All-Polarized Wideband Rectenna Array for Omnidirectional Wireless Energy Harvesting

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2024 IEEE Wireless Power Technology Conference and Expo (WPTCE) | 979-8-3503-4913-9/24/$31.00 ©2024 IEEE | DOI: 10.1109/WPTCE59894.2024.10557393

***Abstract*—In this work, a 3-D omnidirectional multiple polarized radio-frequency (RF) energy harvester (rectenna) array with broadband frequency coverages (2.4–3.1 GHz) is presented. The rectenna array strategically combines 12 single microstrip slot antenna elements placed in a transparent octahedral box. A broadband microstrip slot antenna based on multiple resonant stubs is proposed and studied. By utilizing two pairs of stubs embedded on a defective ground, a reflection coefficient of less than −10 dB can be achieved with broadband characteristics for applications of wireless local area network (WLAN). A broadband rectifier array is designed with 12 rectifier elements arranged in a 360-degree array. All elements are connected in parallel to achieve maximum DC combining and reduce losses caused by feed lines during array formation. The RF-DC conversation efficiency of the rectifier array is 75 % at an input power of 13 dBm. The experimental results show that this rectenna array works well with RF radiations at either horizontal or vertical polarization from various directions.**

***Keywords*—Rectenna array, broadband antenna, 3D omnidirectional, multiple polarization**

I. Introduction

In recent years, with the rapid development of wireless communication techniques and low-power equipment, the demand for battery-less wireless power charging circuits for wireless power transmission (WPT), and wireless energy harvesting (WEH) has increased significantly [1], [2].

Recently, many rectenna types have been reported to promote the application of WPT technology. High-efficiency, multi-band/broadband rectennas, and rectenna arrays represent popular ways to harvest energy that can power sensors [3]–[6]. Uniform rectenna arrays can harvest sufficient RF energy to power some low-power sensors because of their large energy capture areas. These rectennas typically require an increase in the antenna size or the use of complex circuit designs. Generally, ambient RF radiation is random, with multiple paths and polarizations. Using uniform rectennas or arrays to harvest the ambient RF energy has many limitations because of the complex RF environment.

In this work, we proposed an all-polarized wideband rectenna array for omnidirectional wireless energy harvesting. The rectenna array strategically combines 12 single microstrip slot rectenna elements placed in a transparent octahedral box. A broadband rectifier array is designed with 12 rectifier elements arranged in a 360-degree array. All elements are connected in parallel to achieve maximum DC combining. The experimental results show that this rectenna array works well in an ambient RF with multiple paths and polarizations.

II. Broband Antenna Design

The photograph of the broadband antenna is shown in Fig.1. The substrate is FR4 with a dielectric constant of 4.4, a loss tangent of 0.02, and a thickness of 1.5 mm. The overall dimensions of the antenna are 45 × 45 × 1.5 mm³. The multi-frequency characteristic is achieved by introducing branch structures on the antenna's ground plane through slots. The wideband characteristic is achieved by adding multiple branches. To reduce cross-polarization, two vertical gaps are introduced to reduce the distribution of cross-polarization current.

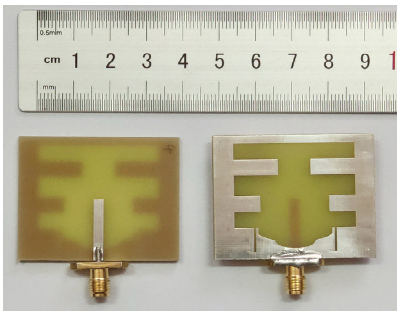


Fig.1. Top layer and bottom layer of the fabricated antenna.

The measured and simulated *S*-parameters of the antenna are shown in Fig.2. Agilent vector network analyzer (Agilent N5230A) was used to measure the antenna's *S*-parameters. The bandwidth with *S*-parameters below −10 dB in the measurement is 2.37 - 3.10 GHz, indicating that the proposed antenna can operate in the 2.37 - 3.1 GHz frequency range. The lowest $|S_{11}|$ value is −30 dB. The difference between the measurement and simulation is mainly due to fabrication errors.

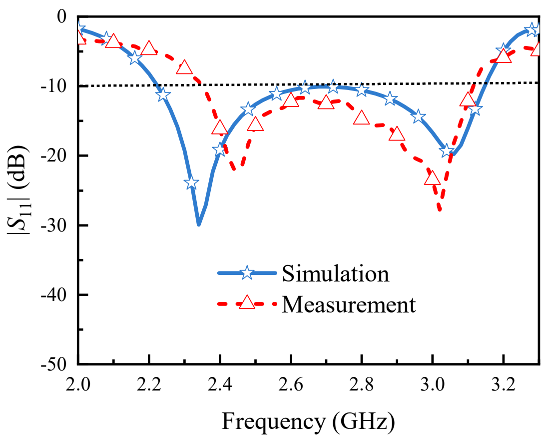
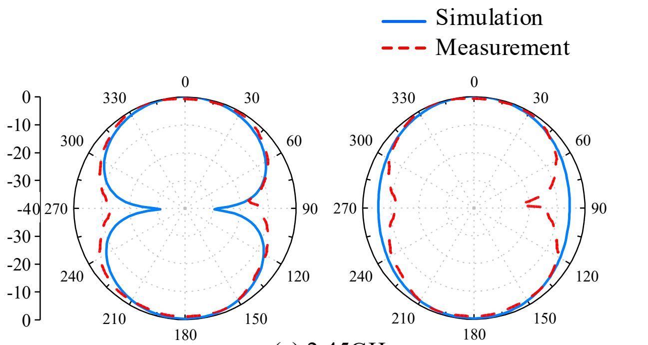
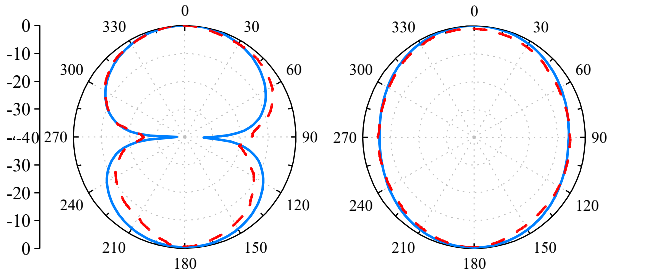


Fig.2. Simulated and measured $|S_{11}|$.

The measured and simulated normalized radiation pattern of the antenna is shown in Fig.3. The radiation pattern of the antenna was tested in a microwave anechoic chamber. The radiation pattern was tested at 2.45 GHz and 2.80 GHz, and the measured results are in good agreement with the simulations. The maximum gain of the antenna measured at 2.45 GHz and 2.8 GHz is 5 dBi and 5.3 dBi, respectively. The antenna exhibits good omnidirectional characteristics in the E-plane and radiates in the +z and -z directions in the H-plane.



(a) 2.45GHz



(b) 2.8 GHz

Fig.3. Measured and simulated normalized radiation patterns at (a) 2.45 GHz, and (b) 2.80 GHz.

III. Rectenna Array Design

The schematic diagram of the rectifier array is shown in Fig.4. The diode used is HSMS-286F. Various lengths of branches T_1 and T_2 are added to achieve impedance matching in various frequency bands realizing a wideband rectifier array. Advanced Design System (ADS) simulation software was used for rectifier array simulation, and an Agilent signal source was used to test the rectifier array RF-DC conversion efficiency. The measured and simulated results are shown in Fig.5. The load of the rectifier array is 1 kΩ. At 2.45 GHz with an input power of 10 dBm, the maximum RF-DC conversion efficiency is 75 %. At an input power of 10 dBm, it can reach 50 % in the frequency range of 2 - 3 GHz. 12 rectifier elements were arranged in a 360-degree array, with the elements connected in parallel to achieve maximum DC combining efficiency and reduce losses caused by feed lines during array formation.

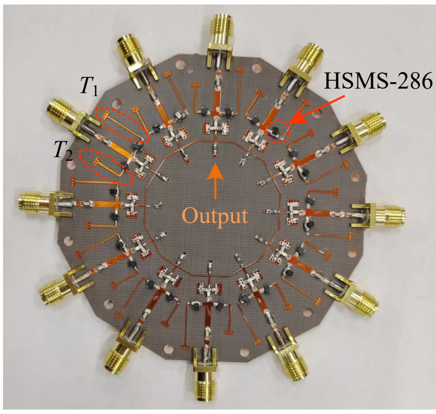


Fig.4. The prototype of a rectifier array with 12 elements.

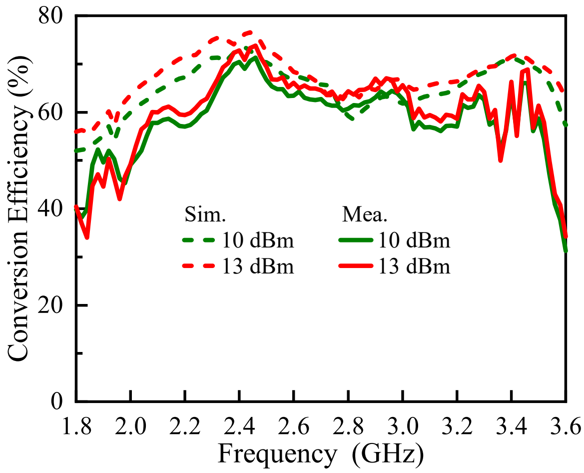
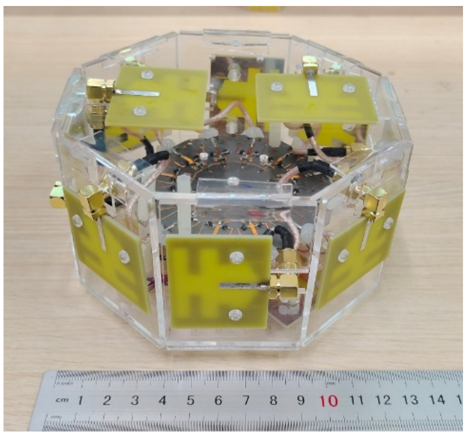
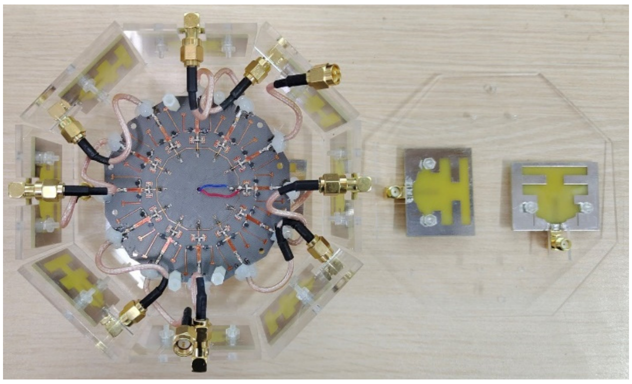


Fig.5. The measured and simulated results of the rectifier array with various input power levels.

Next, the broadband antenna and rectifier array were connected in sequence using coaxial cables and placed in a transparent octahedral box. As shown in Fig.6, we placed 12 antenna units on each surface of the octahedron, with 4 vertically polarized and 4 horizontally polarized antennas on each of the eight sides, and the polarization directions of adjacent units are horizontal and vertical polarization, respectively. Two orthogonal polarized antennas are placed on the top and bottom surfaces of the octahedron. This configuration enables broadband, multi-polarization, and 3D omnidirectional energy harvesting. The internal diagram of the rectifying antenna array is shown in Fig.6(b). The diameter of the rectifying antenna array is 13 cm, and the height is 6 cm.



(a)



(b)

Fig.6. The prototype of the rectenna array.

We placed the rectifying antenna array in a microwave anechoic chamber for measurement. The rectenna array was placed on a rotating platform, and a circularly polarized horn antenna with a gain of 6 dB was used as the transmitting antenna. The distance between the transmitting antenna and the center of the rectifying antenna array was 1.2 m. A digital acquisition device was used to collect the DC voltage on a load of 1 kΩ. A power meter was used to test the output power of the transmitting antenna.

The received power P_r of the rectenna can be calculated by multiplying the effective area of the antenna A_e with the average power density S_{avg} at the surface of the rectenna: [7]

$$P_r = A_e S_{avg} = \frac{P_t G_t A_e}{4\pi D^2} \tag{1}$$

where P_t is the input power of the transmitting horn antenna, G_t, and G_r are the gains of the horn antenna and the proposed antenna, respectively, λ is the wavelength, and D is the distance between the transmitting and receiving antennas ($D = 1.2$ m).

The RF-to-DC conversion efficiency is:

$$\eta = \frac{V_{DC}^2}{P_r \times R_{load}} \times 100\% \tag{2}$$

where V_{DC} is the output voltage, and R_{load} is the DC load resistance, which is realized using a resistor box.

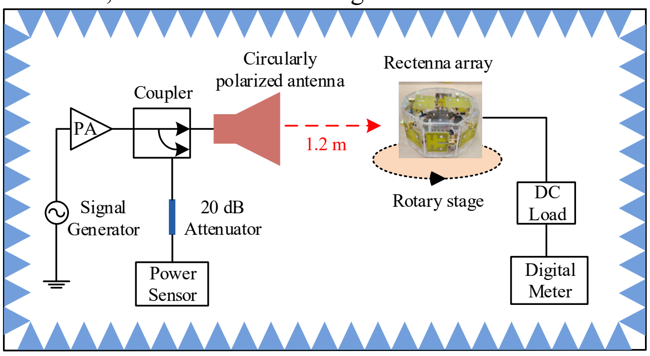
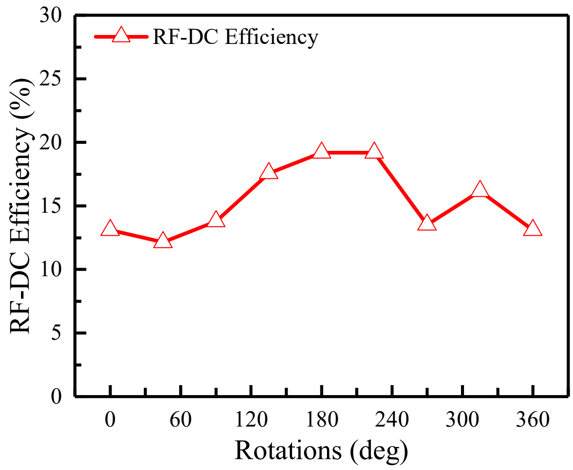
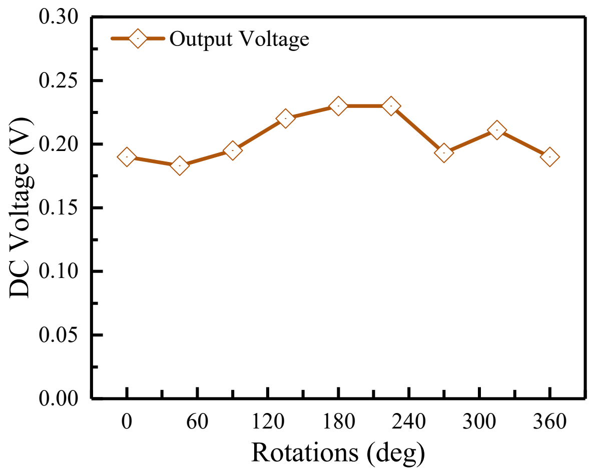


Fig.7. Measurement setup of the rectenna array.

The transmitting power of the transmitting antenna is 28 dBm, and the power density at the receiving rectenna is 11 μW/cm^2. The measured RF-Dc efficiency and output voltage are shown in Fig.8. Due to the use of a circularly polarized transmitting antenna and a linearly polarized receiving antenna, the maximum rectification efficiency of the rectifying antenna array is 20 %. It can be observed that the voltage changes very smoothly, ranging from 0.17 V to 0.23 V, with a variation of 0.06 V.



(a)



(b)

Fig.8. (a) RF-DC efficiency and (b) output DC voltages with the rotation angles 0° to 360°.

IV. Conclusion

In this work, we proposed an all-polarized wideband (2.4 – 3.1 GHz) rectenna array for 3-D omnidirectional wireless energy harvesting. The rectenna array strategically combines 12 single microstrip slot antenna elements placed in a transparent octahedral box. A broadband rectifier array is designed with 12 rectifier elements arranged in a 360-degree array. The RF-DC conversation efficiency of the rectifier array is 75 % at an input power of 13 dBm with a DC load (1 kΩ). All elements are connected in parallel to achieve maximum DC combining. The experimental results show that this rectenna array works well in an ambient RF with multiple paths and polarizations.

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