22.8 dB and VSWR of 1.1. Although there is a shift in resonant frequency, the expected center frequency can still operate with the return loss obtained in the test of 15.1 dB.

The performance of the rectifier voltage doubler circuit on simulation using Multisim 14.1 has good DC voltage simulation results, can increase the voltage results according to the number of rectifier circuit levels. The largest result is 94.67 V at level 14 with an input power of 22 dBm.

The performance of the rectifier doubler circuit in the test obtained a trend of results in accordance with the simulation. Although the results obtained differ more maximally in the simulation, but conceptually it is in accordance with the principle of voltage multiplier. This is due to sensitive factors that cause voltage losses, namely the soldering process, PCB material and component tolerance values. The largest test result obtained was 49.7 V at level 14 with a power input of 22 dBm.

In the implementation of the rectenna harvesting system, it can convert the largest results of 101.98 mV in the 14th level rectifier circuit, then 64.8 mV in the 12th level rectifier circuit, and the last 24.72 mV in the 8th level circuit. Based on the distance, the closer the rectenna distance to the Access Point, the greater the voltage produced.

REFERENCES

- [1] Imanhadi Dwiriandi, Atkisa. Aisah. Rahmad Saptono.(2019).”Rancang Bangun Rectenna Mikrostrip Rectangular Patch untuk Energy Harvesting Pada Frekuensi 1900MHz”. JARTEL Journal (ISSN (print): 2407-0807 ISSN (online): 2654-6531) Vol: 9 Number: 4, December 2019.
- [2] Aritonang, Sus Sulianti Natalia. Heroe Wijanto. Yuyu Wahyu.(2018). "Perancangan Dan Realisasi Rectenna Pada Frekuensi Wifi Untuk Elektromagnetic Harvesting (Panen Gelombang Elektromagnetik)." Faculty of Engineering: Telkom University. Telecommunication Engineering thesis scientific work. eProceedings of Engineering Vol: 5 Number 2.
- [3] Ahmad, Fauzi. Rudy Yuwono. Ali Mustofa. (2014). “Perancangan Rectenna (Rectifier Antenna) Sebagai Pengubah Daya Elektromagnetik Menjadi Schottky DC Pada Frekuensi Wifi 2.4 GHz”. Journal of Electrical Engineering Students, Brawijaya University Vol: 2 Number: 4.
- [4] Dirton, Parubak.(2014). “Rancang Bangun Antena Penyearah (Rectifier Antena) Untuk Pemanen Energi Elektromagnetik Pada Frekuensi GSM 1800 MHz”. Journal of Electrical Engineering Students Universitas Brawijaya 2014 Vol:2 Number 5.
- [5] Abdurrahman, Fiqqi.(2018). "Desain Antena Mikrostrip Rectangular untuk WIFI pada Frekuensi 2,462 GHz dan

- 5, 52 GHz." (2018). Scientific Work -Reference Jom FTEKNIK Vol: 3 Number 2.
- [6] Ardianto, Fajar Wahyu. Renaldy Setyawan. Lanang Farhan Fathir. Yunita Trasma.(2019) "Desain Antena Mirkostrrip Rectangular Patch Array 1x2 dengan U-Slot Frekuensi 28 GHz". Journal of Elkomnika Vol. 7, Number: 1, pp.43-56, January 2019.
- [7] Constantine a, Balanis. (2016) " Antenna Theory Analysis and Design Fourth Edition". John Wiley & Sons, Inc. Hoboken Canada.
- [8] Nugraga, Rawan. (2014). "Perancangan dan Realisasi Rectenna (Rectifier Antena) untuk Frekuensi 900 Mhz–5 Ghz Sebagai Sumber Daya Alternatif untuk Mengisi Baterai Handphone." Faculty of Electrical Engineering: Telkom University (2014). Scientific Paper -Reference. Vol:1 Number:5.
- [9] Ruswanditya, Adhie Surya. Heroe Wijanto Wijanto. Yuyu Wahyu. (2017). "Antena Microstrip MIMO 8x8 Array 2 Patch Rectangular H-Slot Untuk Radio Akses 5G Frekuensi 15 Ghz." TEKTRIKA-Journal of Research and Development of Telecommunications, Control, Computers, Electricity, and Electronics Vol:2 Number:1.
- [10] Rudi, Yuwono. Irfan Mujaihidin. (2019). "Rectifier Using UWB Microstrip Antenna as Electromagnetic Energy Harvester for GSM, CCTV and Wi-Fi Transmitter". Journal of Communication Vol. 14, Number: 11, November 2019.
- [11] Aditya, Putra Aviantoro. Heru Wijanto. Yuyu Wahyu. (2016) "Perancangan dan Implementasi Rectifier Antena dengan Menggunakan Teknik Voltage Multiplier untuk Frekuensi UHF". Faculty of Engineering: Telkom University. Telecommunication Engineering thesis scientific work. eProceedings of Engineering Vol: 3 Number: 3.