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 systems (WPT) 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 novel Fresnel lens phase aligns and then collimates EM waves transmitted at 2.4GHz, allowing for efficient wireless energy transmission. After simulations, a prototype including the phased array transmitter, Fresnel lens, and rectenna receiver was designed and fabricated to test design methodology and efficiency.**

Keywords—Wireless power transmission, phased arrays, Fresnel lens, additive manufacturing process, rectenna

I. Introduction

Energy usage is rapidly growing worldwide, due to population growth and new power-hungry technologies. However, building wired infrastructure for energy transmission is costly, limiting deployment of new clean energy plants. For example, the cost to build wired infrastructure is over $5M per 100km. On the other hand, wireless infrastructure is less expensive (ex, costs can be reduced by 100x compared to wired) and allow for previously inaccessible locations of new sources of energy (ex, windmills on ocean).

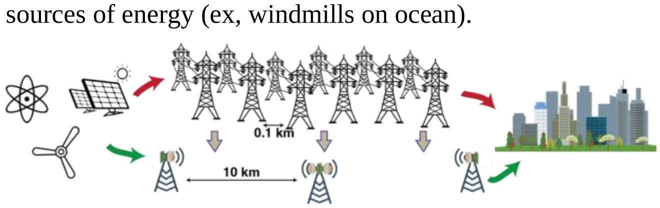


Fig 1. Power Transmission Systems comparison

Currently, Wireless EM solutions for power transmission have not been adopted due to poor efficiency (Friis transmission loss). This research studies how to transfer higher levels of power over longer distance, with lower costs and better efficiencies, using EM wave in the S-band.

The 2.4GHz EM frequency is chosen, as it achieves the optimal balance between lower energy loss and system size. Higher frequencies in the millimeter wave region such as 10 GHz or higher have a high energy loss over distance [1]. Lower frequencies EM waves require a costlier large system size, with a larger transmitter array and a bigger Fresnel lens.

Further, by incorporating a phased array which narrows the EM wave beamwidth, the WPT is smaller, less expensive to build, and results in higher power transmission.

For the WPT design, the novel long range wireless power system consists of a Phased Array and a 2 part Fresnel Lens. The Phased Array is used to narrow the beam and point it to a specific direction. Consisting of 2 original parts, the Fresnel Lens first phase aligns and then collimates the EM waves, allowing for more efficient energy transfer over distance.

II. Background Information

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

A. Friis Transmission Equation

The Friis equation is used to determine the radiated and received power based on gain, power transmitted, wavelength of radiated power, and the distance between the transmitter and the receiver. $\boldsymbol{G_{tx}}$ and $\boldsymbol{G_{rx}}$ are the gain of the transmitter and receiver antenna, $\boldsymbol{r}$ is the distance between the transmitter and receiver, $\boldsymbol{\lambda}$ is the wavelength of the signal and $\boldsymbol{P_{tx}}$ is the transmitted power as seen in Eq 1. A wavelength, $\boldsymbol{\lambda}$, is defined as speed of light, $\boldsymbol{c}$, divided by the frequency, $\boldsymbol{f}$.

$$P_{radiated} = \frac{G_{tx}P_{tx}}{4\pi r^2} \quad P_{rx} = \frac{G_{rx}P_{rad}\lambda^2}{4\pi} = \frac{G_{tx}G_{rx}P_{tx}\lambda^2}{(4\pi r)^2} \qquad (1)$$

As Friis equation dictates, received power decreases with farther distance and shorter wavelengths. Furthermore, a Phased Array increases Transmitter gain by $\boldsymbol{N^2}$ for $\boldsymbol{N}$ antennas.

$$P_{rx} = N^2 \frac{G_{tx}G_{rx}P_{tx}\lambda^2}{(4\pi r)^2} \qquad (2)$$

B. Phased Array Design

A Phased Array Transmitter is an array of power amplifiers and antennas used to narrow and direct an RF beam. A key advantage is that the power gain transmission increases with additional elements by $\boldsymbol{N^2}$ instead of $\boldsymbol{N}$, shown in Eq 2. Each antenna sends out EM waves with different phase shifts. Through constructive interference, these waves combine to produce high gain in a specific direction, following Euler's equations (Fig 2).

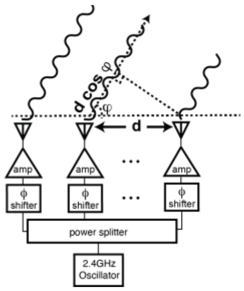


Fig 2. Phased array transmitter where d is the distance between antenna elements, and φ is the angle of the beam direction.

The phase shift required for each antenna are determined Euler's equations presented below in Eq 3-5,

$$R(\phi,\theta) = \sum_{n,m} e^{-j2\pi\left(\frac{d}{\lambda}\right)cos\theta((m-1)sin\phi+(n-1)cos\phi)} \tag{3}$$

$$Wn,m(\chi,\varphi) = e^{+j2\pi\left(\frac{d}{\lambda}\right)cos\varphi((m-1)sin\chi+(n-1)cos\chi)} \tag{4}$$

$$W * R(\phi,\theta) = \sum_{n,m} e^{+j2\pi\left(\frac{d}{\lambda}\right)cos\varphi((m-1)sin\chi+(n-1)cos\chi)} * e^{-j2\pi\left(\frac{d}{\lambda}\right)cos\theta((m-1)sin\phi+(n-1)cos\phi)} \tag{5}$$

where $\boldsymbol{R(\phi,\theta)}$ is real space, $\boldsymbol{W_n}$ are phase shifts, $(\boldsymbol{\chi},\boldsymbol{\varphi})$ is the constant beam steer angle, $\boldsymbol{\lambda}$ is the wavelength, and $\boldsymbol{d}$ is the distance between array elements.

For this WPT system, a 9-element phased array transmitter is designed and used to generate the transmitted power (Fig 3). The narrowed beam width is determined by the number of elements and the separation of $\boldsymbol{\lambda}$**/2** is measured with a half-power beamwidth (HPBW) of 34^o.

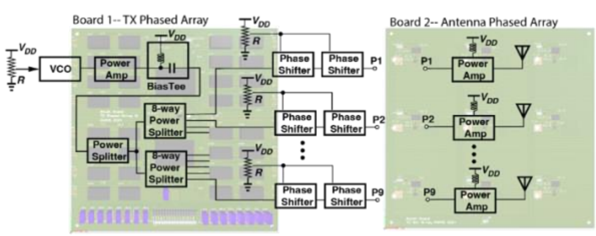


Fig 3. The 2 boards used for the phased array transmitter split as (1) phased aligned frequency generation and (2) antenna array

C. Fresnel Lens

Designed by Bernard Fresnel in 1822 to increase the intensity for lighthouses, the Fresnel lens was originally used to focus and amplify light to prevent ships from crashing at shorelines. The curved surface of a conventional optical lens is replaced with a series of concentric angular rings (Fig 4).

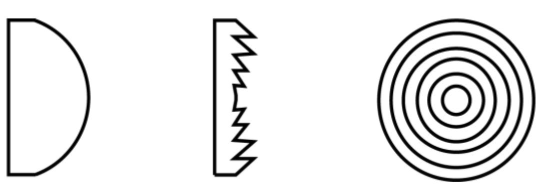


Fig 4. Curved lens versus Fresnel Lens with concentric Rings

The Fresnel Lens collimates and amplifies the signal (Fig 5) with much less material than a regular optical lens.

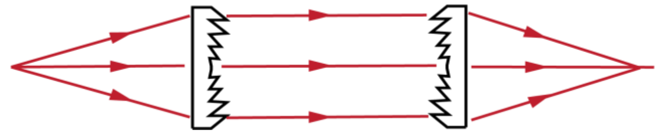


Fig 5. Fresnel Lens collimates and magnifies light waves

In the current literature, Fresnel Lenses designed for EM waves are limited to high frequency Ka–band and V-band millimeter wavelengths (27-60 GHz) [2]. Lower frequencies increase the lens thickness and material cost, because lens thickness is equivalent to the wavelength of the EM wave, thereby limiting research. In this research, new design methods are used to minimize the size/cost of the Fresnel lens at 2.4GHz.

III. Novel Fresnel Lens Design and Fabrication Methodology

Fresnel lens were originally designed for optical waves. The wavelength of optical waves are sub-1um, so phase alignment through the lens is not a concern and only function of the Lens is collimation to focus the light. Therefore, the thickness of the lens material is not a concern, as only the dielectric of the material determines the angles required to collimate the light. For Fresnel Lens designed for EM waves, especially in the S-band where the wavelengths are several centimeters, additional considerations are the phase alignment which is critical for efficient power transmission, as well as maintaining a reasonable thickness to the Lens to avoid high costs.

New design methods for the Fresnel lens in the S-band of the spectrum are incorporated. First, by combining the novel Fresnel lens with a Phased Array, the HPBW required by the lens is limited, resulting in maximum power focusing. The Lens is also designed with a focal length that puts it 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 dielectric of 5 for the S-band, so that Lens can be built using additive manufacturing techniques (3D printing). Third, the Lens consists of two independent parts, first to phase align the angular beam and then to collimate the beam. The phase alignment for the various angles is accomplished by changing the wavelength through the different concentric rings of the Lens. The differing concentric angles on each ring then result in collimation. The design of Lens is provided with more detail in the next section.

A. Fresnel Lens Design

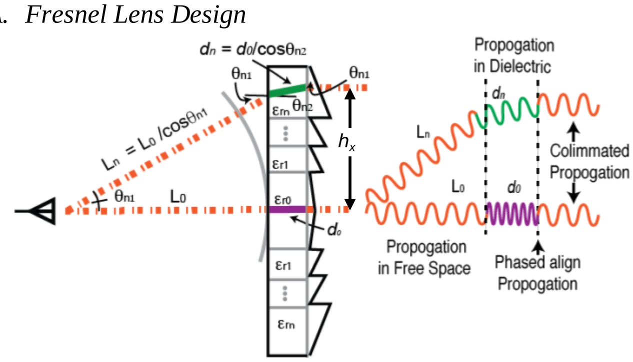


Fig 6. Fresnel Len design methodology to align phase and collimate EM waves at output of lens

The Fresnel Lens provides efficient EM power transmission. This is done through (1) phase aligning the EM waves and then (2) focusing the EM waves into a column, so the EM waves can travel long distance with minimal losses. The novel Fresnel Lens combines a planar and angular Fresnel lenses, as illustrated in Fig 6. This 2 part Lens has not been reported in literature and was developed solely in this research project.

To phase align the incoming EM beam as it hits the Lens in a range of angles, 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, $\boldsymbol{\theta_n}$. The focal length for the lens, $\boldsymbol{L_0}$, and the thickness of the lens, $\boldsymbol{d_0}$, as shown in Eq 6-7. As the incoming EM waves exit each zone of the planar Lens, they will now be phase aligned in the far-field of the phased array.

$$v_{\varepsilon R} = \frac{c}{\sqrt{\varepsilon_R}} \tag{6}$$

$$\lambda_{\varepsilon R} = \frac{v_{\varepsilon R}}{f} \tag{7}$$

$$L_0 + \sqrt{\varepsilon_{r0}}d_0 \; = L_n + \sqrt{\varepsilon_{rn}}d_n \tag{8}$$
$$= \frac{L_0}{cos\theta_{n1}} + \sqrt{\varepsilon_{rn}}\frac{d_0}{cos(\theta_{n1}/\sqrt{\varepsilon_{rn}})}$$

In addition, a thin angular Lens is designed to collimate the phase-aligned EM waves. Snell's law (Eq 9) determines the angle required for collimation for each Fresnel Zone.

$$Snell's\ Law: \quad \frac{sin\theta_1}{sin\theta_2} = \frac{v_1}{v_2} = \sqrt{\frac{\varepsilon_2}{\varepsilon_1}} \tag{9}$$

To achieve the required dielectric for each zone, the Lens is designed using 3D manufacturing techniques with a lattice structure. The development of the lattice structure for the planar and the angular ring is provided in the next section.

B. *Fresnel Lens Fabrication*

The fabricated Lens size is determined by the specifics of the phased-array and lens system. In this system, the half-power beam width of the phased array is 34º, the focal distance is 30cm, and the ABS plastic material used 5. These design parameters dictate a Lens size of 20nm with a thickness of 1.2cm.

Each Lens has a) concentric rings (Fresnel Zone) with an associated dielectric constant to change the wavelength for phase alignment and b) specific angle for each ring depending on the incoming angle of the EM Wave.

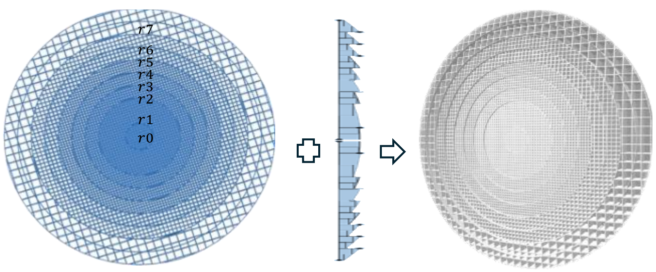
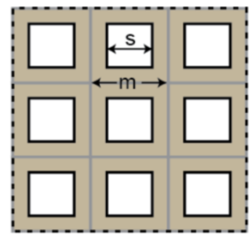


Fig 7. Fresnel Len made of concentric rings and angles designed in Fusion 360 Cad tool

The zones and the corresponding angles are shown in Fig 7. The combined planar and angular lenses were designed using Fusion 360 to provide a stereo-lithography (STL) format of data for both 3-D printing and simulating the design.

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

The density of the structure needed to create the dielectric constant is based on Eq 10.

$$\varepsilon_r = (\varepsilon_{rmax} - 1)\frac{(m^2 - s^2)}{m^2} + 1 \tag{10}$$

Both the s and m dimensions need to be within the tolerance of the 3-D printer. The temperature and the speed of deposition need to be considered for maintaining the correct dielectric densities using the additive manufacturing process.

IV. Simulations of Phased Array and Fresnel Lens

EM simulations using HFSS are used to validate the design of the Phased Array and the Fresnel Lens before the Lens was printed. The Phased Array transmitter is designed using a single micro-strip patch antenna design and then arraying that element similar to the proposed PCB. The two Fresnel lenses were imported into HFSS as STL files directly from the CAD tool. Figures 9 and 10 are the drawn models of the single antenna with and without the Fresnel lens and the phased-array with and with the lenses respectively.

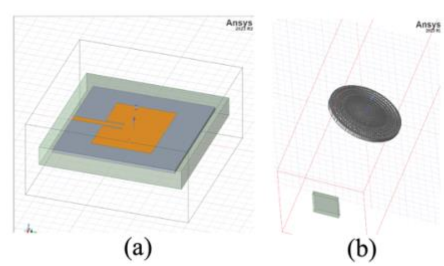


Fig 9. The (a) patch antenna and (b) patch antenna with Fresnel lens with Fresnel lens were modeled in HFSS to provide near field and far-field simulations data

Simulations of a single transmitter element with and without the Fresnel Lens and the Phased aAray with and without the Fresnel lenses were completed to determine if the design methodology and system parameters were correct and valid.

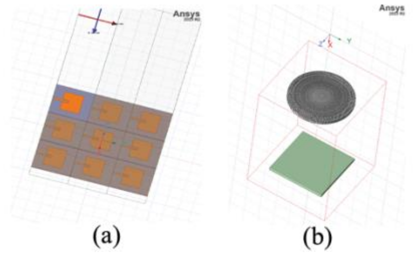


Fig 10. The (a) phased array, and (b) phased array with Fresnel lens were modeled in HFSS to provide near field and far-field simulations data

Near-Field simulations (Fig 11) show that the Phased Array has an additional 18dB of gain compared to the single element transmitter. Simulation with the Fresnel Lens shows 5dB higher power at 0.5m and 8dB higher power at 1m distance. The addition of the Fresnel lens does improve the gain of this WPT system in simulations, and the gain is increased with distance, as expected with phase aligning and collimating the EM waves.

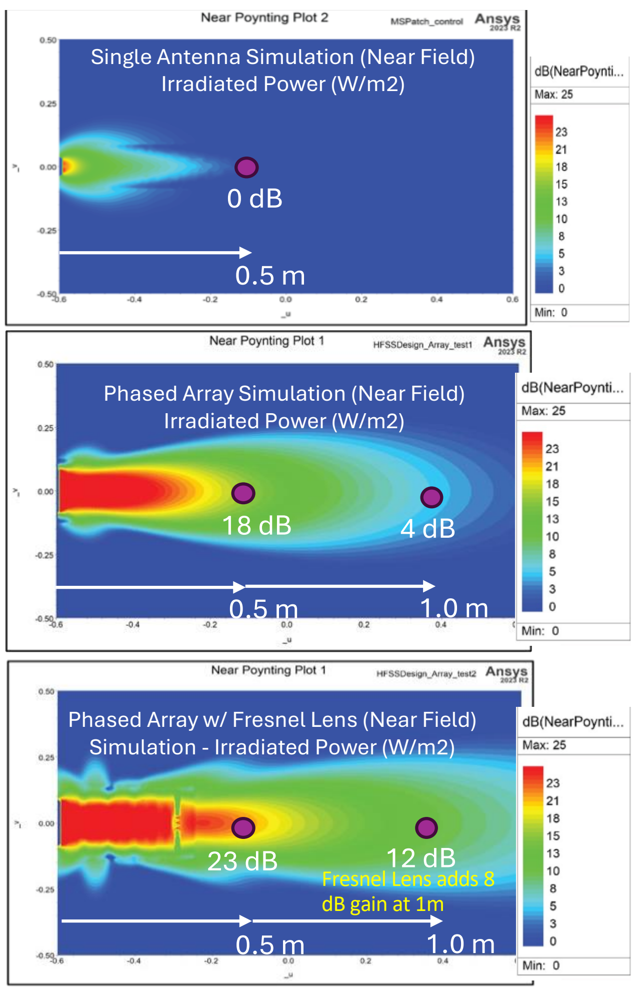
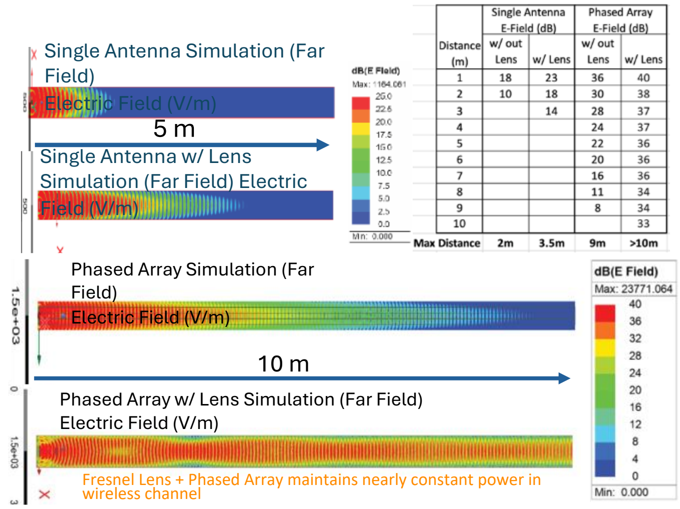


Fig 11. HFSS Near Field Simulations for Single Antenna and Phased Array Antenna with and w/out Fresnel Lens

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 12). The far-field simulations match the prototype measurements, as seen in Section V.



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

V. Experiment and Results

The prototype for the WPT system consists of solar panels for energy generation, PCBs to generate a 9-element Phased Array transmitter to provide 0dBm with a HPBW of 34°, the 2 part novel 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 13.

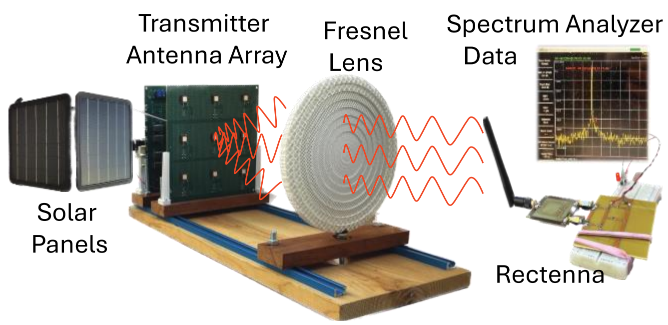


Fig 13. Experimental Setup to measure power transmitted in various conditions of antenna, phased array, and Fresnel lens. Solar Panel is used as power source for antenna array

The focus of the experiments is 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 [4] for power transmission since nonlinear components can be used as well as the antennas for the rectenna and spectrum analyzer. [5] An antenna correction factor is determined for the short-range antenna such that the power transmission of a single element can follow Friis equation in free space. The calibration factor for the antenna used in this research is shown below.

$$ACF(d) = -0.36d^3 + 3.04d^2 - 3.81d + 0.6 \qquad (9)$$

Both the single element and the Phased Array match Friis transmission equation results after antenna calibration (Fig 15). A measured improvement of 17dB with the phased array compared to the single element transmitter is seen in Fig 15.

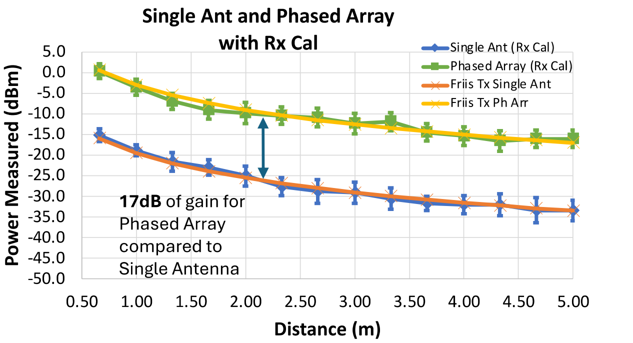


Fig 15. Single Antenna and Phased Array Measurement after Corrections

Fig 16 shows the Fresnel Lens improves power transmission for both the single transmitter and the Phased Array. 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. After 1.5m, the Phased Array shows 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).

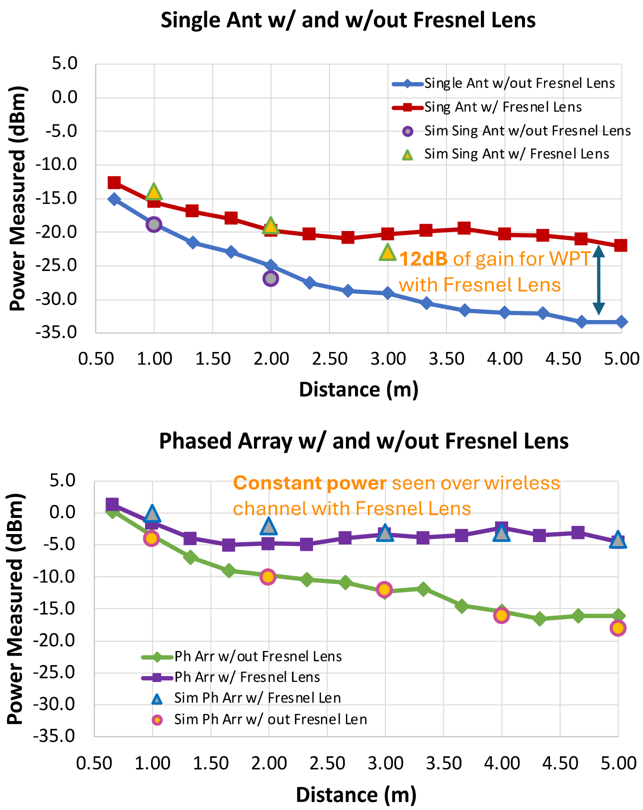


Fig 16. Single Antenna and Phased Array Measurements w/ and w/out Fresnel Lens

Fig 17 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 total the gain. The Angular Lens results in an additional 60% of gain, compared to the planar lens alone.

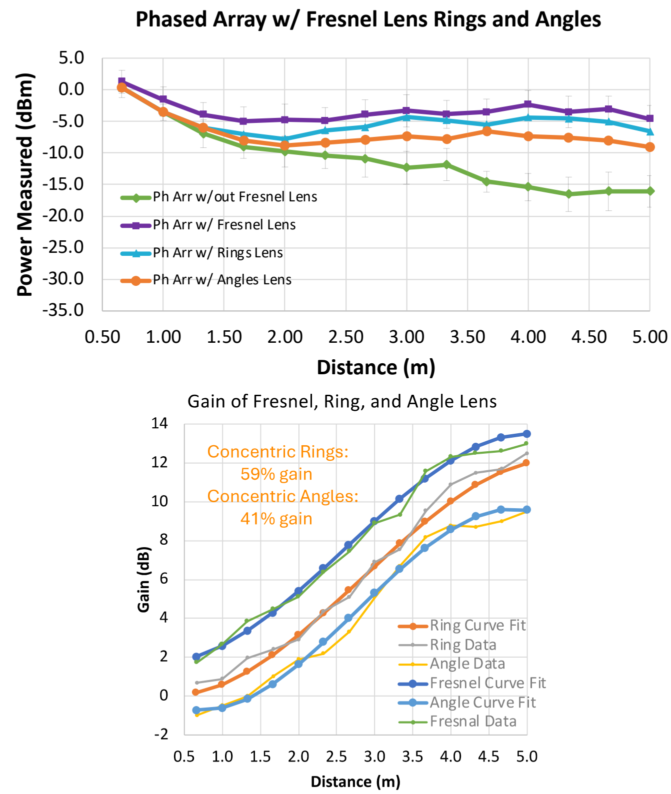


Fig 17. Gain measurements of Phased Array with various configurations of the Fresnel Lens. Gain measurements are curve fitted to estimate impact of each Fresnel Lens Component

VI. Conclusion and Future Work

A novel WPT system using a combination of a transmitter Phased Array and a novel Fresnel lens was designed and fabricated and validated using HFSS simulations and prototype measurement results. The combined planar plus newly invented 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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