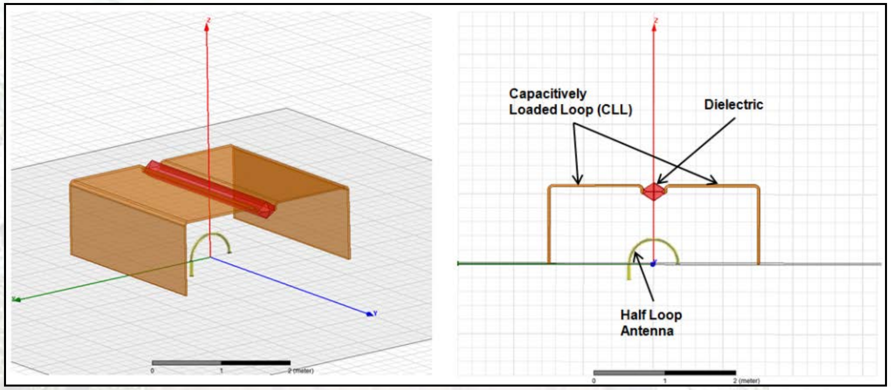
Metamaterial Inspired Electrically Small Antenna



Design Goals

- Electrically small – a few meters in size
- High power – MW output
- Instantaneous bandwidth – a few percent
- Tuning – adjust resonant frequency with structural modification

Project Objective

Design and simulate an electrically small antenna for the 2 – 10 MHz range capable of high power applications

Approach

•Simulate and optimize the design in HFSS for the operational frequency range
•Build a scaled version of the design for operation around 100 MHz

Current Issues

- Tradeoff between size and bandwidth
  - Resonant structure
- High field on surface of dielectric
  - Limits input power
- Losses in the dielectric
  - Increase bandwidth, decrease efficiency

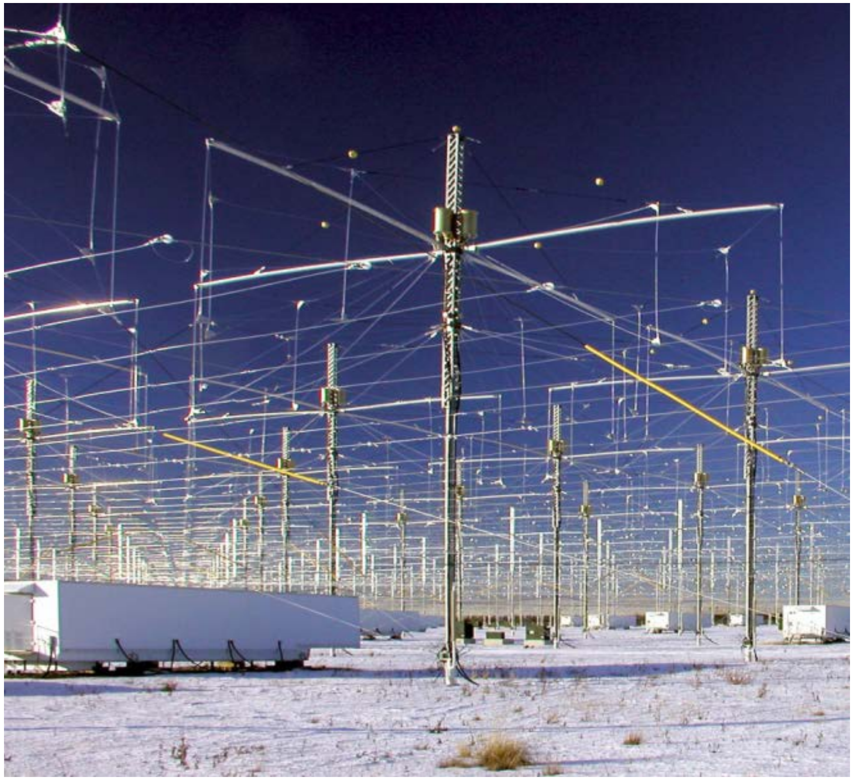
HAARP Facility

- High Frequency Active Auroral Research Program
- Located in southern Alaska
- Transmit high frequency signals into Ionosphere to study effects
- 180 antenna structures in a 12×15 array on ~33 acres

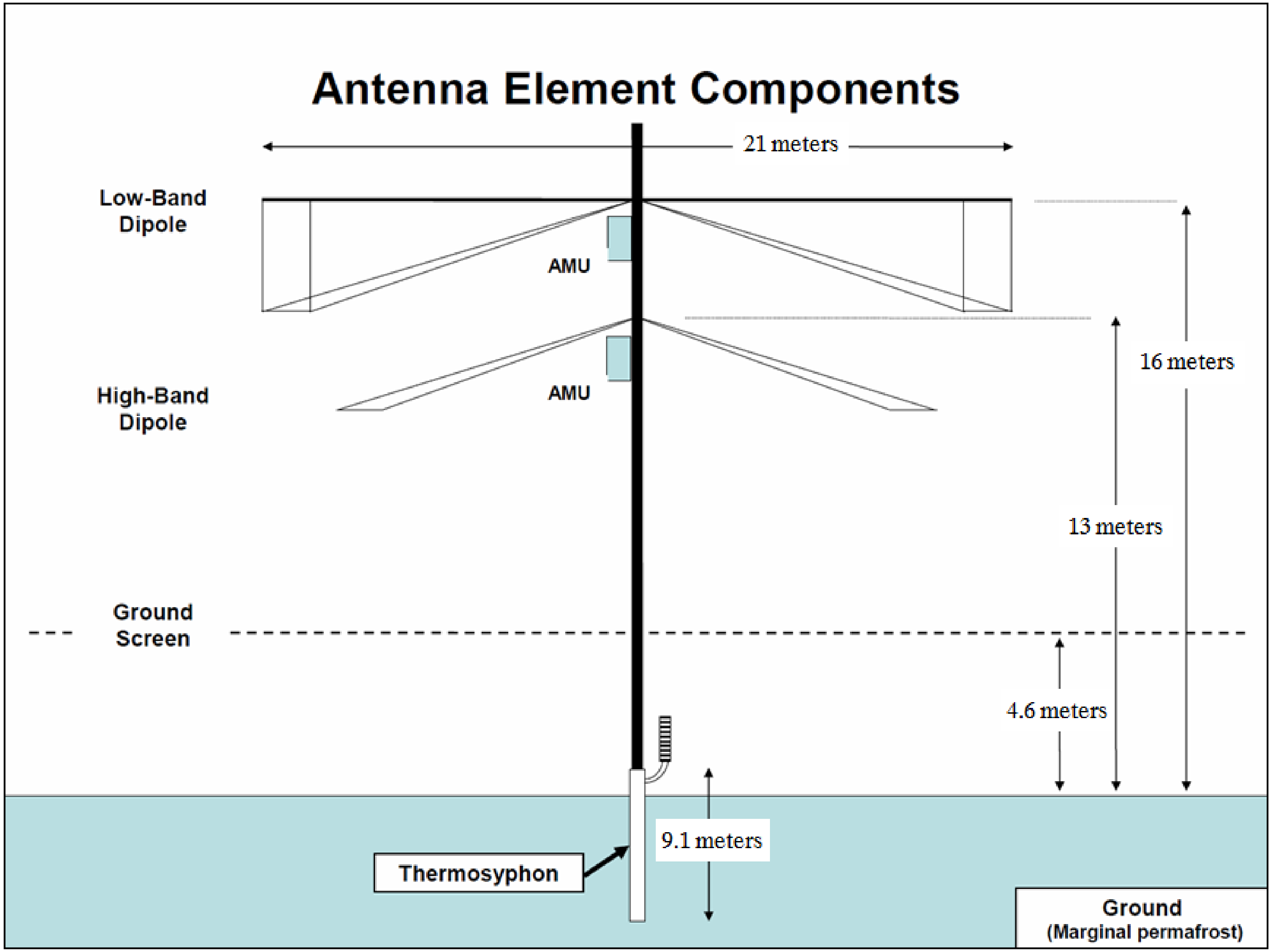
HAARP Facility

Antenna Specifications

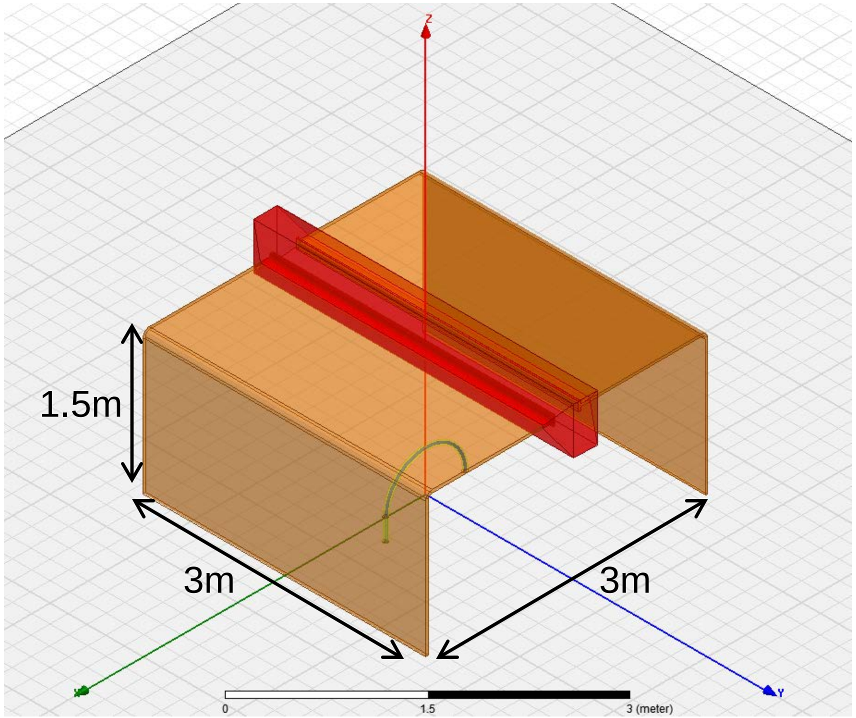
- Crossed dipoles
  - Low Band: 2.8 – 8.4 MHz
  - High Band: 7 – 10 MHz
  - 360 total dipoles
- 10 kW transmitters
  - 3.6MW radiated
  - ERP of 84 – 95 dBW
- Instantaneous Bandwidth
  - 200 kHz at 2.8 MHz - ~7.1%
  - 500 kHz at 10 MHz - ~5%

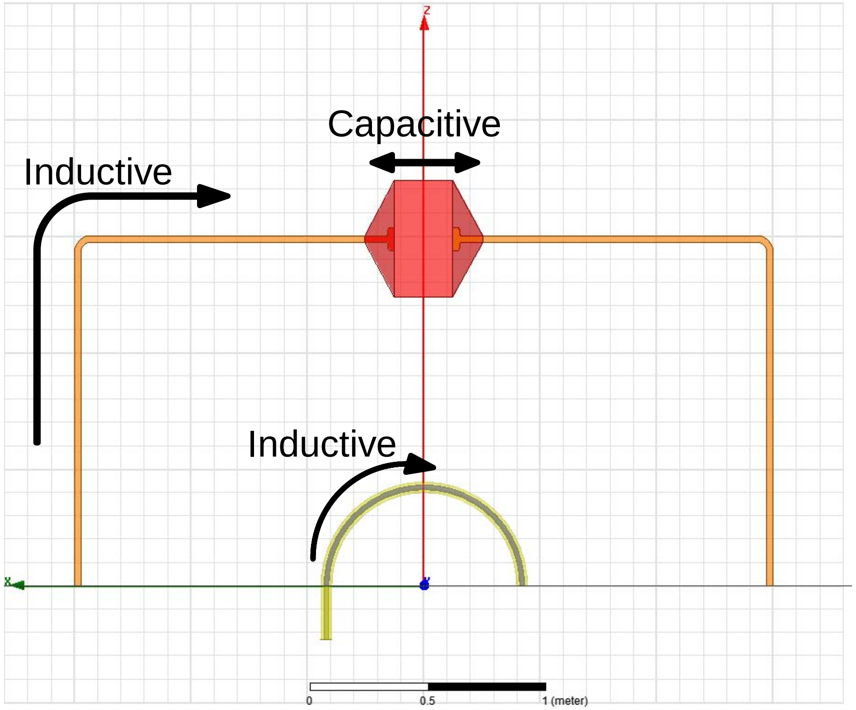


Antenna Dimensions



Design Goal: Electrically Small



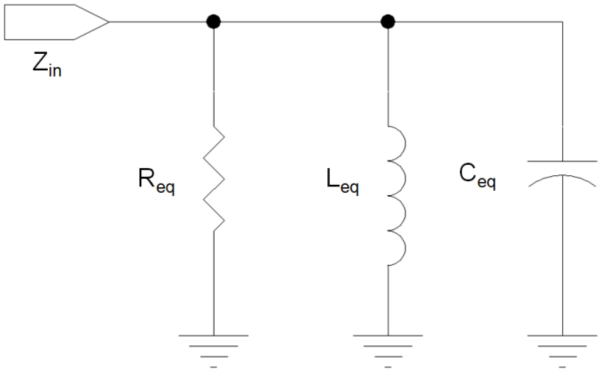


An inductive loop antenna is enclosed by a capacitively loaded loop (CLL). This creates resonance between the two structures at a lower frequency than the loop antenna would have on its own.

Note: the antenna is located on an 11m×11m Perfect-E ground plane.

Antenna Design: *(Erentok, Ziolkowski. “Metamaterial Inspired Efficient Electrically Small Antennas.”)*

Circuit Model



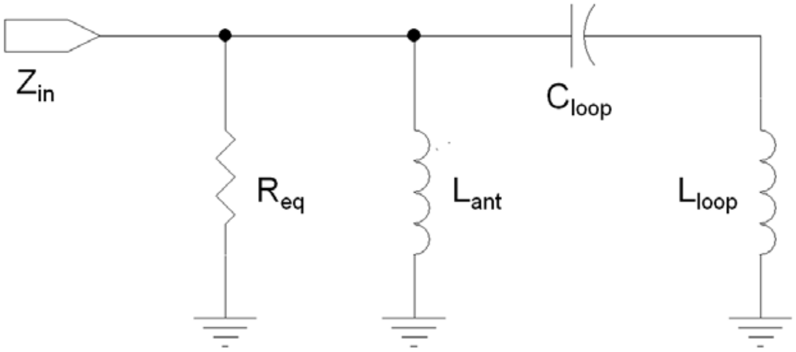
- Simple Circuit Model
  - $\omega_0 = (L_{eq}C_{eq})^{-1/2}$
- Equivalent capacitance of the CLL is

$$C_{eq} = \frac{C_{loop}}{1 - \omega^2 C_{loop} L_{loop}}$$

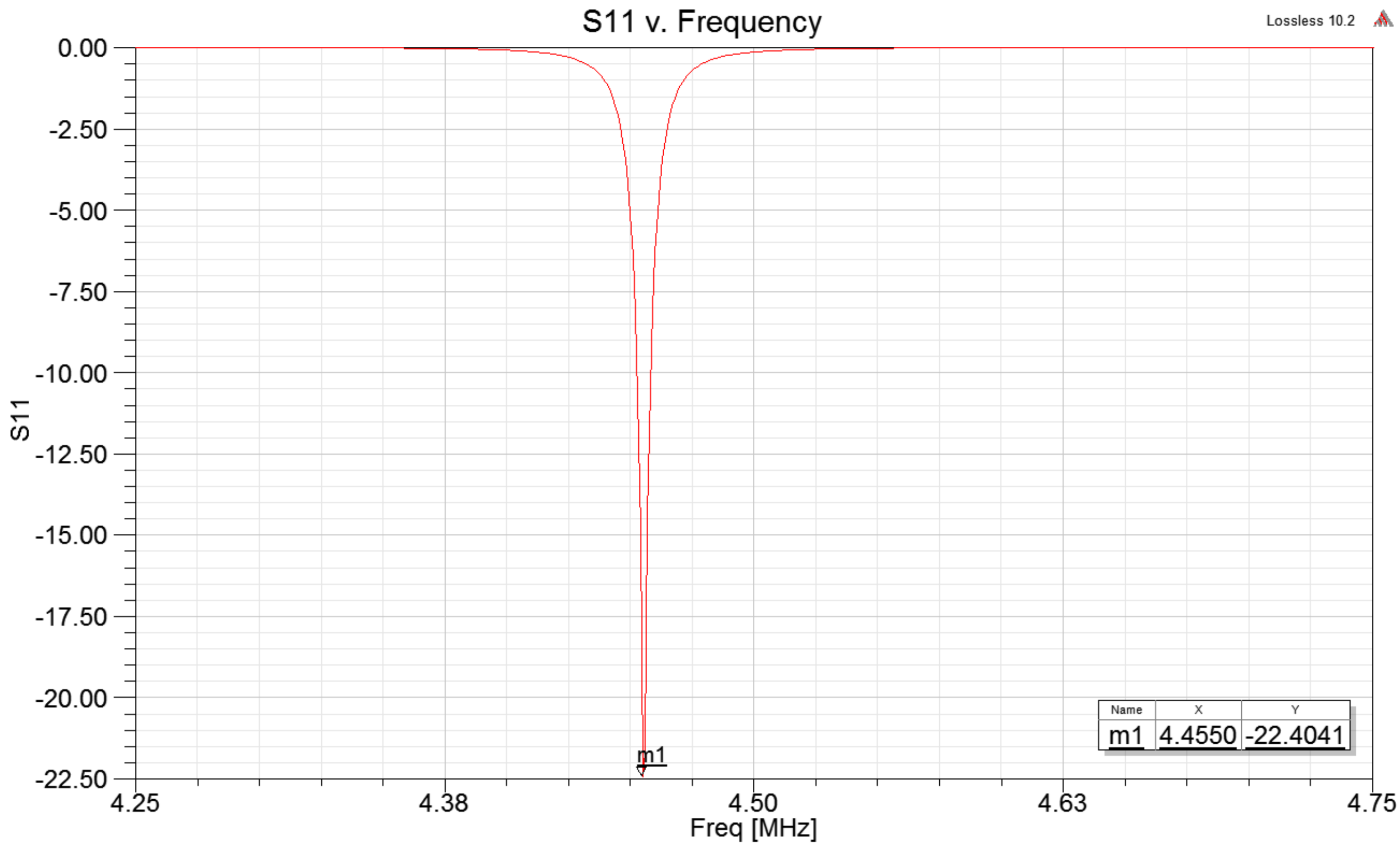
- Two observations:
  - 1. As C_{loop} increases, bandwidth and ω_0 decrease
  - 2. As L_{loop} increases, bandwidth and ω_0 decrease

$$Q = \frac{\omega_0}{B_P} = \omega_0 RC = \frac{\omega_0 R}{L}$$

$$B_P = \frac{1}{RC} = \frac{L}{R}$$

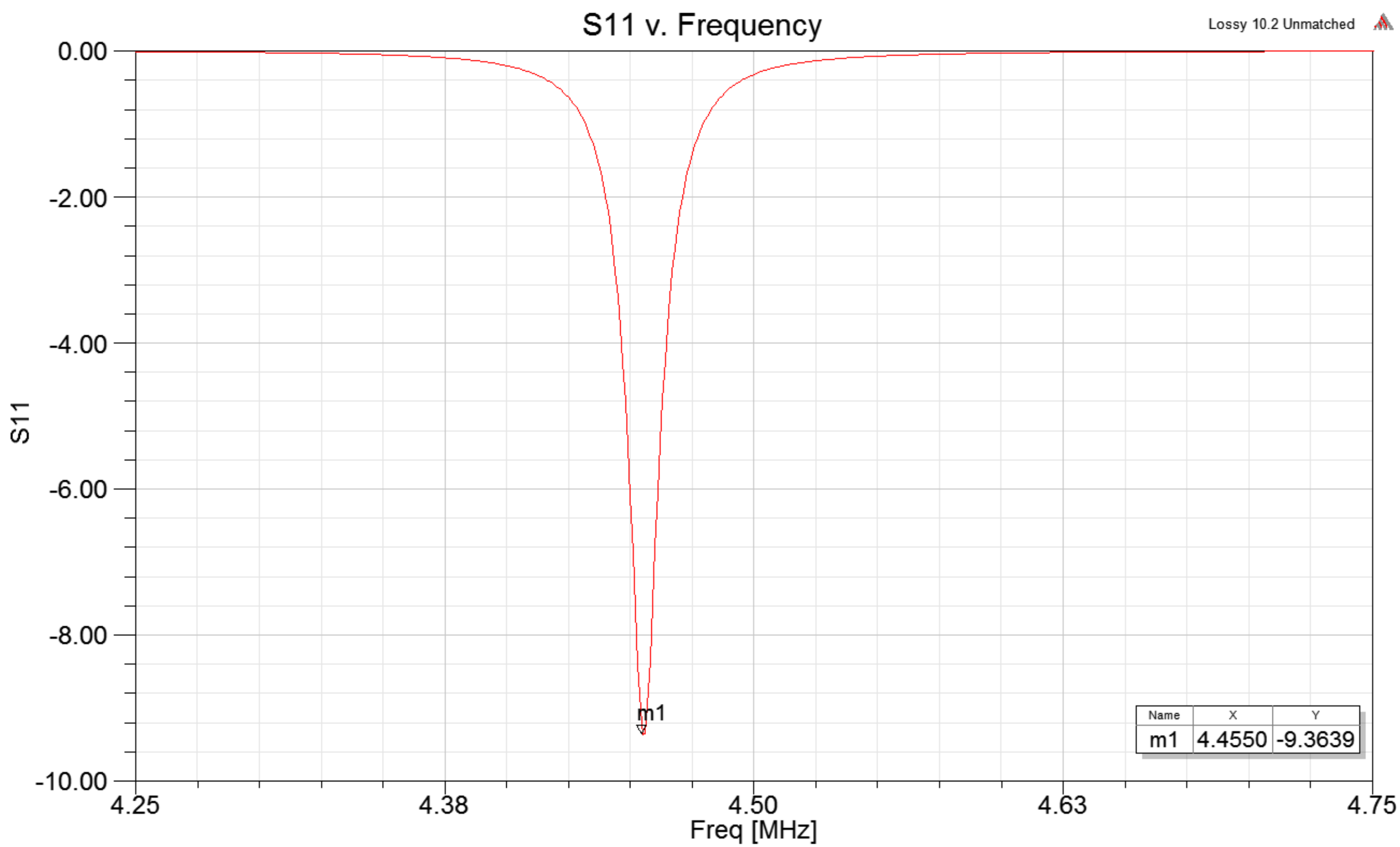


Instantaneous Bandwidth – Lossless Dielectric



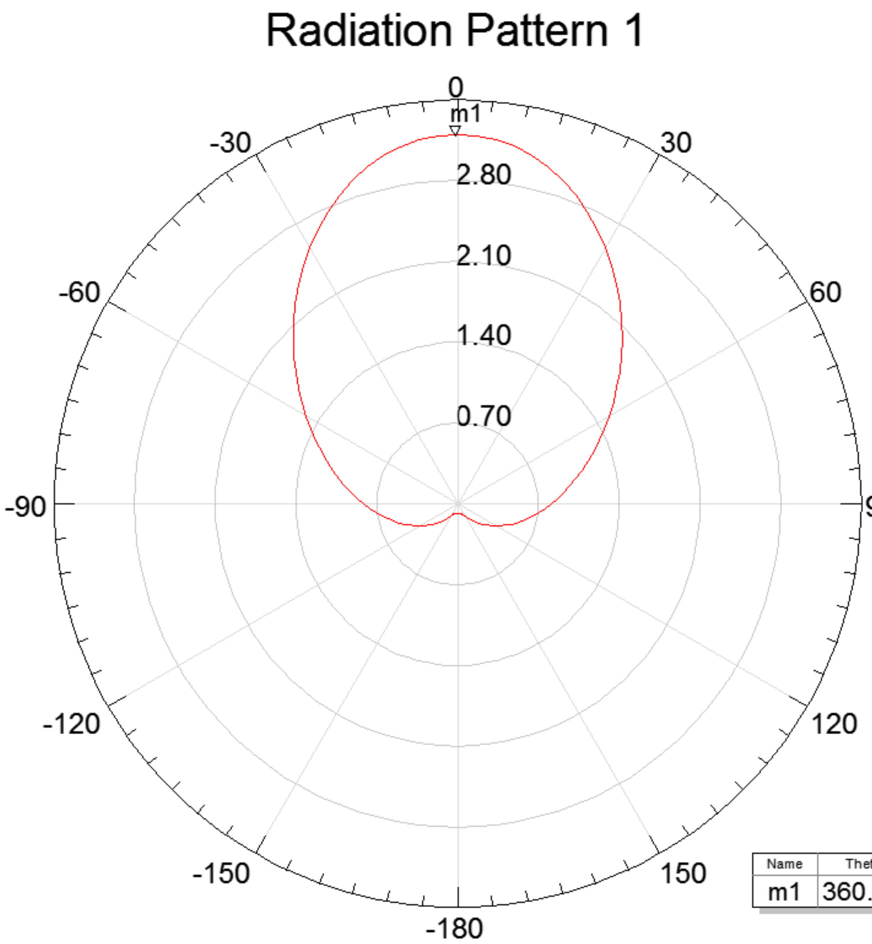
With the current dimensions of 3m×3m×1.5m and a lossless dielectric with ε_r = 10.2, the unmodified antenna's 3dB bandwidth is 0.0383% of the center frequency.

Instantaneous Bandwidth – Lossy Dielectric



When a loss tangent (0.0023) is added to the previous design, the S_{11} changes dramatically. The instantaneous bandwidth is 0.230%, 6 times the lossless bandwidth.

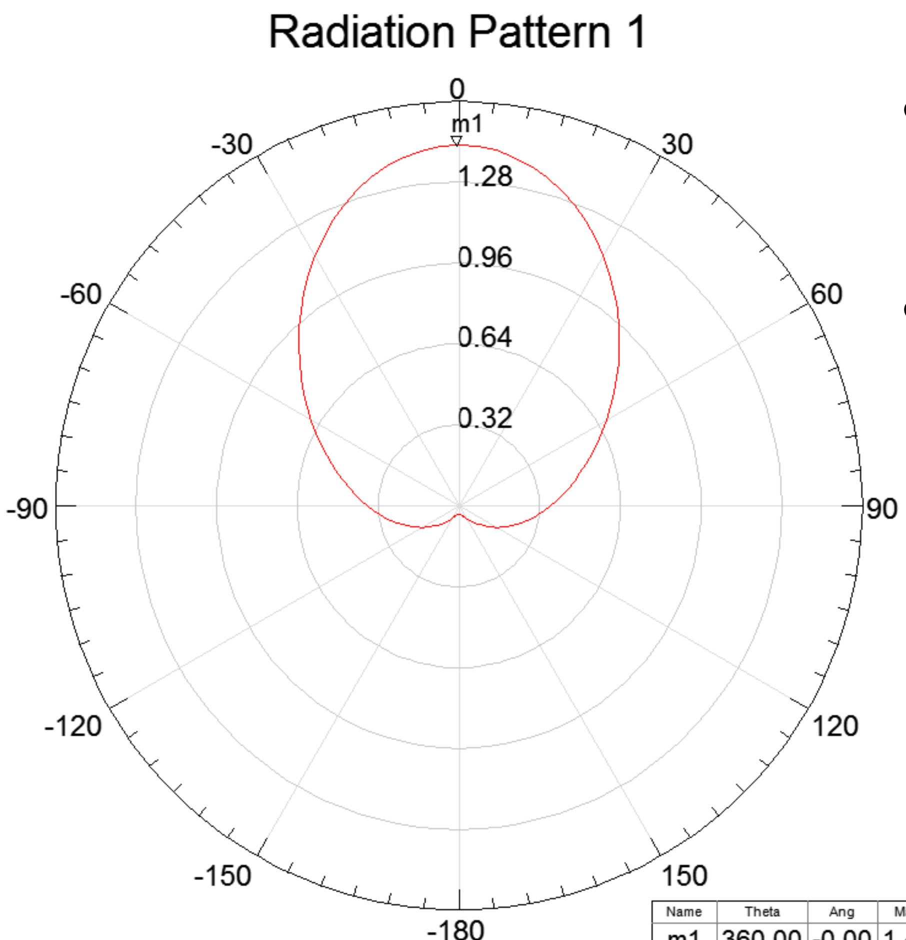
Gain Pattern - Lossless



Name	Theta	Ang	Mag
m1	360.00	-0.00	3.20

- Peak Gain at 0° zenith
  - GP = 3.2 = 5.05 dB
- Twice the gain of a dipole antenna
  - Lossless dielectric

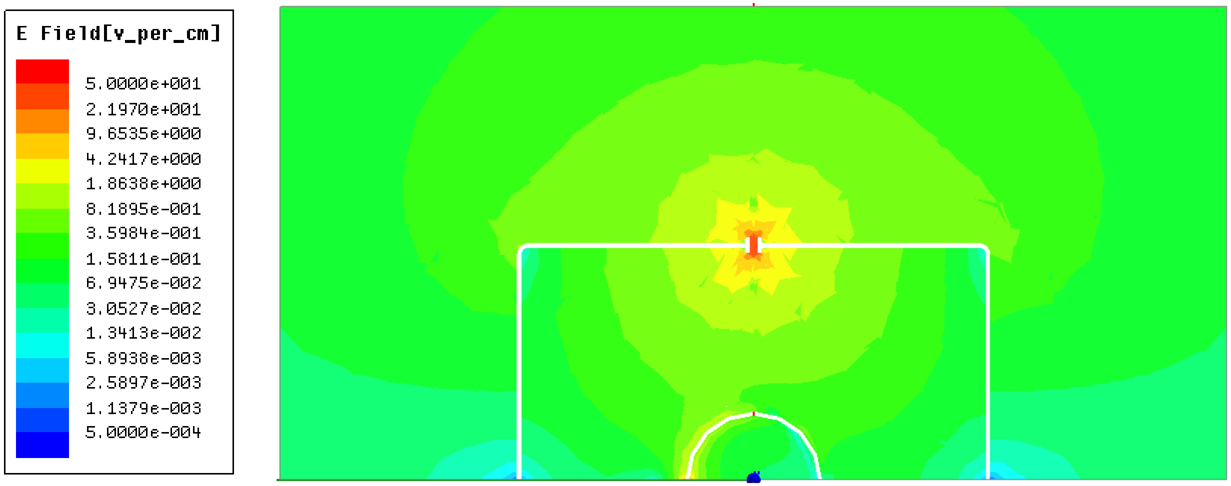
Gain Pattern – Lossy



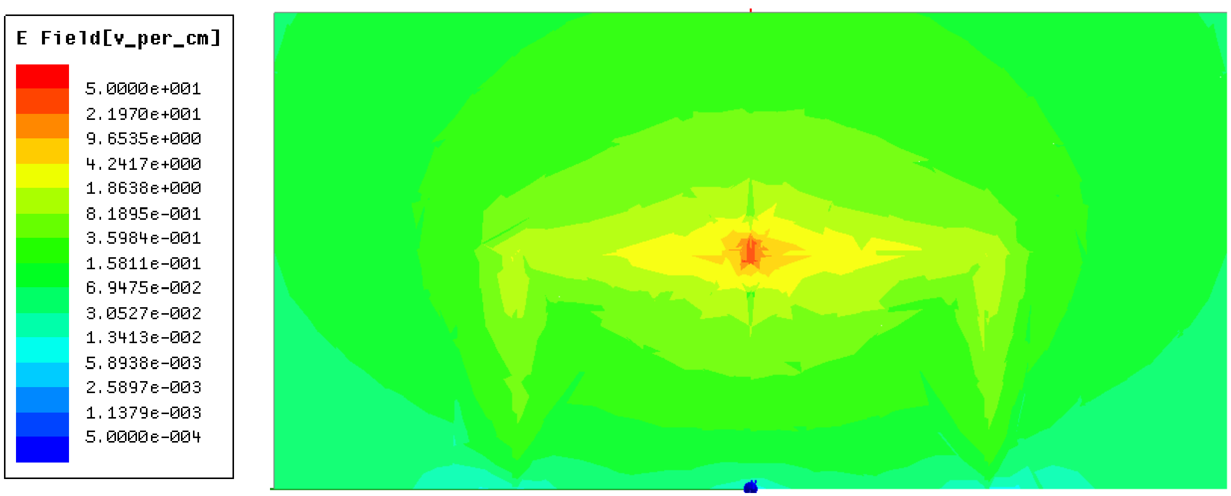
Name	Theta	Ang	Mag
m1	360.00	-0.00	1.43

- Peak Gain at 0° zenith
  - GP = 1.43 =1.55 dB
- Much less gain than with the lossless dielectric
  - Inefficient capacitive geometry

Electric Fields - Lossless



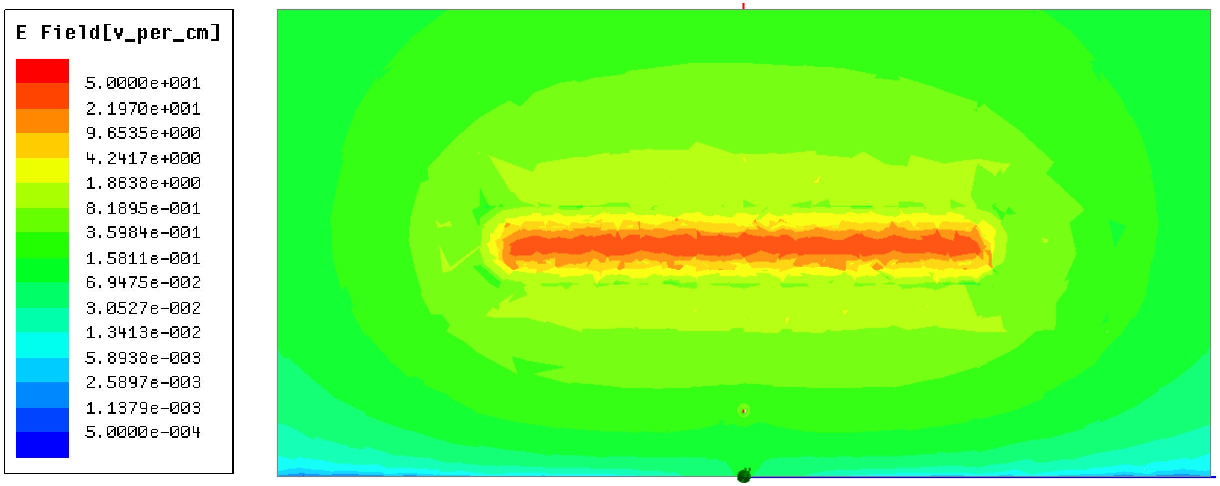
XZ Plane, center of structure.



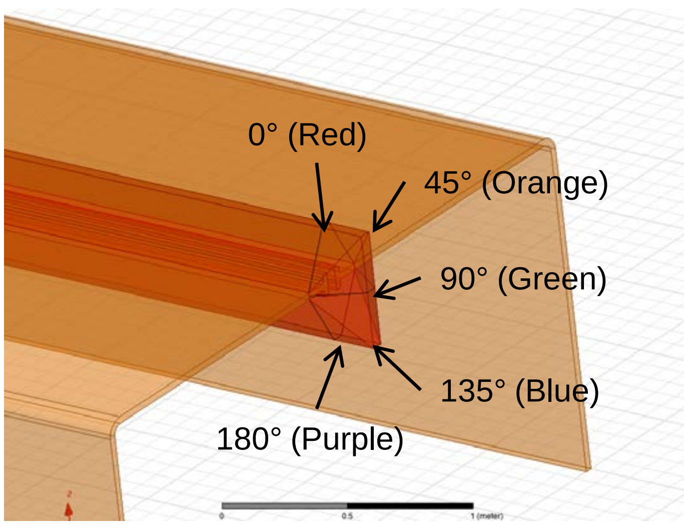
XZ Plane, end of structure.

For field plots: Incident Power of 1W into 50Ω → V_{peak} = 10 V

Electric Fields, Cont’d

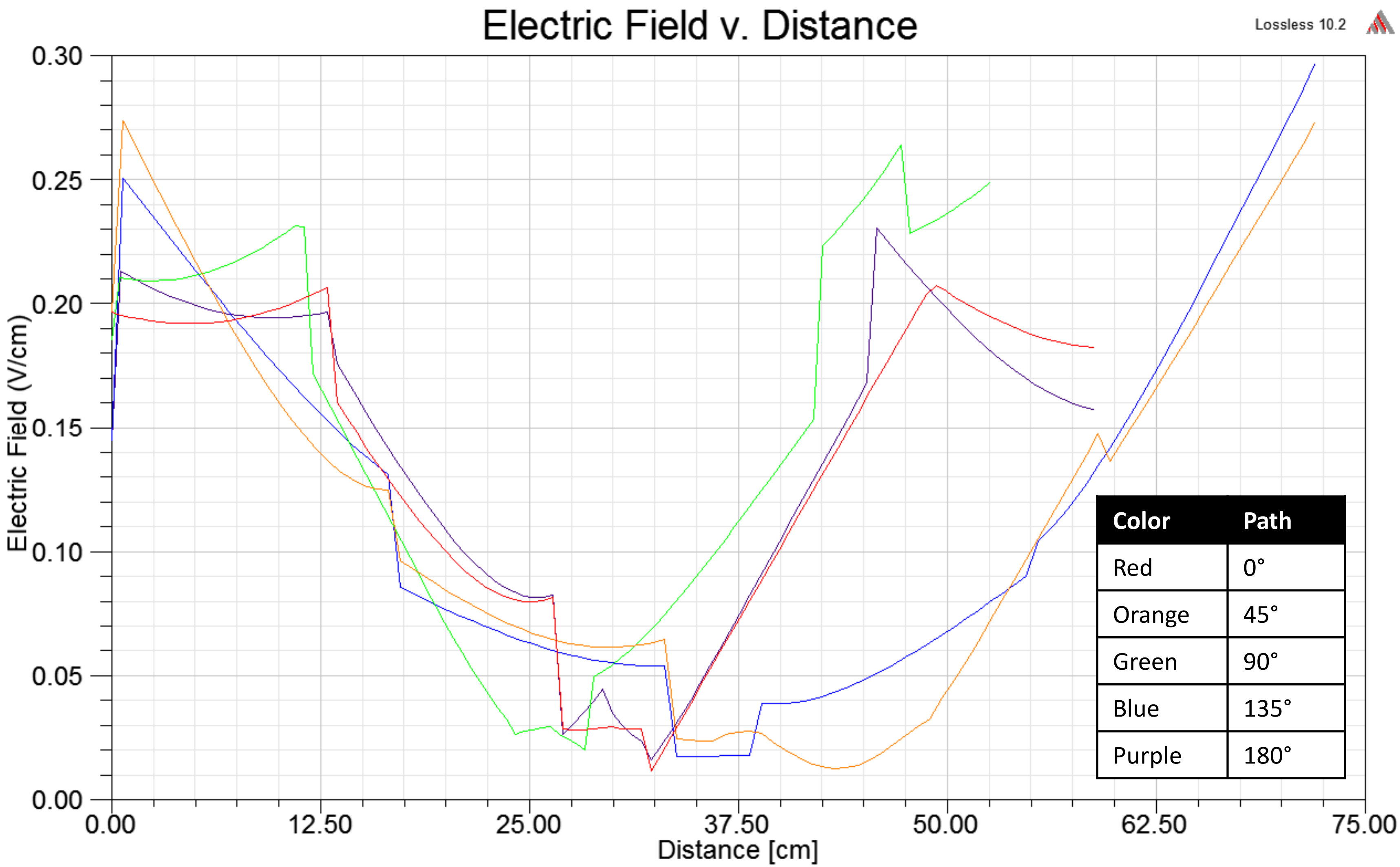


YZ Plane, center of structure.



Five possible breakdown paths are chosen on the edge of the dielectric (ε_r = 10.2, tan δ = 0). The electric field is plotted across these lines, and the voltage is calculated to predict the maximum input power.

Field Along Possible Breakdown Paths



Color	Path
Red	0°
Orange	45°
Green	90°
Blue	135°
Purple	180°

Voltages Across Possible Breakdown Paths

Line of Interest	Voltage	Distance	Point Breakdown	Plate Breakdown
0° (Red)	184.9 V	59 cm	105.3 kW	310.3 kW
45° (Orange)	262.8 V	72 cm	83.6 kW	178.4 kW
90° (Green)	169.4 V	52 cm	125.4 kW	334.7 kW
135° (Blue)	216.2 V	72 cm	123.6 kW	263.6 kW
180° (Purple)	182.7 V	59 cm	130.5 kW	317.8 kW

For the lossy case, the calculated voltages would be lower, since some of the power is dissipated in the dielectric.

Separation	Point Breakdown	Plate Breakdown
52 cm	60 kV	98 kV
60 cm	66 kV	103 kV
72 cm	76 kV	111 kV

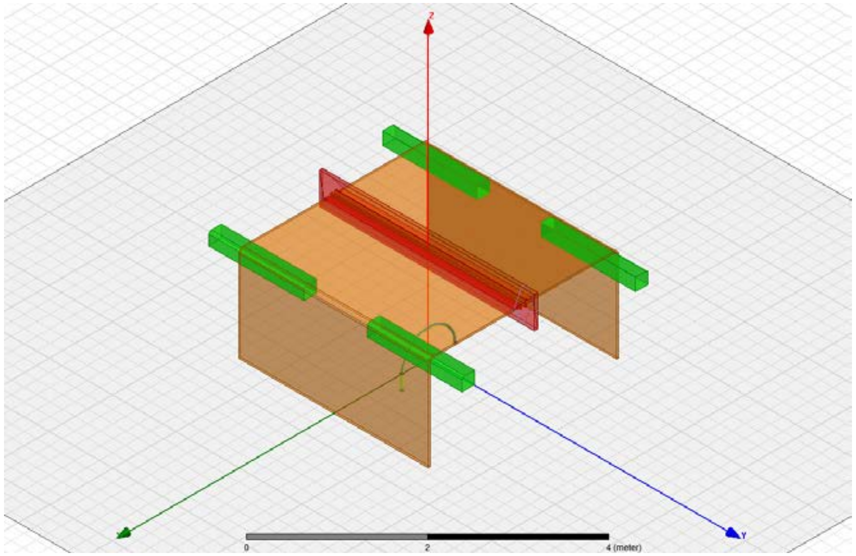
Breakdown data extrapolated from: (Meek and Craggs. "Electric Breakdown of Gases.")

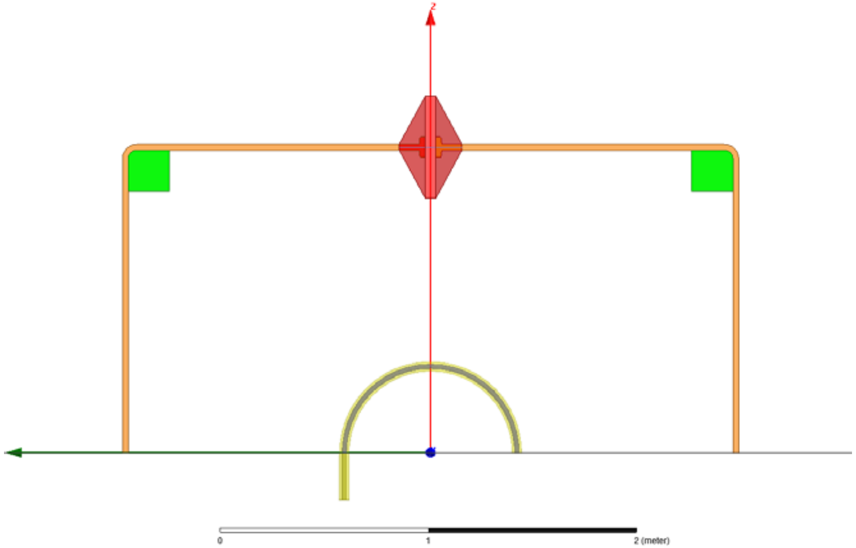
Antenna Parameters

Quantity	Lossless Dielectric	Lossy Dielectric (Unmatched)	Lossy Dielectric (Matched)
Peak Directivity	3.29	3.29	3.15
Peak Gain	3.20	1.43	1.29
Radiated Power	0.968 W	0.384 W	0.408 W
Accepted Power	0.994 W	0.884 W	0.998 W
Incident Power	1 W	1 W	1 W
S_{11} Minimum	-22.4 dB	-9.36 dB	-27.6 dB
Bandwidth/ω_0	0.0383%	0.230%	0.0272%

The effect of the loss tangent on the radiated power and gain is significant. Modifying the geometry of the capacitive element to decrease the electric field, and thus the dielectric losses, should improve both.

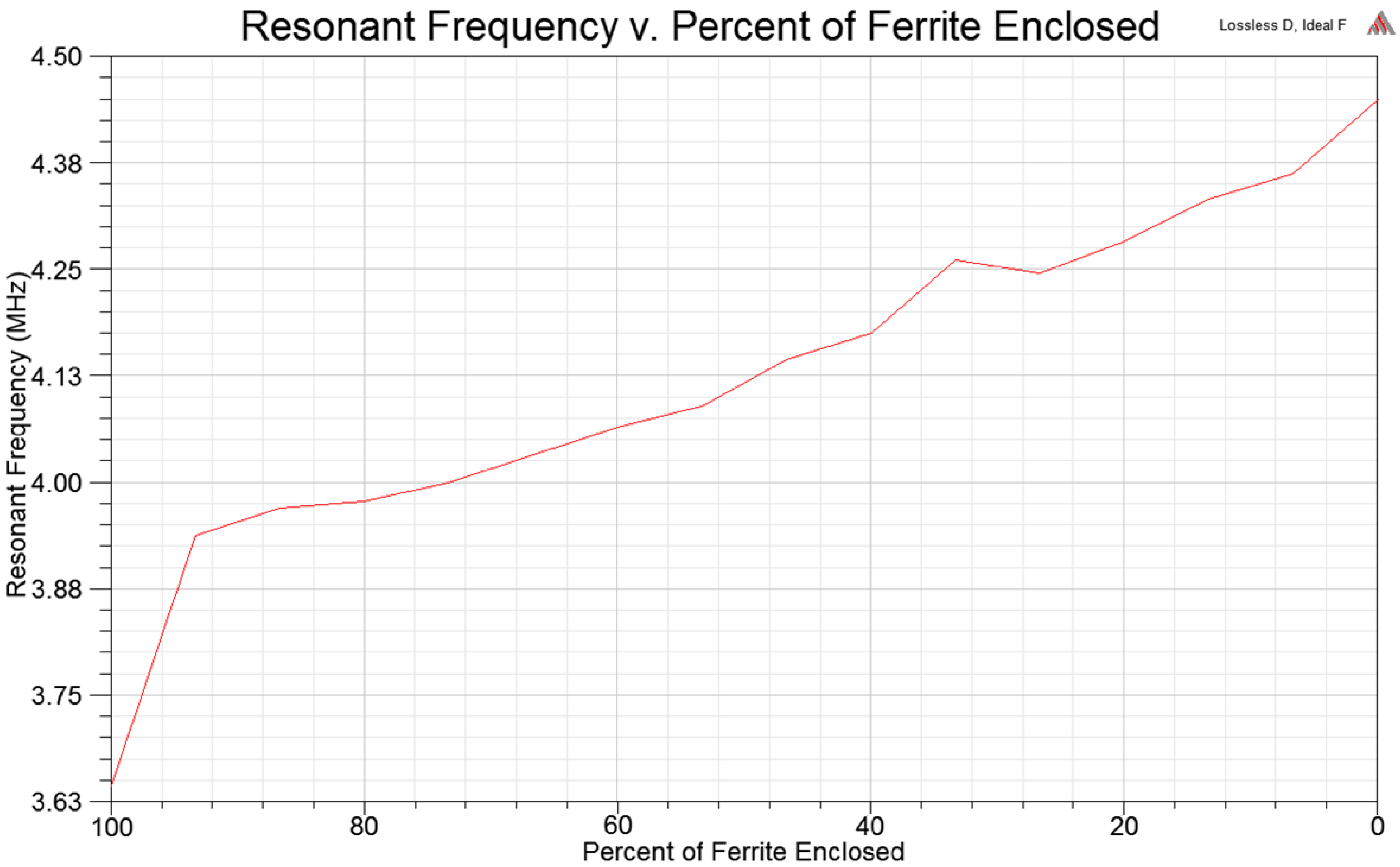
Tuning the Antenna



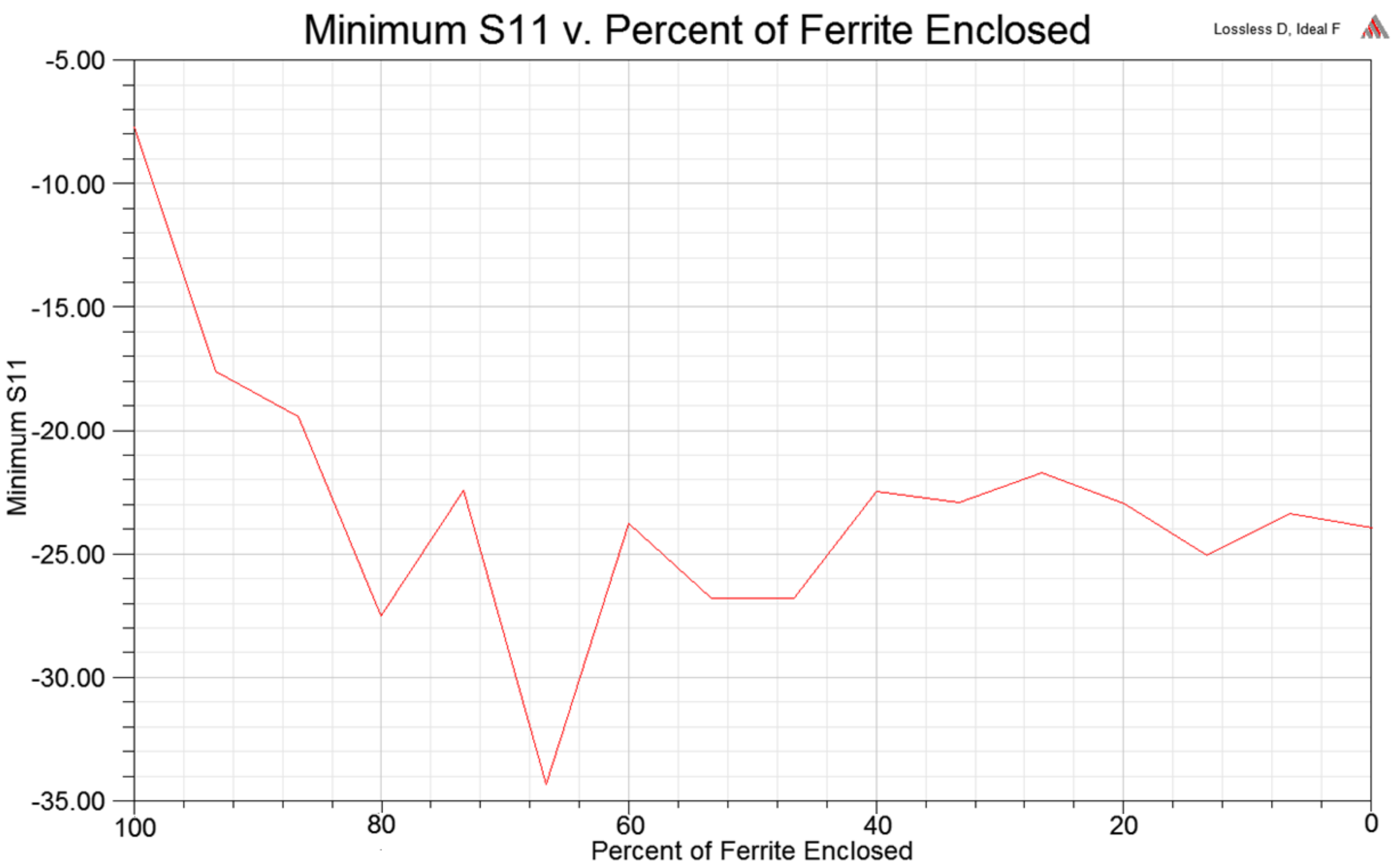


When a material with μ_r = 1000 is put in the corner of the CLL, it increases the inductance of the CLL, which decreases C_{eq} and the resonant frequency. The resonant frequency can be varied by changing the amount of the material enclosed by the loop.

Resonant Frequency Modification



Effect of Modification on S_{11}



Adding the magnetic material has other effects besides modifying the resonant frequency, such as antenna matching and bandwidth. These effects still need to be investigated.

Phased Array Gain Approximation

- HAARP facility has an ERP of 84 – 95 dBW
- Assumptions:
  - Gain of Phased Array: $G_{array} \approx 4\pi Area/\lambda^2$
  - Max distance between elements: $d_{max} = \lambda/(1+\sin(\theta))$
  - Antenna Gain of 2.15 dB (equal to dipole)
- $ERP = P_t + G_{ant} + G_{array} - 2.15 = P_t + G_{array}$
- For HAARP @10 MHz, the total power transmitted is 3.6 MW on 33 acres
  - $G_{array} \approx 10\log(4\pi Area/\lambda^2) = 36$ dB
  - $ERP = 10\log(3.6\ MW/W) + G_{array} = 96$ dBW

Phased Array Gain Approximation

	$P_{element}$	Area (acres)	No. of elements	P_{total} (MW)
2.8 MHz @ Max Input Power	1 MW	30	24	24
2.8 MHz @ Max Area	824 kW	33	26	21.4
10 MHz @ Max input Power	1 MW	2.8	20	20
10 MHz @ Max Area	7.2 kW	33	236	1.7

Requirements for ERP = 95 dBW

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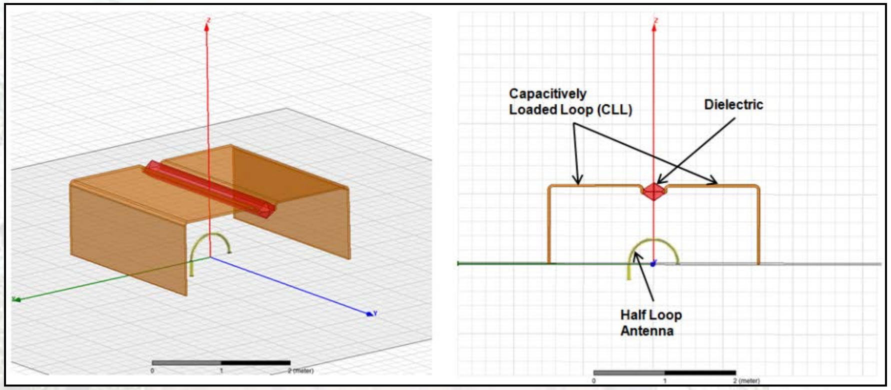

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Future Work

- Modify the capacitive geometry
  - Improve the gain and radiation characteristics when losses are included
  - Decrease the Electric field on the lines of interest to increase input power
- Examine the effects of tuning
  - Probable increase in bandwidth
- Implement other methods to increase bandwidth
  - Add slots in the CLL