Internet-of-Things Sensors Wirelessly Powered by Electrically Small Huygens Dipole Rectenna

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***Abstract*-Internet-of-Things (IoT) sensors are expected to be ubiquitous in a future smart and sustainable society. Due to the exponential growth of device numbers, powering IoT devices by far field wireless power transfer (WPT) is becoming a necessary trend. This paper introduces two IoT sensors (light and temperature) that are wirelessly powered by a highly compact and efficient electrically small Huygens dipole rectenna. The entire system seamlessly integrates two subsystems. One is the metamaterial-inspired electrically small Huygens antenna that organically combines capacitively loaded loop (CLL) and Egyptian axe dipole (EAD) radiators together. The other is the sensor-augmented rectifier in which the output DC voltage varies as a function of the sensor impedance. The developed wirelessly powered systems can sense light or temperature levels and, when attached to an alarm, can send a warning signal if a threshold value is exceeded. Their prototypes were fabricated and tested. The measured results agree very well with their simulated values. The prototypes are highly compact and electrically small (*ka* = 0.73). They represent ideal candidates for many emerging IoT wireless sensor applications.**

I. INTRODUCTION

Internet-of-Things (IoT) sensors are expected to be ubiquitous in any future smart and sustainable society and are being incorporated into the rapid development of 5G wireless systems [1]. Wireless IoT systems will support many applications. These include intelligent cities; smart transport systems; and monitoring in industry, agriculture, medical care and the environment [2].

Given the projected exponential growth of IoT device numbers, it will be impossible to produce and then manually replace the short-life physical batteries for each individual device. Consequently, powering IoT devices with far field wireless power transfer (WPT) techniques has become a necessary trend [3]–[5]. Moreover, WPT technology has the advantage of being able to power multiple IoT devices simultaneously, such as in 5G device-to-device (D2D) communication systems [6]. Figure 1 shows an application example of WPT sensors monitoring wine barrel properties, i.e., sensors embedded on and inside the barrels to monitor parameters such as temperature and alcohol level. Once installed, battery replacement would be tedious and difficult. Thus, WPT to power all of these IoT sensors simultaneously would be a preferred mechanism.

Considering the desired small footprint of IoT sensors, the combination of WPT devices, e.g., rectennas, and sensors should be very compact and highly efficient. However, it is challenging to simultaneously achieve these desired features. This paper introduces the realization of two sensor-augmented electrically small Huygens rectennas that are highly compact and efficient. The diameter of the prototypes is only 0.2 λ_0 (*ka* = 0.73) and they have an AC-to-DC conversion efficiency reaching 88%. WPT light and temperature sensing is successfully demonstrated.

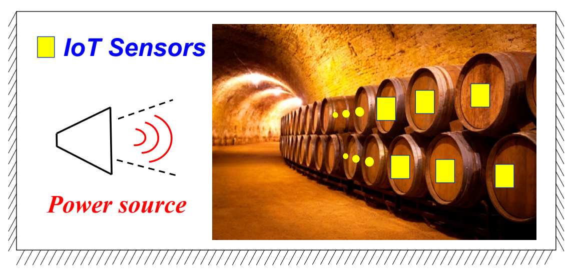

Figure 1. Application example of wirelessly powered IoT sensors installed on and inside sealed objects.

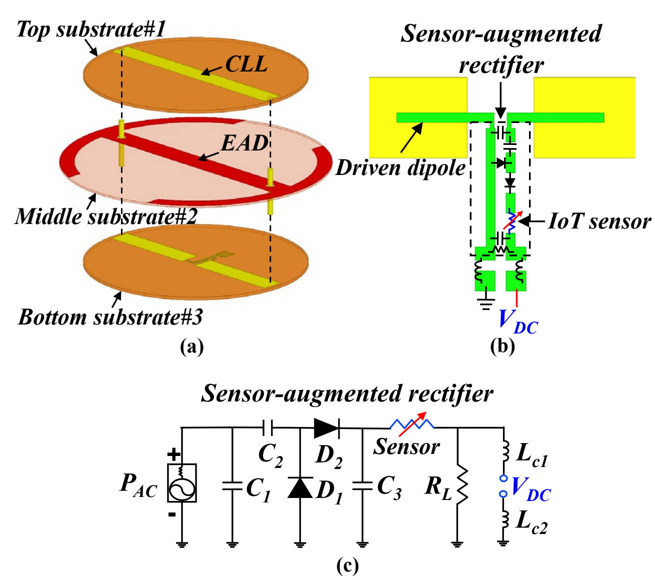

Figure 2. Configuration of a wirelessly powered sensor system facilitated by an electrically small Huygens dipole rectenna. (a) Perspective view. (b) Bottom view. (c) Circuit model of the sensor-augmented rectifier.

II. Designs and Operating Principles

A. *Configuration of Each System*

As shown in Fig. 2, each IoT sensor system consists of two parts. The first is the metamaterial-inspired electrically small Huygens dipole antenna shown in Fig. 2(a). It acts as the wireless power capture element. This antenna was fully discussed in our previous works [7]–[9]. It organically combines capacitively loaded loop (CLL) and Egyptian axe dipole radiators together to produce a cardioid-shaped Huygens radiation pattern (Fig. 3(a)). The second part is the sensor-augmented rectifier. It is a modified version of our previous design [10]. A light or temperature sensor is integrated into the rectifier as a variable impedance as shown in Figs. 2(b) and 2(c). It is seamlessly integrated with the short "driven dipole" of the Huygens antenna as illustrated in Fig. 2(b).

B. *Operating Principle of the Sensor-Augmented Rectifier*

Once the sensor is integrated into the rectifier as shown in Fig. 2 (c), the output DC voltage V_{DC} across the load resistor R_L will be dependent on the impedance of the sensor. By setting a voltage threshold, a certain amount of the sensed parameter can be detected. For example, the impedance of a photocell as a light sensor is highly dependent on the illumination level. In a totally dark environment, its impedance is larger than 1 MΩ. The output voltage V_{DC} is close to 0 V in that case. However, its impedance will quickly drop to several kΩ when the illumination level increases from dark to dim or bright light levels. The corresponding output V_{DC} will then increase to several volts. By setting a proper voltage threshold, the light level can be readily detected. For the purpose of monitoring, an acoustic alarm is attached to the output voltage. It has an activation voltage of 0.8 V. If the sensor is in dark light, no alarm is heard. If it discerns dim or bright light, the alarm sounds. Thus, both the sensor and alarm are fully wirelessly powered.

III. Measured Performance

Two prototypes, a wirelessly powered light and a wirelessly powered temperature sensor, were fabricated and tested. The rectenna without the sensor was measured initially. The results confirmed its excellent wireless power capture capability. As shown in Fig. 3(b), the measured and simulated AC-to-DC conversion efficiencies agree reasonably well with each other. The peak measured efficiency is 88%, which is very close to the simulated value, 87.8%.

The sensing performance of both the wirelessly powered light and temperature sensors are presented in Fig. 4. As noted previously, the activation voltage for the acoustic alarm is 0.8 V. The performance of the wirelessly powered light sensor is shown in Fig. 4(a). The alarm was activated in both a dim and bright environment, but was dormant in a dark one. The wirelessly powered temperature sensor performance is shown in Fig. 4(b). The alarm was activated when the temperature exceeded 65° C. Both experimental results exhibit successful sensing performance. Comprehensive measured results can be found in our reported work [11]. These developed wirelessly powered sensors are excellent representatives of WPT-based sensors for many emerging IoT applications.

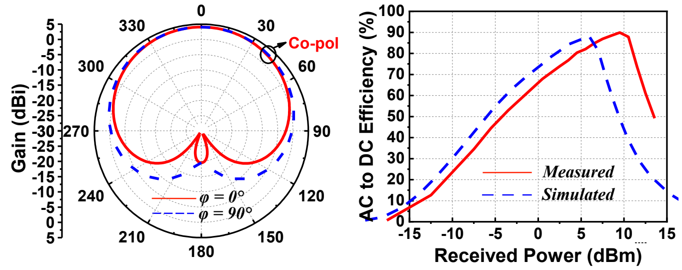

Figure 3. (a) Simulated radiation pattern of the driven antenna. (b) Measured results of the electrically small Huygens rectenna.

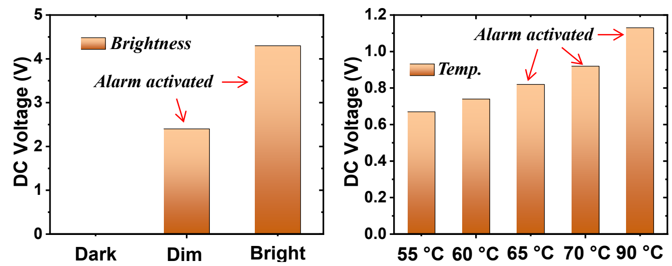

Figure 4. Sensing performance of the wirelessly powered sensors. (a) Light sensor. (b) Temperature sensor.

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