Electrically Small Huygens Dipole Array for 5G Wireless Power Transfer Enabled IoT Applications

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***Abstract* - A 1 × 4 antenna array facilitated by an innovative electrically small Huygens dipole element is reported. The entire array is ultra-thin, being realized on a single PCB substrate. Each of the Huygens linearly-polarized (HLP) dipole elements is the result of a careful integration of one pair of metamaterial-inspired electrically small structures, i.e., an Egyptian axe dipole (EAD) and a capacitively loaded loop (CLL) near-field resonant parasitic (NFRP) element. The EAD acts as the electric dipole radiator; the CLL works as the magnetic dipole radiator. They are oriented orthogonal to each other and are in-phase to radiate identical cardioid-shaped Huygens patterns in both the E- and H-planes. The consequent 1 × 4 Huygens array operates at 2.45 GHz with a high 8.9 dBi peak realized gain. It has a narrow E-plane 3-dB beamwidth, 28˚, and a very broad H-plane beamwidth, 153˚. The developed linear HLP-based array is particularly useful for far-field wireless power transfer (WPT) enabled IoT applications that require broad area coverage.**

Keywords—Antenna array, compact, electrically small antennas, Huygens antennas, internet-of-things (IoT), wireless power transfer (WPT)

I. INTRODUCTION

Wireless Internet-of-Things (IoT) systems will be deployed massively in future smart and sustainable societies facilitated by the rapid development of 5G technologies [1]. Numerous IoT devices will be used in applications for smart cities; intelligent transportation; and environmental monitoring for agriculture, industry, medical care, and hazard warning. Wireless power transfer (WPT) is an emerging technology that will empower these applications [2] – [4]. It is pollution-free and environmental-friendly. In particular, it will eliminate the current large amounts of battery-waste. To enable the WPT function for IoT devices, compact rectennas [5] – [9] have been developed to convert the wireless RF energy into DC power. An antenna array that acts as an efficient wireless source is an indispensable component of a WPT system; it must provide both long distance and large area coverage to deliver electromagnetic energy to those rectennas. It is very challenging to achieve these performance criteria with a compact, ultra-thin, and low cost antenna array.

Linear arrays based on our previously developed single-substrate, electrically small Huygens dipole element reported in [10] are ideal candidates. The entire array can be designed on a single piece of PCB substrate with low fabrication cost. It has broad half-power beamwidth (> 150˚) in the H-plane for large radiation coverage and high directivity (narrow beamwidth in the E-plane) for long distance IoT device operations. To the best of our knowledge, only the design reported in [9] has realized both wide beamwidth and high directivity in an ultra-thin configuration. Nonetheless, the developed electrically small array design reported here is much more compact and does not require plated vias. The demonstrated 1 × 4 HLP array operating at 2.45 GHz achieves a high peak realized gain, 8.9 dBi. It has a narrow 3-dB beamwidth, 28˚, in the E-plane and a broad beamwidth, 153˚, in the H-plane.

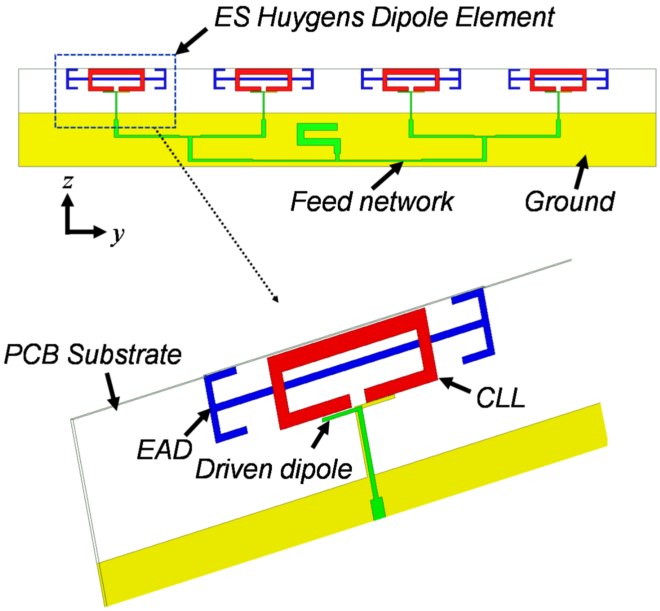
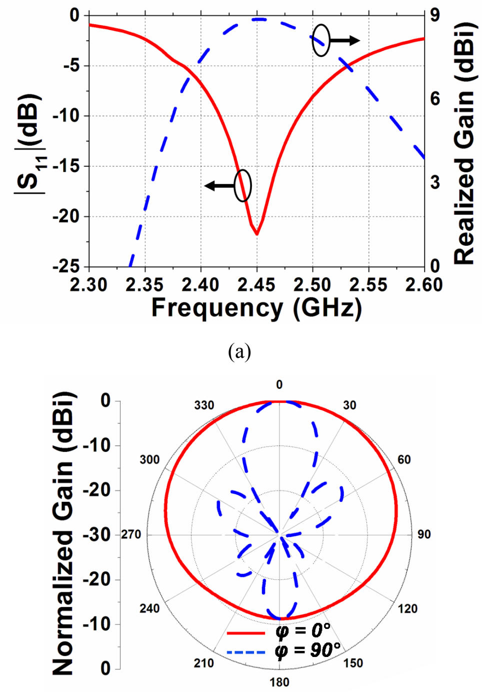


Figure 1. Configuration of the 1 × 4 array of electrically small Huygens dipole antennas on a single, thin piece of PCB substrate.

II. DESIGN CONFIGURATION AND OPERATING PRINCIPLE OF THE ELECTRICALLY SMALL HUYGENS DIPOLE ARRAY

The configuration of the 1 × 4 electrically small Huygens dipole array is shown in Fig. 1. It consists of four HLP elements and a 1-to-4 microstrip feed network. The entire array is designed on single piece of the copper-clad Rogers Duroid^{TM} 5880 substrate with a 0.508 mm thickness, a 2.2 dielectric constant, and a 0.0009 loss tangent. Each Huygens dipole element consists of two metamaterial-inspired electrically small near-field resonant parasitic elements: an Egyptian axe dipole (EAD) printed on the top surface of the PCB and a capacitively-loaded loop (CLL) printed on its bottom surface. The EAD and CLL system is excited by a short driven dipole with one of its arms printed on the top surface and the other on the bottom surface of the PCB. The short driven dipole is connected to a twin-line transmission line extended from a microstrip line of the 1-to-4 feed network. The microstrip of the feed network is etched on the top surface of the PCB and the ground is on the Sidebottom surface. The overall dimension of the array is 36 mm × 238 mm (0.29 λ × 1.94 λ × 0.004 λ), which is much smaller and thinner than the volume (1.2 λ × 2.7 λ × 0.02 λ) of the magneto-electric (ME) dipole array design in [11].



(a)

(b)

Figure 2. Simulated results. (a) $|S_{11}|$ and realized gain values as functions of the source frequency. (b) Radiation patterns at 2.45 GHz.

The broad beamwidth in the H-pane is realized thanks to the Huygens radiation pattern from the HLP element. It has been well demonstrated in [12] – [14] that the orthogonal and in-phase electric and magnetic dipole elements will produce a cardioid-shaped pattern with identical radiations in the E- and H-planes. It is also true for the linear antenna array reported here. The beamwidth in the H-plane remains as broad as the single element. The array formation only narrows the beamwidth in the E-plane. Consequently, both broad radiation coverage and high directivity are realized simultaneously.

III. PERFORMANCE

The full-wave simulations of the array were performed using the commercial software ANSYS Electromagnetics Suite (HFSS), version 19. Fig. 2(a) shows the simulated $|S_{11}|$ and realized gain values as functions of the source frequency. The array is operating at 2.45 GHz with the reflection coefficient being less than -20 dB. The realized gain at 2.45 GHz is 8.9 dBi. The simulated radiation patterns in the two principal vertical planes at 2.45 GHz are shown in Fig. 2(b). As expected, a broad half-power beamwidth, HPBW = 153°, is observed in the H-plane (φ = 0°) and a much narrower beamwidth, HPBW= 28°, is realized in the E-plane (φ = 90°). These performance characteristics make it an ideal candidate as the wireless power transmitter for a variety of WPT-based IoT applications.

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