Electrically Small Huygens Dipole Rectennas for Wirelessly Powering Internet-of-Things Sensors

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***Abstract*-Linearly-polarized (LP) and circularly-polarized (CP) electrically small Huygens dipole rectennas for wirelessly powering compact Internet-of-Things (IoT) sensors at 915 MHz in the ISM band are reported. They are realized through the seamless integration of electrically small near-field resonant parasitic-based Huygens LP and CP antennas with a highly efficient rectifier circuit. The Huygens LP (HLP) antenna achieves a cardioid-shaped realized gain (RG) pattern with RG=3.8 dBi at the targeted frequency. Similarly the Huygens CP (HCP) antenna generates a cardioid pattern with RG=3.2 dBic and a 1.7 dB axial ratio value. Notably, the HLP and HCP antennas have inductive input impedances that facilitate matching directly to the 50-Ω source, thus eliminating a lossy inductor in the original rectifier. The prototyped HLP and HCP rectennas achieve close to 90% AC to DC conversion efficiency. Light and temperature IoT sensors wirelessly powered with custom-designed versions of these rectennas are successfully demonstrated.**

I. Introduction

Electrically small rectennas are important for future wireless Internet-of-Things (IoT) applications. The number of IoT devices are set to experience exponential growth as the current 5G wireless systems rapidly develop [1] – [5] . It is impossible to replace every battery for each IoT device manually given the expected large numbers of them. Furthermore, some IoT devices will be placed in locations not easily accessible, for instance, in human beings [6], [7]. In future wireless ecosystems, wireless power transfer (WPT) to these IoT devices is the only solution. Furthermore, wirelessly powered IoT devices have much longer life circles than battery-based ones. Consequently, compact and highly efficient rectennas, i.e., antennas integrated with rectifier circuits, that enable far-field WPT applications are highly desired.

Forest fire detection and warning based on a wireless IoT sensor network is an example application and is illustrated in Fig. 1. Smoke, humidity, light or temperature sensors could be employed within a forest to detect an impending fire hazard and warn of its dangers. Once these sensors had been deployed, it would be very time consuming and labor intensive to replace their batteries. Consequently, far-field WPT is a very viable solution to wirelessly power or recharge them.

Given the desired small footprint of any IoT sensor, the associated WPT rectennas should be compact in size (electrically small) and have high directivities, broad wireless power capture capacities, and high AC to DC conversion efficiencies. Although significant progress has been made in the development of far-field rectennas, as reported in [8] – [16], it remains very challenging to meet all of the above criteria simultaneously.

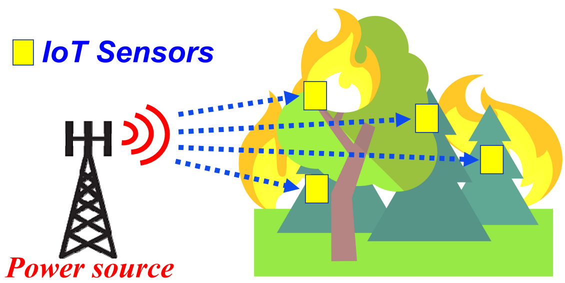


Figure 1. Illustrated wirelessly powered IoT sensor system for forest fire detection and warning applications.

This paper will introduce two electrically small Huygens linearly (LP) and circularly (CP) rectennas that achieve all of the noted criteria at the targeted frequency, 915 MHz, in the ISM band. Moreover, it will be demonstrated that they have been successfully modified to wirelessly power light and temperature sensor systems. They are ideal candidates for many wireless IoT applications including the aforementioned forest fire detection and warning applications, which is particularly crucial for Australia with its history of frequent and devastating forest and bush fires.

II. Design of the Electrically Small Huygens Linearly Polarized and Circularly Polarized Rectennas

A. *Configuration of Each System*

The basic configurations of the electrically small Huygens LP and CP rectennas are depicted in Fig. 2. The HLP rectenna in Fig. 2(a) is realized by the seamless integration of a HLP antenna and a compact, highly efficient rectifier circuit [17]. The entire design requires three disk-shaped PCB substrates, labeled as *Sub#1* to *Sub#3*. The HLP antenna consists of two metamaterial-inspired near-field resonant parasitic (NFRP) elements: the Egyptian axe dipole (EAD) and the capacitively loaded loop (CLL), which are excited by a driven, short printed dipole [18] – [20]. The rectifier circuit is designed on a short strip line that is orthogonally connected to the driven dipole. The entire structure is highly compact with a *ka* value of 0.73 (*k* is the wave number and *a* is the radius of the smallest sphere that encloses the entire structure) and is low profile ~ $0.04\lambda_0$ ($\lambda_0 / 25$).

The corresponding electrically small HCP rectenna is shown in Fig. 2 (b). It consists of a HCP antenna fed by two delayed loop lines and the same rectifier circuit used in the HLP design [21]. The entire structure again requires only three disk-shaped PCB substrates (*Sub#1* to *Sub#3*) and a small rectangular PCB substrate (*Sub#4*). The HCP antenna is constructed on the three parallel disks. A pair of crossed EAD and CLL NFRP elements is excited by the delayed loop line dipoles that are located on the bottom surface of *Sub#3*. The rectifier circuit is printed on *Sub#4;* it is vertically connected to the HCP antenna. The entire structure is highly compact with a *ka* value of 0.77. This value is only slightly larger than that of the HLP design [22].

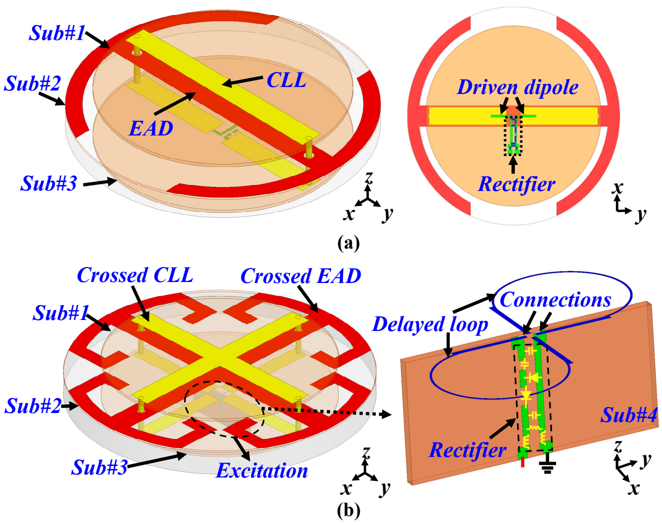


Figure 2. Configurations of the (a) electrically small Huygens LP rectenna, and the (b) electrically small Huygens CP rectenna.

B. Rectenna Performance

One noticeable feature of the developed Huygens rectennas is the elimination of the lossy inductor in the original rectifier circuit that was required for matching the system to 50 Ω. This feature is realized by intentionally designing the input impedances of the HLP and HCP antennas to be inductive values. As shown in Fig. 3, both antennas have inductive impedances around 50 + j150 Ω at the targeted 915 MHz. This value is conjugately matched to the capacitive impedance of the rectifier circuit. For the HLP antenna, this inductive impedance is achieved by slightly increasing the length of the short driven dipole. For the HCP antenna, it is realized by the delayed loop feed structure. The axial ratio value at 915 MHz for the HCP antenna is 1.7 dB.

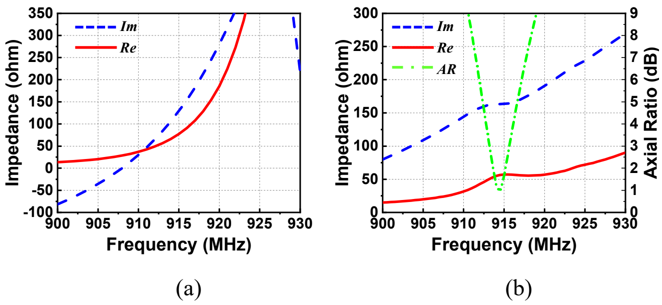


Figure 3. (a) Input impedance of the electrically small HLP antenna. (b) Input impedance and axial ratio of the electrically small HCP antenna.

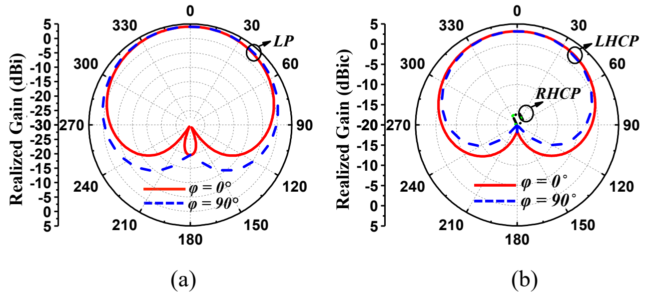


Figure 4. 2D realized gain patterns of the electrically small rectennas. (a) HLP antenna's LP results. (b) HCP antenna's CP results.

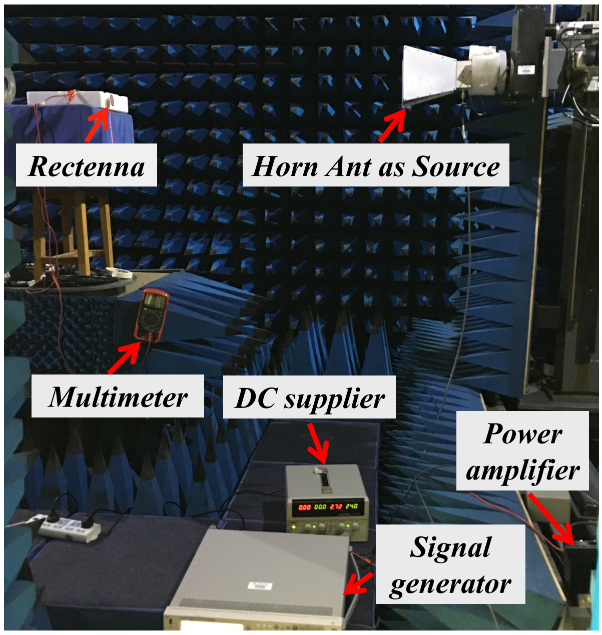
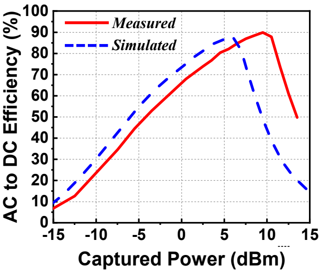


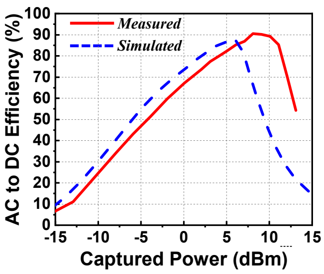
Figure 5. Measurement setup of the far filed WPT rectenna system.

Thanks to the fact that electric and magnetic dipoles are complementary radiators, broad-beam, cardioid-shaped

Huygens radiation patterns are attained as shown in Fig. 4. The patterns indicate that both rectennas have broad-angle and strong wireless power capture capacity. The broadside realized gain values are 3.8 dBi for the HLP antenna and 3.2 dBic for the HCP antenna. It is noted that the realized gain of the HCP antenna is 0.6 dB lower than the HLP antenna. This difference arises from the fact that the HCP structure is more complicated and leads to more conductive losses.



(a)



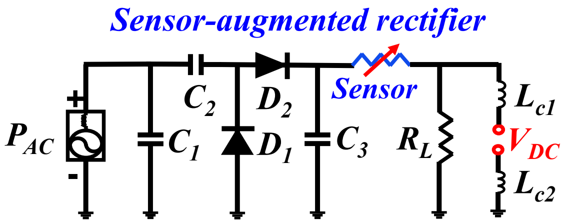
(b)

Figure 6. AC to DC conversion efficiencies. (a) Electrically small HLP rectenna. (b) Electrically small HCP rectenna.

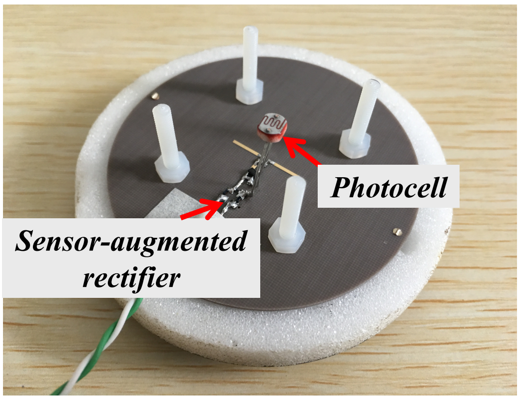
Prototypes of both the HLP and HCP rectennas were fabricated and measured. The measurement setup is shown in Fig. 5. The distance between the source horn antenna and the rectenna under test is 1.2 meters. The AC to DC conversion efficiencies of both rectennas are shown in Fig. 6. They are consistent and agree very well with their simulated values. The peak AC to DC efficiency is close to 90% when the captured power level is near 9 dBm. The measured results show that the developed compact rectennas are ideal candidates for wirelessly powering IoT devices.

III. Demonstration of Wirelessly Powered IoT Sensors Facilitated by the Developed Rectennas

Two wirelessly powered IoT sensors, a light and a temperature version, were developed based on the developed Huygens rectennas. As shown in Fig. 7 (a), the output voltage V_{DC} of the rectifier circuit would be modified if an impedance-dependent sensor was placed in series with the load resistor R_L. A light sensor is realized by adopting a photocell whose impedance is dependent on the ambient illumination level. A temperature sensor is implemented by using a thermistor whose impedance is dependent on the temperature of the environment in which it is in. An alarm is connected to the output of the rectifier; it will ring if the voltage applied to it exceeds 0.8V. This level occurs if the illumination or temperature level exceeds a preset threshold. The prototype of the wirelessly powered light sensor based on the developed electrically small HLP rectenna is shown in Fig. 7 (b). The entire system is highly compact and lightweight. It senses the light level and can be configured to ring in either dim or bright light environments.



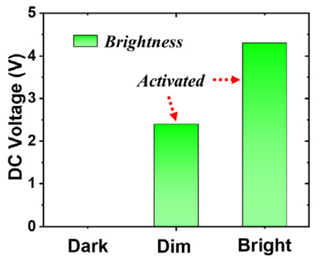
(a)



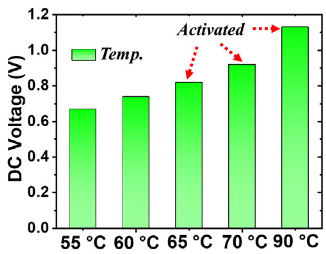
(b)

Figure 7. (a) Circuit model of the sensor-augmented rectifier. (b) Prototype of the wirelessly powered light sensor facilitated by the HLP rectenna.

The measured performance of the wirelessly powered light and temperature sensors based on the electrically small HLP rectenna are presented in Fig. 8. Both systems were tested in an anechoic chamber in which the wireless power was emitted from a horn antenna. The system under test was placed in the far field of the horn. It is observed that the light sensor is dormant in dark, but is activated in dim or bright environments. The temperature sensor was also tested. The alarm was activated if the temperature exceeded 65˚C and was inactive below 65˚C. Similar systems can also be realized based on the HCP rectenna; the power source would then ideally be circularly polarized. The developed sensors are electrically small and fully wirelessly powered. Consequently, they are ideal candidates for wireless IoT applications, in particular, the noted forest fire detection and warning application to safeguard natural resources, lives and properties globally.



(a)



(b)

Figure 8. Measured performance of the HLP rectenna powered sensors. (a) Light version. (b) Temperature version.

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