A Novel Long Range Wireless Power Transmission System Using Fresnel Lenses for S-band EM Waves

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***Abstract*— As energy consumption rapidly increases, there is a need for new and innovative power transmission systems. Wireless Power Transmission (WPT) systems could solve this dilemma, but face limitations due to high energy loss over distance. This project seeks to overcome these challenges by developing a WPT system that transmits energy over distance with minimal loss, using a Phased Array transmitter combined with a novel 3D printed Fresnel Lens. Designed with a high dielectric ABS and consisting of 2 parts, the original Fresnel Lens phase aligns and then collimates EM waves transmitted at 2.4GHz, allowing for efficient wireless energy transmission. After simulations, a prototype consisting of a Phased Array transmitter, Fresnel Lens, and rectenna receiver was designed and fabricated to test design methodology and efficiency. The novel EM Fresnel lens shows promising results, adding 12dB gain at 5m and nearly constant energy in the wireless channel with minimal loss over distance.**

Keywords—Wireless power transmission, phased arrays, Fresnel Lens, 3-D printing, rectenna

I. Introduction

Worldwide energy usage is growing rapidly, due to population growth and new power-hungry technologies. However, building wired infrastructure for energy transmission is costly, limiting deployment of clean energy plants. For example, the cost to build wired infrastructure is over $5M per 100km whereas wireless infrastructure is less expensive (i.e. costs can be reduced by 100x compared to wired), allowing for new sources of energy in previously inaccessible locations.

Wireless EM solutions for power transmission have not been adopted due to poor efficiency (Friis transmission loss) and high costs [1]. This research studies how to improve wireless power transfer over longer distances, with lower costs and better efficiencies, using 2.4GHz S-band EM waves.

A novel long range wireless power transmission (WPT) system was designed with a Phased Array and a 2-part Fresnel Lens. The Phased Array narrows the EM wave beamwidth and points the beam in a specific direction, resulting in a WPT that is smaller, less expensive to build, and has higher power transmission. The Fresnel Lens, designed for EM waves with 2 original parts, first phase aligns and then collimates the EM waves, allowing for efficient energy transfer over distance.

II. Background Information of Fresnel Lenses

EM waves for wireless power transmission are governed by the Friis equation, losing power quadratically as a function of distance. To minimize the significant drop in power over distance, a new system must be designed to counteract this loss.

The Fresnel Lens was originally used to focus and amplify light. The curved surface of a conventional optical lens is replaced with a series of concentric angular rings, thereby collimating and amplifying the signal with less material (Fig 1).

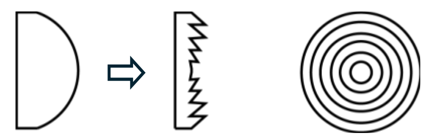


Fig 1. Optical Lens vs Fresnel Lens with concentric rings

Fresnel Lenses designed for EM waves are limited to high frequency Ka–band and V-band millimeter wavelengths (27-60 GHz) in the literature [2]. As lens thickness is equivalent to the wavelength of the EM wave, lens thickness and material costs increase for lower frequencies, resulting in less research around lower frequencies. In this research, new design methods minimize the size and cost of the Fresnel Lens for 2.4GHz.

III. Novel Fresnel Lens Design and Fabrication

This research incorporates new design methods for the Fresnel Lens in the S-band of the spectrum. First, by combining the novel Fresnel Lens with a Phased Array, the HPBW required by the Lens is smaller, resulting in a smaller diameter Lens with greater focusing. The Lens is also designed with a focal length on the border between the near-field and the far-field of the Phased Array. Second, a high dielectric ABS plastic is used with a S-band dielectric of 5, so that Lens can be built using 3D printing. Third, the Lens consists of two independent parts, first to phase align the angular beam and second to collimate the outgoing waves into a beam. Phase alignment, as the incoming waves enter at various angles, is accomplished by differing dielectrics in each concentric ring of the Lens. Collimation results from the differing concentric angles on each ring.

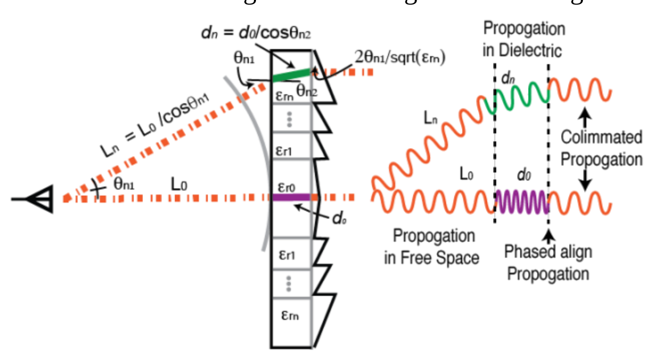


Fig 2. Fresnel Len design methodology to align phase and collimate EM waves at output of lens

A. *Fresnel Lens Design*

The novel Fresnel Lens (1) phase aligns the EM waves and then (2) collimates the EM waves into a beam, so the EM waves can travel longer distances with minimal losses. To achieve this goal the Lens combines a planar and angular Fresnel Lens (Fig 2). The angular Lens for EM has not been reported before and was developed solely in this research.

To phase align the incoming EM angular waves, the planar Lens is designed with concentric rings of different composite dielectric values, $\boldsymbol{\varepsilon_{rn}}$. Each ring is considered a Fresnel Lens Zone. The dielectric value for each Zone is estimated based on the incident angle for each Zone, $\boldsymbol{\theta_n}$, focal length for the lens, $\boldsymbol{L_0}$, and thickness of the lens, $\boldsymbol{d_0}$, (Eq 1-3). After the incoming EM waves traverse each zone, they all exit phase aligned.

$$\upsilon_{\varepsilon R} = \frac{c}{\sqrt{\varepsilon_R}} \tag{1}$$

$$\lambda_{\varepsilon R} = \frac{\upsilon_{\varepsilon R}}{f} \tag{2}$$

$$L_0 + \sqrt{\varepsilon_{r0}}d_0 = L_n + \sqrt{\varepsilon_{rn}}d_n = \frac{L_0}{cos\theta_{n1}} + \sqrt{\varepsilon_{rn}}\frac{d_0}{cos(\theta_{n1}/\sqrt{\varepsilon_{rn}})} \tag{3}$$

To collimate the now phase aligned EM waves (Fig 2), the angular Lens, with different angles for each concentric ring, re-angles the exiting waves into a collimated beam. Snell's law determines the angle required for collimation for each Zone.

B. *Fresnel Lens Fabrication*

The fabricated Lens dimensions are determined by the specifics of the Phased Array. In this system, the half-power beam width of the phased array is 34°, the focal distance is 30cm, and the ABS plastic dielectric is 5. These design parameters dictate a Lens size of 20cm and thickness of 1.2cm.

The combined planar and angular Lens (Fig 3) are designed using Fusion 360 to provide a stereo-lithography (STL) format of data for both 3-D printing and simulating the design.

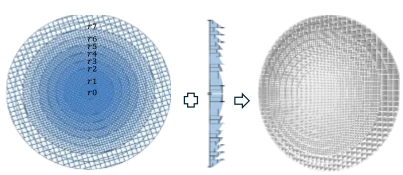
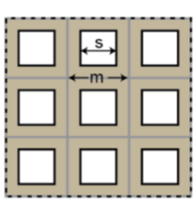


Fig 3. Fresnel Len made of concentric rings and angles designed in Fusion 360 Cad tool

A lattice structure creates the different dielectric constant for each Fresnel Zone [3]. The structure, based on a hole spacing "**s**" and a fill section "**m**", results in different densities, translating into different dielectrics. Fig 4 shows a sample of the lattice structure, and the dielectrics required for each zone.



			m	s
ε_{r0}	=	4.36	2	0.8
ε_{r1}	=	4.19	2	0.9
ε_{r2}	=	3.79	2	1.1
ε_{r3}	=	3.44	2	1.25
ε_{r4}	=	3.04	2	1.4
ε_{r5}	=	2.65	3	2.3
ε_{r6}	=	2.22	6	2.5
ε_{r7}	=	1.76	6	5.6
ε_{r8}	=	1.39	8	7.6

Fig 4. Lattice structure for Fresnel Len and table to generate dielectric constants for each Fresnel Zone

The density of the structure to create the dielectric constant is:

$$\varepsilon_r = (\varepsilon_{rmax} - 1)\frac{(m^2 - s^2)}{m^2} + 1 \tag{4}$$

Both the **s** and **m** dimensions need to be within the tolerance of the 3-D printer. The 3D printer's maximum temperature, nozzle size, cooling rate and printing speed need to be accounted for.

IV. Simulations of Phased Array and Fresnel Lens

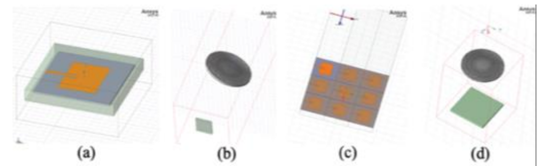


Fig 5. The (a) patch antenna and (b) patch antenna with Fresnel lens, (c) phased array, and (d) phased array with Fresnel lens were modeled in HFSS to provide near field and far-field simulations data.

EM simulations with HFSS were completed to determine the design methodology and system parameters of the Phased Array and Fresnel Lens, prior to printing the Lens. The Phased Array transmitter is designed using a single micro-strip patch antenna design and then arraying that element into a proposed PCB. The Fresnel Lens was imported into HFSS as STL files directly from the CAD tool. Fig 5 (a-d) are the drawn models of the Single Antenna with and without the Fresnel Lens, and the Phased Array with and without the Lens, respectively.

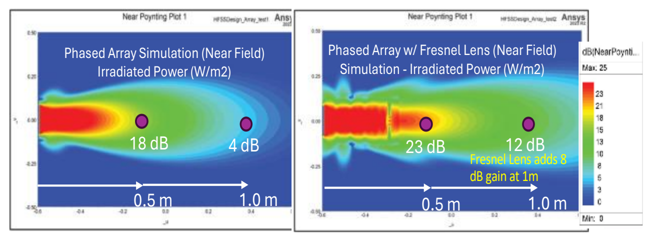
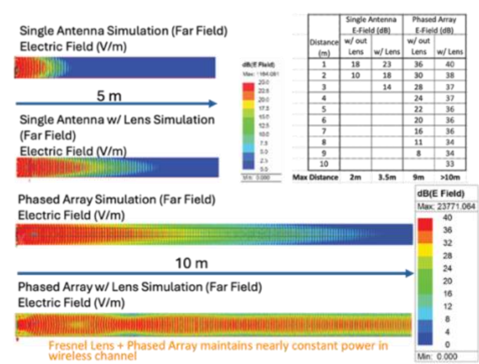


Fig 6. HFSS Near Field Simulations for Phased Array Antenna with and w/out Fresnel Lens

Near-Field simulations show a) the Phased Array adds18dB of gain compared to the Single element Transmitter and b) the Fresnel Lens adds 5dB of power at 0.5m and 8dB higher power at 1m distance, versus no Lens (Fig 6). In simulations, the Fresnel Lens improves the gain of this WPT system, with the gain increasing over distance, as expected with the Lens phase aligning and collimating the EM waves.



Distance (m)	Single Antenna E-Field (dB) w/ out Lens	Single Antenna E-Field (dB) w/ Lens	Phased Array E-Field (dB) w/ out Lens	Phased Array E-Field (dB) w/ Lens
1	18	23	36	40
2	10	18	30	38
3		14	28	37
4			24	37
5			22	36
6			20	36
7			16	36
8			11	34
9			8	34
10				33
Max Distance	2m	3.5m	9m	>10m

Fig 7. HFSS Far Field Simulations for Single Antenna with & w/out Fresnel Lens and for Phased Array Antenna with and w/out Fresnel Lens and Table of Electric Field estimated Data

The Far Field simulations also demonstrate a) the Fresnel Lens gain increases with distance and b) the combination of the Phased Array and Fresnel Lens system provides almost constant power over 10m of distance (Fig 7). The far-field simulations closely match the prototype measurements, as seen in Section V.

V. EXPERIMENT AND RESULTS

The prototype for the WPT system consists of solar panels for energy generation, PCBs to create a 9-element Phased Array transmitter to provide 0 dBm with a HPBW of 34º, the novel 2-part Fresnel Lens with a focal distance of 30cm, and a spectrum analyzer and rectenna to determine the RF and DC power in the wireless channel as shown in Fig 8.

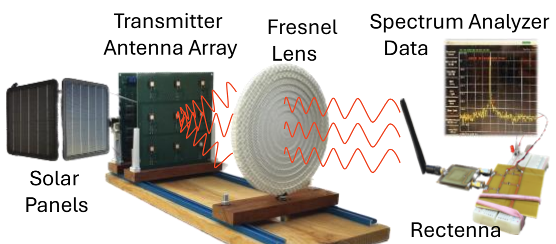


Fig 8. Experimental Setup to measure power transmitted in various conditions of antenna, phased array, and Fresnel lens. Solar Panel is used as power source for antenna array

Experiments were conducted to determine the RF power level in the wireless channel as a function of distance. The assumption is that the transmitter can be designed efficiently for power transmission, with nonlinear components as well as antennas for the rectenna and spectrum analyzer [4,5]. To model power transmission of the transmitters to follow Friis equation in free space, an antenna correction factor is determined for the short-range antenna. The calibration factor for the antenna used in this research is shown below.

$$ACF(d) = -0.36d^3 + 3.04d^2 - 3.81d + 0.6 \qquad (5)$$

Both the single element and the Phased Array match the Friis transmission equation results with antenna calibration. A measured improvement of 17dB with the Phased Array compared to the single element transmitter is seen (Fig 9).

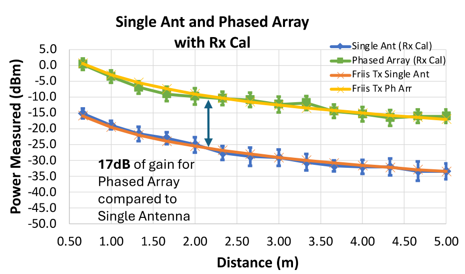


Fig 9. Single Antenna and Phased Array Measurement after Corrections

Fig 10 shows the Fresnel Lens improves power transmission. Both the Single Antenna and Phased Array exhibit 12dB of gain at 5m distance. Further, the gain increases with distance, similar to the HFSS far field simulations. Additionally, after 1.5m, the Phased Array shows nearly constant power, as the Fresnel Lens phase aligns and collimates the transmitted power. Since the Phased Array transmitter has a narrower HPBW compared to the Single Antenna, there is less initial loss prior to collimation (8dB loss for single transmitter vs 5dB loss for Phased Array).

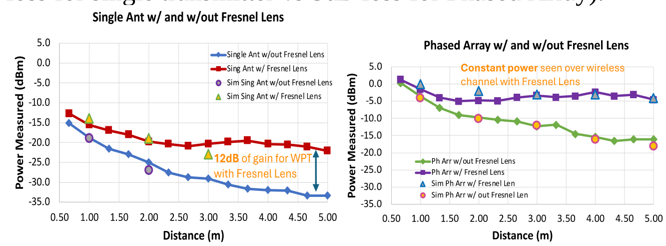


Fig 10. Single Antenna and Phased Array Measurements w/ and w/out Fresnel Lens

Fig 11 shows the relative contribution between the 2 parts of the Fresnel Lens. The Ring Lens contributes 59% of the total combined Lens gain and the Angular Lens provides 41% of the total gain. Compared to the planar lens alone, the Angular Lens results in an additional 60% of gain.

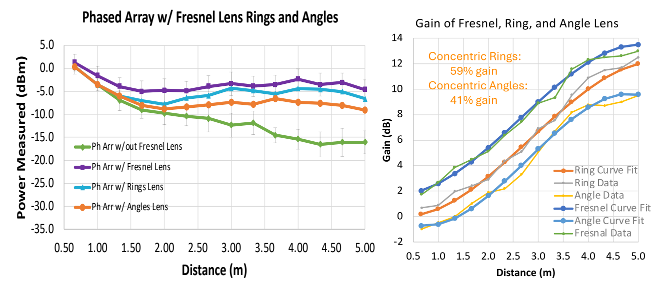


Fig 11. Gain measurements of Phased Array with various configurations of the Fresnel Lens. Gain measurements are curve fitted to estimate impact of each Fresnel Lens Component

VI. CONCLUSION AND FUTURE WORK

A novel WPT system using a combination of a transmitter Phased Array and a novel EM Fresnel Lens was designed, fabricated, and validated using HFSS simulations and prototype measurement results. The combined planar plus newly developed angular Fresnel lens provides an extra 60% of power gain, compared to a single planar Fresnel Zone lens. Constant power was measured up to 5m with current WPT system. In order to reduce initial transmitter losses, future work will design a Phased array with narrower HPBW along with a larger 2 part Fresnel Lens optimized for the near field, thereby resulting in closer EM capture and reducing loss due to stray EM waves.

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