Electrically Small, Highly Efficient, Huygens Circularly Polarized Rectenna for Wireless Power Transfer Applications

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***Abstract*—This paper introduces the first realized electrically small, highly efficient, Huygens circularly polarized (HCP) rectenna for wireless power transfer applications. It is designed to operate at the 915 MHz in the corresponding ISM band. It is realized through the seamless integration of an electrically small HCP antenna and a highly efficient rectifier circuit. The electrically small HCP antenna consists of four electrically small near-field resonant parasitic (NFRP) elements: two Egyptian axe dipoles (EADs) and two capacitively loaded loops (CLLs). The rectifier is a full-wave rectifying circuit based on HSMS286C diodes. It is integrated with the HCP antenna on its bottom layer via a coplanar stripline (CPS) without occupying any additional space. A HCP rectenna prototype was successfully fabricated and tested. It is electrically small (ka < 0.77) with a radius $R = \lambda_0$ / 8 and a height $H = \lambda_0$ / 25. Excellent CP radiation absorption capacity is observed. The measured peak AC to DC conversion efficiency reaches 82%. Being electrically small and highly efficient, the reported HCP rectenna is an ideal candidate for wirelessly powering internet-of-things (IoT) devices in many emerging IoT applications.**

Keywords*—*Circular polarization, electrically small antennas, Huygens antennas, internet-of-things (IoT), near field resonant parasitic elements, rectennas, rectifier circuits

I. INTRODUCTION

Internet-of-Things (IoT) devices and applications are anticipated to experience exponential growth in the 5G era [1]. It is estimated that the number of IoT devices will reach 30 billion units by the year 2020 [2]. Powering these IoT devices through far-field wireless power transfer (WPT) is a major technology trend. It is simply impractical to have to change bulky and short-life batteries for every IoT device. Moreover, some of IoT devices are anticipated to be embedded into material and biological structures, making battery replacement difficult if not totally unserviceable [3]. Electrically small Huygens antennas as reported in [4] – [6] are excellent candidates for enabling WPT functions in IoT applications. They have compact footprints, are broadside receivers, and exhibit cardioid-shaped radiation patterns in their broadside direction. Furthermore, CP rectennas are able to absorb wireless energy from incident fields with random polarizations, avoiding the polarization mismatch problem that arises in LP systems [7] – [9]. The first realized electrically small, highly efficient, Huygens CP (HCP) rectenna is introduced in this paper. A highly efficient, full-wave rectifying circuit based on HSMS286C diodes is seamlessly integrating with an electrically small HCP antenna. The entire structure is electrically small (ka < 0.77), low profile (1/25 λ_0), and achieves a peak 82% AC to DC conversion efficiency.

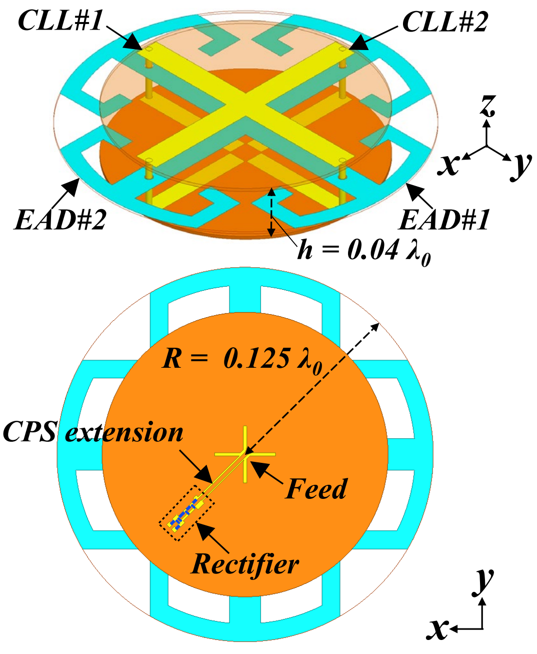


Fig. 1 Configuration of the electrically small Huygens CP (HCP) rectenna for wireless power transfer (WPT) applications. 3D view and bottom view.

II. DESIGN OF THE ELECTRICALLY SMALL HUYGENS CIRCULARLY POLARIZED (HCP) RECTENNA

A. *Rectenna configuration*

The configuration of the electrically small HCP rectenna is shown in Fig. 1. The HCP antenna is realized with four metamaterial-inspired near field resonant parasitic (NFRP)

elements: two Egyptian axe dipoles (EAD#1 and EAD#2) and two capacitively loaded loops (CLL#1 and CLL#2). They form two crossed dipole structures. The design and prototype was fabricated from three circular pieces of the Rogers™ 5880 substrate and four vertical metallic posts. The top and bottom substrate layers have a 0.787 mm thickness; the middle one is 0.508 mm thick. A compact rectifying circuit is positioned on the bottom side of the bottom layer of the HCP antenna. It is integrated seamlessly with the unbalanced cross dipole feed of the HCP antenna with a section of coplanar stripline. The coplanar stripline is intentionally extended from the feed to avoid any interference and coupling with it. The entire structure is highly compact ($ka < 0.77$) and low profile ($\lambda_0/25$), which is ideal for most IoT applications. Moreover, the rectenna exhibits broad-angle CP EM-wave absorption capacity as shown in Fig. 2. As a radiator, the HCP antenna operates at 915 MHz in the corresponding ISM band and has the Huygens (cardioid) radiation patterns oriented along its broadside direction. The $|S_{11}|$, axial ratio and realized LHCP gain values at 915 MHz are -16.0 dB, 1.25 dB, and 2.9 dBic, respectively. The 3-dB beamwidth of the pattern is from -67° to +67°.

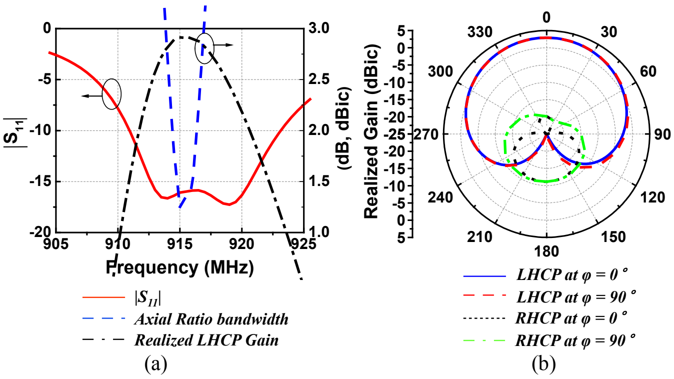


Fig. 2 Simulated HCP antenna performance characteristics at 915 MHz. (a) $|S_{11}|$, AR and realized gain values as functions of the source frequency. (b) 2D realized gain patterns.

B. Design of the rectifier

The full-wave rectifying circuit (rectifier) layout is shown in Fig. 3. It converts the input AC power (EM waves) into output DC power. The rectifier consists of two rectifying diodes, an input matching circuit, and an output load resistor. An inductor L and two capacitors C_1 and C_2 constitute the input impedance matching network for a 50 Ω power source. The inductor L also acts as low pass filter to prevent the higher order harmonics that are generated by the nonlinear diodes from being reradiated. The capacitor C_2 also acts as the power storage component of the full-wave rectifier during each negative portion of the incident sinusoidal signal. The capacitor C_3 in the output side of the rectifier acts as a high pass filter that smooths the output DC voltage.

The rectifier was implemented and seamlessly cascaded with the CPS feedline of the HCP antenna. Two 560 nH inductors are added on the output side as RF chokes. The HSMS286C diodes from Broadcom™ were selected as the major rectifying components. They are in an easily soldered series package. The lumped inductors and capacitors are from Murata™. All these lumped components are in surface-mount device (SMD) packages with a 0403 (1 mm) size. The realized rectifier is highly compact. Its length is only 7.3 mm. The finalized optimized values of these components are: L = 22 nH; C_1 = 0.4 pF; C_2 = 100 pF; C_3 = 100 pF; and R_L = 5.1 KΩ. It is noted that the rectifier is not directly connected to the cross dipole feed but extended 13 mm away from it. This is to minimize the coupling between the rectifier and the feed structure portions of the HCP system.

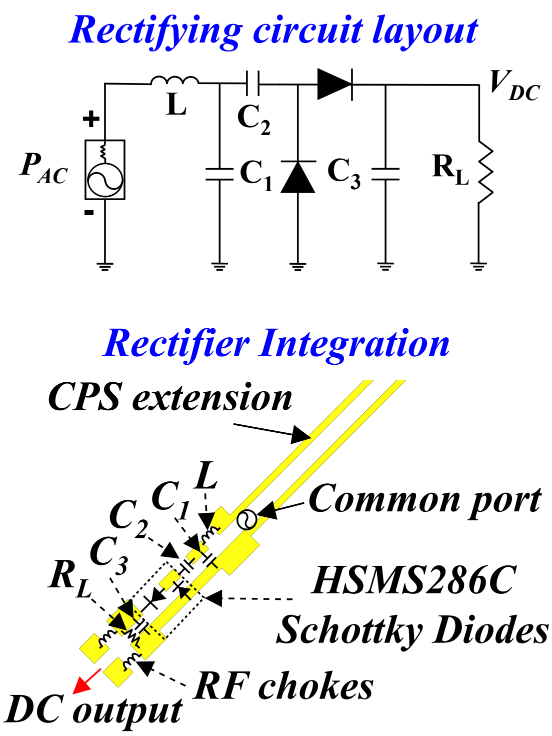


Fig. 3 Diagram of the rectifying circuit layout and details of its integration with the HCP antenna.

III. Measurement Results

The electrically small rectenna was fabricated, assembled and measured. A Rohecell™ foam was adopted to support the structure during the measurements. The measurement environment was set up as shown in Fig. 4. The setup consists of several parts. A horn antenna illuminates the rectenna. A signal generator acts as the power source. A power amplifier with its DC power supply magnifies the radiated wireless power. A multimeter was used to measure the output DC voltage. There were several RF cables for requisite connections between these devices. Since the specifications of the measurement environment are known, as listed in the lower right side of Fig. 4, the Friis transmission equation [10] is used to calculate the power density of the incident wave on the rectenna. The AC to DC conversion efficiency is determined by the ratio between the measured output DC power and this incident wave power.

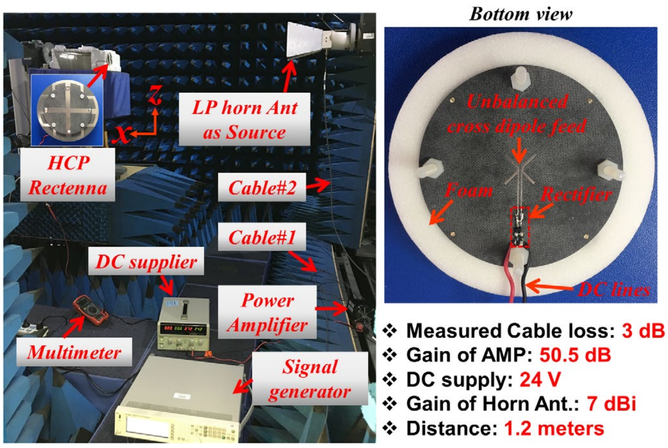
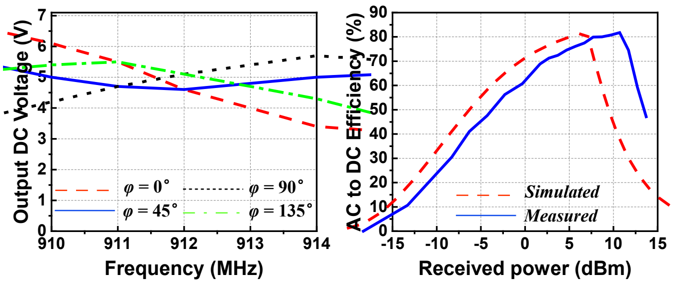


Fig. 4 Electrically small HCP rectenna measurement setup and the known characteristics of its major components.

The output DC voltage values of the electrically small HCP rectenna as functions of the source frequency were measured by rotating the rectenna around the y-axis (broadside direction) for every 45 degrees as shown in Fig. 5(a). The power of the incident wave was set to 8.7 dBm. Similar DC voltages: 5.5 V, 4.7 V, 4.7 V, and 5.5 V, are observed at 911 MHz for the 45°, 90°, 135° and 180° rotation, respectively. These measured values confirm the very good CP EM-wave absorption capacity of the HCP rectenna.

Fig. 5(b) compares the measured and simulated AC to DC conversion efficiencies. The peak measured efficiency value (81.8%) agrees very well with the simulated one (81.6%). The AC to DC conversion efficiency is larger than 50% when the received power widely ranges from -4 to 14 dBm. The shift (around 2 to 3 dBm) between the measured received power results with respect to their simulated values is due to the discrepancy between simulation model and the actual parameters of the nonlinear diodes.



(a) (b)

Fig. 5 HCP rectenna results. (a) Output DC voltages as functions of the source frequency for different rotation angles. (b) Comparison of the measured and simulated AC-to-DC conversion efficiencies as functions of the incident power.

IV. Conclusion

The first realized electrically small Huygens circular polarized rectenna was presented. Prototype of the optimized HCP rectenna design was fabricated, assembled and tested. The measured results successfully demonstrate its high AC to DC conversion efficiency. Being highly compact, low profile, efficient while also being lightweight and easy to fabricate, the developed HCP rectenna is an ideal candidate for wirelessly powering IoT devices in the emerging 5G era.

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