Phased Array-Free Multi-Directional 5.8 GHz Wireless Power Transmission Using A Fresnel Lens

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***Abstract*—Steerable arrays are often developed based on complex phased arrays or lossy beamforming networks, making them unsuitable for pervasive wireless power transmission (WPT) applications. Here we propose the first sub-6 GHz quasi-optical beam-steering WPT dielectric lens-based system. The lens has an area of 16.6λ_0^2 with a height of 0.83λ_0, achieving an aperture efficiency of 44.7% and a gain improvement of 10 to 14 dB from 5.2 to 6.5 GHz. A $\pm 60^\circ$ beam-scanning angle is achieved with linear feed displacements, resulting in a 1 Steradian half-power beamwidth. The proposed design could enable switchable and multi-beam transmitters, with broad-beam high-gain rectennas.**

I. Introduction

Long-range wireless power transmission (WPT) is of great significance for powering remote maintenance-free sensors [1]. The channel losses represent the efficiency bottle-neck [2] leading to an increased demand for directional and steerable antennas, to reduce the path-loss of beamed power.

High-gain transmitters allow the power to be focused over meters-range [3]. For example, a quasi-optic power focusing setup recently demonstrated a 63.7% beam efficiency at a distance of 7.6 m at 5.8 GHz [4]. However, bulky parabolic reflectors were required. Furthermore, while phased arrays continue to attach interest in large-scale WPT arrays [5], off-the-shelf shifters have a high insertion loss (typically >2 dB) and complex feeding networks are still required. On the receiver side, large-area RF power collectors have been widely explored including broadband a [6] and flexible electrically-small surfaces [7]. Multi-beam rectennas have been reported using 3D arrays beamforming networks [8], but with increased power-combining losses [9].

In this paper, we present a 5.8 GHz WPT system based on a 3D-printable Fresnel lens for license-free WPT applications. When fed with a 7-8 dBi source, the lens can increase the gain by up 14 dB with a 60° half-power beamwidth.

II. Lens Design and Analysis

While planar beamforming lenses [10] and beamforming networks [8] have been reported in rectennas, they incur additional losses and only provide an improved angular coverage on a single spherical cut as opposed to a solid 3D angle. The proposed system is based on a grooved Fresnel lens, shown in Fig. 1. The radius of each section R is calculated using

$$R_i = \sqrt{2Fi(\lambda_0/P) + (i\frac{\lambda_0}{P})^2} \qquad i = 2, 3, ...P \qquad (1)$$

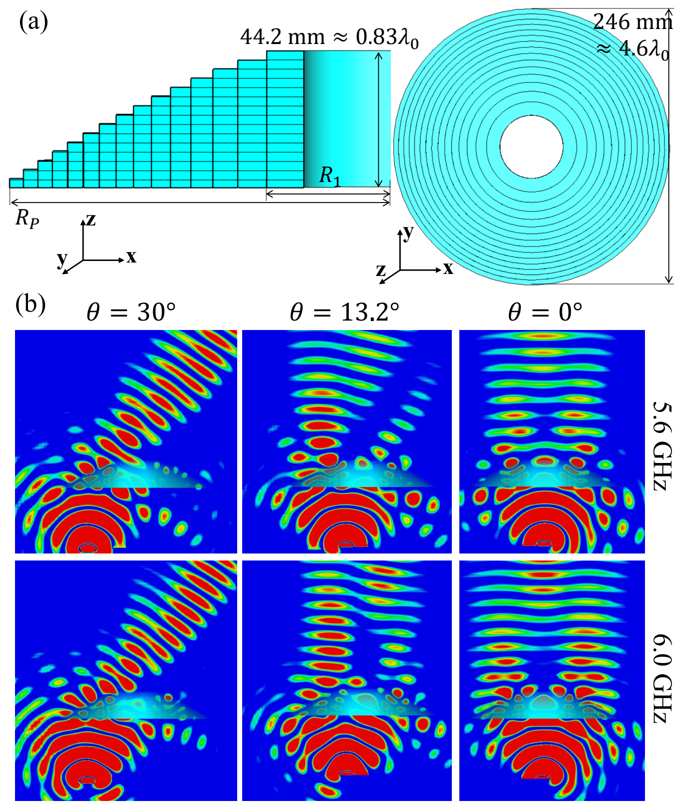

Fig. 1. (a) Layout and dimensions of the grooved Fresnel lens. (b) simulated E-field distribution showing the multi-beam-steering capability.

where P is the phase correcting index, λ_0 is the free-space wavelength (for 5.8 GHz), and F is the focal length [11]. The lens is designed based on an ABS-based 3D-printable PREPERM TP20280 filament, with ϵ_r=4.4 and tanδ=0.004. The permittivity is not graded as the phase transformation is achieved using the height of the rings, with the inner ring having ϵ_r=1 and therefore left as air.

To evaluate the beam-scanning performance of the lens for a directional WPT transmitter, the lens was simulated in CST Microwave Studio with a waveguide port. Fig. 1(b) shows the simulated E-field response at 5.6 and 6.0 GHz. The lens was fed by a source at $x = y$ =0 mm, x=48 mm, and x=96 mm for main-lobe at θ=0°, 13.2°, and 30°, respectively. The far-field response is shown in Fig. 2, where the beam-scanning can be observed in Fig. 2(a). The advancement over prior planar lens-based WPT implementations can be seen in Fig. 2(b)-

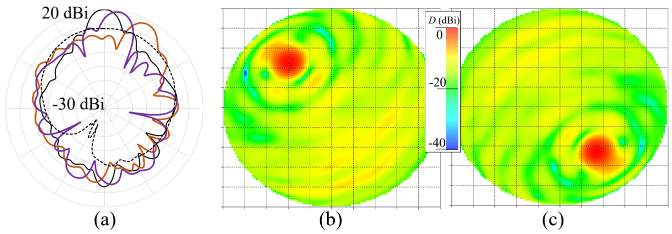

Fig. 2. Simulated far-field gain of the lens-based transmitter: (a) polar plot over the E-plane for varying feeding points (radius scaled to 5 dBi per division); (b) normalized 2D far-field gain for a bore-sight source; (c), (d), off-center beam-steering for a source at $x = y = 96$ and $x = y = -96$ mm, respectively.

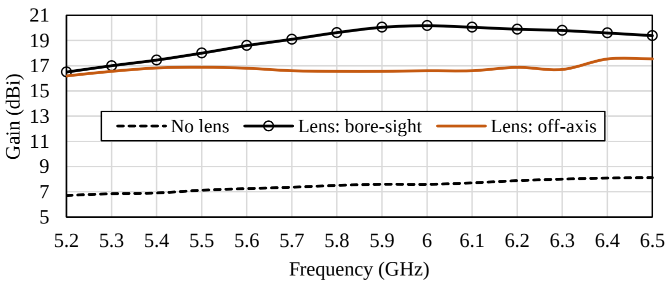

Fig. 3. Simulated gain with and without the grooved lens over the 5.8 GHz band for $\theta = 0°$ (bore sight) and $\theta \approx 30°$.

(d), where the power can be transmitted or harvested across approximately 1 Steradian with a -3 dB coverage. The gain improvement by the lens is shown in Fig. 2, over the 5.2 to 6.5 GHz bandwidth. The peak gain is observed for both a boresight transmitter at $\theta = 0°$, and at $\theta \approx 30°$ for a transmitter with an x displacement of 96 mm.

III. WPT Rectenna Performance

A microstrip voltage doubler rectifier is designed based on a RO4051b substrate and a Bat15-04R Schottky diode. The rectifier is matched using a series capacitor with distributed harmonic termination at the output. Fig. 4 shows the rectifier's RF-DC power conversion efficiency (PCE) over frequency and power, in the 5.8 GHz band, matching the bandwidth of the lens observed in Fig. 3.

In a WPT system with 8 dBi Yagi-Uda feeding antennas, over 1 mW DC power can be delivered over a range of 10 m with 1 Steradian angular coverage, representing over 20× improvement in the DC output compared to a system operating at 915 MHz [7]. This can be achieved using a 1 W source and the proposed rectifier based on the free-space path loss when using transmitting and receiving lenses.

IV. Conclusions

We presented a lens-based WPT system operating at 5.8 GHz for long-range license-free applications, featuring a 10–14 dB gain improvement from 5.2 to 6.5 GHz with a 1 Steradian coverage. It is shown that a 3D-printable lens could enable a steerable WPT transmitter without phase-shifting mechanisms, or to enable a passive rectenna to maintain a 1 Steradian beam without a lossy feeding network. Experimental results will be presented at the conference.

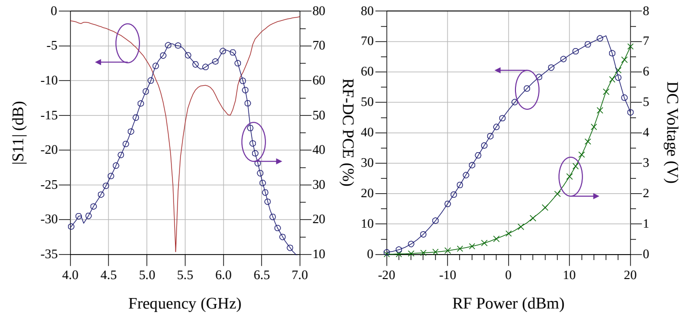

Fig. 4. Harmonic balance simulated RF-DC performance of the 5.8 GHz rectifier for a 1 kΩ load: (a) rectifier's S_{11} and PCE over frequency at 10 dBm input power, and (b) DC output and PCE over power at 5.8 GHz.

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