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Simulation and Analysis of Radio Frequency Energy Harvesting System Operating at 2.45 GHz Frequency

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Abstract

This paper proposed study of an RF energy harvesting system at 2.45 GHz using a rectifier and an antenna so called rectenna. Inset-fed micro-strip rectangular patch antenna array is fabricated. The rectifier circuit, employing Schottky diodes (HSMS-2850), converts AC power from the antenna to DC for RF detection. Analysis of the antenna's design and parameters such as directivity, return loss, gain, and VSWR is done using high-frequency simulator software (HFSS). The antenna's geometry, including patch length, patch width, inset-distance, inset-feed, and gap is calculated using derived formulas and online simulation tools. Using the inset fed feeding technique, we present and confirm the performance of a rectangular patch antenna using single and multiple patch configurations in this study. The single patch is then fed into a 2x1 array antenna using the inset-fed technique to maximize directivity and boost gain. The rectenna circuit is simulated via advanced design system (ADS) software, yielding good results.

Keywords: Rectenna, RF energy harvesting, rectifier, Schottky diode.

INTRODUCTION

Wireless power harvesting, particularly through radio frequency (RF) energy is an emerging field of research with promising prospects for powering low-power electronic devices like Bluetooth sensors, health monitoring systems. Utilizing rectennas, RF energy harvesting employ RF signals emitted by various sources such as TV and mobile phone towers, radio stations, and Wi-Fi routers.

Wireless applications are crucial in almost every aspect of telecommunications. In the field of wireless communications technology, antenna is the most significant device. Some of the well-known antennas are patch antennas, slot antennas, parabolic reflectors, and folded dipole antennas with lightweight, low profile, simple design and ease of fabrication are the preferred choice. In terms of technology, microstrips are well known for their low cost. However, gain of the antenna has become the drawback for all these years. According to previous research patch antenna arrays can be improved for better gains over the single element. The patch can be of any shape whether triangular, rectangular, circle to name a few. These antennas have a resonance frequency of 2.4 GHz, these are ideal for wireless network and ISM bands.

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This ambient RF energy, radiating from modern technological infrastructure like cell towers and base stations, presents a significant resource for energy harvesting. Researchers emphasize the advantages of RF harvesters over other ambient energy sources, citing their predictability reliability,

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and capacity to simultaneously power multiple nodes. Moreover, advancements in semiconductor technology have sustained the realization of RF energy harvesting, facilitating continuous operation of sensors important for structural health monitoring and other engineering applications.

The motivation behind our research is to design such a rectenna that overcomes the basic limitations of antenna designing. The main goal is to increase the rectennas bandwidth and conversion efficiency at low input power and design such a wideband rectenna that can be integrated with any wireless device, capturing the ambient RF energy of different frequencies convert and rectify it to DC power. The second motivation behind this research is to design a rectenna array having improved conversion efficiency.

R.F. ENERGY HARVESTING

Since batteries are the primary power source for low power portable electronics, due to their confined lifespan they must be repeatedly recharged. But carrying chargers around is impractical, which emphasizes the need for a more dependable power source and environmentally friendly. Energy harvesting involves capturing and storing external energy sources including solar and wind power for wireless devices like those found in wearable electronics and Wireless Sensor Networks (WSNs), appears as a suitable substitute.

Numerous studies have explored the development of efficient rectifiers for RF energy harvesting applications. Mutee et al. [3, 4] showcased a highly efficient single-branch dual-band rectifier operational at frequencies of 2.45 GHz, utilizing the SMS-7630 diode for detection within a power range of -10 to -30 dBm. Shenyi et al. [10, 11] analyzed broadband rectenna design for wireless energy harvesting, attaining a conversion efficiency of over 40% across the 1.75–2.5 GHz band using both single-branch and two-branch rectifier circuits [5].

Mei-Juan et al. [8] developed a grounded coplanar waveguide (GCPW) broadband rectenna operating at 2.45 GHz, featuring a new broadband slot antenna with high gain and a wide half-power beamwidth, resulting in a broadband performance from 2.2 to 2.6 GHz with a conversion efficiency of 72.5%.

In Wireless communication systems Radio Frequency signals would be the most suitable renewable energy source. Energy sources are based on light, vibration, and heat, and are not continuously present everywhere. The EH application devices are categorized as far-field and near-field. The RF-EH system is shown in Figure 1. offers a sustainable approach to supply power to low-powered electronic systems. Among the common low-powered electronic systems include the wireless sensor networks (WSN), internet of things (IoT)-powered devices, and smart metering systems. The energy generated by

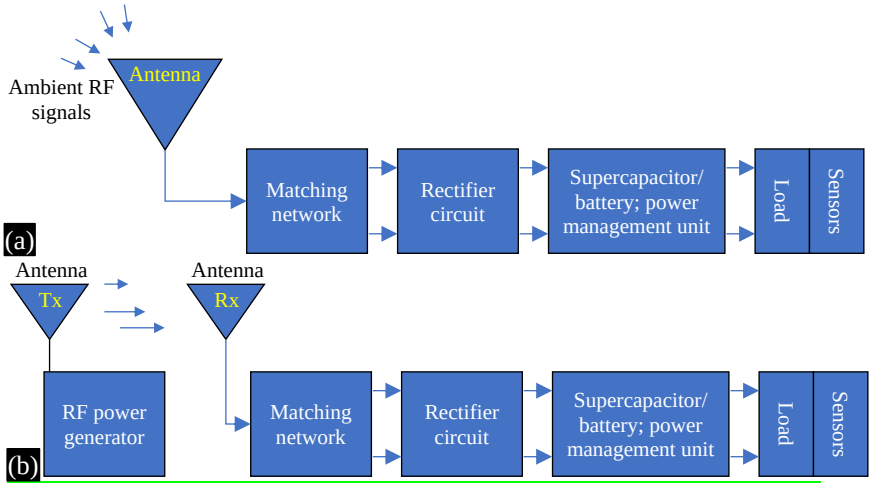

Figure 1. Block diagram of RF-EH system (a) RF energy harvesting, (b) Wireless power transfer.

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powerful RF signals can be used to charge the energy storage unit of RF-EH circuits. Supercapacitors or rechargeable batteries are time-efficient compared to weak signals to power integrated circuits. A holding capacitor or supercapacitor is used to keep the direct current voltage (DC voltage) that is used to power them [6, 7].

PATCH ANTENNA AND ITS CHARACTERISTICS

Microstrip patch antennas have consistently accumulated significant attention among researchers due to their diverse benefits, including their compact size, lightweight nature, cost-effectiveness, and integration capabilities with circuits. Traditionally, microstrip patch antennas were set up with linear polarization. However, in certain scenarios such as satellite communication, is preferred owing to its immunity to variations in transmitter or receiver orientation [1].

In this study, we introduce and validate the performance of a rectangular patch antenna employing both single and dual patch configurations, utilizing the inset-fed feeding technique. Subsequently, the single patch, fed with inset-fed technique, is configured into a 2x1 array antenna to enhance gain and optimize directivity. Employing the High Frequency Structure Simulator (HFSS), the antennas are designed at a frequency of 2.45 GHz utilizing microstrip technology, implemented on FR-4 substrate. To validate the work, the antennas are simulated and analyzed, evaluating key metrics including return loss, directivity, gain, and radiation efficiency [2].

RECTIFIER

The second component of the RF harvesting system is the rectifier, where the output from the antenna is provided into the rectifier's input. For converting alternating current (AC) into direct current (DC) this device is responsible. In this study, HSMS 2850 Schottky diodes are employed for detecting Wi-Fi signals operating at 2.45 GHz. In RF energy harvesting, it is important to utilize diodes with high switching speeds and zero-biased voltages due to the small, harvested power from the antenna and the need to minimize losses.

In a cooperative feed network, the microstrip lines are interconnected in a manner that assures the total power is added through each feed. To enhance gain and facilitate the creation of antenna arrays with multiple elements this cooperative feed network is employed. The greater the number of elements, the higher the antenna gains, at the expense of a narrower bandwidth and increased directional characteristics.

ANTENNA GEOMETRY

In our study, we employ HFSS software to design and analyze a microstrip inset-fed rectangular dual patch antenna array. For the rectifier design, we utilize the ADS simulator. The antenna design consists of three principal components: the ground plane, the substrate surface, and the patch structure. Utilizing an FR4 substrate with a dielectric constant of 4.4, a rectangular feed located at the center of the patch serves as the antenna's feeding mechanism. The dimensions of the antenna are determined through mathematical computations. Specifically, the width and length of the patch antenna are calculated according to established methodologies [9–12].

The effective relative permittivity of free space:

$$\varepsilon_{reff} = \left(\frac{\varepsilon_r+1}{2}\right) + \left(\frac{\varepsilon_r-1}{2}\right)\left[1 + 12\frac{h}{\omega_f}\right]^{\frac{-1}{2}}$$

$$\lambda g = \frac{\lambda_0}{\sqrt{E_{reff}}} \qquad \lambda_0 = \frac{c}{f_r}$$

The width of patch is:

$$w_p = \left(\frac{c}{2fr}\right)\sqrt{\frac{2}{\varepsilon_r+1}}$$

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The length of patch is:

$$L_P = \frac{\lambda_0}{2\sqrt{\varepsilon_{reff}}} - 2\delta L$$

$$\delta_L = h \times \left[\frac{\left(\varepsilon_{reff} + 0.3\right)\left(\frac{\omega_P}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right)\left(\frac{\omega p}{h} + 0.8\right)}\right]$$

The width of feed line is:

$$w_f = \left[\frac{8e^A}{e^A - 2}\right] \times h$$

$$A = \left(\frac{z_0}{60}\right)\left[\frac{\varepsilon_r + 1}{2}\right]^{\frac{1}{2}} + \left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1}\right)\left[0.23 + \frac{0.11}{\varepsilon_r}\right]$$

The length of feed line is:

$$L_f = \frac{\lambda_g}{4}$$

The output impedance of antenna:

$$Z_o = R_{in} \cos^2\left[\frac{\pi}{L_P \times d}\right]$$

SIMULATION AND RESULTS

The RF energy harvesting system includes two main components: the antenna, designed to capture ambient RF energy, and the rectifier circuit, which converts AC signals into DC. Initially, we determined the configuration or shape for efficient RF energy reception. Utilizing HFSS simulation software facilitated antenna design and parameter analysis is shown in Figure 2 and Antenna Reflection Coefficient is shown in Figure 3.

For rectification, Schottky diodes were chosen, and ADS software is used for rectifier circuit design. Through the application of fundamental formulas, antenna dimensions such as feed length, feed width, patch-width, patch-length, inset-gap, and inset-distance were derived. All dimensions were expressed in millimeters (mm). Our design utilized a resonance frequency of 2.45 GHz, a substrate thickness (h) of 1.6, and a dielectric constant (εr) of 4.4, corresponding to FR-4 material.

In HFSS, we constructed two distinct antennas: the single-patch microstrip antenna and the dual-patch microstrip antenna with an inset feed. Subsequently, we conducted separate simulations to assess various performance metrics, including gain, directivity, VSWR, and reflection coefficient, for each antenna configuration is shown in Figures 5–14. In Table 1, antenna parameters and values are shown.

Table 1. Antenna parameters and values.

Antenna parameter	Value
ε_r	4.4
h	1.6 mm
Freq	2.45 GHz
w_f	3.08 mm
L_f	14.58 mm
w_p	37.26 mm
L_P	28.83 mm
λg	58.33

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Single Patch Microstrip Antenna

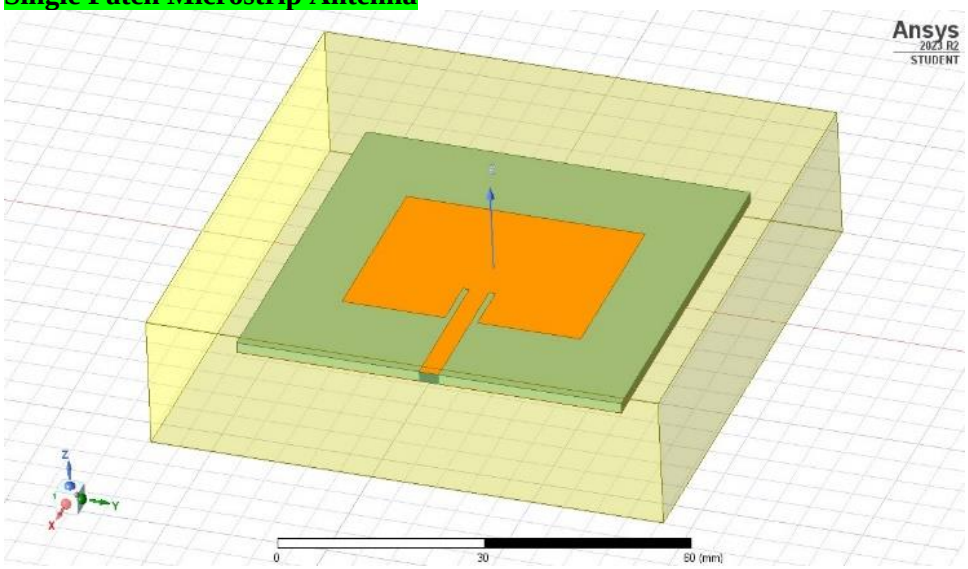

Figure 2. Single patch microstrip inset feed antenna in HFSS.

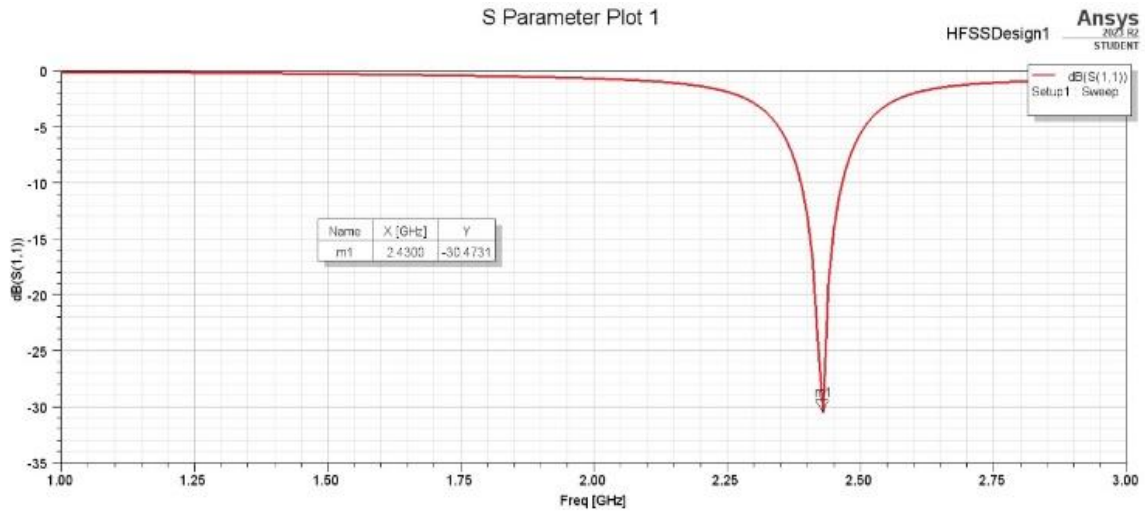

Figure 3. Antenna reflection coefficient.

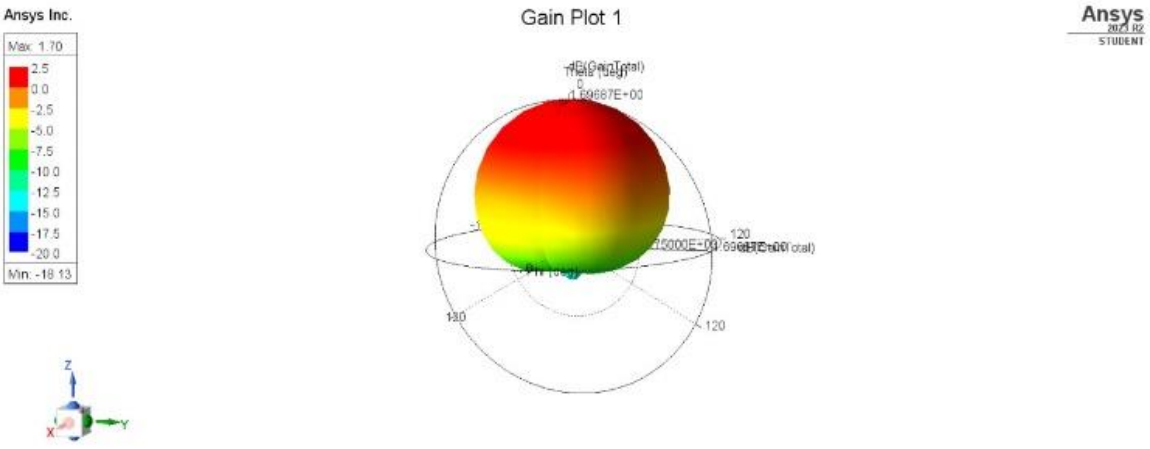

Figure 4. Antenna gain.

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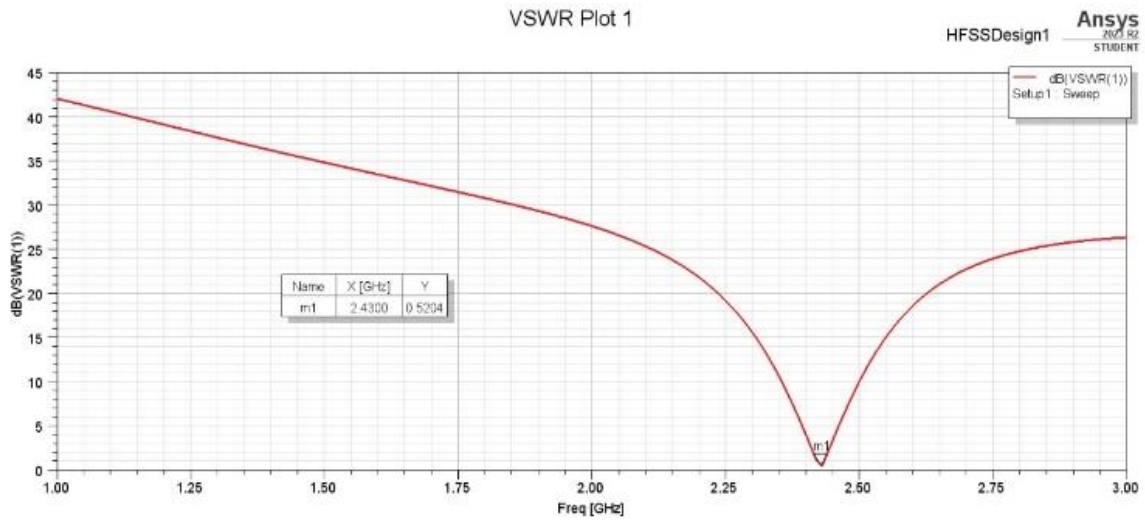

Figure 5. Antenna VSWR.

Dual Patch Microstrip Antenna

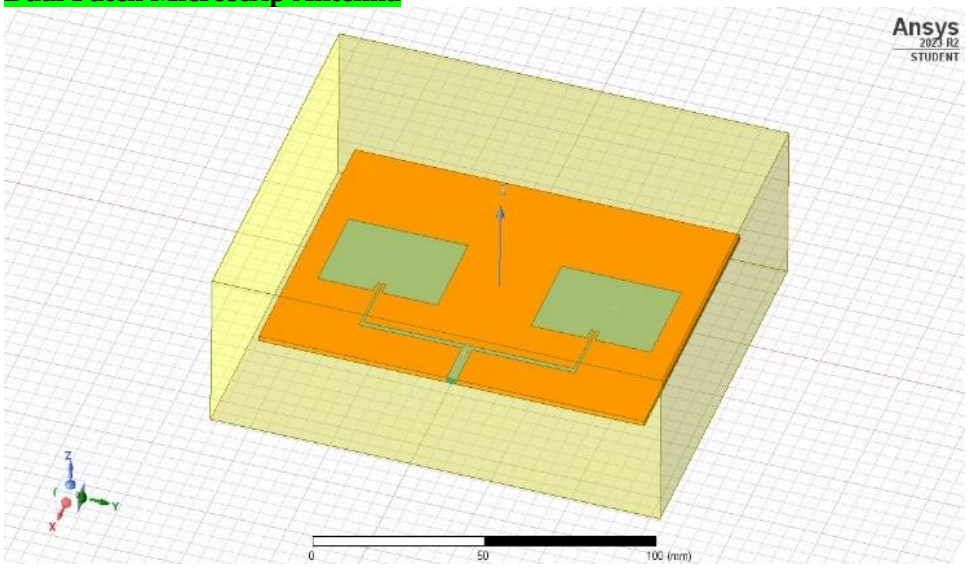

Figure 6: Dual patch microstrip inset feed antenna in HFSS.

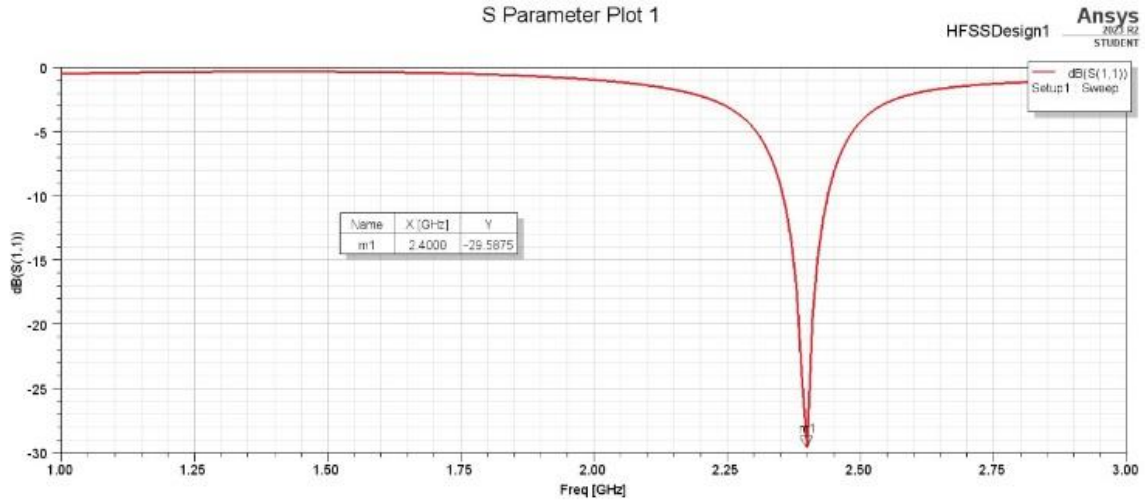

Figure 7. Antenna reflection coefficient.

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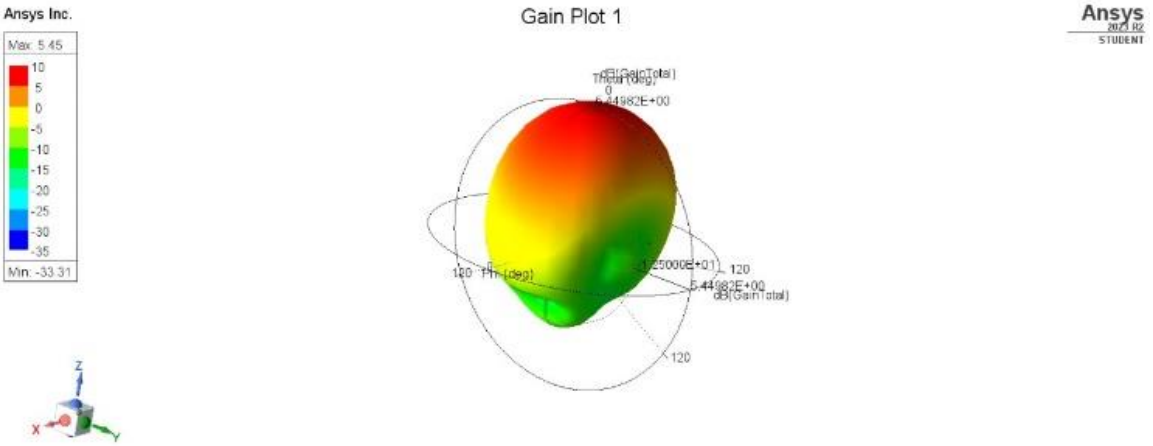

Figure 8. Antenna gain.

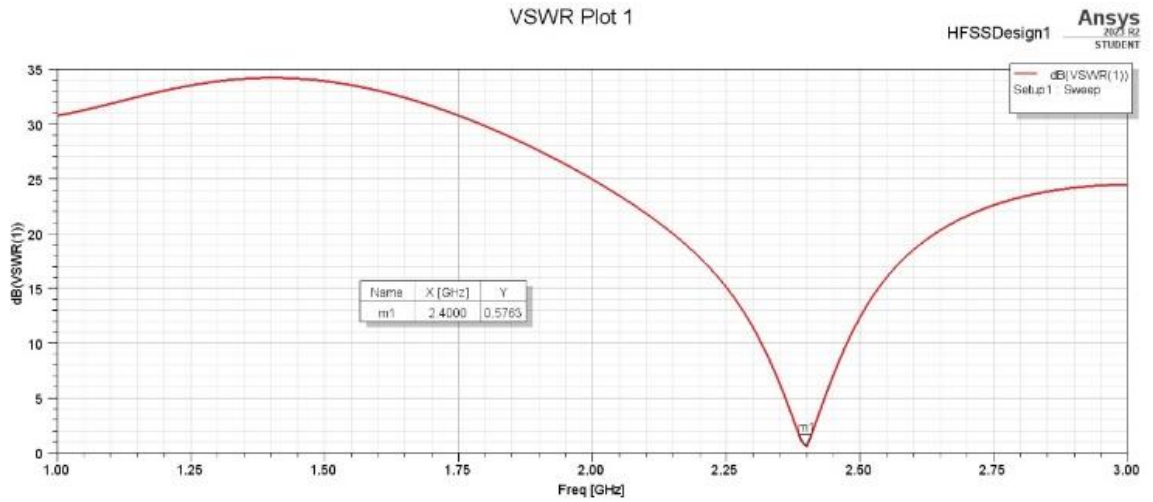

Figure 9. Antenna VSWR.

Rectifier Design in ADS

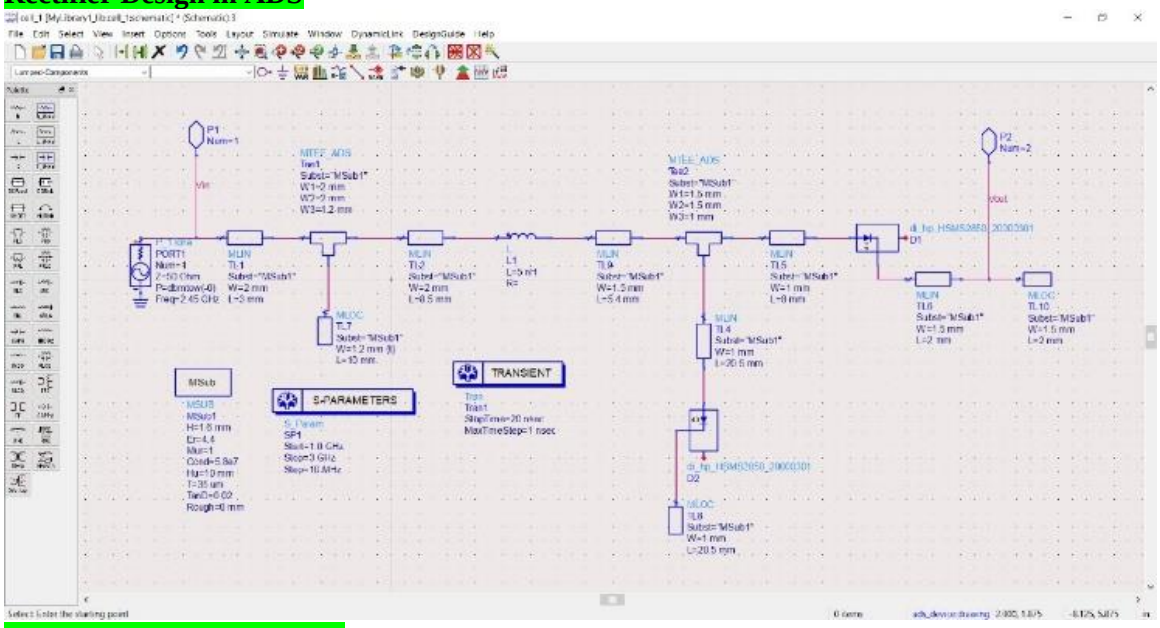

Figure 10. Rectifier in ADS.

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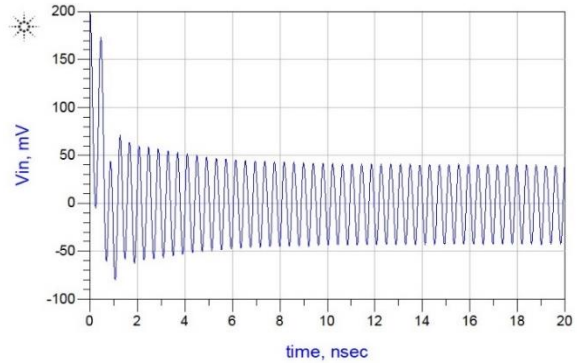

Figure 11. Vin (-10 dbm).

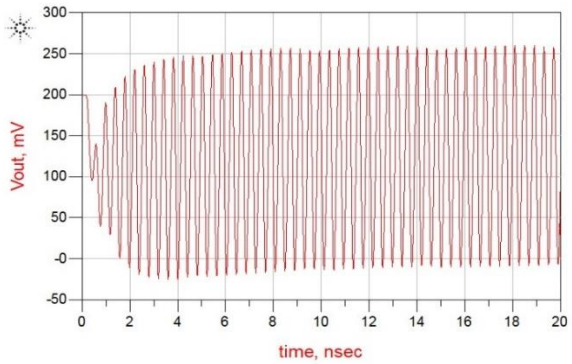

Figure 12. Vout at -10 dbm input power.

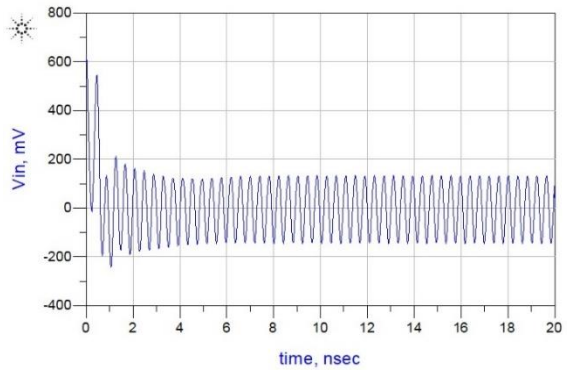

Figure 13. Vin (0 dbm).

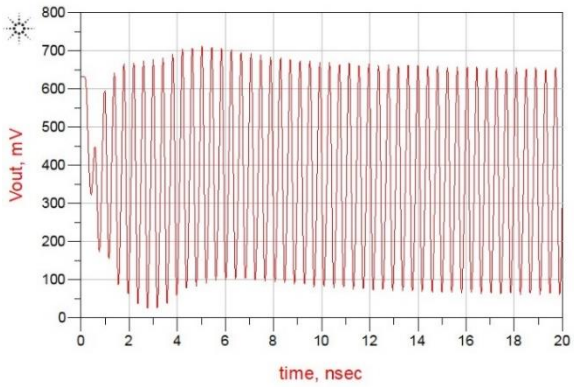

Figure 14. Vout at 0 dbm input power.

CONCLUSION

This study investigates the design of rectennas for applications operating on low power consumption. The voltage output provided by a single unit range between 300 and 800 millivolts, depends upon the distance separating the transmitter and receiver. Notably, as the input power increases from 10 dBm to 26 dBm, the output voltage proportionally rises from 50 to 100 milliwatts. While the current may be insufficient to power electronic sensors or LEDs individually, the aggregation of multiple units in parallel can augment the current output to meet the desired threshold.

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