Electrically Small Huygens Dipole Rectennas for Wireless Power Transfer Applications

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***Abstract*–A series of electrically small Huygens dipole rectennas are reviewed in this paper. Their design concepts rely on the integration of electrically small Huygens dipole antennas with a highly efficient AC-to-DC rectifier circuit. The basic radiating elements of these Huygens systems are two metamaterial-inspired, electrically small, near-field resonant parasitic (NFRP) elements: an Egyptian axe dipole (EAD) and a capacitively-loaded loop (CLL), and a dipole antenna. The AC-to-DC conversion circuit is a full-wave rectifier circuit based on two Schottky diodes and lumped RLC elements. By properly integrating and arranging the NFRP and dipole elements with the rectifier, four rectennas have been developed. They are a low-profile electrically small Huygens linearly-polarized (HLP) rectenna, a low-profile electrically small Huygens circularly-polarized (HCP) rectenna, a dual-functional HLP rectenna and antenna system, and an ultra-thin electrically small HLP rectenna. They are ideal candidates for wireless power transfer applications in 5G Internet-of-Things (IoT) ecosystems.**

***Index Terms*–electrically small antennas, Huygens pattern, Internet-of-Things (IoT), rectenna, ultra-thin, wireless power transfer**

I. Introduction

Internet-of-Things (IoT) systems have been developing rapidly in recent years and are enabling an immense near-term global economic growth [1]. Far field wireless power transfer (WPT) enabled IoT applications are an emerging technology and an important major future trend associated with the rapid development of 5G IoT ecosystems [2]. WPT-enabled IoT devices enjoy many advantages because they are battery-free and, hence, environmentally friendly; and they are capable of operating in remote places without manual maintenance. With the market demand for IoT devices embedded into more compact and smaller platforms, the reduction of the size of the WPT-enabling rectenna becomes a major challenge.

Although extensive research related to compact rectennas has been reported, it has remained difficult to achieve ultra-compact sizes, low costs, excellent wireless power capture capabilities, and high AC-to-DC conversion efficiencies at the same time. To address this challenge, we have successfully developed a series of rectenna systems that integrate electrically small Huygens dipole antennas (HDAs) with a highly efficient rectifier circuit.

As shown in Fig. 1, the electrically small HDAs consist of two metamaterial-inspired near-field resonant parasitic (NFRP) elements: as an Egyptian axe dipole (EAD) and a capacitively-loaded loop (CLL) [3]. The EAD acts an electric dipole and the CLL functions as a magnetic dipole. These effective dipole elements are arranged orthogonally and are excited by a dipole antenna to obtain the same amplitude and phase. A Huygens cardioid radiation pattern is realized. This unidirectional, broad beamwidth radiation characteristic is very attractive for WPT applications. These HDAs have higher efficiencies and directivities in comparison to traditional electrically small antennas. The Huygens rectennas are combinations of these HDAs and an efficient AC-to-DC rectifier circuit. As illustrated, the latter is a full-wave design based on two Schottky diodes and lumped RCL elements. The AC-to-DC conversion efficiency of our rectennas in the targeted operating frequency band, the 915 MHz ISM band, reaches 90%.

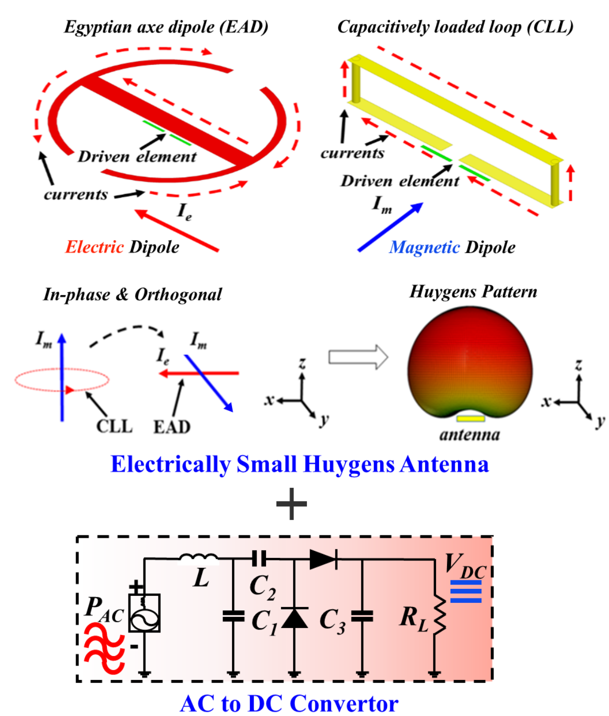


Fig. 1. Design concept of an electrically small Huygens rectenna.

II. A Series of Electrically Small Huygens Dipole Rectennas Developed by the Authors

A. Low-profile Huygens linearly polarized (HLP) rectenna

The low-profile electrically small Huygens LP (HLP) rectenna shown in Table I was developed in [4]. It consists of three disk-shaped PCB substrates. The diameter of the HLP rectenna is only 0.23 λ_0 and its profile is only 0.04 λ_0. Note that it has a broadside Huygens pattern, i.e., the peak directivity is normal to its surface. It is electrically small, its *ka* value being 0.72, where *k* is the free-space wavenumber and *a* is the smallest sphere that encloses the entire HLP rectenna. Note that an antenna is considered to be electrically small if $ka \leq 1$. The measured maximum AC-to-DC conversion efficiency reached 88.9% when the received power was 9.0 dBm.

B. Low-profile Huygens circularly polarized (HCP) rectenna

Considering the polarization mismatch issue in applications where the IoT devices may have random orientations [5], the low-profile electrically small Huygens CP (HCP) rectenna shown in Table I was developed in [6]. To achieve the maximum AC-to-DC conversion efficiency, the HCP rectenna has a delayed-loop excitation of the dipole design. Thus, the rectifier circuit requires an additional small piece of PCB to be attached orthogonal to the bottom of the radiator. The entire prototype remained electrically small, $ka \sim 0.77$; it achieved a very high measured AC-to-DC conversion efficiency, 90.6%.

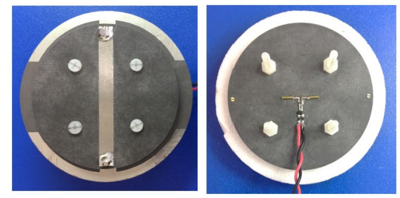
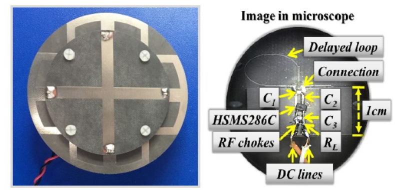
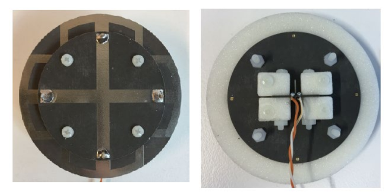
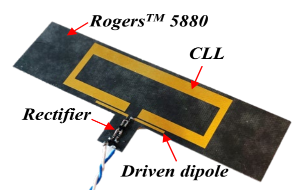
C. Dual-functional HLP rectenna

Considering an IoT system that requires both power and data transmission enabled simultaneously, the dual-functional electrically small HLP system shown in Table I was developed in [7]. It provides both WPT and communication functions. Its HLP antenna and orthogonal rectenna operate independently because excellent isolation (> 30 dB) between them was achieved. The antenna mode's measured resonance frequency was 910 MHz, a shift of only 5 MHz (0.5%) from the targeted 915 MHz. The rectenna mode's measured peak AC-to-DC conversion efficiency was 87.2%, only a 0.57% difference from its simulated value of 87.8%.

D. Ultra-thin Huygens linearly polarized (HLP) rectenna

These Huygens rectenna designs each required three stacked PCB substrates. To reduce the fabrication complexity, the ultra-thin HLP rectenna shown in Table I was developed in [7]. The entire ultra-thin design, including the EAD, the CLL, the short-driven dipole, and the rectifier circuit, was designed and realized on a single piece of PCB substrate. Its Huygens peak lies in the plane of the substrate. Thus, its profile, 0.12 λ_0, is higher than the previous low-profile design (0.04 λ_0). Nevertheless, its thickness is only 0.508 mm, being $\lambda_0 / 645$ at 915 MHz. The measured peak efficiency is 88% when the received power is 10.4 dBm. To demonstrate the feasibility of them wirelessly powering real IoT devices, WPT-enabled temperature and light sensors have been also developed as reported in [9].

TABLE I: A Series of Electrically Small Huygens Dipole Rectennas Developed by the Authors

<table>
<tr><th>Rectenna Type</th><th>Configuration</th><th>Ref.</th></tr>
<tr><td>Low-profile HLP Rectenna</td><td></td><td>[4]</td></tr>
<tr><td>Low-profile HCP Rectenna</td><td>
</td><td>[6]</td></tr>
<tr><td>Dual-Functional HLP Rectenna</td><td></td><td>[7]</td></tr>
<tr><td>Ultra-Thin HLP Rectenna</td><td>
</td><td>[8]</td></tr>
</table>

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