

RESEARCH ARTICLE

A Design of Wideband Circular Polarization Microstrip Antenna for RF Energy Harvesting

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Abstract

This research investigates the design, simulation, and measurement of a compact $65 \times 65 \text{ mm}^2$ microstrip patch antenna intended for effective Radio Frequency Energy Harvesting (RFEH) rectenna systems operating at the 2.45 GHz frequency band. The proposed antenna structure features a unique circular patch geometry with strategically removed portions on the right and left sides, combined with the incorporation of a Defective Ground Structure (DGS). The antenna was designed using the commercially available CST Microwave Studio software and subsequently fabricated and characterized through rigorous measurements conducted at the Indonesia Digital Test House. Measurement results demonstrate a significant bandwidth enhancement, covering a wide operating frequency range from 1.780 GHz to 4.390 GHz, with a measured peak gain of 3.41 dBi at 2.45 GHz. The antenna exhibits circular polarization with an exceptionally low measured axial ratio of 0.080 dB. The radiation pattern analysis reveals directional radiation characteristics in the x-z plane, while the y-z plane exhibits near-omnidirectional radiation. These results, obtained through a combination of rigorous simulations and accurate measurements, demonstrate the feasibility and effectiveness of the proposed antenna design for practical RFEH applications.

Keywords: circular polarization, radio frequency energy harvesting, wideband microstrip antenna

I. INTRODUCTION

The pervasive use of wireless technologies in modern society has resulted in a significant amount of electromagnetic energy being emitted into the environment. While these wireless devices enable seamless connectivity and communication, a substantial portion of the radiated energy is wasted. This wasted energy presents a significant opportunity for sustainable energy harvesting. By leveraging the principles of RF energy harvesting, we can effectively capture and utilize this ambient energy to power a wide range of electronic devices, including wireless sensor networks, wireless power transfer systems, wireless charging infrastructure, and various Internet of Things (IoT) devices. This approach offers a promising solution to the challenges associated with battery reliance, enabling continuous and sustainable operation of these devices while minimizing environmental impact. Recent advancements in RF energy harvesting technologies, coupled with the increasing availability of RF energy sources, have generated significant interest in this field, paving the way for a future where a wide range of electronic devices can be powered wirelessly and sustainably [1, 2].

Effective Radio Frequency Energy Harvesting (RFEH) systems rely heavily on rectennas, which integrate an antenna and a rectifier circuit. Conventional rectennas, however, typically exhibit narrowband characteristics, resulting in limited efficiency in harvesting RF energy across a wide range of frequencies. This limitation significantly restricts the practical applications of RFEH systems. To overcome this challenge, the development of miniaturized broadband rectennas is crucial. These advanced rectennas can efficiently convert ambient RF energy into DC power, enabling the operation of a wide range of self-powered electronic devices, including electronic watches, smart gadgets, mobile phones,

and various sensor applications. Broadband and multiband antennas play a pivotal role in enabling the efficient operation of these broadband rectennas, particularly at low input power levels, by effectively harvesting RF energy across a broad spectrum of frequencies [3].

Microstrip antennas, also known as patch antennas, have emerged as a prominent technology in microwave and millimeter-wave applications due to their compact size, lightweight structure, and ease of fabrication. These antennas find widespread applications in various wireless systems, including wireless communications, radar systems, mobile networks, and consumer electronics such as mobile phones and tablets. A typical microstrip antenna consists of a metallic patch conductor, a dielectric substrate, and a ground plane. Key advantages of microstrip antennas include their small size, ease of integration with other electronic components, and relatively low production costs [4]. In recent years, the increasing demand for advanced wireless systems, particularly those utilizing circular polarization (CP) techniques, has spurred significant research efforts towards the development of high-performance microstrip CP antennas [5].

Circularly polarized (CP) antennas are highly advantageous in a wide range of wireless systems, including GPS, RFID, WLAN, WPT, RFEH, and biomedical applications. The primary advantage of CP antennas lies in their reduced sensitivity to orientation changes, making them highly robust in dynamic environments where the antenna orientation may vary significantly [6]. Common examples of CP antennas include corner-cut microstrip antennas, helix antennas, and spiral antennas.

Microstrip antennas have established themselves as a crucial technology in a wide range of military and commercial

applications. However, the ongoing miniaturization of wireless devices necessitates the development of increasingly compact antenna solutions. This has driven researchers to explore various techniques for reducing antenna size while maintaining performance [7]. Radio Frequency Energy Harvesting (RFEH) systems are particularly vital for powering energy-constrained applications such as wireless sensor networks, which often operate in resource-limited environments. The demand for high-efficiency energy harvesting has spurred the need for innovative approaches to enhance the performance of these systems. Microwave engineering has emerged as a promising technology for improving the efficiency and effectiveness of RFEH systems [8]. This paper will provide a comprehensive overview of the key components of RFEH systems, with a primary focus on the design, simulation, and fabrication of microstrip receiving antennas, which play a critical role in the efficient harvesting of ambient RF energy.

II. RFEH SYSTEM

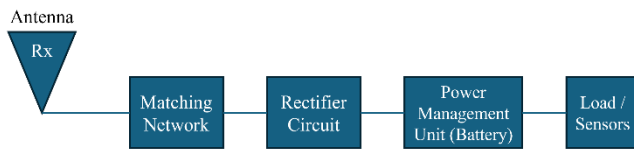


Fig.1. Block Diagram of RFEH

Radio Frequency (RF) energy harvesting offers a promising solution for powering various applications in environments where other ambient energy sources like light, vibration, and thermal gradients are unavailable. This process involves converting electromagnetic energy from the surrounding environment into usable electrical energy. An RF energy harvesting system, or rectenna, typically comprises a receiving antenna to capture RF signals, an impedance matching network to optimize power transfer, and a rectifier circuit to convert the captured RF energy into DC power. As illustrated in Fig. 1, the receiving antenna can capture RF signals from various sources, including TV towers, FM/AM radio stations, mobile phones, base stations, and wireless networks. Depending on the specific application, the antenna can be designed to operate on a single frequency band, multiple bands, or even over a broad range of frequencies to efficiently harvest energy from different sources [9].

A. Matching Network

In RF energy harvesting systems, an impedance matching network is indispensable for maximizing power transfer from the receiving antenna to the rectifier circuit, thereby minimizing transmission losses and enhancing voltage gain and sensitivity [10]. To achieve optimal performance, matching circuits typically employ a combination of resistive and reactive components (inductors and capacitors) to minimize power dissipation. The successful design of the matching network is critical for achieving optimal system output. However, the non-linear characteristics of the rectification device, which exhibit variations with changes in input power and frequency, particularly in ambient RF environments, pose significant challenges in the design process. Moreover, the fluctuating nature of ambient RF power levels demands the design of matching networks that can effectively operate over a wide range of input power levels. The rectifier circuit plays a crucial role in converting

the RF signals captured by the antenna into a usable DC voltage [11].

B. Rectifier Circuit

A microwave rectifier is a device that converts received RF power into DC power. A rectenna, a key component in RF energy harvesting systems, integrates a receiving antenna and a microwave rectifier circuit. These circuits typically utilize diodes and impedance matching networks to generate DC voltage. The efficiency of the rectification process is highly dependent on impedance matching. Typical RF-DC conversion efficiencies range from moderate levels, with the highest reported values reaching 60% at 5.8 GHz and approximately 50% at 2.45 GHz.

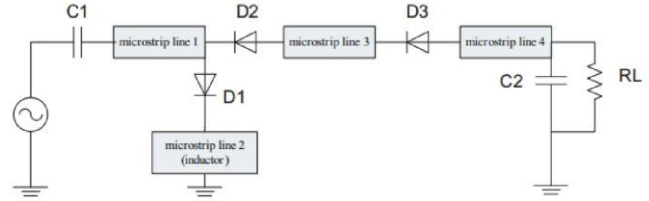


Fig.2. Rectifying circuit

Fig. 2 shows one of the structures of rectifier circuits and the formulas for estimating the rectification efficiency are as follow [12] [13]:

$$\eta_0 = \frac{\text{DC Output Power}}{\text{Incident RF Power}}$$

$$\eta_c = \frac{\text{DC Output Power}}{\text{Incident RF Power} - \text{Reflected RF Power}} = \frac{V_0^2}{R_L P_R}$$

Where η_0 is the overall efficiency, η_c is the rectifier conversion efficiency, P_R is the received RF power of the rectifier circuit and V_0 is the DC output voltage across the load resistor, R_L .

C. Receiving Antenna

The preceding sections have outlined the key components involved in generating, matching, and converting RF power within an RFEH system. However, the successful operation of any RFEH system ultimately relies on the effective capture of ambient RF energy. This crucial task is performed by the receiving antenna. The surrounding environment contains a multitude of sources of ambient RF energy, and the receiving antenna is responsible for capturing this energy and delivering it to the subsequent stages of the system. By combining an antenna with a rectifier, we create a rectenna, a fundamental unit for RF energy harvesting. To optimize energy harvesting efficiency, it is essential to employ antennas with desirable characteristics such as wide bandwidth, wide-angle reception, and circular polarization. These characteristics enhance the ability of the antenna to capture RF energy from various directions and mitigate the impact of potential misalignments between the receiving antenna and the source of RF energy. Notably, circular polarization offers a distinct advantage in RFEH systems. By utilizing circular polarization, we can minimize losses caused by cross-polarization, which arise when the polarization of the received signal differs from the polarization of the receiving antenna. This inherent robustness of circular polarization enhances the efficiency of power reception and improves the overall performance of the RFEH system.

In the past, a wide range of rectenna designs, including single-band, multi-band, and broadband configurations, have been proposed in the literature [5-14]. While significant progress has been made, existing designs often exhibit limitations. For instance, a 2.45 GHz rectenna incorporating a cross-shaped slot achieves a size reduction of 32.5% [3] but suffers from low efficiency (38.2%). A high-performance 2.45 GHz rectenna with a gain of 8.6 dBi has been reported [6], but its use of an expensive RT/Duroid 6002 substrate limits its practicality. Dual-band operation has been achieved through various techniques, including the use of SRRs [10], arc-shaped slots [11], tree-shaped patches [12], and aperture-coupled multilayer structures [13]. However, many existing designs exhibit limitations such as polarization sensitivity, low antenna gain, increased design complexity, and an inability to generate DC power solely through antenna operation.

This paper presents the design, simulation, and fabrication of a compact microstrip patch antenna operating at 2.45 GHz, specifically intended for integration into Radio Frequency Energy Harvesting (RFEH) systems. To achieve the desired performance, a novel approach is employed, utilizing a circular patch geometry with strategically removed portions on the right and left sides, coupled with the incorporation of a Defective Ground Structure (DGS). This unique design is expected to exhibit several key advantages, including circular polarization (CP) capability, which enhances robustness in varying signal environments, wideband operation to capture a wider spectrum of RF energy, wide-angle reception to improve energy collection from various directions, and cost-effective fabrication to facilitate practical implementation. The subsequent sections of this paper will provide a detailed account of the research, design, simulation, and fabrication process of this 2.45 GHz microstrip patch antenna, along with an analysis of its performance characteristics.

III. METHODOLOGY OF ANTENNA DESIGN

The design of the microstrip patch antenna follows a rigorous iterative process.

1. A mathematical model is developed based on established electromagnetic principles to predict the antenna's behavior.
2. This theoretical model is then validated and refined through rigorous simulations. If the simulated results do not meet the desired performance criteria, the design parameters are iteratively adjusted and re-simulated until the desired performance is achieved.
3. Finally, the optimized design is fabricated, and its actual performance is experimentally verified through measurements.

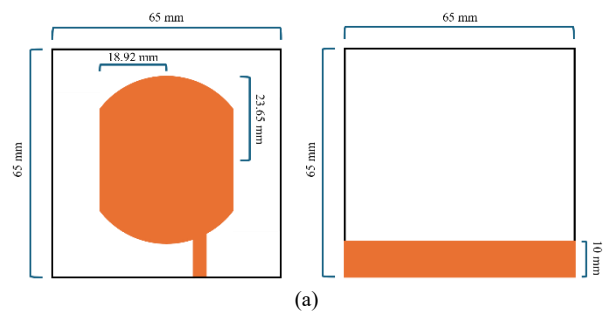
The performance of a microstrip patch antenna is strongly influenced by several critical parameters, including the resonant frequency, the dielectric constant of the substrate, and the substrate thickness [3]. In this design, FR-4 is selected as the substrate material due to its favorable combination of cost-effectiveness and suitable dielectric properties. FR-4 exhibits a relative dielectric permittivity of $\epsilon_r = 4.3$, a dissipation factor ($\tan \delta$) of 0.02, and a thickness of 1.6 mm. The overall dimensions of the antenna are constrained to 65 mm x 65 mm. A schematic representation of the basic antenna setup is presented in Figure 3.

IV. ANTENNA DESIGN

The prospective antenna prototype is a conventional microstrip antenna synthesized on an FR-4 substrate, a widely used and cost-effective material with a relative dielectric permittivity (ϵ_r) of 4.3, a thickness of 1.6 mm, and a dissipation factor ($\tan \delta$) of 0.02. The integration of a Defective Ground Structure (DGS) into the antenna design is anticipated to significantly improve its performance. Specifically, the DGS is expected to increase the impedance bandwidth of the antenna while potentially shifting the resonant frequency.

To ensure optimal performance, the antenna design incorporates several key strategies. Firstly, to achieve wideband operation, the impedance bandwidth is optimized, and circular polarization is implemented. Secondly, to enhance overall efficiency, the circular patch geometry is modified with strategically removed sections on the right and left sides. As depicted in Figure 3, a Defective Ground Structure (DGS) is integrated into the design. The DGS serves to broaden the impedance bandwidth and may also induce a shift in the resonant frequency. The proposed design is centered around an operating frequency of 2.45 GHz.

The geometry of the proposed antenna is illustrated in Figure 3. To achieve the desired performance characteristics, namely wideband operation and circular polarization (CP) radiation, the design incorporates a novel approach. The proposed radiating element adopts a modified circular patch with bilateral truncated edges, integrated with a Defective Ground Structure (DGS) to induce circular polarization and extend the impedance bandwidth. This modified patch geometry is further enhanced by the integration of a Defective Ground Structure (DGS), as depicted in Figure 3(a). The overall dimensions of the antenna are 65 mm x 65 mm. The circular patch has a radius of 23.65 mm, with 20% of the radius removed from both the right and left sides, resulting in 18.92 mm from the center to the edge of the patch. To further enhance performance and promote omnidirectional radiation, the antenna features a rectangular ground plane with a width of 10 mm at the bottom. The design of the antenna was conducted using CST Studio Suite Software, followed by rigorous simulations to optimize performance. As illustrated in Figure 3(b), the fabricated antenna exhibits a compact form factor, making it suitable for various applications. The small dimensions of the antenna, coupled with its wideband operation and circular polarization capabilities, make it particularly well-suited for integration into Radio Frequency Energy Harvesting (RFEH) systems for wireless sensors, which often have stringent size constraints and operate in challenging environments.



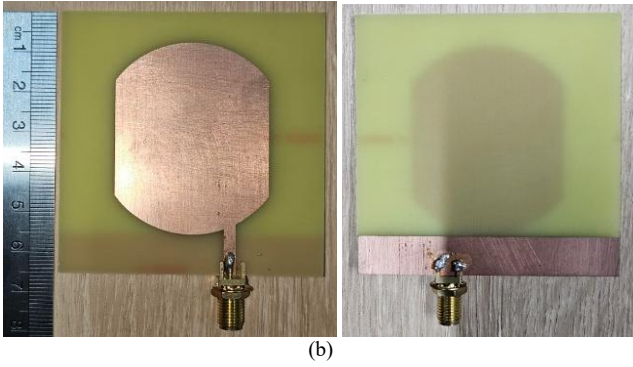


Fig.3. Design of Antenna (a) simulation, (b) fabrication

V. THE ANTENNA PERFORMANCES

To validate the performance of the proposed antenna, this section presents a comparative analysis of key antenna parameters, including Return Loss, VSWR, Axial Ratio, Radiation Pattern, and Gain. These parameters were evaluated both through simulations conducted using CST software (as described in Section IV) and through experimental measurements. The measurements were performed using a Rohde & Schwarz ZNA43 Vector Network Analyzer within a fully anechoic chamber at the Indonesia Digital Test House (IDTH) laboratory. Figure 4 illustrates the measurement setup within the anechoic chamber.

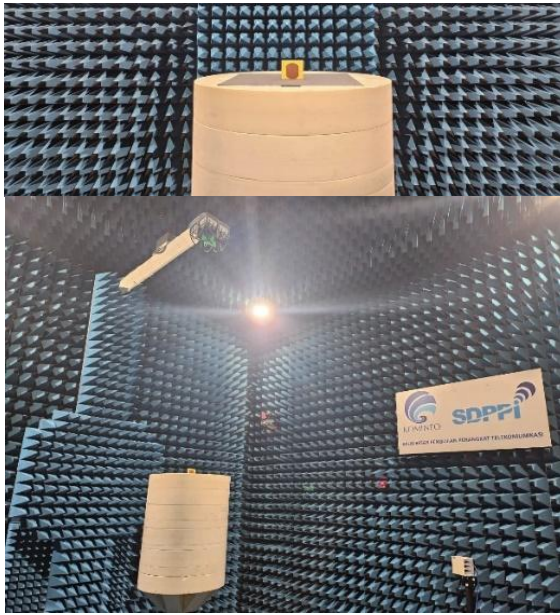


Fig.4. Measurement Setup

A. Return Loss and VSWR

Figure 5 presents a comparative analysis of the simulated and measured return loss of the antenna across a frequency range extending from 1 GHz to 6 GHz. At the designated operating frequency of 2.45 GHz, the simulated return loss exhibits a value of -24.892 dB, while the measured return loss is -22.975 dB. A well-designed antenna typically exhibits a return loss value below -10 dB [14], indicating efficient impedance matching and minimal signal reflection. Based on these results, the operating frequency band is determined to be 1.735 - 4.585 GHz from simulation and 1.780 - 4.390 GHz from measurement, demonstrating the wideband characteristics of the proposed antenna design. This broad

operating bandwidth is a significant advantage for energy harvesting applications, as it enables the efficient capture of RF energy from a diverse spectrum of sources. Notably, this frequency range encompasses numerous technologies widely utilized in Indonesia, including cellular frequencies such as GSM1800MHz, LTE1800MHz, WCDMA2100MHz, LTE2100MHz, and LTE2300MHz, Wi-Fi frequencies such as WLAN2.4GHz, and satellite communication bands at 2.6 GHz and 3.5 GHz. This wideband capability ensures that the antenna can effectively harvest energy from a diverse range of RF sources, maximizing its potential for energy harvesting applications in various real-world scenarios, including wireless sensor networks, Internet of Things (IoT) devices, and other low-power applications.

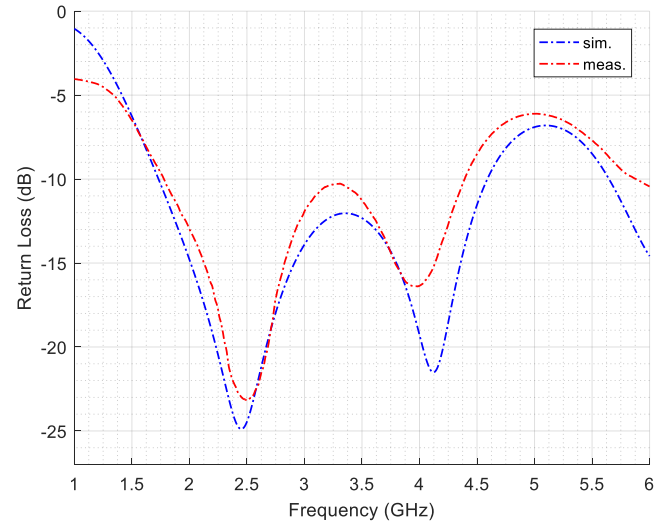


Fig.5. Return Loss

VSWR, or Voltage Standing Wave Ratio, quantifies the ratio of the maximum to minimum radio frequency voltage levels at the antenna's input/output port [15]. An ideal VSWR value of 1 signifies perfect impedance matching, minimizing signal reflections. While an ideal VSWR of 1 is difficult to achieve in practice, acceptable values typically fall below 2 [16]. Figure 6 illustrates the simulated and measured VSWR values across the operating frequency range. At the 2.45 GHz operating frequency, the simulated VSWR is 1.121, while the measured VSWR is 1.177, both of which fall well within the acceptable limit. These results demonstrate effective impedance matching and validate the antenna's suitability for operation at the 2.45 GHz frequency.

Minor discrepancies between the simulated and measured VSWR values can be attributed to variations in material properties between the simulated model and the actual fabricated prototype. The CST Microwave Studio simulation utilizes a virtual model of the FR-4 substrate with a defined dielectric constant ($\epsilon_r = 4.3$), a loss tangent ($\tan \delta$) of 0.02, and a thickness of 1.6 mm. However, in the actual fabrication process, slight variations in the material properties of the FR-4 substrate, particularly the loss tangent ($\tan \delta$), may occur. These subtle variations in material properties can influence the antenna's performance and contribute to the observed differences between simulated and measured VSWR values.

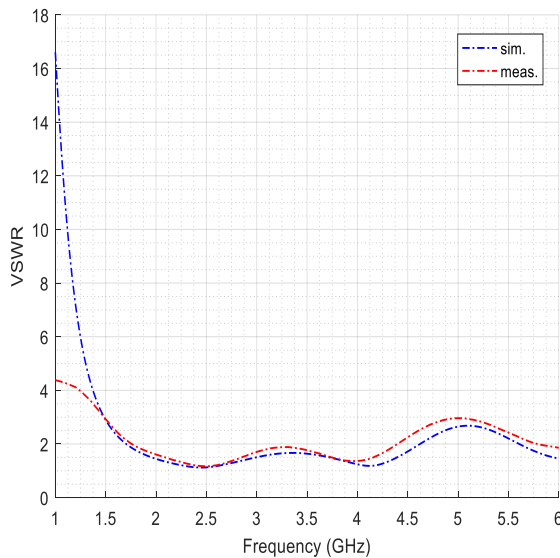


Fig.6. VSWR

B. Polarization

The Axial Ratio (AR) is a crucial parameter that characterizes the circular polarization of an antenna. Ideally, the axial ratio for perfectly circularly polarized fields is 0 dB. While achieving an ideal value of 0 dB is challenging in practice, deviations from circular polarization are generally considered acceptable within a 3 dB limit. Figure 7 presents the simulated and measured axial ratio curves of the antenna. At the 2.45 GHz operating frequency, the simulated and measured axial ratios are 2.209 dB and 0.080 dB, respectively. Although a slight discrepancy exists between the simulated and measured values, both results fall well below the 3 dB threshold, confirming the successful generation of circular polarization.

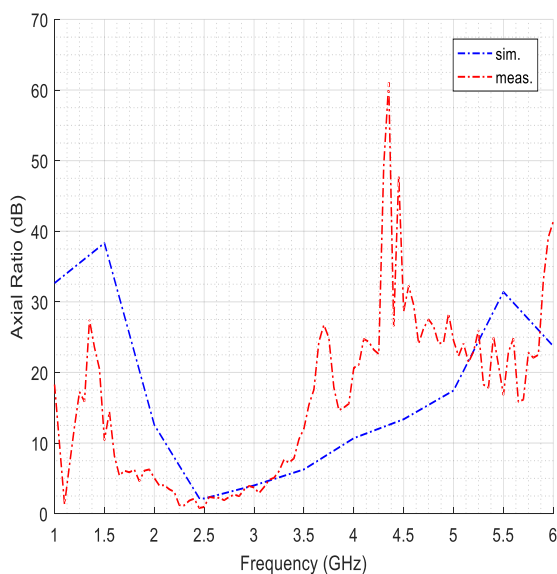


Fig.7. Axial Ratio

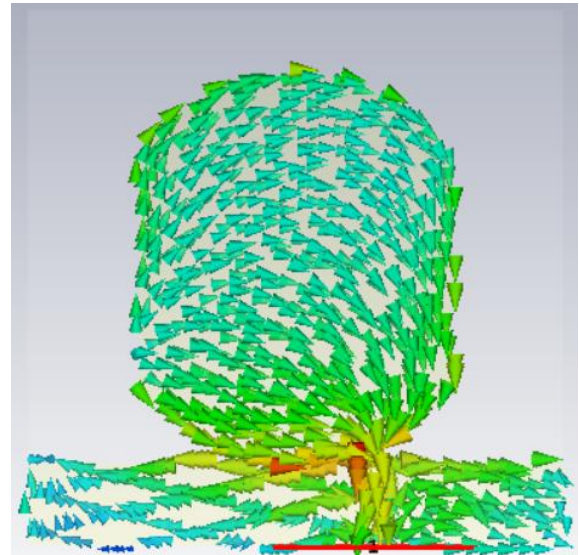


Fig.8. Power Flow

Furthermore, the simulation results of the receiving antenna, depicted in Figure 8, indicate a right-handed rotation of the power flow, confirming the generation of Right-Handed Circular Polarization (RHCP). Circular polarization offers several key advantages in Radio Frequency Energy Harvesting (RFEH) systems. By mitigating the impact of polarization mismatch between the transmitting and receiving antennas, circular polarization enhances the efficiency of power reception. This is particularly beneficial in scenarios where the polarization of the transmitted signal may deviate from the ideal orientation, such as variations in the orientation of the transmitting antenna (e.g., horizontal vs. vertical polarization).

C. Radiation Pattern and Gain

In the field of antenna design, the radiation pattern, or antenna pattern, describes the directional characteristics of the radio waves emitted by the antenna, revealing the spatial distribution of radiated power. Antenna gain is a crucial parameter that quantifies the maximum effectiveness with which the antenna can direct the power received from the transmitter towards a specific direction. Figure 9(a) presents a 3D visualization of the radiation pattern, comparing the simulated and measured results. The red beam in the plot indicates the direction of maximum radiation, which is observed to be directed towards the front, back, top, and partially towards the right and left sides. The maximum gain at the operating frequency of 2.45 GHz is determined to be 3.872 dB from simulation and 3.41 dB from measurement, demonstrating good agreement between the simulated and measured results. Figures 9(b) and 9(c) depict the 3D radiation patterns in the front and back planes, respectively, further corroborating the close agreement between simulation and measurement results. The observed radiation pattern exhibits a near-omnidirectional characteristic in all directions except downwards, indicating that the antenna radiates energy relatively uniformly in the horizontal plane. This near-omnidirectional radiation pattern is highly desirable for many applications, as it ensures that the antenna can effectively transmit and receive signals from various directions without the need for precise antenna orientation.

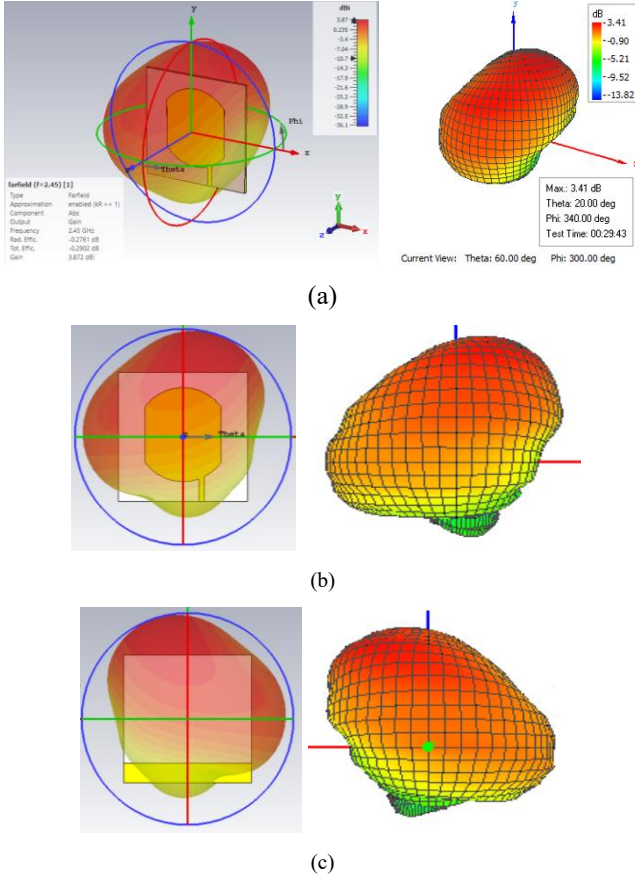


Fig.9. The simulation and measurement radiation pattern in 3-dimensional.
(a) perspective, (b) front, (c) back

Figures 10(a) and 10(b) illustrate the radiation patterns in the x-z and y-z planes, respectively. The radiation pattern analysis reveals directional radiation characteristics in the x-z plane, while the y-z plane exhibits a near-omnidirectional radiation pattern. A comparison of the simulated and measured radiation patterns reveals good agreement. The peak gain is observed in the positive direction of the z-axis, perpendicular to the radiator surface. The beamwidths in both the x-z and y-z planes exhibit similar characteristics. While the measured radiation pattern exhibits some minor fluctuations due to the 5-degree measurement step, the overall shape and characteristics closely resemble the simulated results.

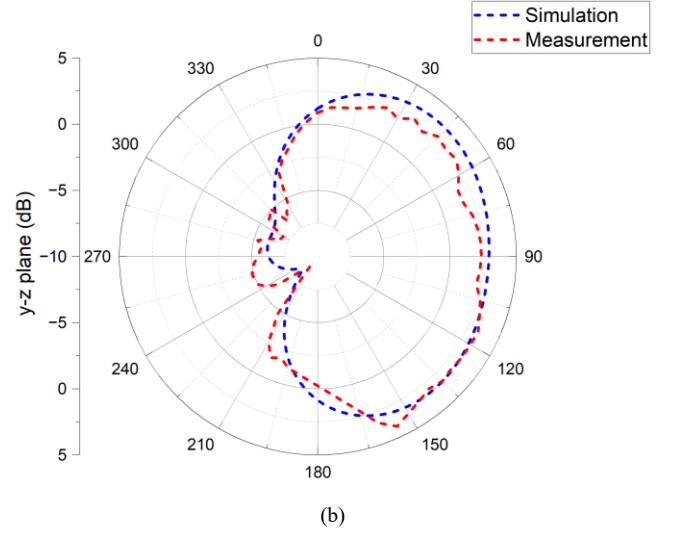
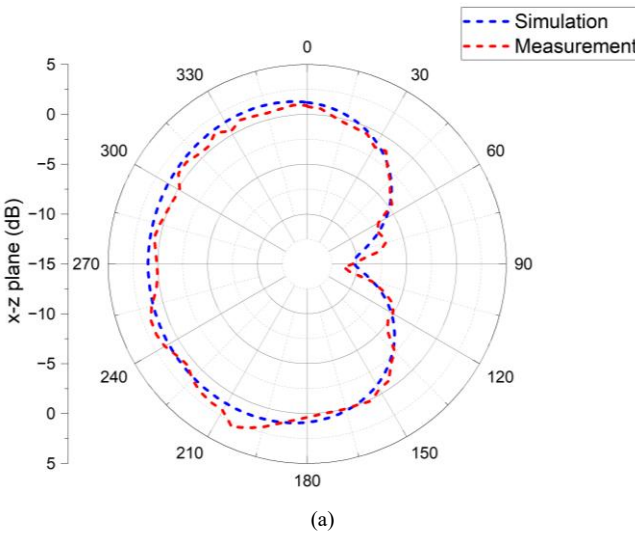


Fig. 10. Simulated and measured 2D radiation patterns.
(a) x-z plane, (b) y-z plane

D. Performance Comparison

Table 1 summarizes the comparison of antenna parameters obtained from simulation and measurement. While minor discrepancies exist between the simulated and measured results, the overall performance demonstrates good agreement, validating the design and fabrication of the antenna. For efficient RF energy harvesting, the antenna should exhibit broad bandwidth, moderate gain, and an omnidirectional radiation pattern. The fabricated antenna meets these criteria, making it suitable for implementation in RFEH systems. Effective RF energy harvesting also necessitates a properly impedance-matched rectifier circuit. The system is capable of operating across a wide range of frequencies, including 1.8–2.2 GHz, 2.3 GHz, 2.4 GHz, 2.5 GHz, 3.2 GHz, 3.4–3.6 GHz, and 4.2–4.3 GHz, encompassing numerous communication bands. This enables the harvested RF energy to power various electromagnetic devices, providing a reliable energy source for applications requiring continuous operation.

TABLE I. COMPARISON BETWEEN SIMULATION AND MEASUREMENT

Parameter	Result at 2.45 GHz	
	Simulation	Measurement
Return Loss	-24.892 dB	-22.975 dB
VSWR	1.121	1.177
Axial Ratio	2.209 dB	0.080 dB
Radiation Pattern	Near-omnidirectional	Near-omnidirectional
Gain	3.872 dB	3.41 dB
Operating band ^a	1.735 - 4.585 GHz	1.780 - 4.390 GHz

^a obtained from Return Loss value ≤ -10 dB

VI. COMPARISON WITH RELATED WORK

Table II presents a comprehensive comparative analysis of the proposed antenna design with a selection of relevant research findings from recently published literature. This comparative analysis provides valuable insights into the unique characteristics and potential advantages of the proposed design within the context of existing research in the

field. By comparing key performance parameters and design methodologies, this analysis facilitates a deeper understanding of the proposed design's strengths and

weaknesses, and its potential contributions to the advancement of antenna technology.

TABLE II. COMPARISON OF THE RELATED WORK WITH SUGGESTED DESIGN

Reference	Dimension (mm ²)	Height of Substrate (mm)	Substrate Material	Frequency band (GHz)	Polarization	Radiation Pattern
[3]	40 x 45	1.6	FR-4	1.975 to 4.744	Linear	-
[8]	240 x 150	1.6	FR-4	2.45	Linear	High directional
[17]	16 x 22	1.6	FR-4	4.06 to 10.02	Circular	Near omnidirectional
[18]	53 x 20	0.5	Teflon	2.4 to 3.5	Linear	Omnidirectional
[19]	44 x 44	1.6	FR-4 (glass fiber)	2.25 to 4.0	Circular	Near omnidirectional
[20]	37 x 33	1.6	FR-4	3.1 to 10.6	Circular	Near omnidirectional
[21]	39.3 x 47.5 (patch)	1.6	Rogers RT/duroid	2.45	Circular	Omnidirectional
[22]	60 x 60	1.6	FR-4	2.39 to 2.45	Circular	Directional
[23]	69.95 x 39.5	0.508	Arlon	2.42 to 2.48	Dual linearly polarized	-
[24]	40 x 35	1.6	FR-4	1.84 to 2.95	Linear	Omnidirectional
[25]	40 x 35	1.6	FR-4	2.78 to 4.86	Linear	Omnidirectional
Proposed	65 x 65	1.6	FR-4	1.780 to 4.390	Circular	Near omnidirectional

This work demonstrates a significant advancement in the design of energy harvester antenna at 2.45 GHz. The system incorporates a compact antenna with wideband characteristics and circular polarization, achieved through the implementation of a simplified geometry structure. This approach enhances the overall performance of the rectenna. The antenna exhibits a wide frequency range, circular polarization, and near-omnidirectional radiation characteristics, making it well-suited for powering low-power sensors in diverse RFEH applications. The combination of these features enhances the efficiency and robustness of the energy harvesting system.

VII. CONCLUSION

This research demonstrates the successful operation of a microstrip antenna at the 2.45 GHz frequency. The performance of the antenna was validated through both simulation and measurement. The simulated and measured operating bandwidths were found to be 1.735 - 4.585 GHz and 1.780 - 4.390 GHz, respectively. The simulated and measured axial ratios were 2.209 dB and 0.080 dB, respectively. These results demonstrate that the antenna exhibits desirable characteristics for a wideband, circularly polarized antenna, including broad bandwidth, low axial ratio, and a near-omnidirectional radiation pattern. The compact size of the antenna makes it a promising candidate for integration into Radio Frequency Energy Harvesting (RFEH) systems. However, to fully realize its potential for energy harvesting, further research is necessary to develop and integrate a suitable rectifier circuit that can efficiently convert the harvested RF energy into DC output, thereby creating a complete rectenna system.

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