A Compact and Highly Efficient Circularly Polarized UWB Rectenna for Wireless Power Transfer Application

Nabanita Saha
The University of Texas at Dallas
Dallas, TX 75080, USA

Sunanda Roy
The University of Texas at Dallas
Dallas, TX 75080, USA

Ifana Mahbub
The University of Texas at Dallas
Dallas, TX 75080, USA

2024 IEEE Radio and Wireless Symposium (RWS) | 979-8-3503-4045-7/24/$31.00 ©2024 IEEE | DOI: 10.1109/RWS56914.2024.10438555

***Abstract*—In this paper, a low-profile and compact circular polarized (CP) rectenna with a compact ultrawideband (UWB) rectifier circuit to transfer power wirelessly at 3.2 GHz is presented. The size of the proposed rectenna is 0.19λ_o × 0.19λ_o. The new L-L input impedance matching demonstrates increased stability and maintains a consistently stable power conversion efficiency across a wider range of input power levels. With a compact size, the UWB rectifier offers an impressively wide bandwidth spanning from 2 to 3.5 GHz. The maximum power conversion efficiency (PCE) of 60% has been measured with a 50Ω load at 3.2 GHz. The power conversion efficiency (PCE) of the rectifier reaches up to 45% at -10 dBm input power level at 3.2 GHz frequency. The maximum PCE of the rectifier is 60% at 0 dBm input power. The proposed rectenna offers excellent resilience to misalignment due to its circularly polarized receiving antenna.**

***Index Terms*—Circular polarized, Wireless power transfer, ultrawideband.**

I. Introduction

In recent years, wireless power transfer system has been a vibrant focus in many domains, ranging from medical devices, consumer electronics, and electric vehicles to industrial automation and remote sensors [1]. In the modern era of high transmission rates and extended communication ranges, Radio Frequency (RF) and Electromagnetic (EM) technologies have a pivotal role to play due to some advantages such as eliminating the need for physical connectors, enabling hassle-free charging, reducing wear and tear on devices, and providing a safer and more convenient method of power transfer [2].

In wireless power transfer (WPT) systems, rectennas play a crucial role in receiving electromagnetic (EM) radiation and converting it into direct current (DC). The power conversion efficiency serves as the major indicator of the performance in this process. The design of a rectenna involves considerations such as the efficiency of energy conversion, the matching of antenna impedance with rectifier's input impedance, and the optimization of components to achieve maximum power output. As technology advances, rectennas are being explored for more efficient and widespread applications in the field of wireless power transmission. For transmitting power wirelessly to a moving target, a rectenna needs to have the following characteristics: 1) compact structure, 2) low profile, 3) sufficient gain, and 4) resilience to the loss due to the misalignment between the transmitter and receiver. Unlike linearly polarized antennas, circularly polarized (CP) antennas demonstrate a higher tolerance to misalignment between the transmitter and the receiver. Circularly polarized rectennas can receive power from various orientations and can mitigate multipath interference which makes them highly adaptable for dynamic environments. Their capability to efficiently capture energy from diverse angles and reject cross-polarized signals enhances overall efficiency in wireless power harvesting applications. For wireless energy transmission to mobile targets, they are better suited than the linearly polarized rectennas [3].

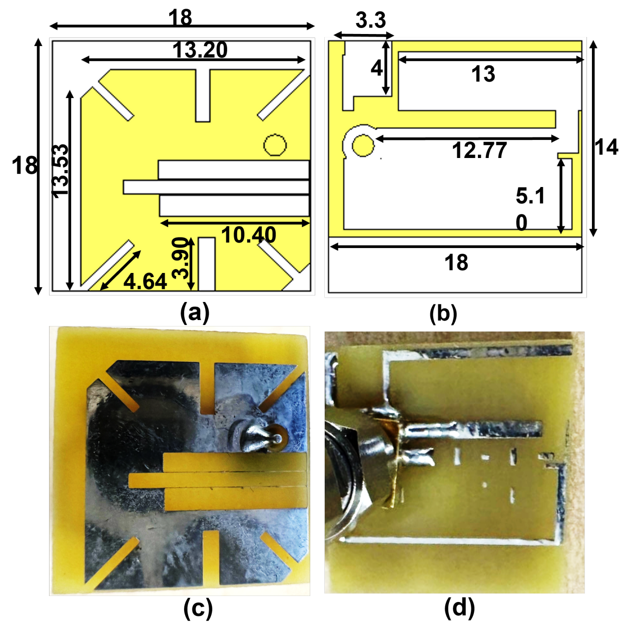

Fig. 1. Layout of the proposed rectenna. Simulated models (a) top view. (b) bottom view; Fabricated prototypes (c) top view. (d) bottom view (Units: mm)

Rectenna designs frequently employ antennas with wide-slot and printed monopoles, but these antennas have bidirectional radiation characteristics [7]–[8], which not only cause low gain in radiation but also cause interferences for mutual coupling between the adjoining devices, decreasing the power conversion efficiency. A broadband rectenna integrated with

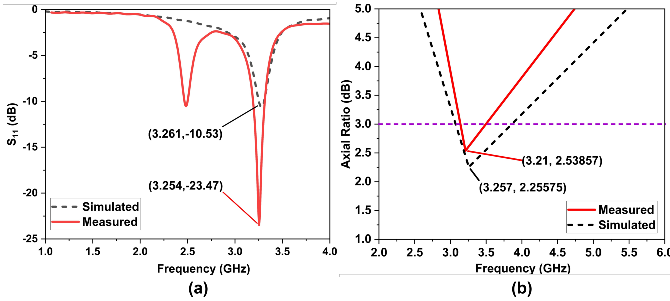

Fig. 2. Simulated and Measured performance parameters of the CP antennas. (a) S_{11}. (b) Axial ratio

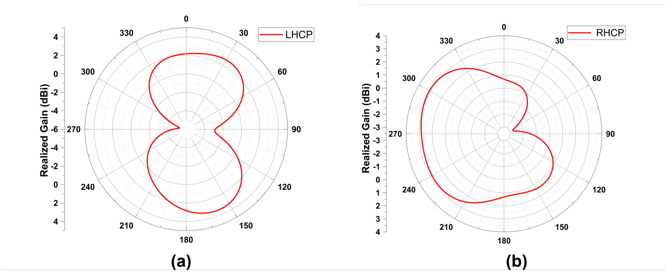

Fig. 3. Far-field radiation pattern (a) Left-hand circular polarization (b) Right-hand circular polarization

a varactor-based matching stub is demonstrated to achieve a more compact and simplified design [9]. The requirement for an extra biasing network made the system more complex. In addition, the varactor diode introduced additional losses and resulted in a non-uniform power conversion efficiency (PCE) throughout the intended frequency range.

The contributions of this work are: 1) design of a low-profile and compact circular polarized antenna to transfer power to the mobile targets, and 2) implementation of a novel approach to create an ultra-wideband (UWB) rectenna with high efficiency by utilizing a resonant structure. To enable easy broadband optimization, the matching stub incorporates a *LL*-parallel tank circuit, which provides frequency-dependent impedance transformation. Since the impedance of the *LL* circuit changes with frequency, the designed stub transforms into a frequency-dependent impedance matching stub. This feature allows for an effective impedance setting in the rectifier circuitry.

II. Design of the Antenna and the Rectifier

A. Design of the antenna

The design layout with the performance parameters of the circular polarized patch rectenna is depicted in Fig. 1. The slotted circular polarized antenna has the benefit of small size and circular polarization. The simulation process is conducted using Computer Simulation Technology (CST) software. The receiver antenna's dimension is $0.19\lambda_o \times 0.19\lambda_o$ (18 mm × 18 mm) at 3.2 GHz frequency. The CP antenna is designed on an FR4 substrate which is 1.6 mm thick. The dielectric constant of the FR4 substrate is 4.3 and the loss tangent is 0.02. For both the radiating patch and the ground patch, Copper (Cu) has been selected as a metallic conductor. The thickness of the copper layer is 0.018 mm. The slots of the radiating patch (top layer) and the ground patch(bottom layer) are designed in a manner that provides the feature of circular polarization. Apart from enabling CP operation, the slots also extend the current path of the radiation patch, effectively reducing the antenna size at the same frequency.

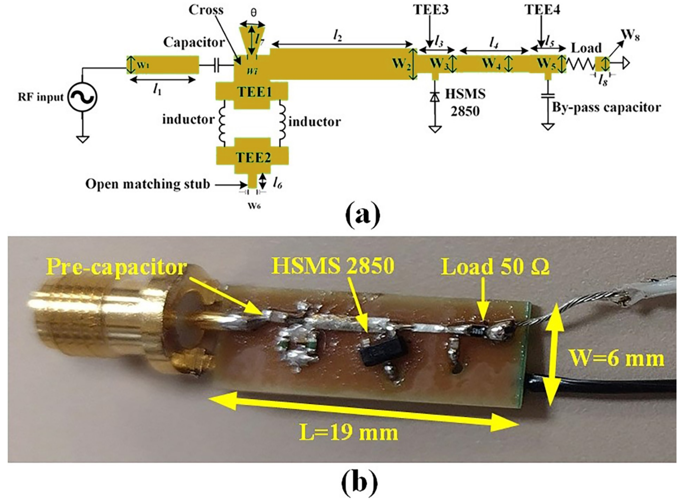

Fig. 4. Proposed (a) rectifier circuit structure (b)Fabricated prototype

B. Design of the rectifier

Using a resonant structure as the matching stub, a novel method for creating a highly effective rectenna to apply in an ultra-wideband (UWB) system is proposed in this study. In the proposed rectifier circuit, an *LL* (LC-like) tank resonant circuit is connected parallely with an open matching stub. This open stub is strategically placed between the pre-capacitor and the rectifier to create a frequency-dependent matching structure to achieve impedance matching across a broad range of frequencies. The schematic design of the proposed rectifier circuit is illustrated in Fig. 4(a) and the fabricated prototype is depicted in Fig. 4(b). To protect the receiving antenna from the potential damage caused by reverse rectified DC current, a pre-capacitor with the value of 6.8 pF is incorporated. To address low to medium power levels, a Schottky diode of model number HSMS 2850, is connected to the circuit in a shunt configuration. The breakdown voltage and the built-in voltage of the schottky diode is 3.8 V and 0.35 V respectively. The Schottky diode is connected with a resistance of 50 Ω in series, and two inductors of 1 nH in parallel. The voltage waveforms are smoothened and high-order harmonics are decreased using a bypass capacitor with the value of 0.5 pF, which functions as an output filter along with the pre-capacitor. The matching circuit is designed using a series of microstrip lines with increasing impedances in a gradual manner.

III. Simulated and Experimental Results

The S_{11} values obtained from the simulation and the measurement of the designed antenna are shown in Fig. 2(a). The simulated and the measured values show good agreement. Fig. 2(b) illustrates the simulated and measured axial ratio (AR).

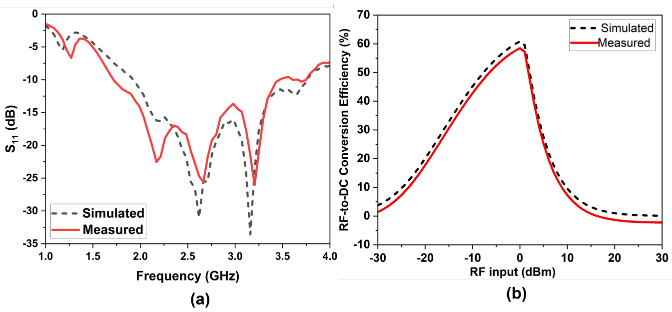

Fig. 5. (a) S_{11} parameter and (b) RF-to-DC conversion efficiency of the proposed UWB rectifier

TABLE I
PERFORMANCE COMPARISON OF THE RECTENNA WITH THE STATE-OF-THE ARTS

Parameters	[7]	[8]	This work
Frequency (GHz)	3.6	2.45	3.2
Polarization	LP	LP	CP GHz
Rectifier Dimension	51 mm × 88 mm	54 mm × 42 mm	19 mm × 6 mm
Input power level	0 dBm	0 dBm	0 dBm
Load resistance	3 kΩ	3.8 kΩ GHz	50Ω
Output voltage	1.3 V	4.2 V	1.5 V
PCE	9%	46.5%	60%

The value of the axial ratio is less than 3 dB, indicating the circular polarization. In Fig. 3, the LHCP and RHCP radiation patterns of the designed antenna at 3.2 GHz are illustrated. In this design, the dominating polarization of the RX antenna is left-handed circular polarization. The realized gain value of the antenna is 2.74 dBi.

The prototype as presented in Fig. 3(b) is fabricated to measure the performance parameters of the designed rectifier. The size of the area of the proposed rectifier is $19 \times 6\ mm^2$. The Keysight P5024A vector network analyzer (VNA) has been used to measure the S_{11} value of the CP antenna and the rectifier. The simulated and measured plot of the rectifier's scattering parameter against operating frequency is shown in Fig. 5(a). The UWB rectifier shows a highly wide bandwidth (from 2 to 3.5 GHz) and small dimension. The circuit's novel matching network results in a good match between the measured and simulated value of the S_11. The total power conversion efficiency (PCE) is defined as,

$$PCE(\%) = \frac{P_{outDC}}{P_{inAC}} \times 100\% \quad (1)$$

Here, P_{outDC} is DC output power and P_{inAC} is RF input power. The simulated and measured power conversion efficiency and the output voltage of the rectenna are plotted in Fig. 5(b) and Fig. 6, respectively. Across the measured input power range, the RF-to-DC conversion efficiency reaches 60% at an input power of 0 dBm. Additionally, the system achieves a 1.5 V output DC voltage with a load resistance of 50Ω. Table I shows a comparison of the performance parameters of this work with other state-of-the-art works. The proposed rectifier size is much smaller compared to the prior works. The PCE of the proposed rectenna is much higher than the prior works at 0 dBm input power level.

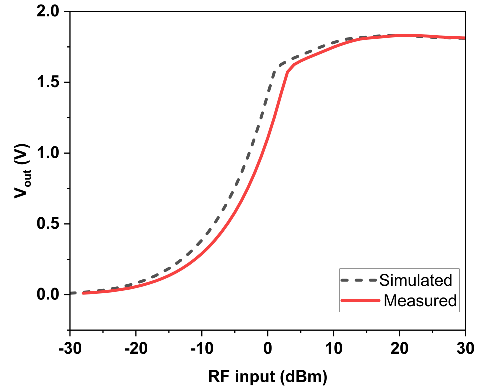

Fig. 6. Simulated and measured output voltage versus RF input power level of the rectenna

IV. CONCLUSION

In this paper, a compact and highly integrated circularly polarized rectenna is presented. Its lightweight and thin planar profile make it suitable for wireless power, especially when the location of the terminal varies with time. transfer systems. In the simulation, a peak power conversion efficiency of 60% has been obtained with 0 dBm input power at 3.2 GHz. With its exceptional performance, the proposed rectenna design is ideally suited for various practical, low-power devices. As a result, its applicability extends to various battery-free wireless applications.

ACKNOWLEDGMENT

This work is supported by the National Science Foundation (NSF) under grant No. ECCS 2309413.

REFERENCES

[1] Z. Zhang, H. Pang, A. Georgiadis and C. Cecati, "Wireless Power Transfer—An Overview," in IEEE Transactions on Industrial Electronics, vol. 66, no. 2, pp. 1044-1058, Feb. 2019, doi: 10.1109/TIE.2018.2835378.

[2] M. A. Ullah, R. Keshavarz, M. Abolhasan, J. Lipman, K. P. Esselle and N. Shariati, "A Review on Antenna Technologies for Ambient RF Energy Harvesting and Wireless Power Transfer: Designs, Challenges and Applications," in IEEE Access, vol. 10, pp. 17231-17267, 2022, doi: 10.1109/ACCESS.2022.3149276.

[3] J. S. Row, "The design of a squarer-ring slot antenna for circular polarization," IEEE Trans. Antennas Propag., vol. 53, no. 6, pp. 1967–1972, Jun. 2005.

[4] I. Adam et al., "A simple wideband electromagnetically fed circular polarized antenna for energy harvesting," Microw. Opt. Technol. Lett., vol. 59, no. 9, pp. 2390–2397, Sep. 2017.

[5] M.-J Nie, X.-X. Yang, G.-N. Tan, and B. Han, "A compact 2.45 GHz broadband rectenna using grounded coplanar waveguide," IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 986–989, 2015.

[6] Lu, P., Yang, X.-S., Li, J.-L. Wang, B.-Z. Polarization reconfigurable broadband rectenna with tunable matching network for microwave power transmission. IEEE Transactions on Antennas Propag. 64, 1136–1141 (2016)

[7] H. Tafekirt, J. Pelegri-Sebastia, A. Bouajaj and B. M. Reda, "A Sensitive Triple-Band Rectifier for Energy Harvesting Applications," in IEEE Access, vol. 8, pp. 73659-73664, 2020, doi: 10.1109/ACCESS.2020.2986797.

[8] C. -Y. Hsu, S. -C. Lin and Z. -M. Tsai, "Quadband Rectifier Using Resonant Matching Networks for Enhanced Harvesting Capability," in IEEE Microwave and Wireless Components Letters, vol. 27, no. 7, pp. 669-671, July 2017, doi: 10.1109/LMWC.2017.2711578.