Low-cost Software-controlled Phase Shifting Network for Generating Spatiotemporally Variable Waveforms

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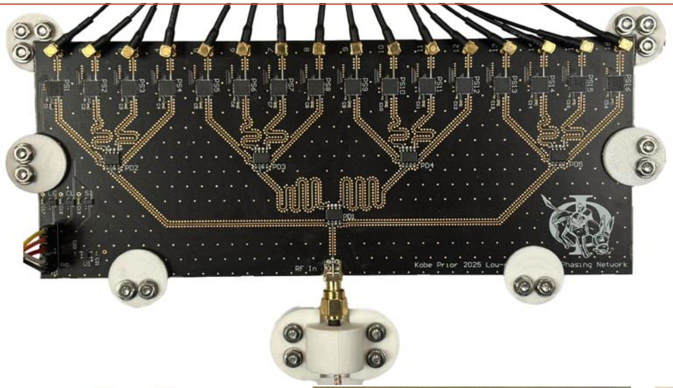
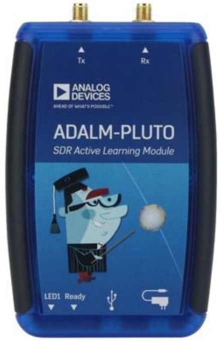
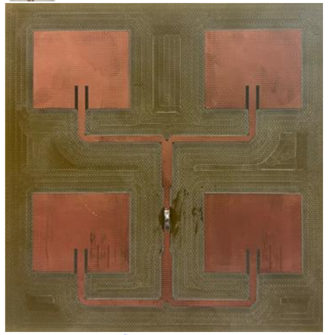
Antenna, RFID, and Computational EM Group

Outline

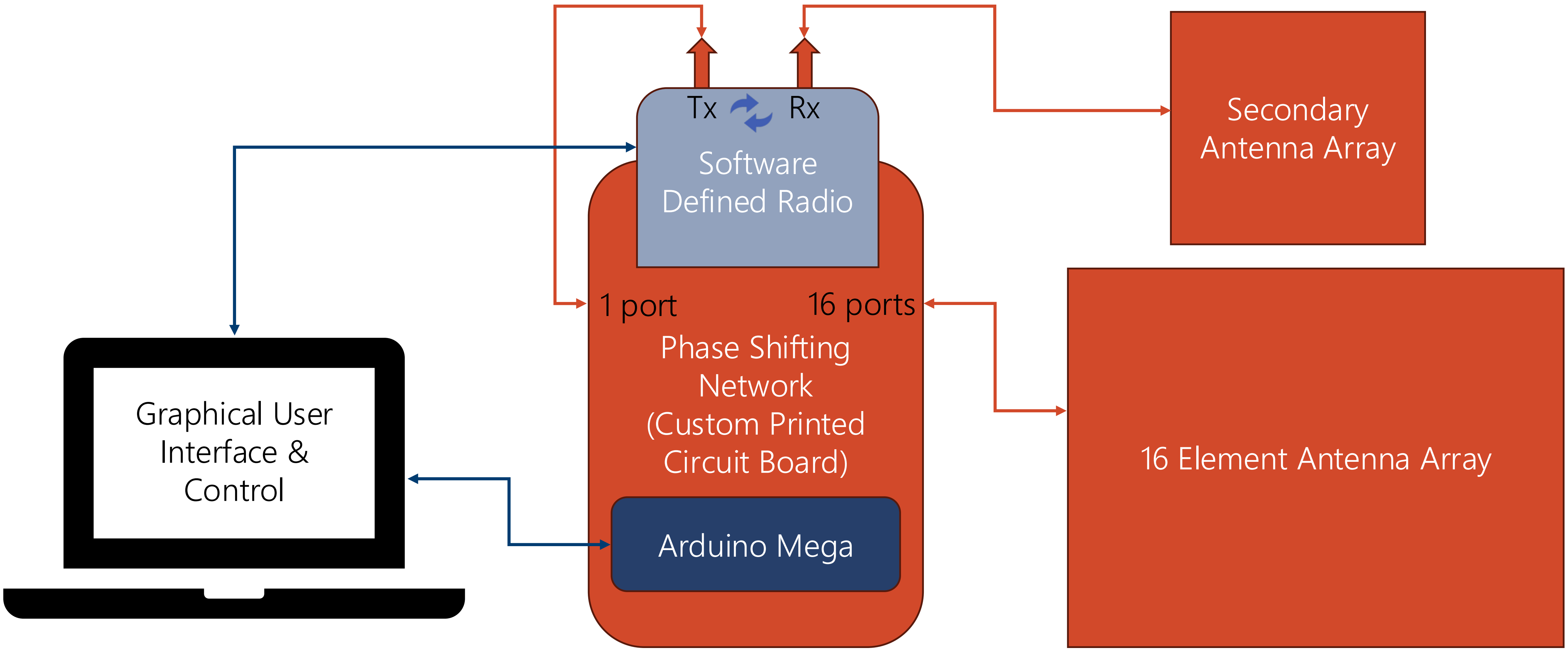
- Description of System Components
  - Phase Shifting Network
  - Software Defined Radio
  - Microcontroller
  - Antenna Arrays
  - Mechanical Assembly
- Characterizing System Performance
  - Scattering Parameters
- Graphical User Interface
  - Phase Calibration
  - Beam Steering Demonstration
- Structured Waveforms
  - Hermite Gaussian (HG)
  - Laguerre Gaussian (LG)
- Future Work





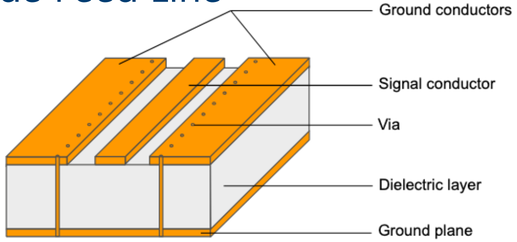



System Components

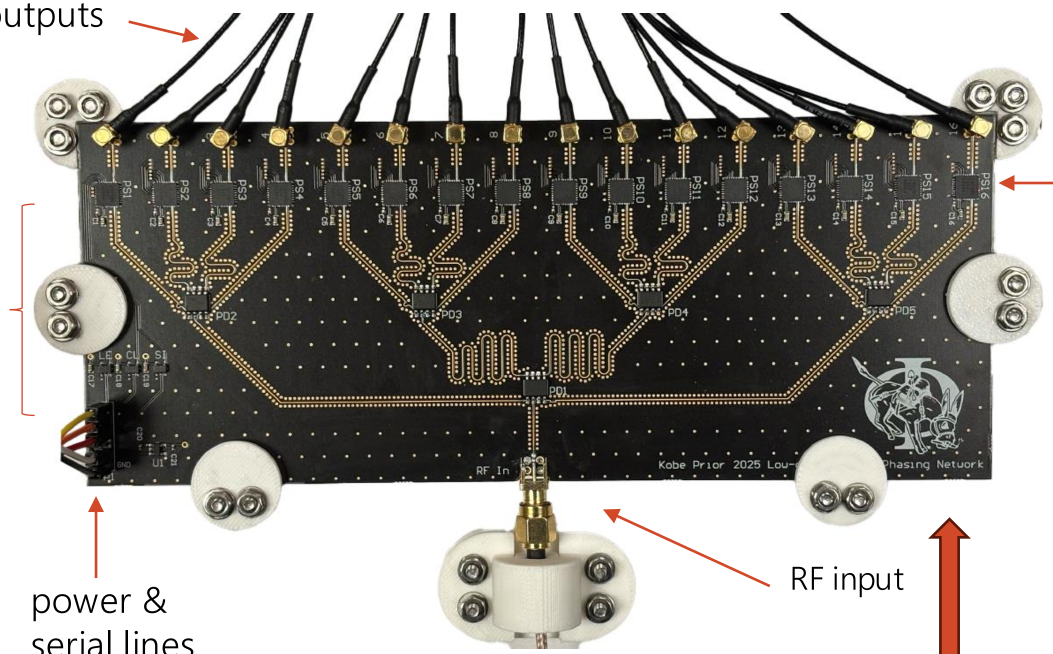


Custom Built Phase Shifting Network

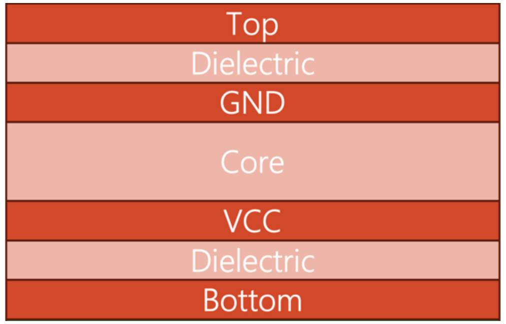
- 16 8-bit digital phase shifters (PE44820)
  - Each phase shifter has a unique address
  - Each is controlled using 3 Serial Lines
    - Serial In (SI): Loads the phase control word
    - Clock (CLK): Advances data into the device
    - Latch Enable (LE): Updates the phase output
  - $102\ \mu s$ is required to adjust all 16 phase shifters
- Grounded Coplanar Waveguide Feed Line



- 16 MMCX to SMA Cables
  - These cables connects the phase shifters to the elements of the antenna array
- 16:1 (5 4:1) Wilkinson Power Divider(Tx)/Combiner(Rx)
- Logic Level Shifters
  - Converts 5V logic level signals from MCU to 3.3V
- Voltage Regulator
  - Uses MCU 5 V and provides 3.3 Vcc to all chips

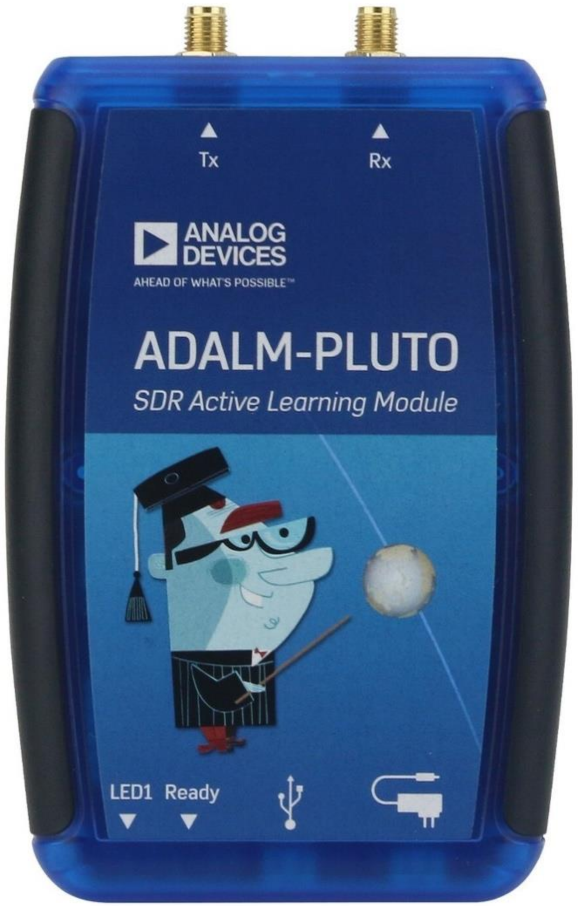


Top: 1oz copper pour
Dielectric: $\epsilon = 4.2$, 0.12 mm
GND: 0.5 oz copper pour
Core: $\epsilon = 4.2$, 1.1644 mm
VCC: 0.5 Oz copper pour
Bottom: 1 oz copper pour



4-Layer Board

Software Defined Radio

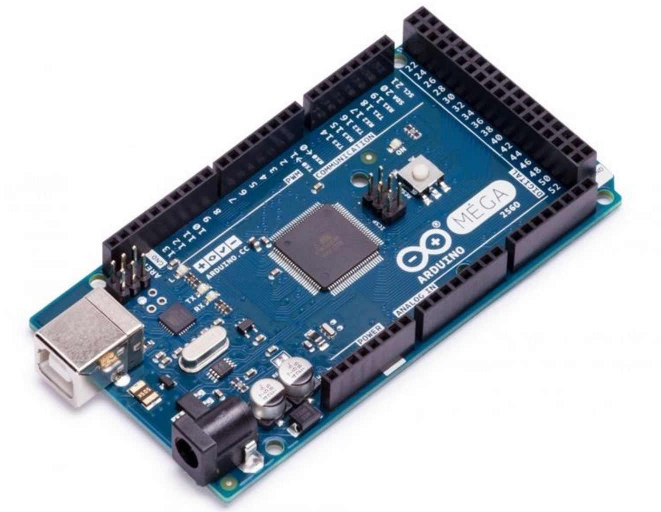


- Full duplex software defined radio (ADALM-PLUTO)
- A continuous wave is transmitted to provide a tone at a configurable frequency using a cyclic buffer
- Received power is computed as the mean of the squared magnitudes of complex baseband samples

$$P = \frac{1}{N_{\text{avg}}} \sum_{k=1}^{N_{\text{avg}}} \left(\frac{1}{M} \sum_{n=1}^{M} |r_k[n]|^2 \right)$$

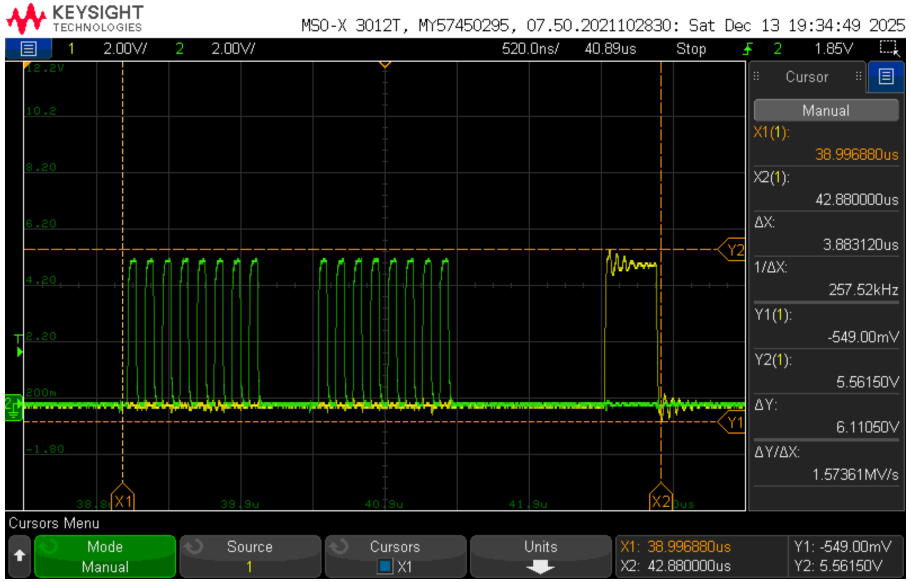
- Received power plots are generated using the average of $N_{avg} = 4$ received buffers.

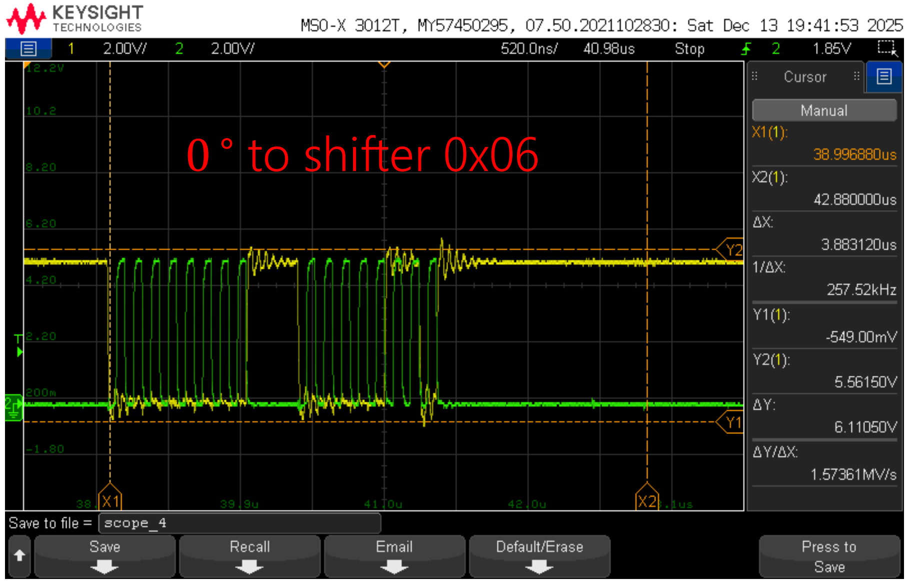
Arduino Mega Microcontroller



Clock

Latch Enable (Top)
Serial In (Bottom)

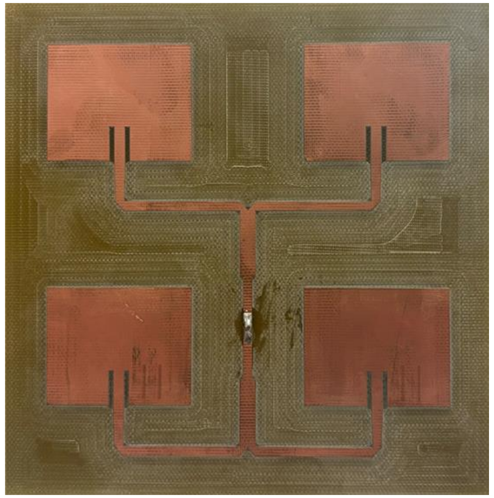




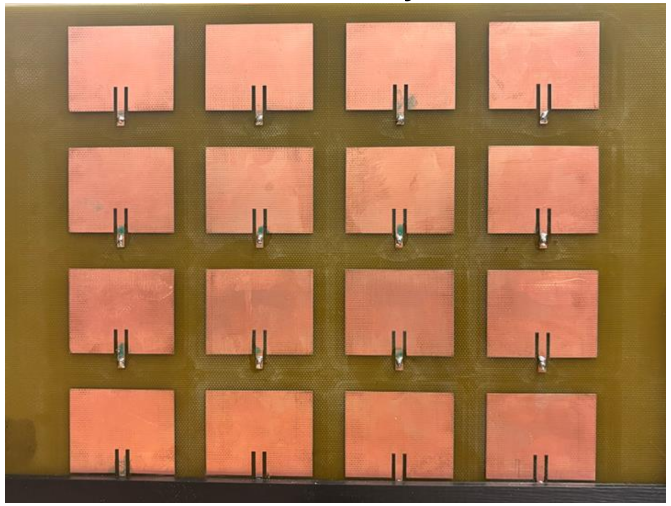
- Hardware Serial Periferial Interface (SPI)
  - Clock rate = 8 MHz
- Serial Connection to Computer
  - The computer sends phase words to the Arduino to preprocess and latch into the phase shifters

Transmit and Receive Antenna Arrays

Secondary

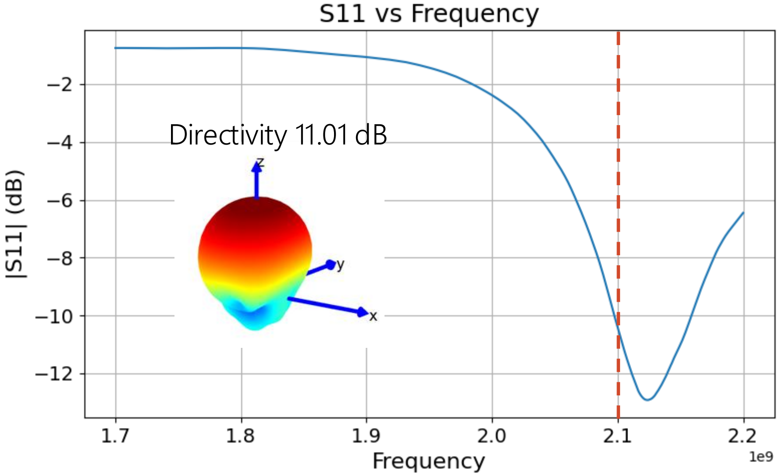


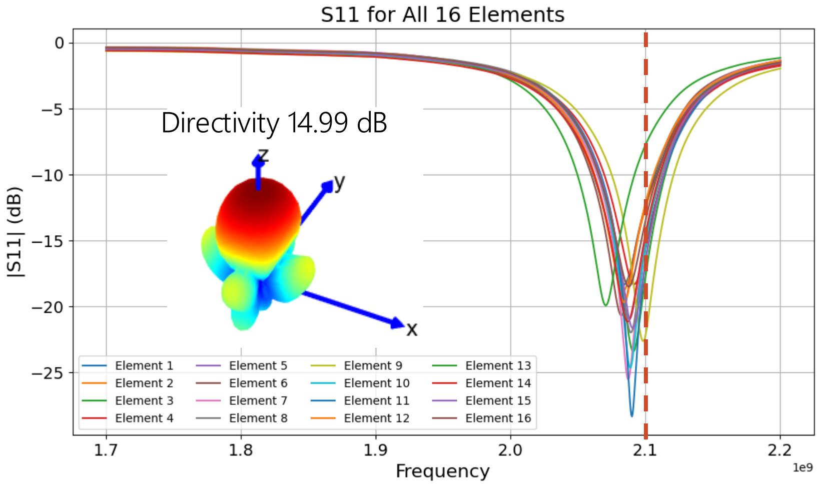
Primary



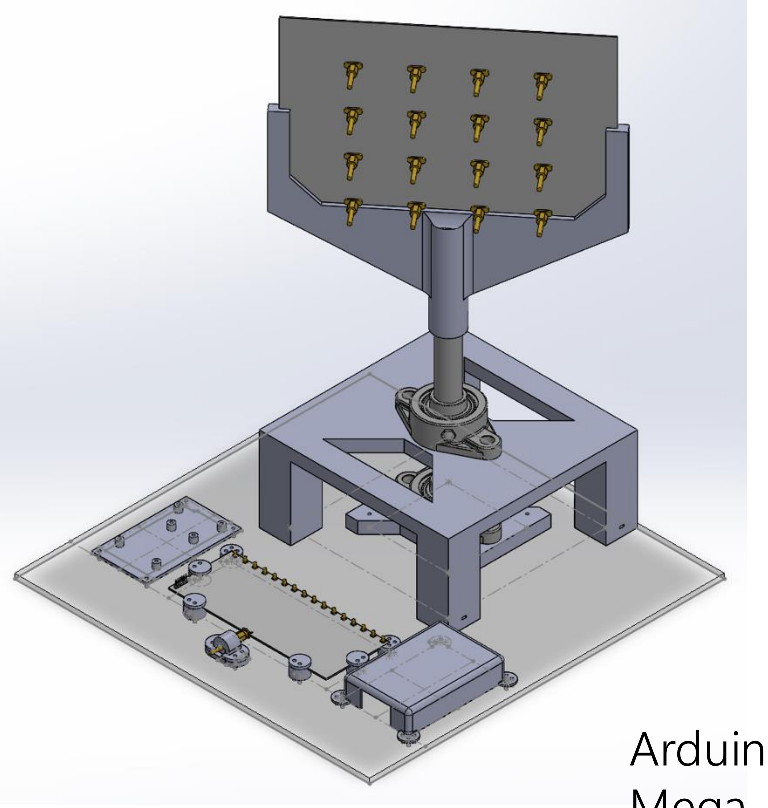
Simulation Results using CEMS

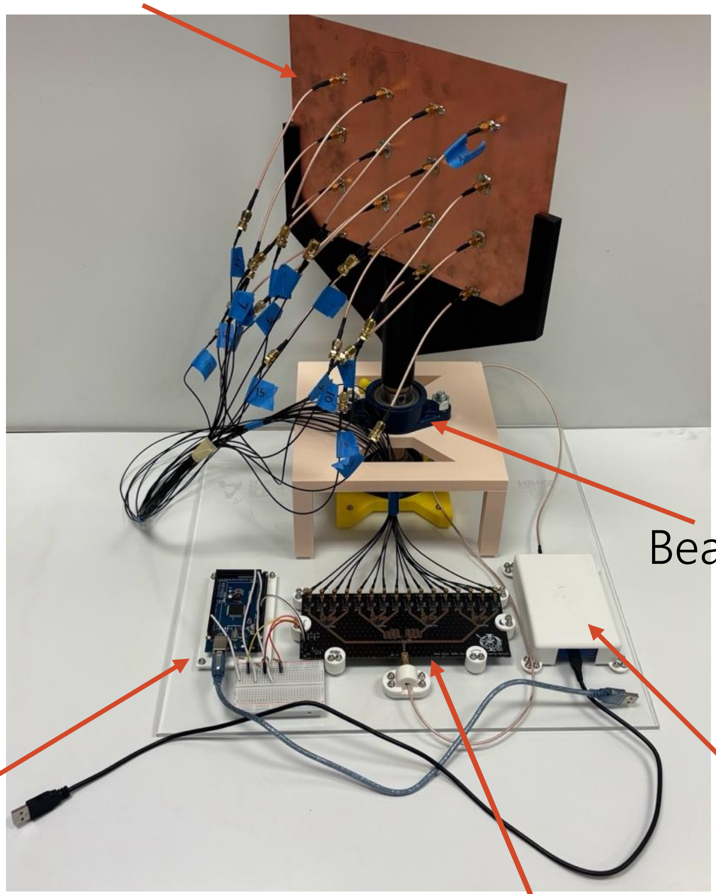
Measured Input Reflection Coefficient





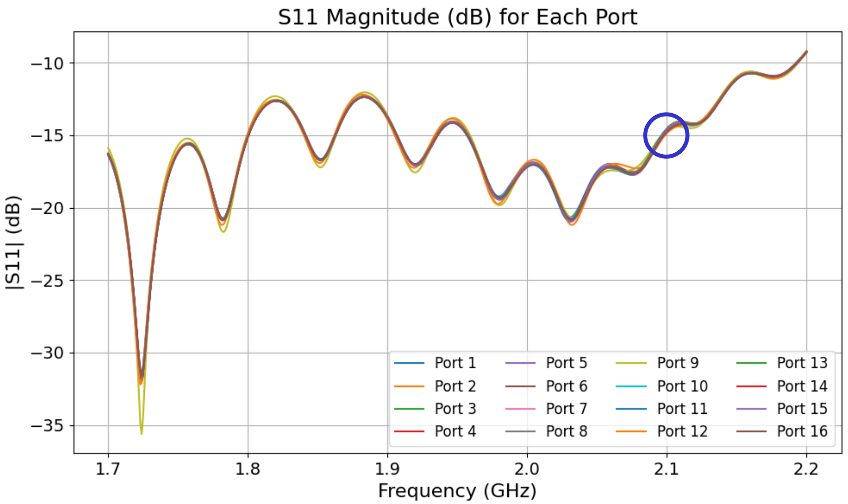
Mechanical Assembly

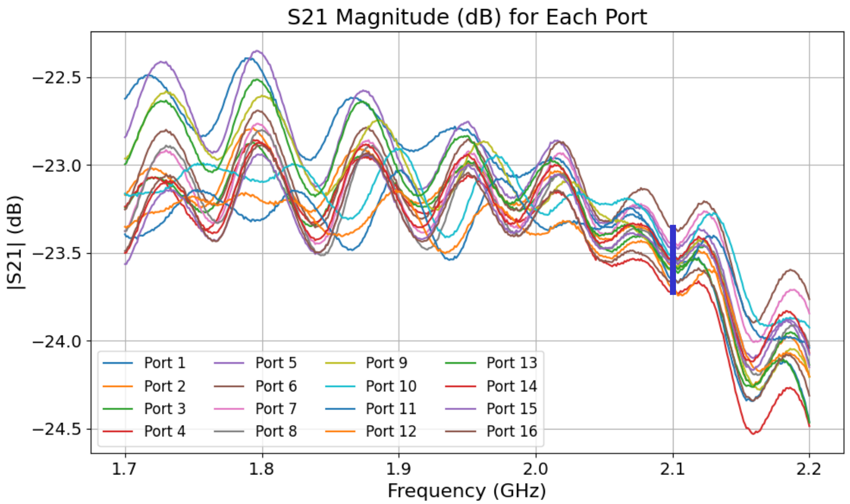


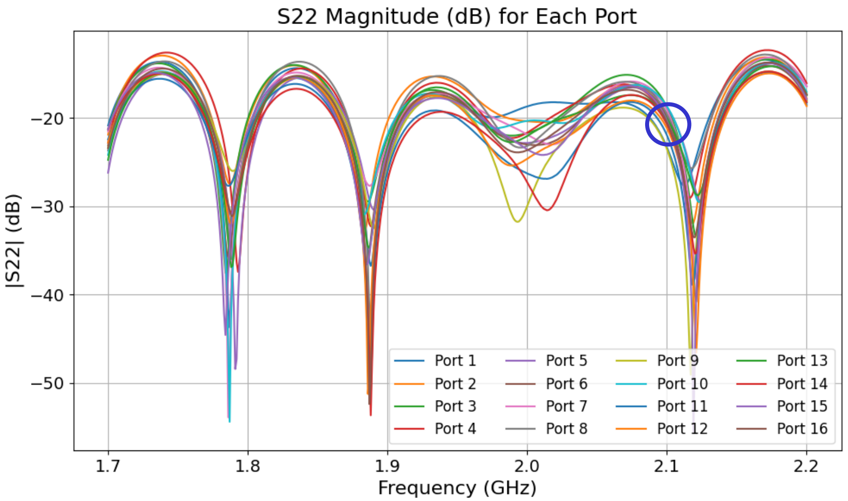


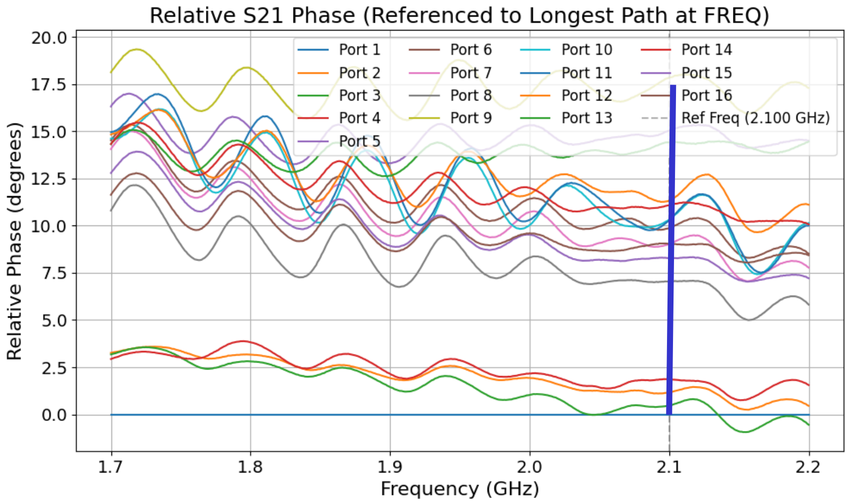
- The mechanical design for the system includes:
  - 3D Printed Parts
    - Array stand upper and lower
    - PLUTO SDR mount
    - Arduino mount
    - Clips for phase shifter board
  - Laser cut ¼" thick acrylic base plate
  - Two bearings
  - M3 bolts and nuts secure everything to the base plate

16 Ports Scattering Parameters







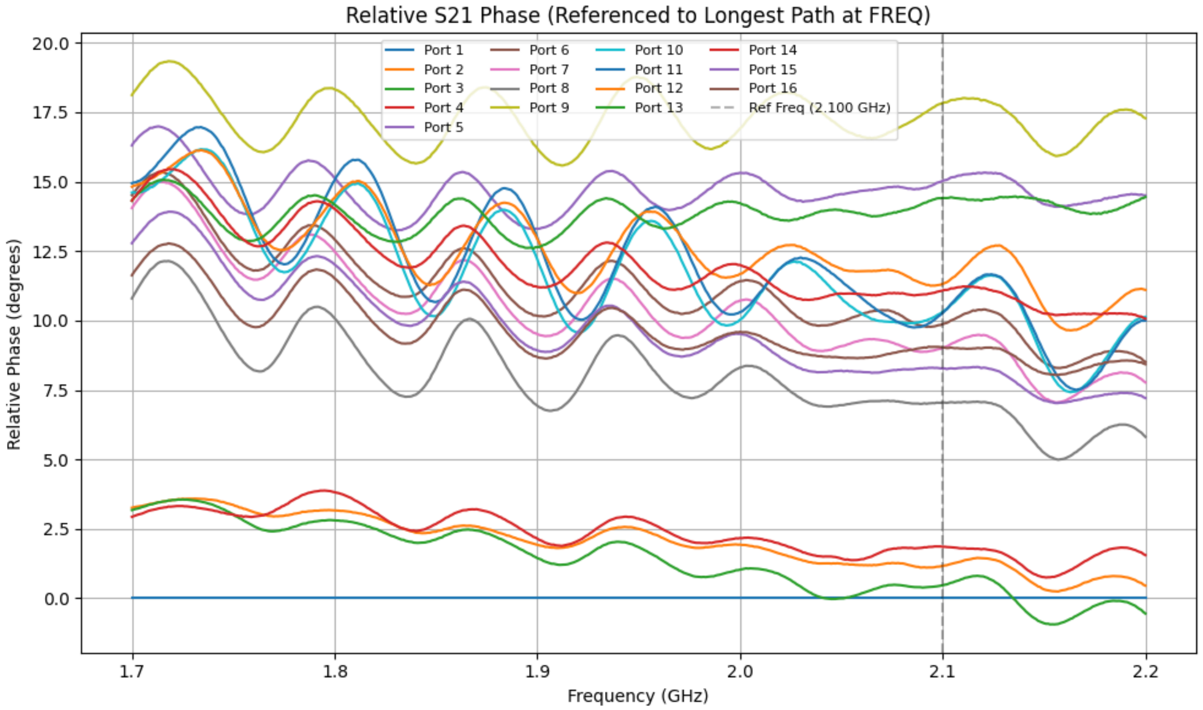


@2.1 GHz

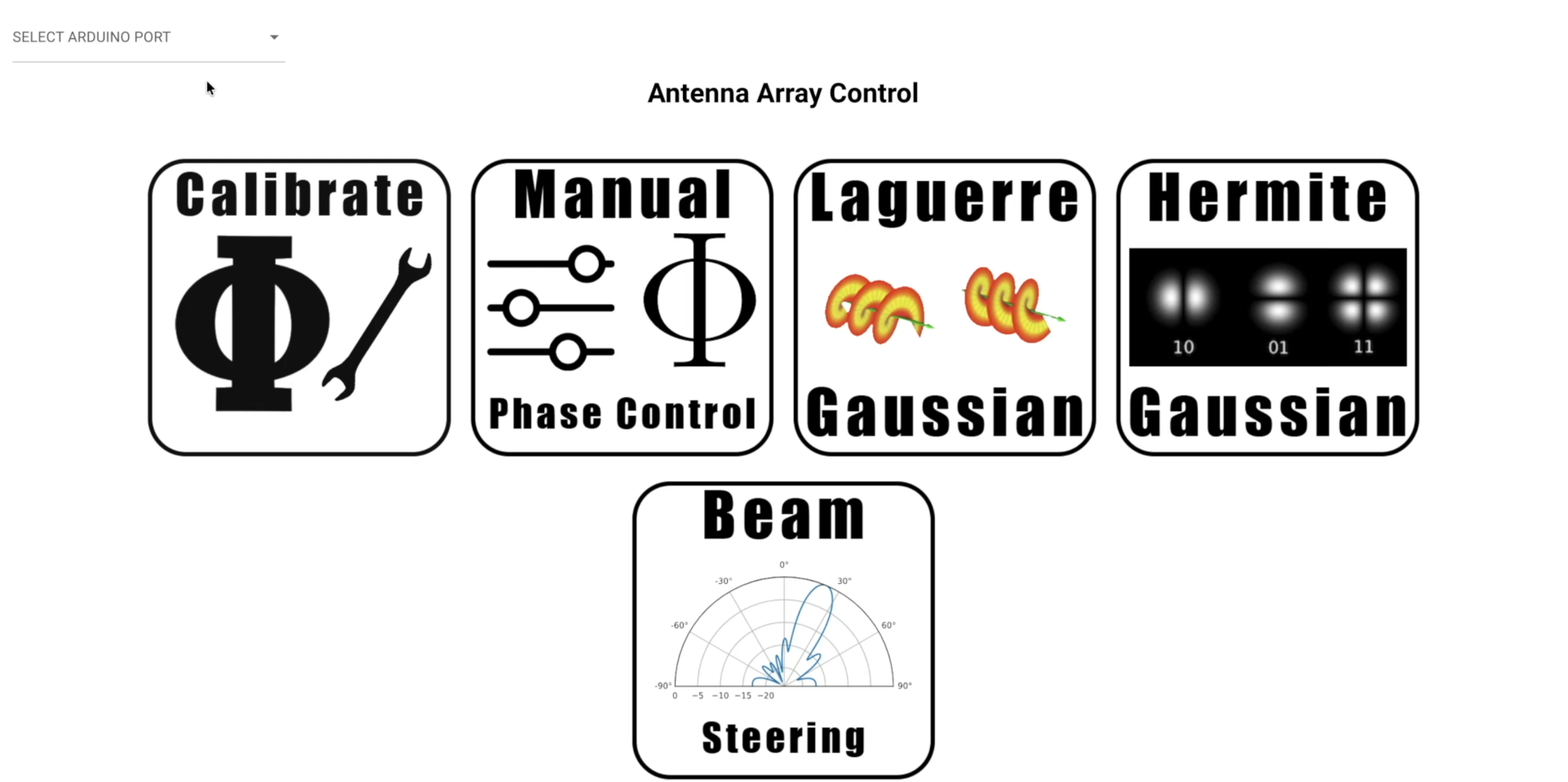
- Insertion loss difference is maximum of 0.5 dB
- Maximum phase difference of 17.5 degrees (to be calibrated to have 0 phase difference with software)
- S11 and S22 at all ports are all at the same level

Calibration Process

- Determine the largest phase offset
- Compute the difference in phase and store them into *phase_offsets* variable
- Before sending phases to the microcontroller, adjust the phase offsets of each element to coincide with the largest phase offset.
- This is all automated in the graphical user interface, which generates the required calibration
- A **short video is shown on the following slide** demonstrating the calibration process within the graphical user interface



Calibration Process using Graphical User Interface

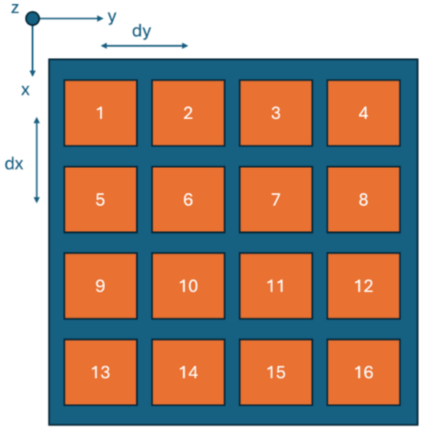


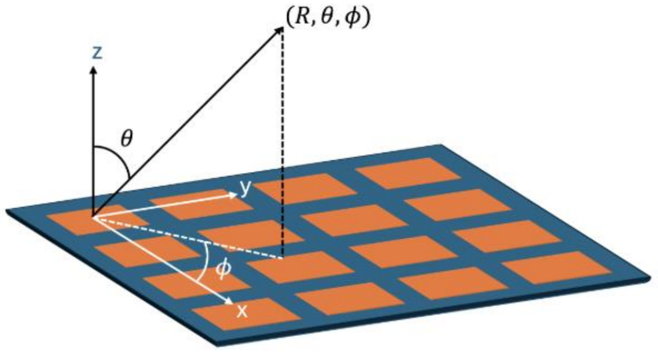
Beam Steering Graphical User Interface

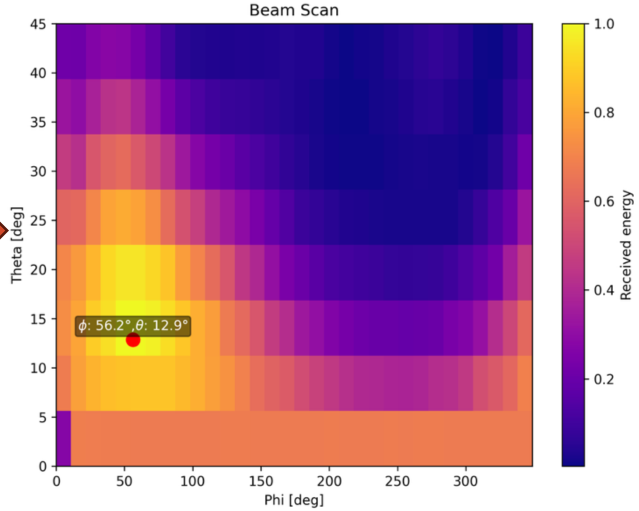
- The Beam Steering page has two features
  - Transmit Mode
    - The user requests an angle to steer to (θ_0, ϕ_0)
    - Appropriate phases are computed to steer the main lobe in that direction using progressive phase shifts:

$$\beta_x = -kd_x \sin\theta_0 \cos\phi_0, \quad \beta_y = -kd_y \sin\theta_0 \sin\phi_0$$

    - Then the receive antenna (2x2) will capture the strongest signal in (θ_0, ϕ_0) direction
  - Receive Mode operates in a similar way
    - 256 different phase states are assigned sequentially to the 16-element array scanning a range of angles $\theta \in [0,45], \phi \in [0,360)$ and average energy is sampled at each phase state.
    - One of the states produces the largest energy related to the direction of the incident beam from the 2x2 array.
    - An example is shown for an approximate received signal at $\theta = 12.9°, \phi = 56.2°$







Example AoA Estimation
$\theta = 12.9°, \phi = 56.2°$

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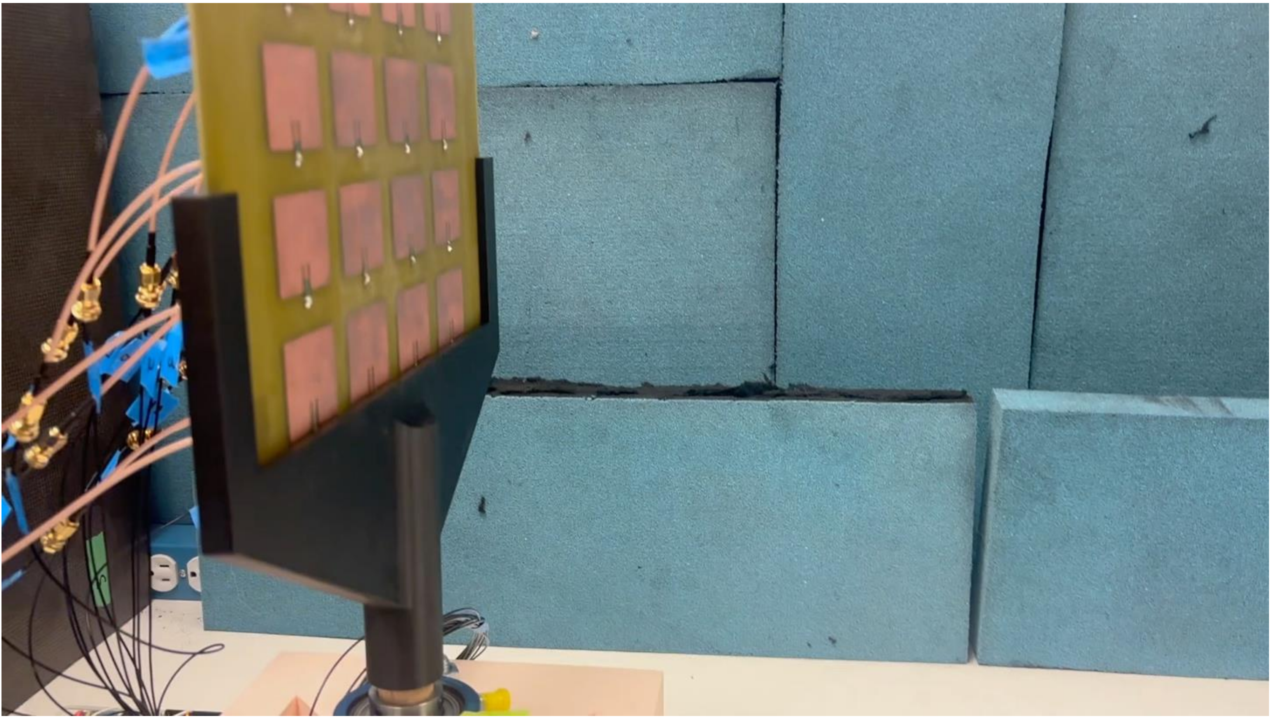
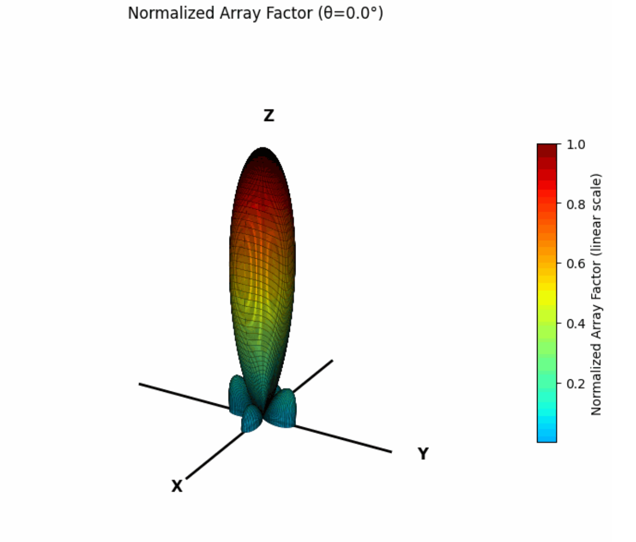
Beam Steering Transmit Mode Demonstration

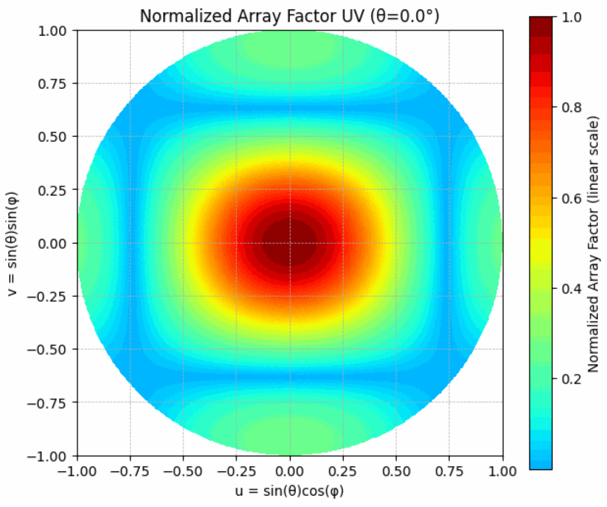
Live Received Plot to Identify Main Lobe Direction

*Sticky note is marked at 15 degrees



Array Factor Animation $\theta \in [0°, 60°], \phi = 90°$





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Phase Assignment for Hermite Gaussian Modes

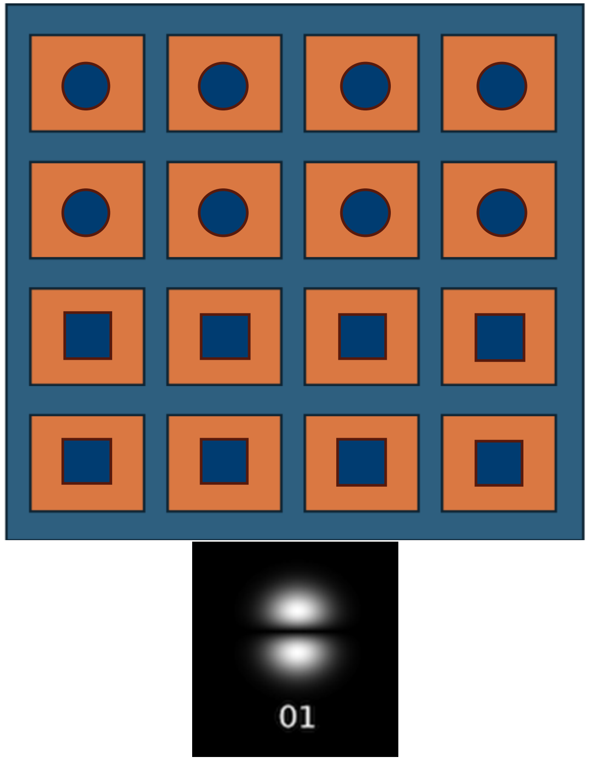
Several Hermite Gaussian Waveforms can be approximated with the following phase assignments. CEMS full wave simulation software is used to generate directivity plots

● 0 Degrees

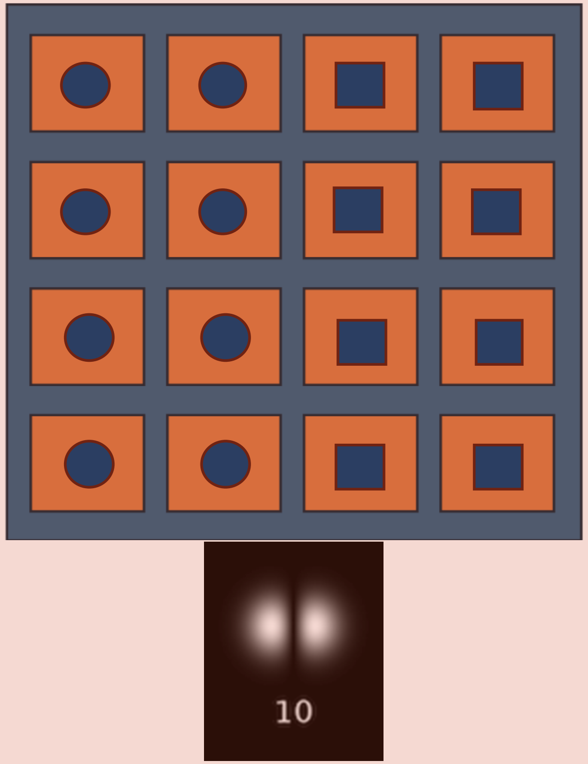
■ 180 Degrees

$$\boldsymbol{E}_{HG}(x,y,z) = \frac{E_{xo}}{w(z)} H_m\left(\sqrt{2}\frac{x}{w(z)}\right) H_n\left(\sqrt{2}\frac{y}{w(z)}\right) e^{-\frac{r^2}{w_0^2(z)\left(1+i\frac{z}{z_r}\right)}-i\psi_{m,n}} e^{-ikz}\, \hat{\boldsymbol{x}}$$

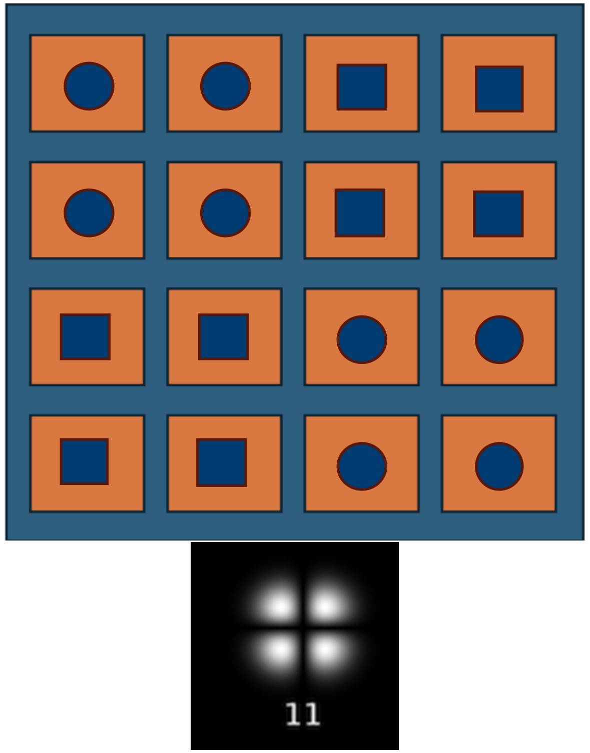
HG_{01}



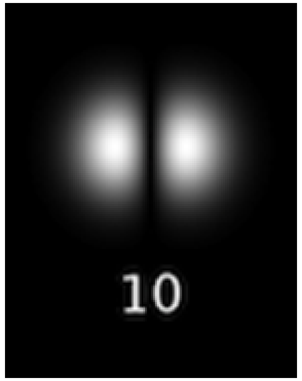
HG_{10}

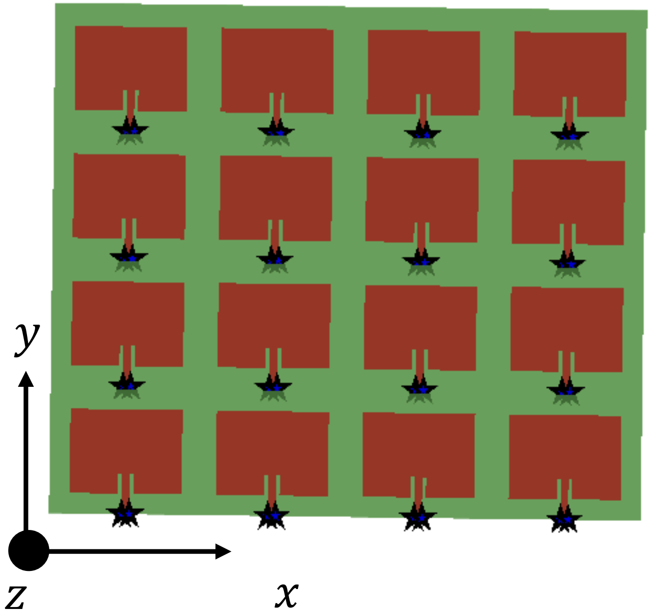


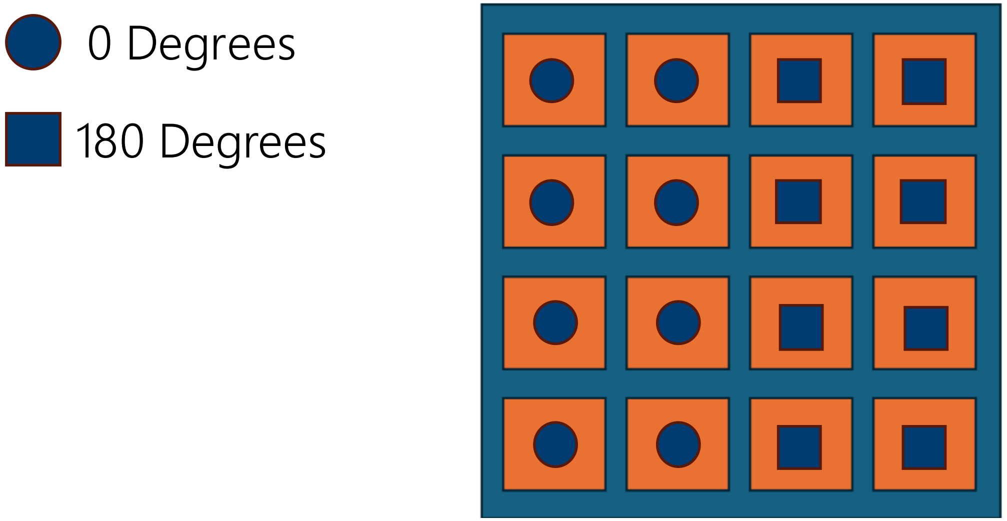
HG_{11}

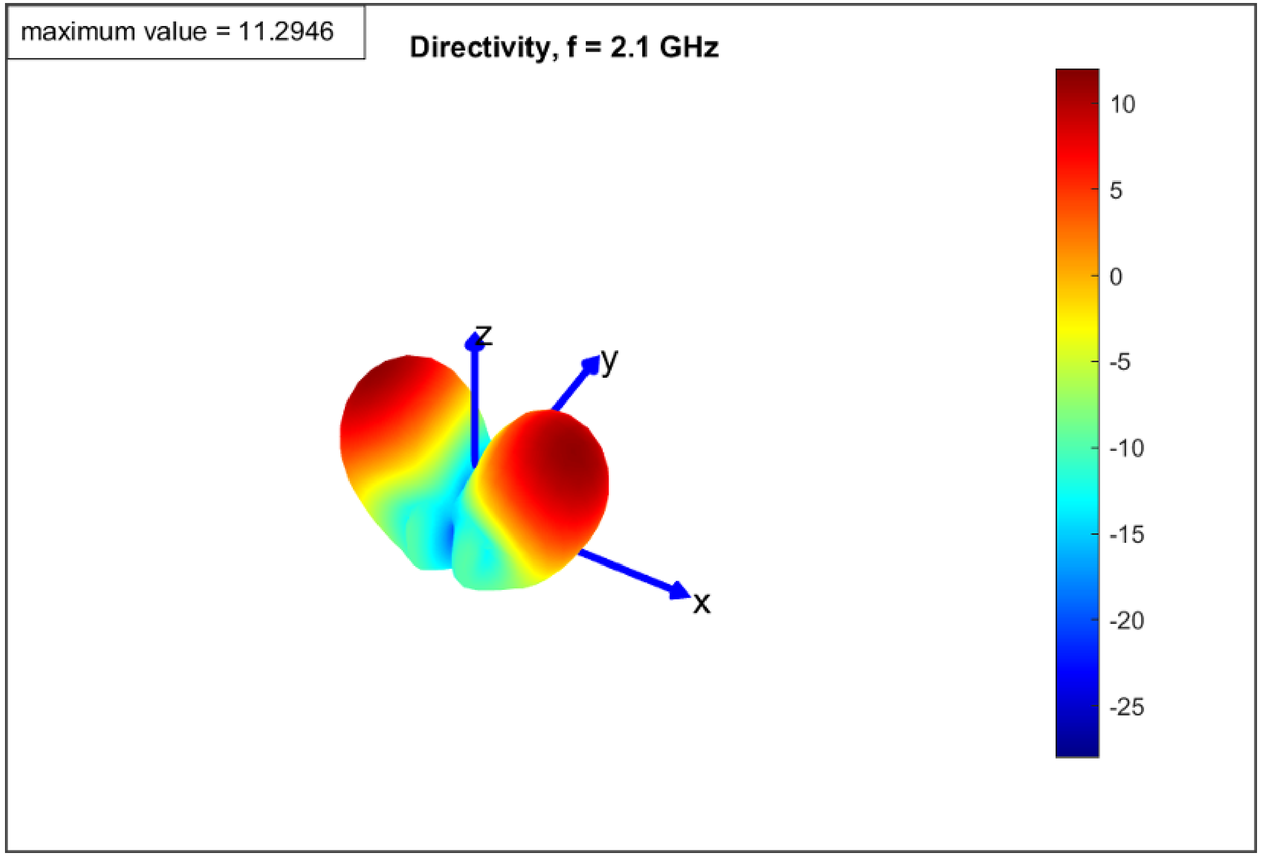


Structured Waveforms: Hermite Gaussian Mode (1,0)

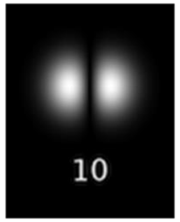


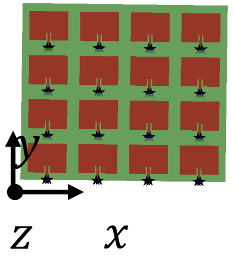


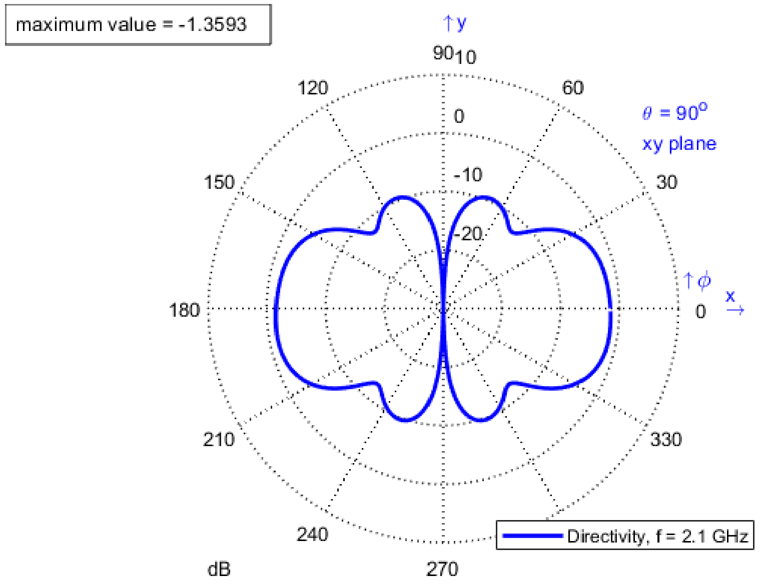


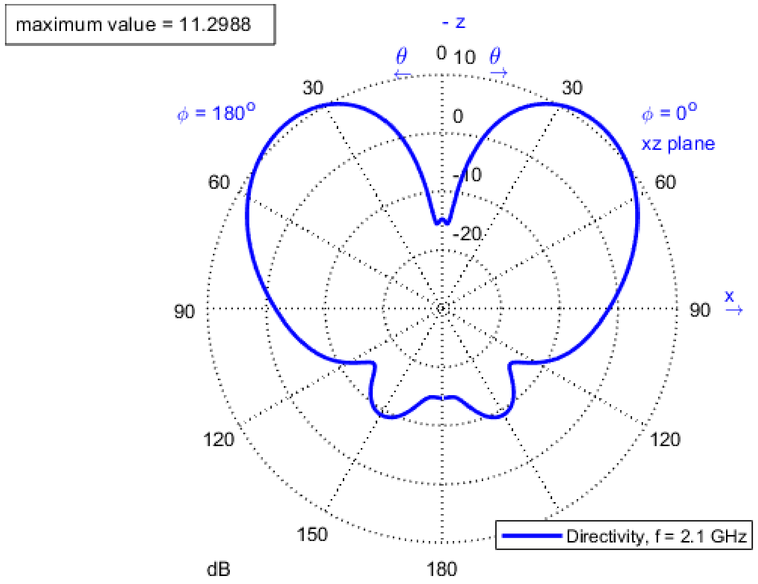


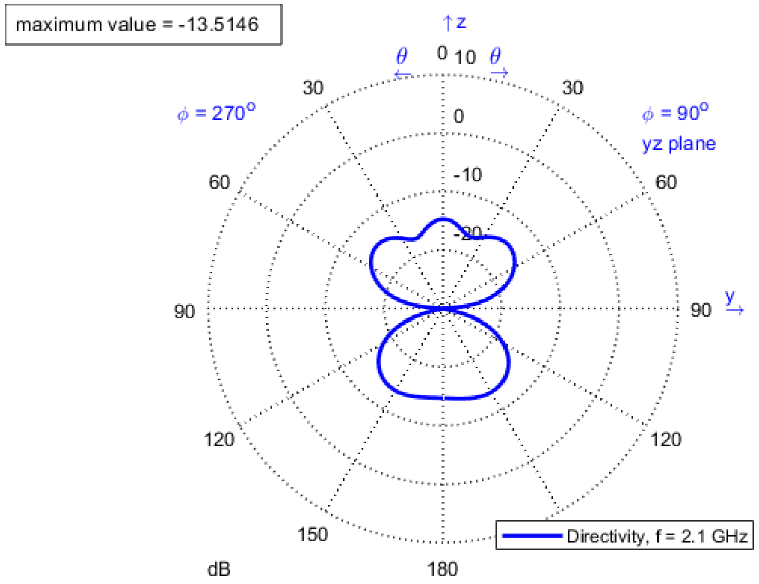
Structured Waveforms: Hermite Gaussian Mode (1,0)











Phase Assignment for Laguerre Gaussian Modes

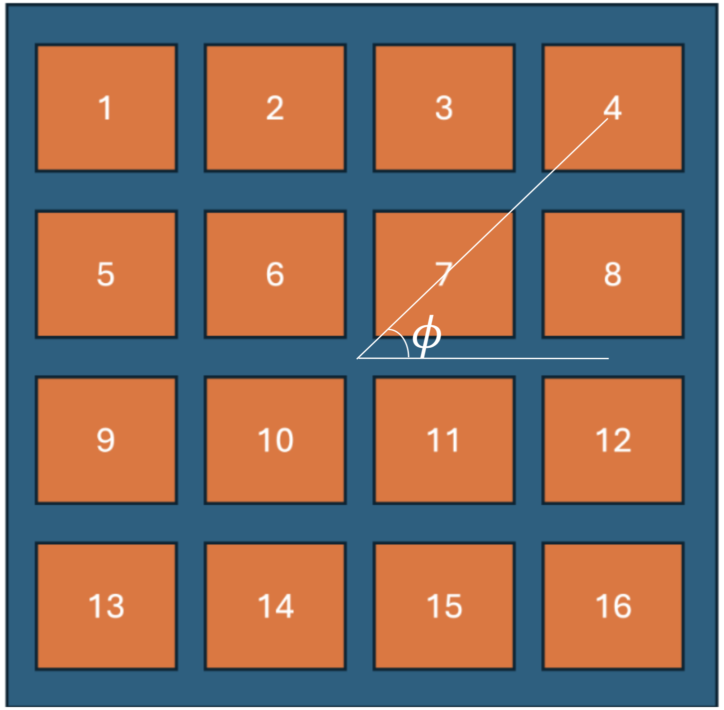
$$\boldsymbol{E}_{LG}(r,\phi,z) = \frac{E_{xo}}{w(z)}\left(\frac{r\sqrt{2}}{w(z)}\right)^{|L|} e^{-\frac{r^2}{w^2(z)}} L_p^{|L|}\left\{\frac{2r^2}{w^2(z)}\right\} e^{\frac{jkr^2}{2R(z)}} e^{j|L|\phi} e^{j[2p+|L|+1]\psi(z)} e^{-jkz}\,\hat{\boldsymbol{x}}$$

To approximate modes p=0, L=-2,-1, and 2 multiply the phase column by the mode number L

$$\phi = \arctan(d_y/d_x)$$

d_y = vertical distance from center

d_x = horizontal distance from center

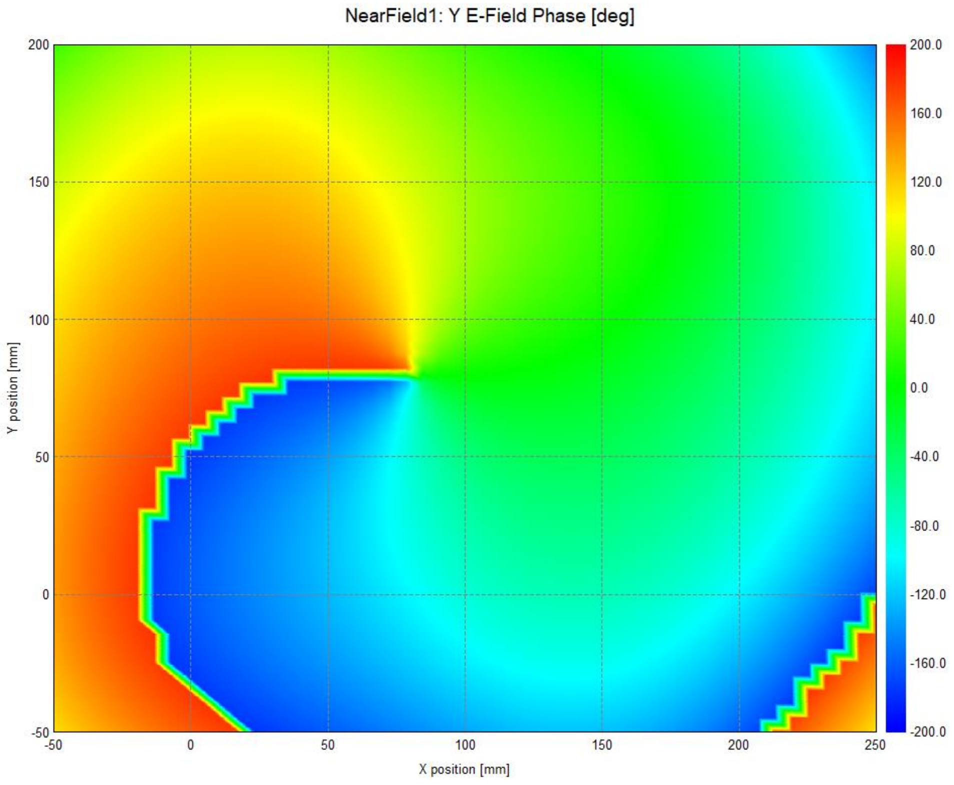


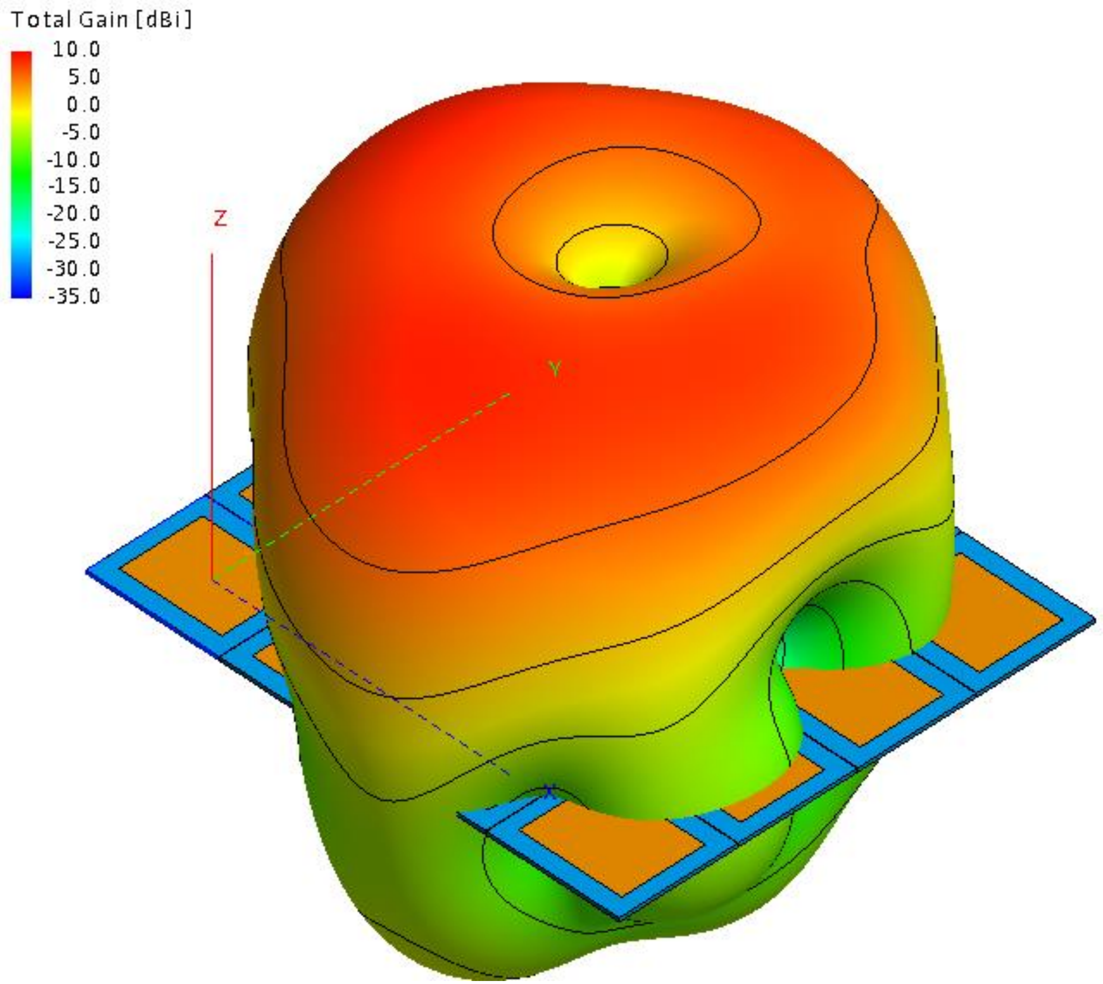
Mode p=0 L=1

Element	Phase (deg)	Element	Phase (deg)
1	140.2	9	195.5
2	111.8	10	219.8
3	68.2	11	320.2
4	39.8	12	344.5
5	164.5	13	219.8
6	140.2	14	248.2
7	39.8	15	291.8
8	15.5	16	320.2

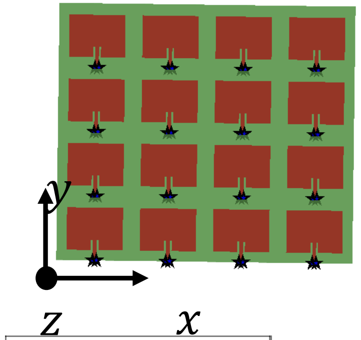
Laguerre Gaussian Mode p=0, L=1

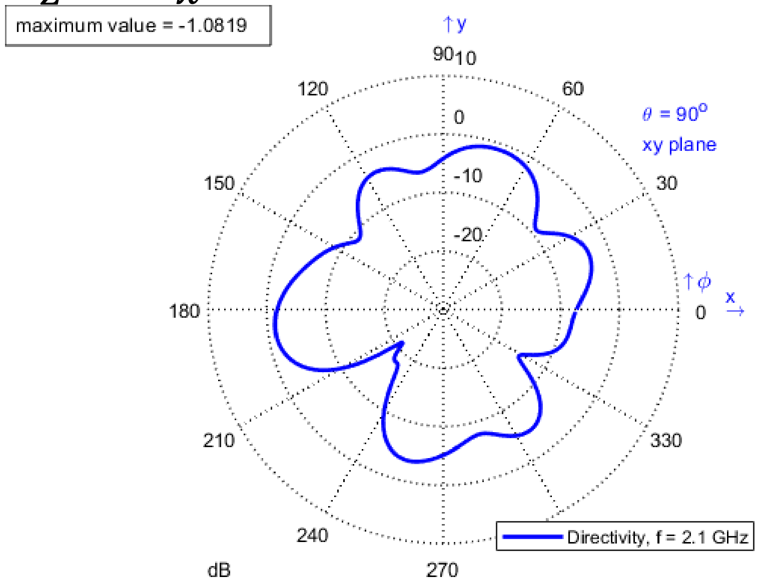
For LG mode 1, the near-field electric field phase is plotted using Feko to confirm helicity.

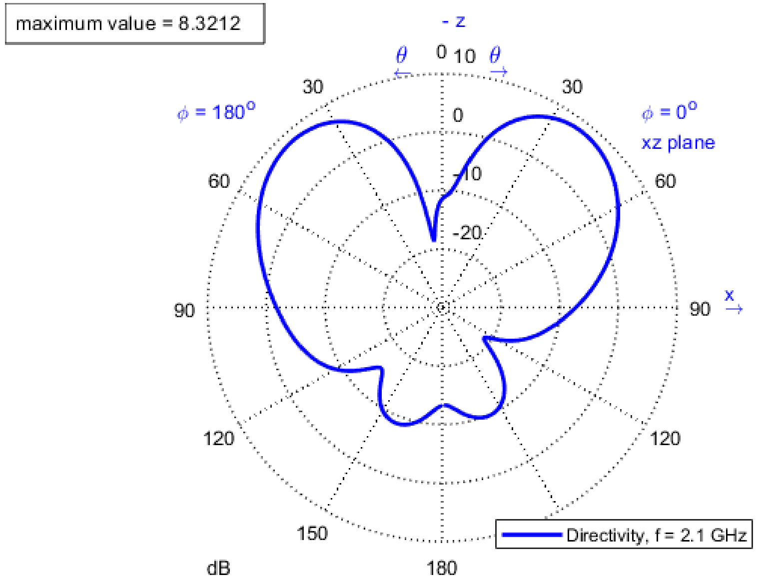


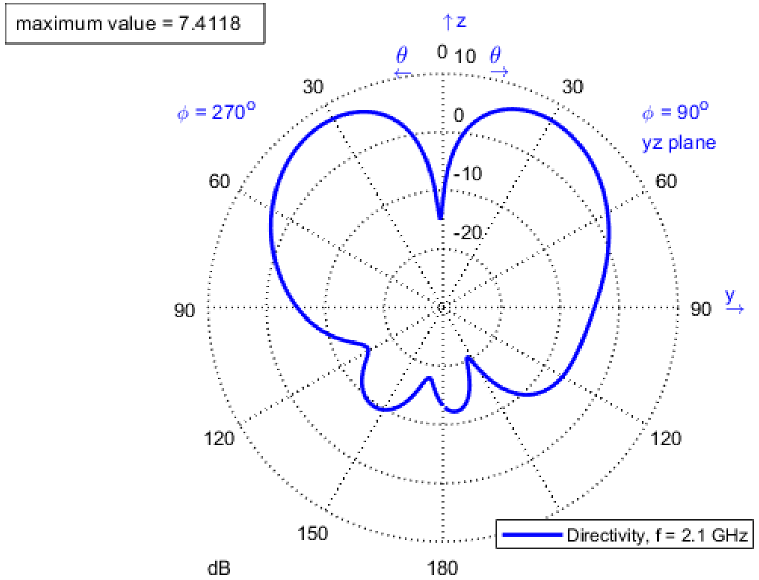


Plane Cuts for Laguerre Gaussian Mode p=0, L=1









Future Work

- Design and fabrication of sixteen-element concentric uniform circular array for pure multimodal excitation.
- Measure scattered field from different targets of different materials and shapes.
- Prepare a classroom demonstration to introduce students to the concept of phased array applications.

Acknowledgements

This project received support from:

VICEROY (Griffis Institute, Air Force Laboratory)

Defense Advanced Research Projects Agency (DARPA) EMON Project

/dev/cu.usbmodem101

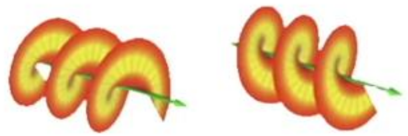
Antenna Array Control

Calibrate

Manual

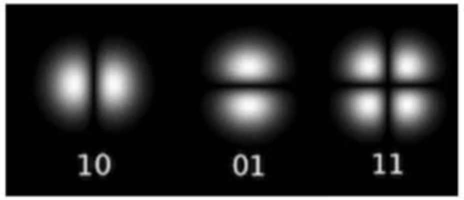
Phase Control

Laguerre



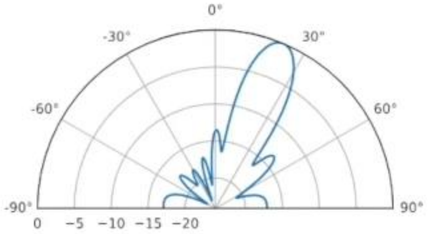
Gaussian

Hermite



Gaussian

Beam



Steering