High Directivity, Omnidirectional Horizontally Polarized Antenna Array for Wireless Power Transfer in Internet-of-Things Applications

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***Abstract*-A high directivity, compact, omnidirectional horizontally polarized (OHP) antenna array is developed for wirelessly powering internet-of-things (IoT) devices. The antenna array is realized by seamlessly inserting several phase inverters inside an electrically long $TE_{0.5,0}$ mode open waveguide. The phase inverter consists of a meandered slot and eight shorting vias. The meandered slot creates an interdigitated structure on the top surface of the waveguide; it introduces capacitance. The eight shorting vias are placed in an alternating pattern on the two sides of the slot; they produce inductance. The combination of the slot and vias forms a bandpass effect and inverts the electric fields in the waveguide. Consequently, a collinear and in-phase magnetic dipole array is realized. A compact eight-element OHP magnetic dipole array is designed, fabricated and measured. The measured results confirm the design concept and high directivity (10.4 dBi), omnidirectional HP radiation pattern has been achieved.**

I. Introduction

Omnidirectional antennas are widely used in modern wireless communication systems due to their large radiation coverage over a set of 360˚ directions [1] – [4]. In particular, omnidirectional horizontally polarized (OHP) antennas are becoming more and more attractive as a polarization diversity alternative to vertically polarized antennas [5] – [7]. Moreover, it has been proved that the use of the horizontally polarized antennas achieves higher reception power levels than those provided by vertically polarized systems [8].

A specific application of a high directivity OHP antenna system is illustrated in Fig. 1. It is an ideal candidate for wirelessly powering internet-of-things (IoT) devices, e.g., IoT sensors for forest fire detection and warning applications. These wirelessly powered (WP) sensors will measure data such as temperature, humidity, and smoke density, and will send this information to a gateway for processing. The WP function facilitates battery-less operation in difficult to reach or even inaccessible locations. To achieve their WP capability, such sensors need to be integrated with rectennas [9] – [12], i.e., rectifying antennas that convert incident RF power into DC power. A high directivity, efficient OHP antenna is thus highly desired to power such WP-based sensor networks.

Although many high directivity OHP antennas have been reported to date [13] – [18], it remains very challenging to achieve high directivity, compact size, simple fabrication process, and sufficient bandwidth all at the same time. This paper introduces an OHP antenna array that achieves all of these desired features at the first time. Consequently, it is the ideal source for wireless powering IoT sensors in any of the 360˚ directions surrounding it.

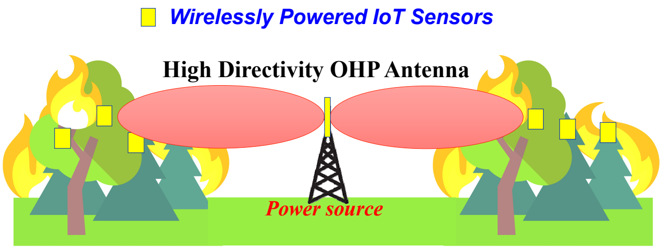


Figure 1. Illustrated IoT sensor system that is wirelessly powered by a high directivity, OHP antenna for forest fire detection and warning applications.

II. Design, Operating Principles and Measured Results of the High Directivity, OHP Antenna Array

A. Configuration of the antenna array

The configuration of the OHP antenna array is shown in Fig. 2. It consists of two Rogers™5800 substrates whose relative permittivity and loss tangent are 2.2 and 0.0009, respectively. Substrate#1 has a thickness of 1.575 mm. It fills two $TM_{0.5,0}$ mode open waveguides into which four phase inverters are integrated. The two center-fed waveguides are realized with substrate-integrated-waveguide (SIW) technology. Each phase inverter is a combination of a meandered slot and eight shorting vias distributed in an alternating pattern on both sides of the slot. The dimension of *Sub#1* and the phase inverters are L = 137 mm, W = 6.8 mm, l_{s1} = 2.9 mm, l_{s2} = 0.85 mm, and w_s = 0.1 mm. Substrate#2 is attached beneath *Sub#1* and has a thickness of 0.508 mm. A microstrip feedline (1 to 2 power divider) is printed on the bottom side of *Sub#2*. It excites the both of the $TM_{0.5,0}$ mode SIW-based waveguides through two shorting probes in the middle. Several tuning stubs are adopted to achieve good impedance matching to a 50-Ω source. The entire structure is compact and easy to fabricate. Its total volume is only 0.07 × 0.22 × 4.3 λ_0^3.

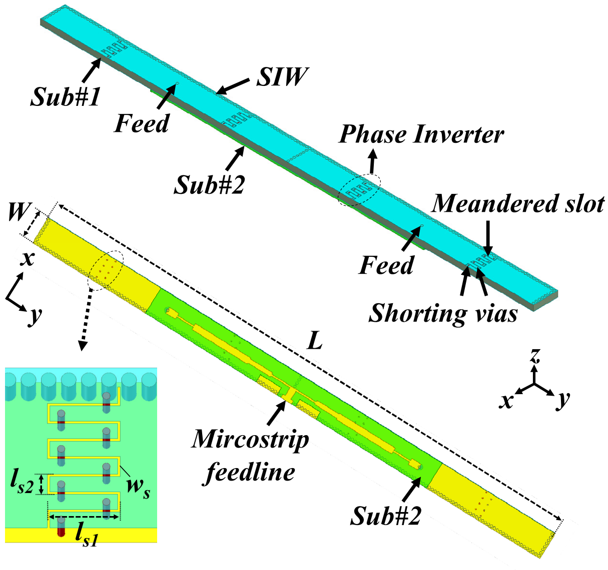


Figure 2. Configuration of the high directivity, omnidirectional, horizontally polarized antenna array.

B. Operating principles

The essence of this design is the realization of eight collinear and in-phase magnetic dipoles. As illustrated in Fig. 3, the E-field distributions along the open side of the waveguides without the phase inverters indicate that there are eight half-wavelength sections. Each section forms a magnetic dipole. Without the inverters, four of these magnetic dipoles have a reversed phase as shown. Consequently, the resulting radiation pattern is split (has a null) in the omni-plane (zx, φ = 0˚plane). The peak gain is only 7.5 dBi.

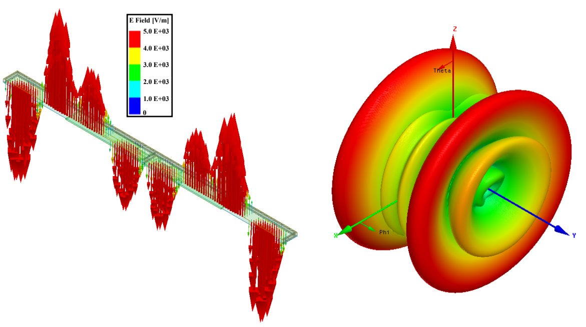


Figure 3. E-field distribution on the $TE_{0.5,0}$ waveguide mode without the phase inverters and the 3D radiation pattern it produces at 10 GHz.

The four phase inverters are integrated seamlessly into the waveguides to achieve the same phase for all eight magnetic dipoles. The meandered slot of each phase inverter creates an interdigitated structure on the top surface of the waveguide. It introduces a capacitance. The eight shorting vias placed in the alternating pattern on both sides of the slot produce an inductance. The combination of the slot and vias forms a bandpass filter effect and inverts the electric fields of the waveguide, i.e, flips the direction of those fields by 180˚. The electric field distribution in the structure is depicted in Fig. 4 (a) during one period of the source frequency. The effectiveness of these phase inverters is quite apparent. All of the E-fields along the opening of the waveguide are now in-phase and resonate together. Consequently, the phase inverters facilitate the realization of eight collinear, in-phase magnetic dipoles. Hence, high directivity, omnidirectional radiation patterns have been realized as shown in Fig. 4 (b).

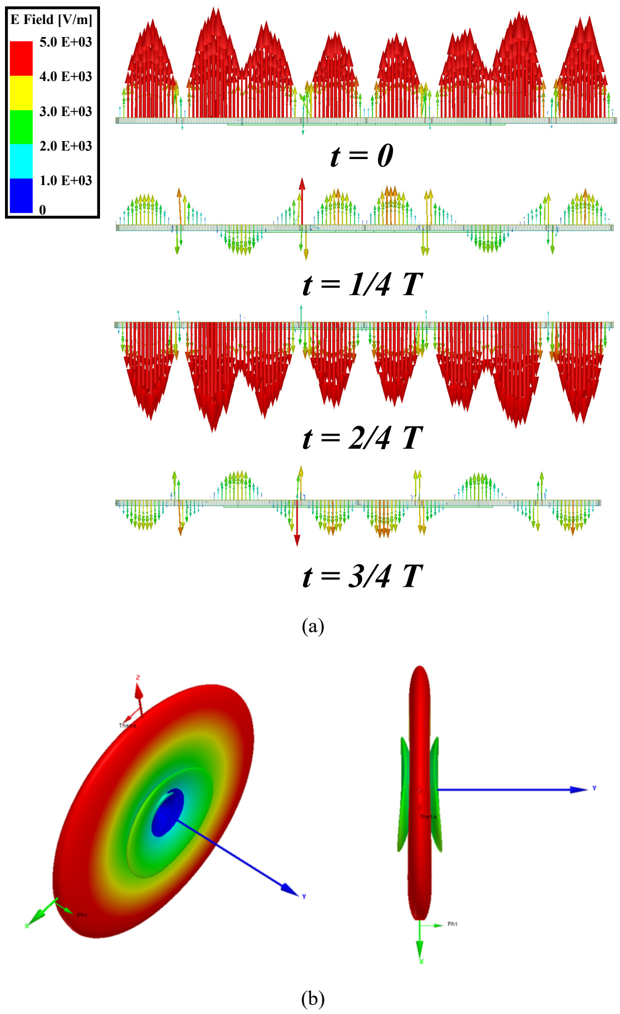
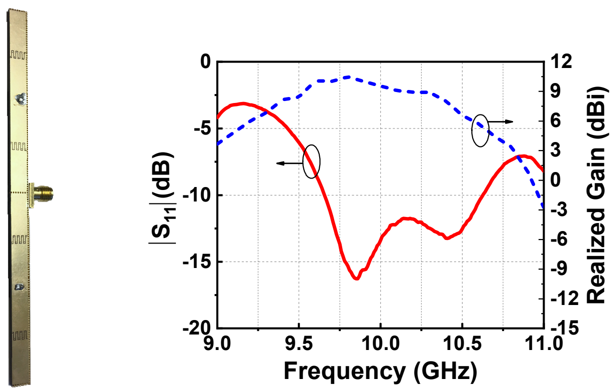


Figure 4. (a) Electric field distributions along the opening of the waveguide in one period of time T corresponding to the source frequency, 10 GHz; and (b) 3D radiation patterns at 10 GHz.

C. Measurement results

The fabricated antenna prototype is shown in Fig. 5. It is clear that it is compact. It is very light-weight. The prototype was tested with a Keysight™ Vector Network Analyzer (VNA) and a MVG far-field compact range system.



(a) (b)

Figure 5. (a) Fabricated antenna prototype. (b) Measured $|S_{11}|$ and realized gain values as functions of the source frequency.

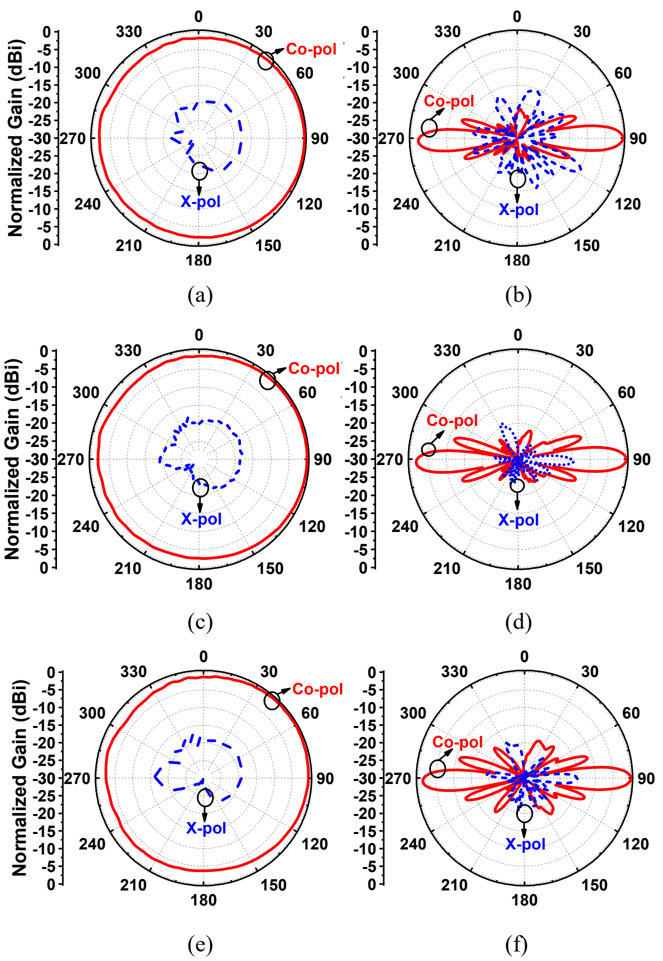


Figure 6. Measured radiation patterns. (a) Omni-plane at 9.8 GHz; (b) Vertical plane at 9.8 GHz; (c) Omni-plane at 10 GHz; (d) Vertical plane at 10 GHz; (e) Omni-plane at 10.2 GHz; (f) Vertical plane at 10.2 GHz;

The measured $|S_{11}|$ and realized gain values are shown in Fig. 5. The overlapping 10-dB impedance and 3-dB realized gain bandwidth covers 800 MHz from 9.6 to 10.4 GHz (8% fractional bandwidth). The peak realized gain is now 10.4 dBi; it achieves a 2.9 dB gain enhancement in comparison to the system without the phase inverters. The radiation patterns in both the omni-plane (zx, $\varphi = 0^{\circ}$plane) and the horizontal (xy, azimuthal, $\theta = 90^{\circ}$) plane are shown in Fig. 6. Very good omnidirectional HP radiation performance is observed. The cross polarization level is greater than 17 dB and the gain variation in the omni-plane is less than 3.0 dB.

III. Conclusions

The basic design, operating principles and measurement results for a high directivity, compact, omnidirectional horizontally polarized (OHP) magnetic dipole antenna array were reported. As will discussed in the presentation, this OHP array has superior performance characteristics (to the best of our knowledge) when compared to all of the previously reported OHP antenna arrays. As will also be demonstrated, this OHP array is an ideal candidate as the power source for wirelessly powering IoT devices such as small battery-less sensors.

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