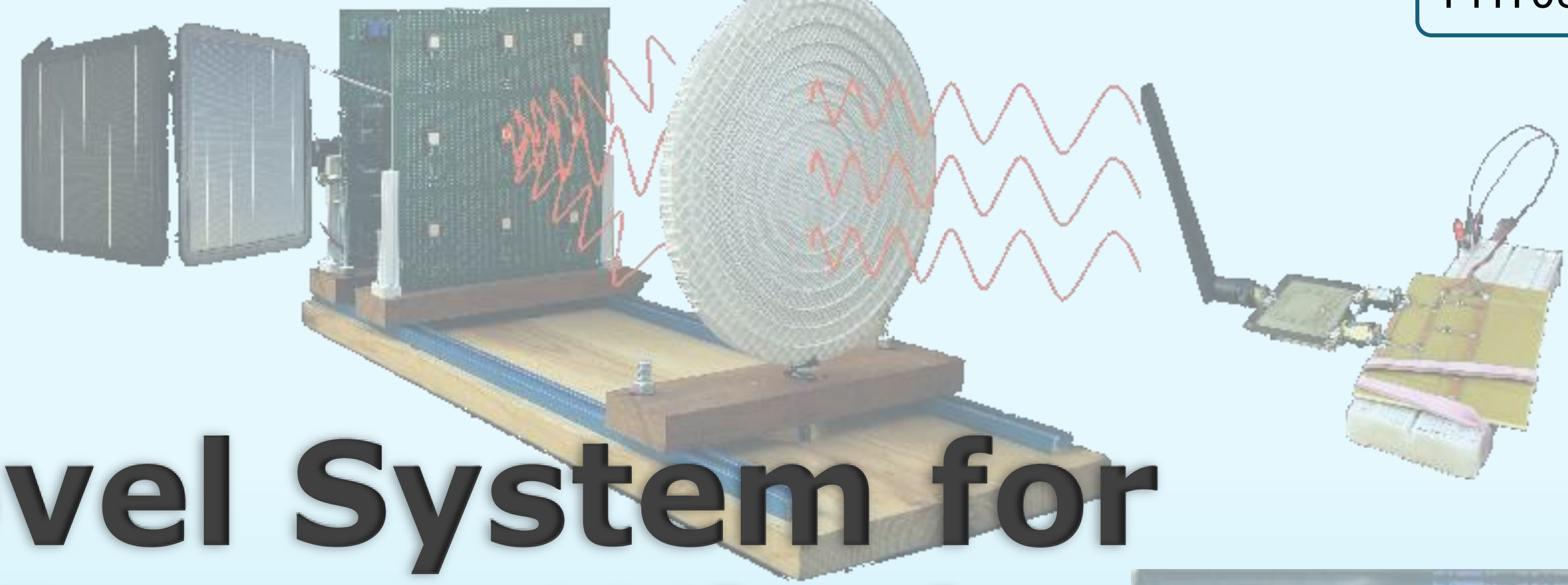
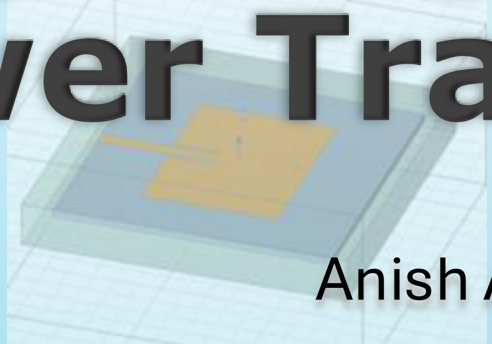
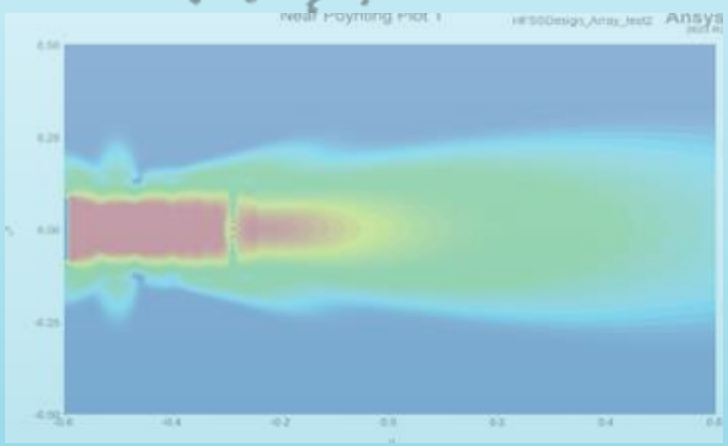


PHY031

A Novel System for Long Range Wireless Power Transmission





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Problem

- Energy consumption growing exponentially (Fig. 1)
  - Population growth and new power-hungry technologies drive greater energy usage. Currently **180,000 TWh** of energy is used globally
- Wired infrastructure for energy transmission is costly, limiting choices
  - Expensive: **~$5M per 100 km**. Power tower needed **every 100 meters**
  - Limitations: New clean energy plants can't be too far from cities. Older buildings need extensive re-wiring for more power transmission
- Current Wireless EM Solutions: not adopted due to poor efficiency. Energy is lost as a function of distance (quadratic decay, Friis transmission equation)

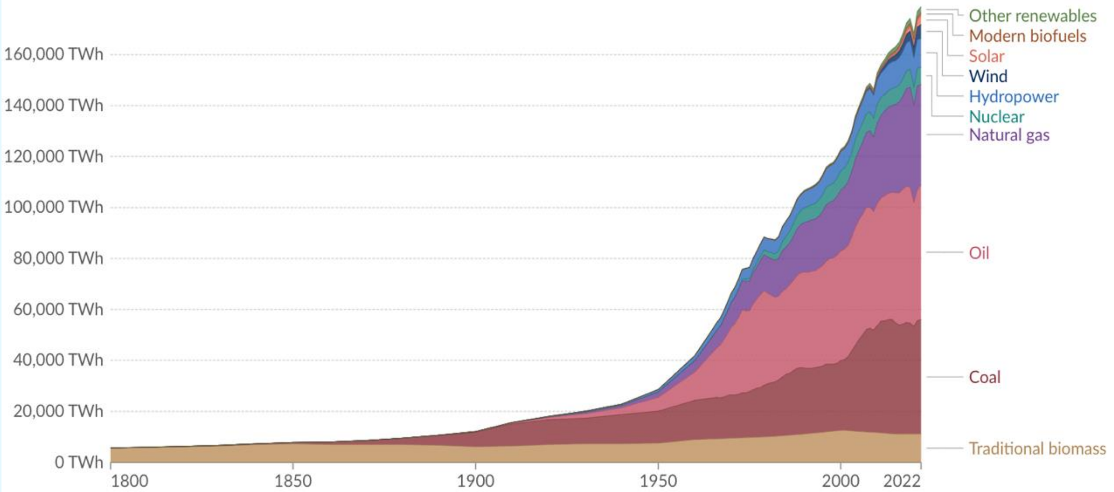


Fig 1: Global Energy Usage over Time in years
Source: Energy Institute - Statistical Review of World Energy (2023), Smil (2017)

Proposed Solution

- Goal: Efficient power transmission wirelessly over distance, via beaming EM waves where energy stays near constant over distance
- My Original Wireless Power Transmission (WPT) System:
  - 2.4GHz EM waves transmit power: selected as optimal mix of size and efficiency, while minimizing atmospheric impact
  - Components: Phased Array & Original Fresnel Lens designed for EM transmission.
  - Efficiency: WPT phase aligns and collimates EM power waves, resulting in near constant power over distance.
- Wireless Cost: long range cost reduced 100x **(~$50K per 100 km)** with towers using line-of-sight transmission ~**every 10,000 meters**. Shorter distances: minimal remodel costs

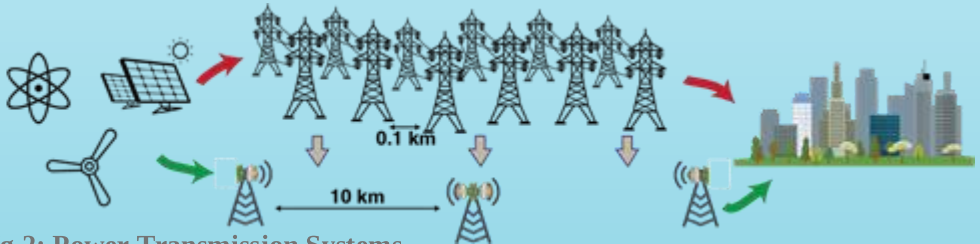


Fig 2: Power Transmission Systems

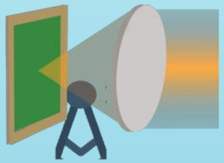


Fig 3: WPT Array and Lens Transmitter

Scope of Project

- Novel Wireless Transmission Power system using 2.4GHz EM waves has been invented
- An original design for a for a Fresnel lens to use with S-band microwaves (2.4GHz) is designed and 3-D printed
- Phased Array Transmitter is designed and implemented using IC components and Printed Circuit Board (PCB)
- Transmitter and Lens elements were studied and simulated with Matlab and an EM Solver (HFSS)
- A Rectenna designed with copper tape and ICs on a FR4 PCB to test RF conversion to DC Power
- Prototype measurements taken and compared to simulation data and to current literature

<u>**This work was performed in a home setting**</u>

Engineering Goals and Research Hypothesis

Engineering Goals:

- Design and Build a Wireless Power Transmission System (WPT) with improved efficiency & lower cost, compared to present day published solutions.
- Build a Rectenna based receiver to show how the WPT can create DC energy to power LED lights

Research Hypothesis:

- An original EM Fresnel Lens design as part of the WPT system can provide significant gain from additional phase alignment and collimation of the EM waves. This innovation, coupled with phased array transmitters, will improve WPT power efficiency over distance.

Background Information

Current Wireless Power Transmission Systems

- Commercial WPT: based on induction charging. Works well over very short distances (<4cm) with efficiencies around ~80%
- RF Harvesting: for very low power. RF communication signals converted to power with IOT sensors. newly emerging field.
- EM based WPT: currently being researched for distances of 1-2 meters with published literature efficiencies of 20-35%
- Very Long Distance WPT: in experimental phase, such as Cal Tech’s Solar Power MAPLE (Microwave Array for Power Transmission)
- My research: new methodology to improve efficiencies compared to current literature for EM based WPT, so can be used for medium distance (medical device implants, wireless charging across a room) and stepping-stone for long distance (clean energy power sources)

Phased Array Transmitter

- An array of power amplifiers and antennas used to narrow and direct an RF beam
- Key advantage: increases power gain transmission by N^2 instead of N.
- 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:

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

$$\mathbf{W}_{n,m}(\chi,\varphi) = e^{+j2\pi\left(\frac{d}{\lambda}\right)\cos\varphi((m-1)\sin\chi+(n-1)\cos\chi)} \quad \text{(Eq 2)}$$

$$W * \mathbf{R}(\phi,\theta) = \sum_{n,m} e^{+j2\pi\left(\frac{d}{\lambda}\right)\cos\varphi((m-1)\sin\chi+(n-1)\cos\chi)} * e^{-j2\pi\left(\frac{d}{\lambda}\right)\cos\theta((m-1)\sin\phi+(n-1)\cos\phi)} \quad \text{(Eq 3)}$$

Where R(ϕ, θ) is real space, W are phase shifts, (χ, φ) is the constant beam steer angle, and λ is the wavelength

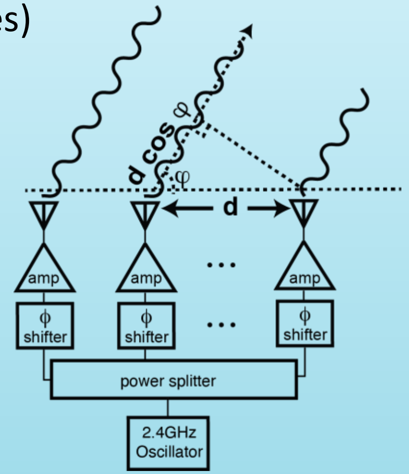


Fig 4: Phased array transmitter where d is the distance between antenna elements, and φ is the angle of the beam direction

Background Information

Friis Transmission Equations:

- Friis Equation for Transmission: determines radiated and received power based on gain and power transmitted, wavelength of radiated power, and distance between the transmitter and receiver antenna. G_{tx} and G_{rx} are the gain of the transmitter and receiver antenna, r is the distance between the transmitter and receiver, λ is the wavelength of the signal and P_{tx} is the transmitted power. A wavelength, λ, is defined as speed of light, c, divided by the frequency, f.

$$P_{radiated} = \frac{G_{tx}P_{tx}}{4\pi r^2} \qquad P_{rx} = \frac{G_{rx}P_{rad}\lambda^2}{4\pi} = \frac{G_{tx}G_{rx}P_{tx}\lambda^2}{(4\pi r)^2} \quad \text{(Eq 3)}$$

- Power Transmission: From Friis equation, received power decreases with: 1) farther distance (by $1/r^2$) and 2) higher frequency (shorter wavelength) waves.
- Friis Equation with Phased Array: for N antennas, the Transmitter gain increases by N^2

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

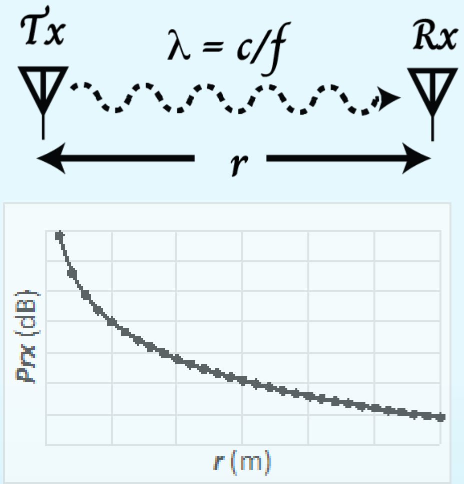


Fig 5: Wireless transmission between a transmitter(Tx) and receiver(Rx) where is the wavelength, c is the speed of light, and f is the frequency of the EM wave . Plot shows how power decays as function of distance.

Fresnel Lens:

- Designed initially by Bernard Fresnel in 1822 to increase the light intensity for light houses, preventing ship crashes
- Replaces curved surface of conventional optical lens replaced with a series of angular concentric rings (Fig 6)
- Collimates and magnifies the light (Fig 7) with much less material than a standard optical lens

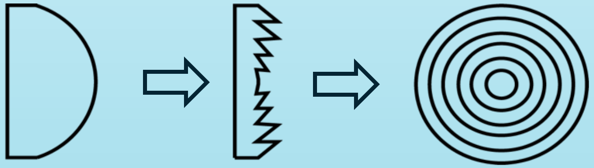


Fig 6: Curved lens can reduce to Fresnel Lens with concentric Rings

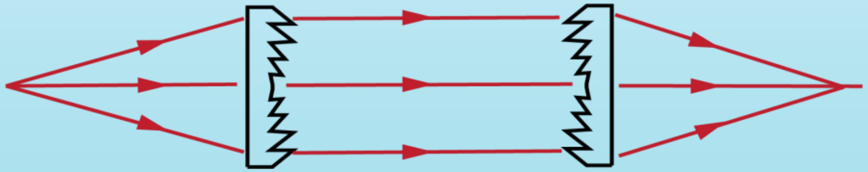


Fig 7: Fresnel Lens collimates and magnifies light waves

- Current EM Fresnel Lens: Designed for EM waves but limited to high frequency Ka–band and V-band millimeter wavelength band (27-60 GHz). Lower frequencies increase the lens thickness and material cost, because lens thickness is equivalent to the wavelength of the EM wave.

Design & Build Goals

- Design WPT System with Phased Array and EM Fresnel Lens at 2.4GHz :
  - 2.4GHz (Microwave S-Band Frequency): Optimal EM frequency due to ideal mix of higher power efficiency, lower cost and minimal atmospheric loss. Lower frequencies costlier due to increased transmitter size. Higher frequencies are inefficient with more power loss.
  - Phased Array: 1) narrows EM beam angle with gain and 2) can use smaller diameter/thinner Fresnel lens (half power beamwidth)
  - Original EM Fresnel Lens: Vertically phase aligns and collimates EM waves into a focused EM beam, thereby increasing power transmission.
- Build: prototype WPT system with lower power to determine effectiveness of design as proof of concept
  - 9-element Phased array transmitter that provide 0 dBm of RF power each
  - Original 2.4GHz EM Fresnel lens that is 3D printed
  - Mountable system to test Transmitter and Lens with correct focal distance
- Build: Rectenna to determine enable RF to DC power conversion
- Research Requirements to Scale WPT: for each use case, determine sizes of phased array and Fresnel lens needed for WPT system

Design of 2.4GHz Phased Array Transmitter

- Phased Array Transmitter: narrows EM beam angle and adds gain
  - Voltage control oscillator creates 2.4GHz signal, amplifiers increase gain, power splitters split the signal to 9 separate paths, and antennas are used to radiate power
  - Phase shifters are used to change phase and align phases at output
- Components for Printed Circuit Board (PCB): selected based on frequency and gain
- PCB Design: using Altium software with RF techniques
- PCB Fabrication: at Advanced Circuits on 2-layer FR4 board
- Phase alignment calibration: completed using Network Analyzer

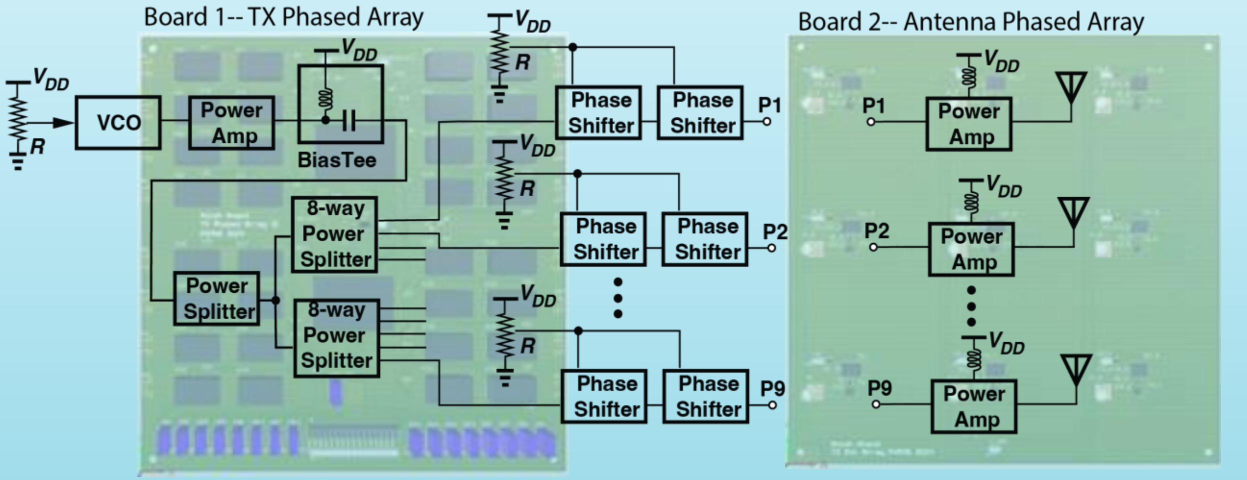


Fig 8: The 2 boards used for the phased array transmitter split as (1) phased aligned frequency generation and (2) antenna array

Design of Original 2.4GHz EM Fresnel Lens

- Lens Goal: efficient EM power transmission due to 1) phased alignment of waves and 2) angling of waves into a collimated EM beam (Fig 11).
- Novel EM Lens: 1) Concentric Rings (unique design) 2) Concentric Angles (never reported for EM)
- Concentric Rings: Phase aligns EM waves as they exit the Lens (Fig 11). Each ring has a different dielectric (Fig 10), determined by original formula (Eq 6). Desired dielectrics obtained in 3D printing via lattice structure with differing densities (Fig 9)
- Concentric Angles: to collimate waves, Snell's law (Eq 7) used to derive an angle for each ring (Fig 10)
- Lens size: 20cmX1.2cm determined by Phased Array Half-Power Beam Width (34 °), focal distance (30cm), and dielectric constant of ABS material (ε_{rmax} = 5.0 at 2.4GHz) which was then 3-D printed

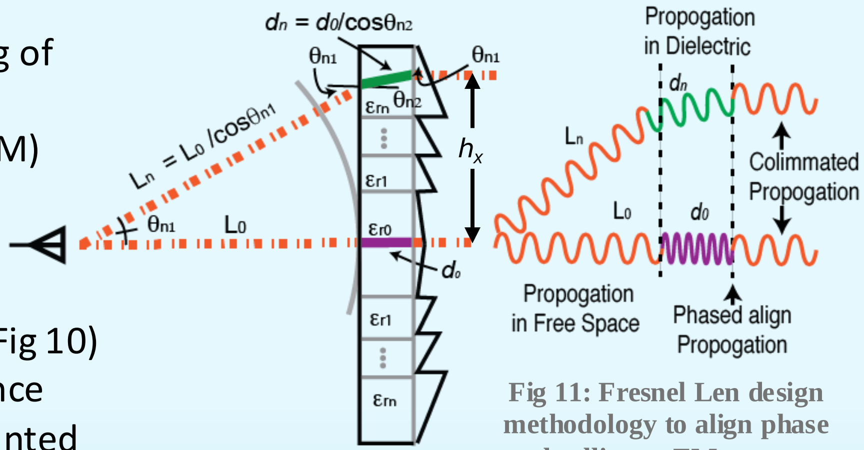
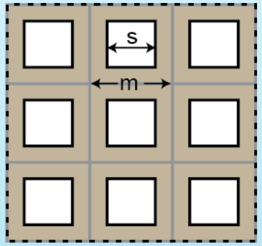


Fig 11: Fresnel Len design methodology to align phase and collimate EM waves at output of lens

$$\varepsilon_r = (\varepsilon_{rmax} - 1)\frac{(m^2 - s^2)}{m^2} + 1 \quad \text{(Eq 5)}$$



			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 9: Lattice structure for Fresnel Len and table to generate dielectric constants for each Fresnel Zone

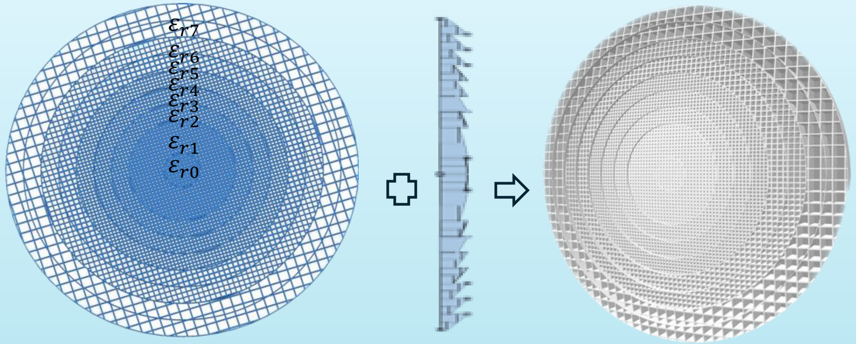


Fig 10: Fresnel Len made of concentric rings and angles designed in Fusion 360

$$L_0 + \sqrt{\varepsilon_{r0}}\,d_0 = L_n + \sqrt{\varepsilon_{rn}}\,d_n = \frac{L_0}{\cos\theta_{n1}} + \sqrt{\varepsilon_{rn}}\frac{d_0}{\cos(\theta_{n1}/\sqrt{\varepsilon_{rn}})} \quad \text{(Eq 6)}$$

$$v_{\varepsilon R} = \frac{c}{\sqrt{\varepsilon_R}},\ \lambda_{\varepsilon R} = \frac{v_{\varepsilon R}}{f}. \quad Snell's\ Law: \frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \sqrt{\frac{\varepsilon_2}{\varepsilon_1}} \quad \text{(Eq 7)}$$

Design of Rectenna

- Rectenna: built with copper tape on FR4 material (Fig 12)
- Antenna matching: 50 Ohm matching for Rectenna input
- Diodes: used to rectify EM waves to generate DC power

Fig 12: Rectenna Design, Matching methodology and S11 plot after matching Rectenna input

Methods

Theoretical Calculations:

- Friis Equations for transmission used to determine expected theoretical power as a function of distance

Simulation Method:

- Original Matlab code written to determine Phased Array Antenna gain
- Simulation of Antennas and EM Fresnel lens conducted in an EM simulator, Ansys High Frequency System Simulator (HFSS), to determine the validity of phase alignment and collimating properties of the Fresnel Lens for focal distance of 30cm using 2.4GHz EM waves.

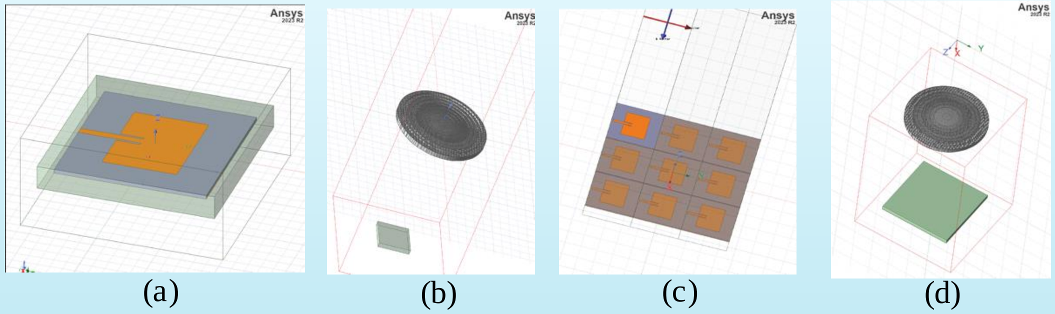


Fig 13: The (a) patch antenna, (b) patch antenna with Fresnel lens, (c) phased array, and (d)phased array with Fresnel lens were modeled in HFSS to provide near field and far-field simulations data

Experimental Method (Prototype):

- Measurements using spectrum analyzer at various distances from Single Antenna and Phased Array (with and without Fresnel lens) taken to determine the power transmission
- Rectenna used to determine RF to DC Power conversion at distance for WPT System

Data Analysis Method:

- Measurement data compared to theoretical expectation for power transmission
- Receiver antenna limitations are calibrated to determine true performance of WPT system energy transmission in wireless channel

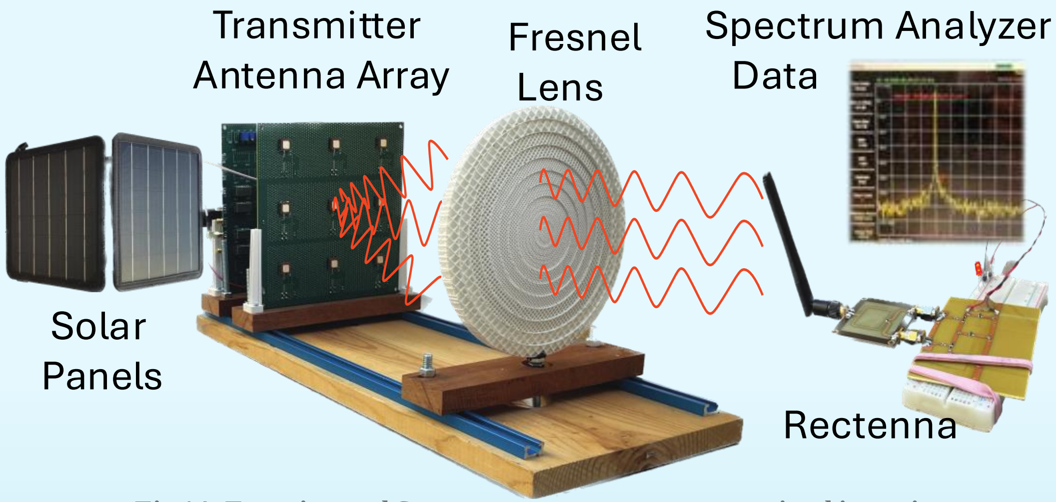


Fig 14: Experimental Setup to measure power transmitted in various conditions of antenna, phased array, and Fresnel lens. Solar Panel is used as power source for antenna array

Experiment Formulation

Independent Variables:

- Frequency of EM wave, power transmitted, phased array gain, rectenna gain

Dependent Variables:

- Radiated and Received power over distance

Constants:

- Focal distance, temperature and humidity, measurement apparatus and equipment

Controls and comparisons:

- Theoretical and simulated calculations vs experimental data from prototype

Simulation Results

Matlab Simulations for Phased Array

- Simulations for 9 element phased array shows gain of 18dB and angle of beam 34° (Fig 15)

HFSS Simulations

- EM Simulations validate gain from Fresnel Lens due to phase alignment and collimation
- <u>Near Field Simulations</u>: phased array shows **18dB** of gain. Addition of Fresnel Lens results in **5 dB** of gain at 0.5 meter and **8 dB** of gain at 1 meter
- <u>Far Field Simulations</u>: Fresnel lens gain increases with distance (Table 1). Adding EM Fresnel lens to Phased Array results in nearly constant power over 10m, which is not seen in Phased Array alone.

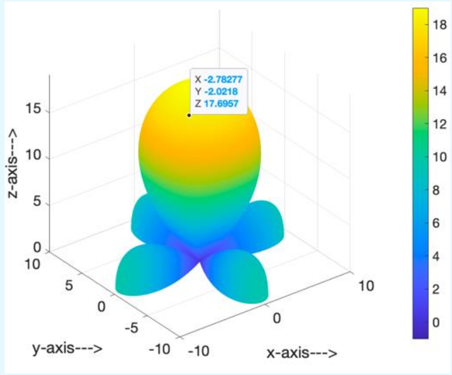


Fig 15: Matlab simulation of phased array transmitter

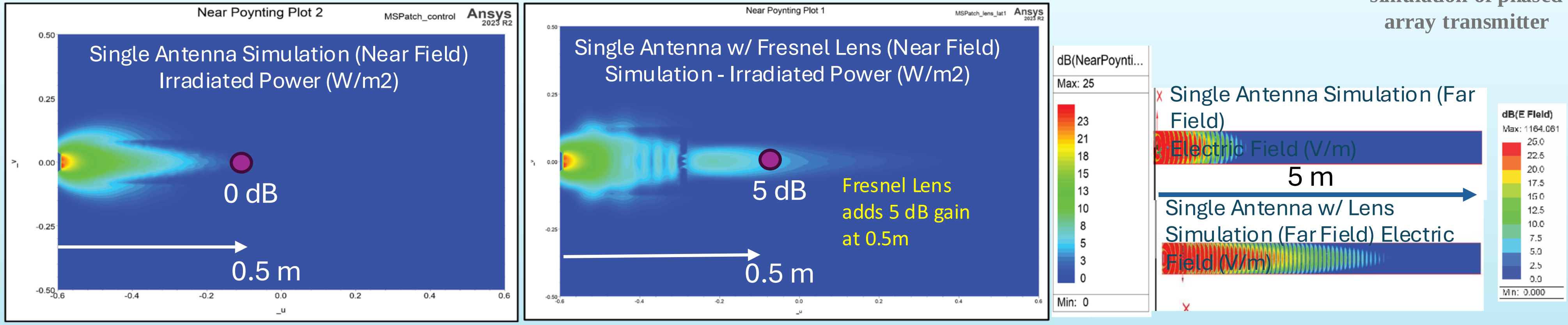


Fig 16: HFSS Near Field and Far Field Simulations for Single Antenna with and w/out Fresnel Lens

Distance (m)	Single Antenna E-Field (dB)		Phased Array E-Field (dB)	
	w/ out Lens	w/ Lens	w/ out Lens	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**

Table 1: Electric Field estimated Data

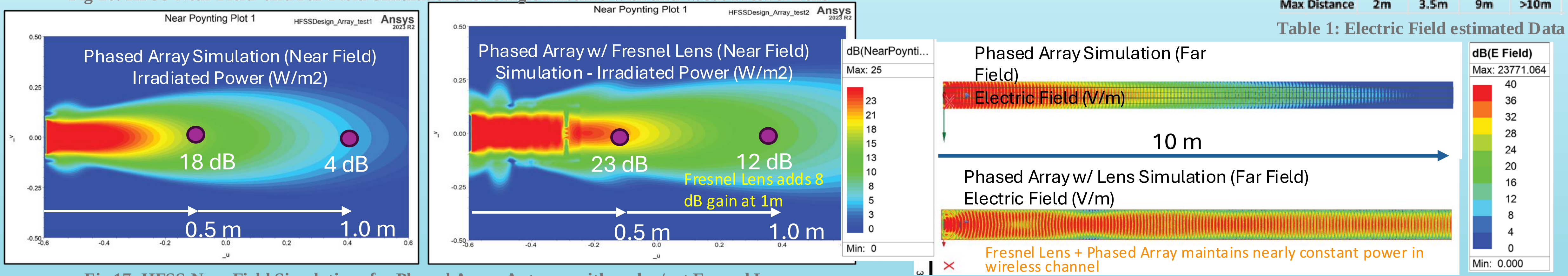


Fig 17: HFSS Near Field Simulations for Phased Array Antenna with and w/out Fresnel Lens

Prototype Results of Single Antenna and Phased Array Transmitter

- <u>Measurements</u>: recorded 3x at each distance using a spectrum analyzer
- <u>Single Antenna</u>: power transmission follows Friis Transmission equation well up to 2 meters in distance (Fig 18)
- <u>Phased Array Transmitter</u>: **17dB** gain compared to a Single Antenna at 5 meters of distance (Fig 19)
    - Prototype Results match Simulations: Gain is within 1dB of expected value of 18dB based on Matlab & HFSS simulations
    - Gain validates Phase Array is calibrated correctly
    - Loss over distance is similar for Phased Array as Single Antenna with measurements from dipole antenna receiver
- <u>Antenna Correction Factor</u>: beyond 2 meters, both Single Antenna and Phased Array display lower than expected results, due to partial field cancellation of dipole antenna. All antennas show some loss compared to predicted measurements, requiring a correction factor.
    - To model ideal receiver: receiver antenna is calibrated with multiple independent signals across measured distance

$$\textit{Antenna Correction Factor}(d) = -0.36d^3 + 3.04d^2 - 3.81d + 0.6$$

- <u>Results of Antenna Correction Factor</u>: mean measured values of both single antenna and phased array antenna are within the 3 standard deviations of expected values from Friis Transmission equation (Fig 20), validating Antenna Correction Factor formula .

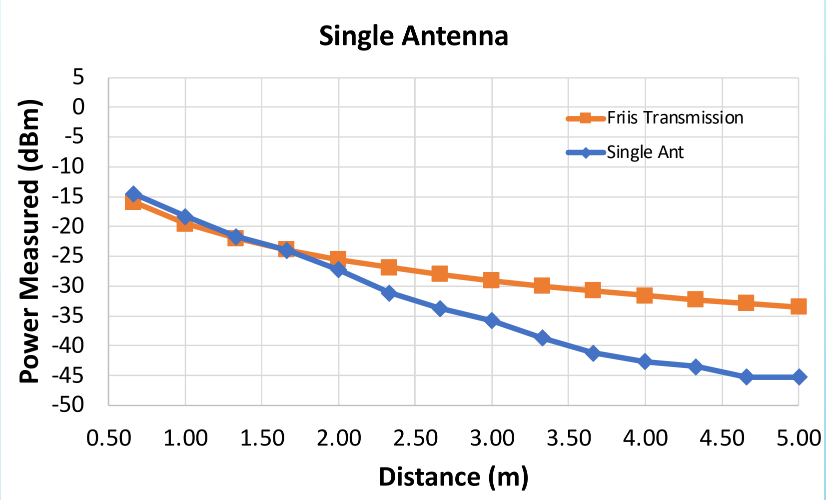


Fig 18: Single Antenna Measurement and Theoretical Data

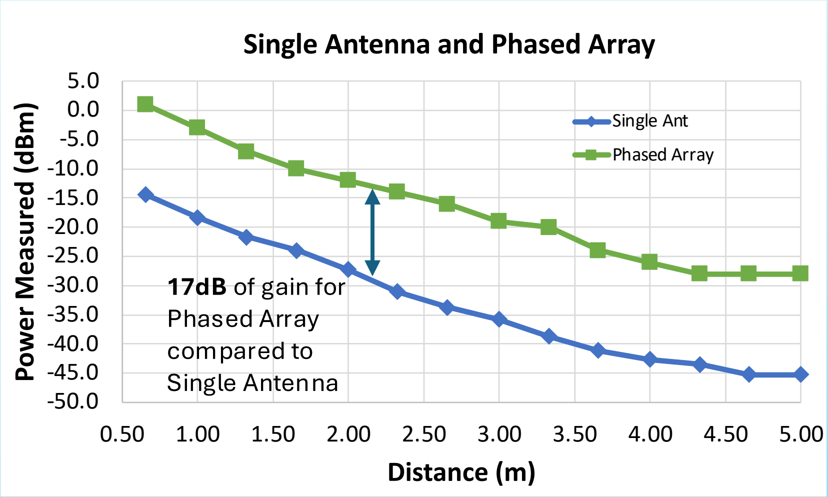


Fig 19: Single Antenna and Phased Array Measurement

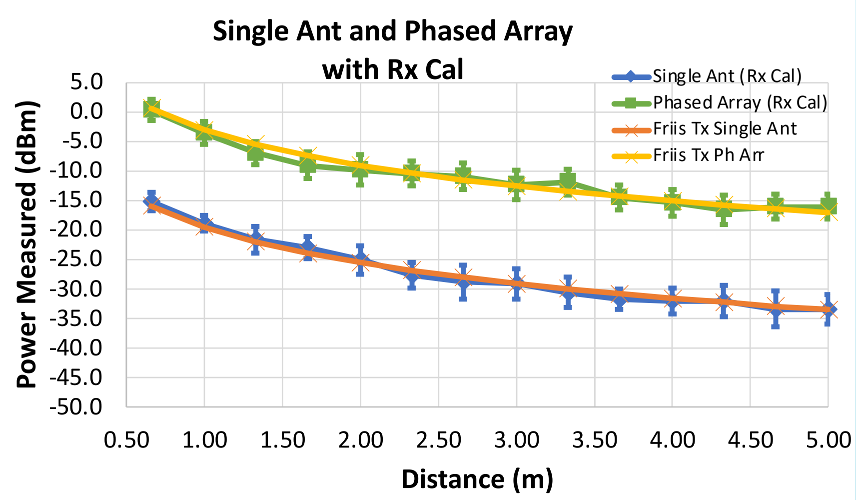


Fig 20: Single Antenna and Phased Array Measurement after Corrections

Prototype Results for EM Fresnel Lens

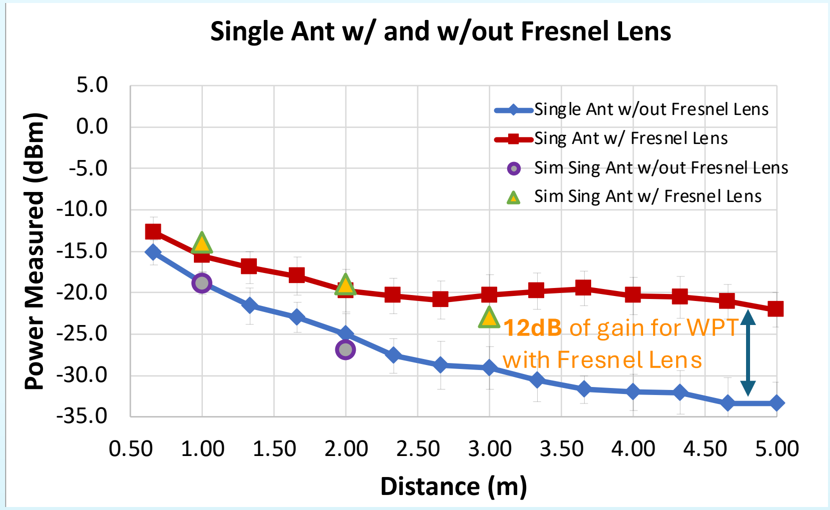


Fig 21: Single Antenna Measurement w/ and w/out Fresnel Lens

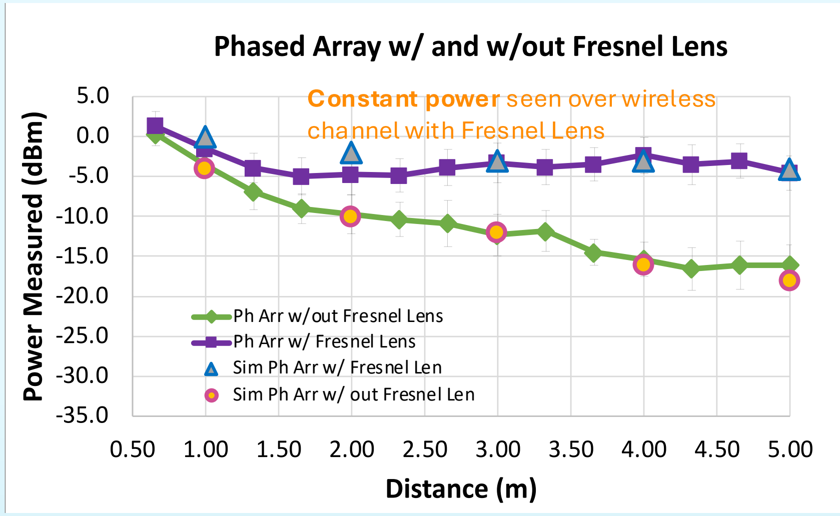


Fig 22: Phased Array Measurement w/ and w/out Fresnel Lens

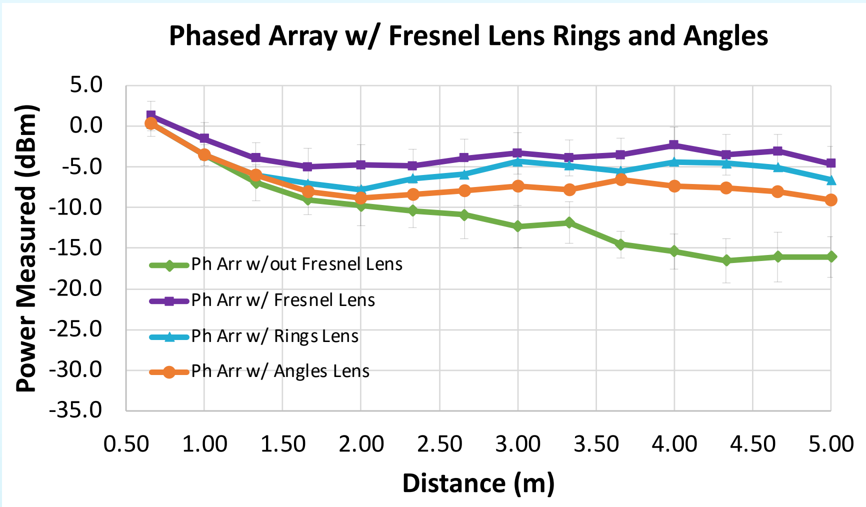


Fig 23: Phased Array Measurement with various configurations of the Fresnel Lens

- <u>EM Fresnel Lens Results</u>:
  - Gain: Lens adds 12dB of gain at 5m, for both Single Antenna or Phased Array (Fig 21, 22)
  - Collimation: measured power remains almost constant after 1.5m for Phased Array (Fig 22,23), showing EM waves are phase aligned & collimated due to Lens
  - Prototype Results Compared to Far Field Simulations: show similar trend lines (Fig 22)
- <u>Breakdown of Gain from EM Fresnel Lens</u>:
  - Concentric Rings component: contributes 59% of total gain due to phase alignment.
  - Concentric Angles component: contributes 41% of total gain due to collimation (Fig 24)

Efficiency of WPT System (RF to DC power):

- Phased array data correlates with transmitted RF power of 8 dBm
- Rectenna output at 1.5 meter is 1.7 V and load current of 3 mA
- $P_{TX\text{-}RF}$ to $P_{RX\text{-}DC}$ is measured at **81% efficiency** (RF to DC power)

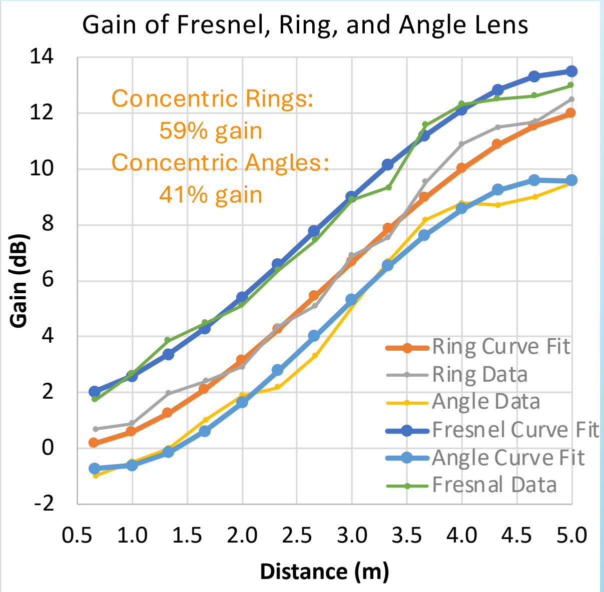


Fig 24: Gain measurements of Phased Array with various configurations of the Fresnel Lens
Gain measurements are curve fitted to estimate impact of each Fresnel Lens Component

Conclusions

- A novel 2.4GHz WPT system is designed, simulated in Matlab and HFSS, built from scratch, and tested
- The novel WPT system demonstrates that a wireless power transmission channel with high efficiency can be developed with minimal loss using a Phased Array and an original Fresnel Lens for EM designed from first principles
    - The Phased Array shows over 17dB of gain (~50x power increase compared to baseline single antenna), where 18dB is theoretically possible
    - The EM Fresnel Lens maintains constant power over several meters (from 1.5m to 5m). The Fresnel lens gain increases with distance. At 5m, the gain is over 12dB (~16x power increase compared to baseline wihtout Fresnel Lens).
    - Concentric Rings portion of EM Fresnel Lens use a new methodology for 3D printing and provides ~60% of the total Gain
    - Concentric Angles portion of EM Fresnel Lens has never been reported for EM Lens and provides ~40% of the total Gain
- The EM Fresnel Lens provides over 12dB gain (~16x power increase). A similar gain would require a 4x larger Phased array. By reducing the number of Phased Array elements by ~ 75%, there is less thermal loss and reduced cost
- A matched charge rectifying Rectenna was designed from scratch to convert the RF energy transmitted to DC power
    - RF energy transmitted converted to DC power $\mathbf{P}_{TX\text{-}RF}$ to $\mathbf{P}_{RX\text{-}DC}$ is measured at **81% efficiency** for wireless power channel at 1.5m with current rectenna and up to 5m or more with improved receiver antenna
- My WPT system provides better efficiency of wireless power transmission at a lower cost, compared to current literature (Table 1)

Next Steps

- To improve close-in losses: 1) Phased Array will have more elements (4X4) to reduce the Half Power Beam width (HPBW) and 2) EM Fresnel lens will be re-designed with a larger diameter to capture fringe EM waves that are escaping around edges in near-field
- To minimize the Fresnel Lens diameter: the EM lens will be re-designed for a closer near-field focal point
- Improved Rectenna antenna design with larger aperture to more efficiently receive EM power over longer distances

Reference	Frequency	Tx Power	Distance	Cost	Efficiency
Brown[1]	2.45 GHz	38 dBm	760 cm	$$$	51%
Gowda [3]	5.8 GHz	13 dBm	40 cm	$	33%
Yang [7]	5.8 GHz	25 dBm	100 cm	$$	47%
Hajimiri[5]	10 GHz	17 dBm	100 cm	$$	63%
Park [4]	5.8 GHz	6 dBm	50 cm	$	20%
Nusrat [8]	2.4 GHz	15 dBm	20 cm	$	19%
This work	**2.4 Ghz**	**8 dBm**	**150 cm**	**$**	**81%**

Table 1: Comparison of this work to reported WPT systems. The low cost ($) systems have simple antenna systems, the medium cost ($$) systems have expensive antenna systems, and the high cost system of the historical Brown design (3-meter diameter parabolic antenna) is extremely expensive

Potential Use Cases: Short, Medium, and Long Range

Wireless charging of medical devices (short distance): Deep implants where induction charging in inefficient and unsafe. Avoids repeated surgeries for battery replacement since battery has a limited lifespan.

- Pacemaker: requires 100mW of power annually. WPT charging can be done annually at doctor's office in 10-minute span using power levels like the prototype of 10dBm (10mW)
- Deep brain implants: requires 925mWH per 100 days, which corresponds to 10.2mWH per day. Currently patients need to wear inductive charging collar 30 minutes daily or 4 hours weekly, which cannot be done during sleep. Using the prototype, 13dBm (20mW) of power would be transmitted, fully charging the device over a 5-hour period during sleep.

Wireless charging in indoor and outside setting (medium distance): Requires larger arrays and lenses

- Indoor Conference Room: Wireless charging of phones and laptops requires 100W WPT system, which can be achieved by 32 element phased array with each element providing 20 dBm of power
- Electric Car Charging: Requires 30kWH per 100 miles. A WPT system with a 128-element phased array where each element provides 30dBm (1W) of power can provide required power

Transporting energy from power plants to inner city (long distance):Requires larger arrays and lens and receivers

- Small City: to power 10,000 homes each using 10,000kWH annually, a system of 1024 array elements with 40dBm (10W) per element could transmit power from clean energy source to central receiver with battery
- Solar Power from Space: Solar panels on satellites in low Earth orbit at ~200km (non-stop production). Good option to charge power stations around the world. Highly efficient, non-destructive green energy

Fig 25: WPT for deep medical implants

Fig 26: WPT for indoor conference room

Fig 27 (up): WPT for charging electric vehicles

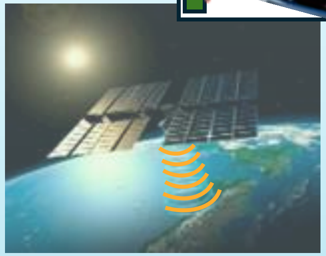


Fig 28 (left): WPT for long-range solar transmission

Credit: Mark Garlick/ Science Photo Library

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All images are Original except if noted