"Antennas and Beamformer Architectures for Army Platforms

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Outline

- Introduction, military needs for antennas
- Some practical uses for metamaterials
- Some funded work
  - Placement insensitivity
  - Mitigate loading effects
  - Realized gain enhancement
- Metamaterial-driven lens optics
- Bandwidth/gain improvements
- Conclusions

Military Needs: Low-Profile, Wideband Antennas for Radio and other Systems

PROBLEM

- Antennas always seem to cause problems
  - Obscure LOS
  - Need installing / removal / Tuning (Tweaking)
  - Get damaged or break
- Everyone wants conformal Antennas
  - Platforms (UAVs, Vehicles, Ships)
  - Soldier (Helmet Antennas, Body Antennas)
- Present Conformal types
  - Mostly resonant antennas
  - Microstrip Patch Antennas / Arrays
  - Meander Ant. / Arrays (Dist. Resonant), Etc.
  - Fewer with good impulse response even in-band

PERFORMANCE LIMITS

- Too Thick with needed reflective backplane
  - Typically need ~1/4 wavelength standoff
  - Adding dielectric makes it heavy & expensive
- Narrow Band
  - Rarely > few % relative bandwidth
- Limited FOV
  - Resonant currents determine pattern
  - Pattern nominally perpendicular to surface
- Suboptimal Arrays
  - Element spacing > Lambda/2 (grating lobes)

CAUSE OF LIMITS

- **Backplane reflector needed to prevent unwanted radiation in undesired directions**
- **Absorber can sometimes be used, but with undesirable consequences**
  - Thickness, Weight, Cost, Ruggedness, etc.
  - Surface waves can form & radiate elsewhere
- **Backplane reflector causes most of the problems and performance limits:**
  - Causes need for 1/4 wave standoff (thickness)
  - Limits Bandwidth because of same
  - Carries currents that changes pattern

Approved for public release; distribution unlimited.

SOLUTION APPROACH

- **Need to eliminate Backplane Reflector**
- **Replace with Artificial Magnetic Conductor (AMC)**
  - Reflection undergoes no phase shift upon reflection
  - Antenna can be placed very close to AMC
  - Antenna and AMC then still both in phase
  - AMC eliminates backward radiation just like reflective backplane.

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Electrically Small Antennas and Metamaterials

- Metamaterials present themselves as an additional “tool set” for designing and enhancing conformal antenna performance
  - **Metamaterial magnetic ground planes can reduce planar antenna sizes**
    - **Applicable to conformal platform applications**
  - **Metamaterials can be used to impedance match embedded antennas in platforms - improving bandwidth**
  - **Metamaterials can be used to reduce mutual coupling between antennas operating at different frequencies**
    - **Mitigate co-site interference**
    - **Improve array performance**
- Additional comments: For practical Army needs, metamaterials could:
  - **Bring electrically small antennas closer to Chu’s limit for bandwidth. Non-Foster matching excluded.**
  - **Help to create aperture efficiencies close to 100%.**
  - **Reduce the size of the antenna, bearing in mind that the “size” of the antenna must include the real estate of the entire metamaterial/antenna structure.**

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Placement Insensitivity

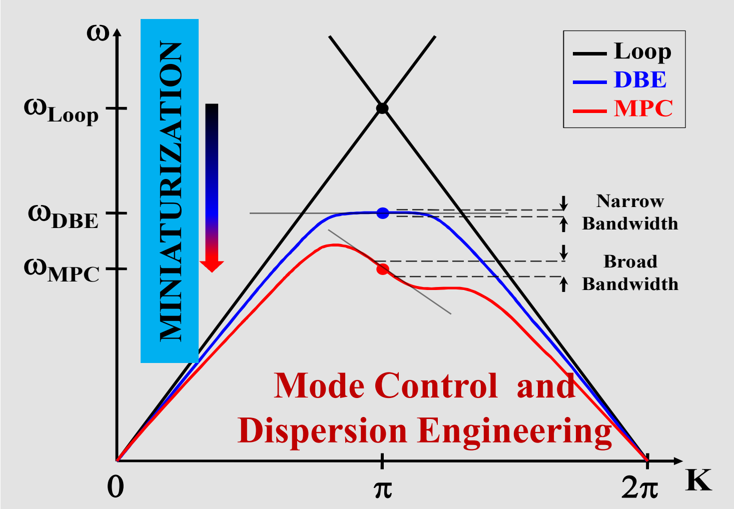
• Many systems require “slap on” antennas. The performance of these antennas can be adversely affected by placement on the platform.

• Surrounding the antenna with metamaterials can mitigate (but probably not completely eliminate) these unwanted effects.

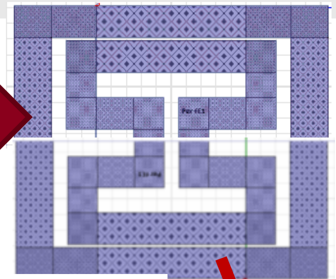
• This is particularly important for impedance matching.

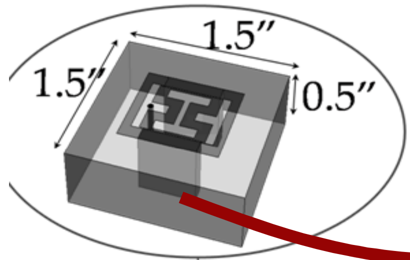
Placement issues

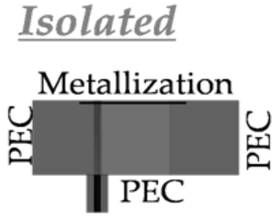
Goal: Employ smaller size (metamaterial) antennas based on slow wave modes to suppress detuning & reduce platform effects



Cascaded Unit Cells to Form Antenna

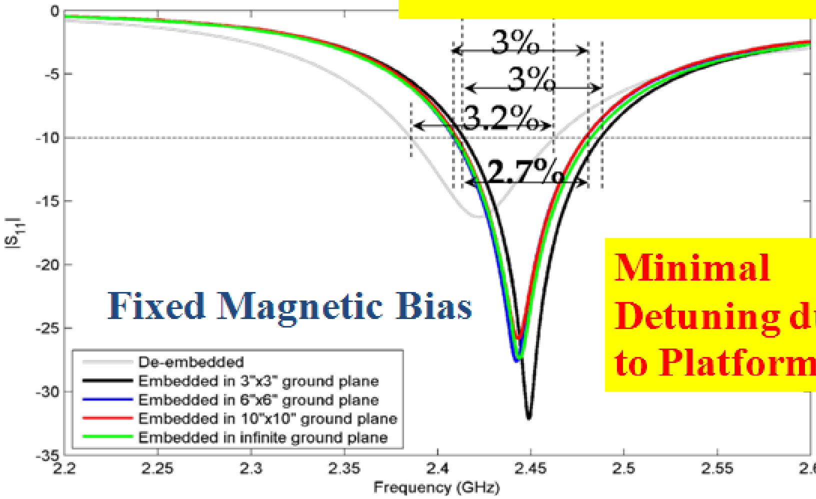




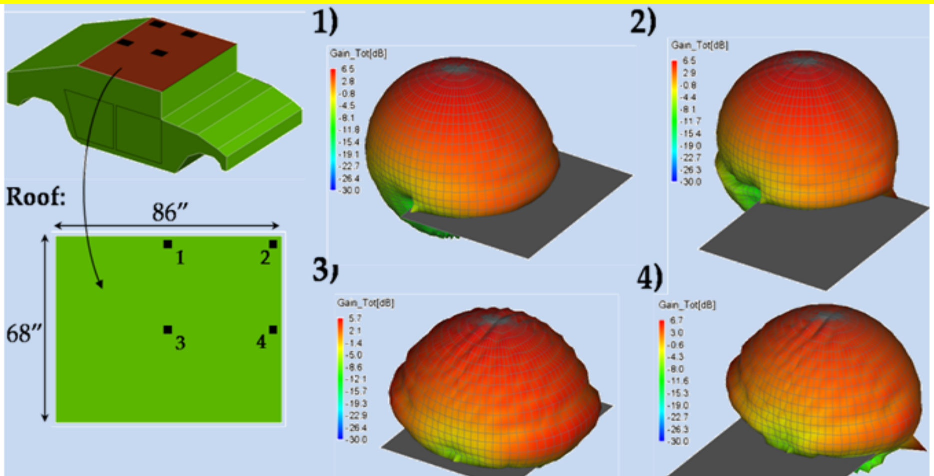


Small ferrite inserts increase bandwidth

New slot-based/recessed MPC antenna is much less immune to detuning



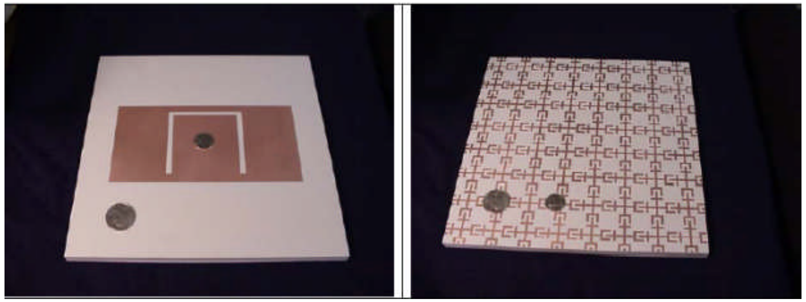
Minimal Detuning due to Platform



Minimal Ripple in Gain Pattern

Mitigation of Loading Effects

- An antenna placed on dielectric material (e.g., a patch antenna) will lose bandwidth due to the interaction with dielectric material.
- Such considerations have important implications for integration of antennas onto Army platforms.
- Surrounding the antenna with metamaterials (actually, placing the metamaterials underneath the patch) can mitigate (but probably not completely eliminate) these unwanted effects.
- The University of Michigan has shown that the "lost bandwidth" can be recovered by placement of a planar metamaterial surface just below the patch.



CERDEC/University of Michigan

Improvement in Realized Gain

Directivity: D_o

(Parameter quantifying beam shaping - usually constrained by aperture size)

Gain: $G_o = \varepsilon_{cd} D_o \quad 0 \le \varepsilon_{cd} \le 1$

(takes into account the antenna's internal losses)

Realized gain: $G_o = (1 - |\Gamma|^2)\, \varepsilon_{cd} D_o$

(takes into account the impedance match to a transmission line)

Metamaterials can help all three, but the best improvements we have seen are with respect to measured improvements in realized gain.

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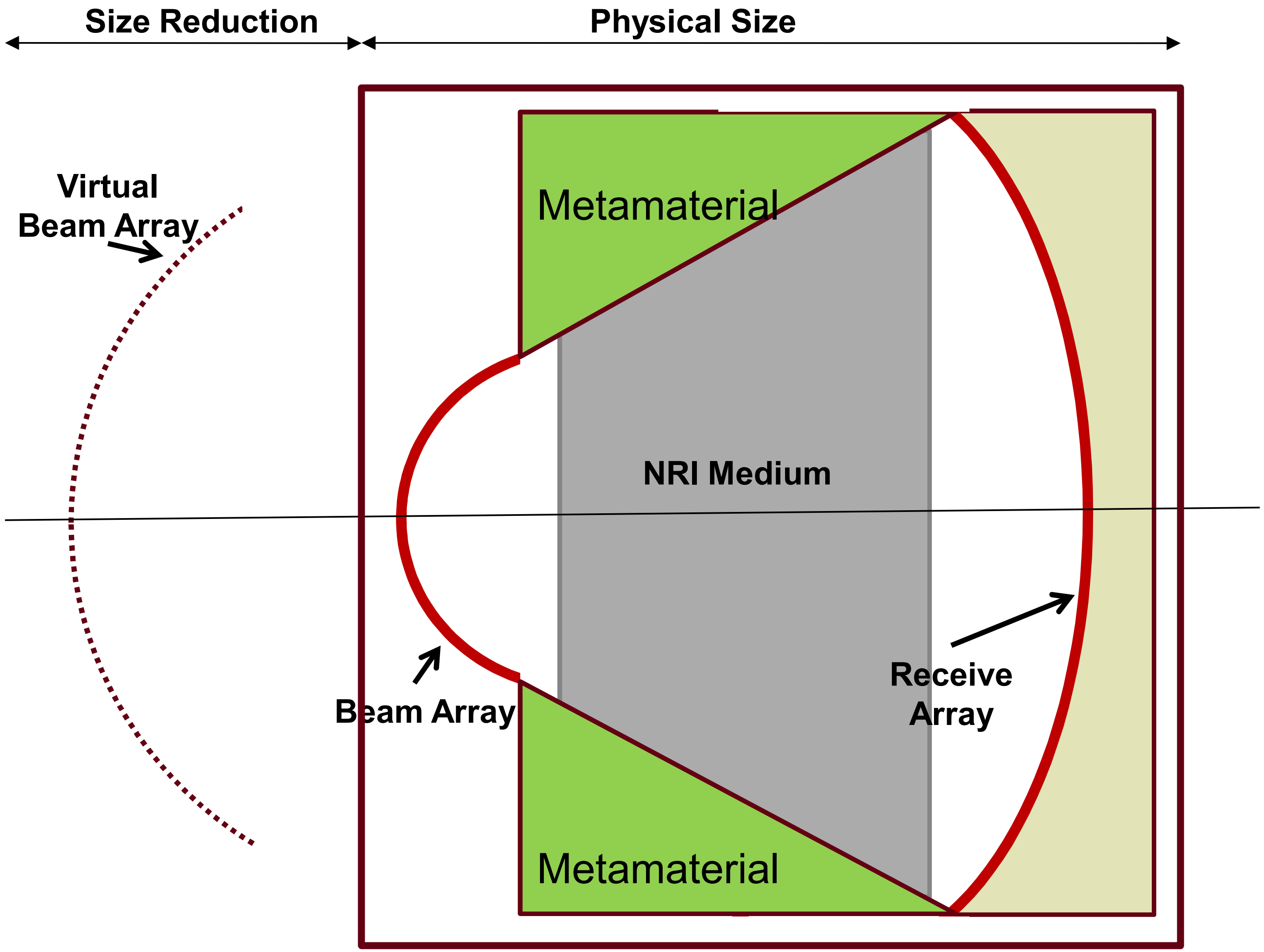
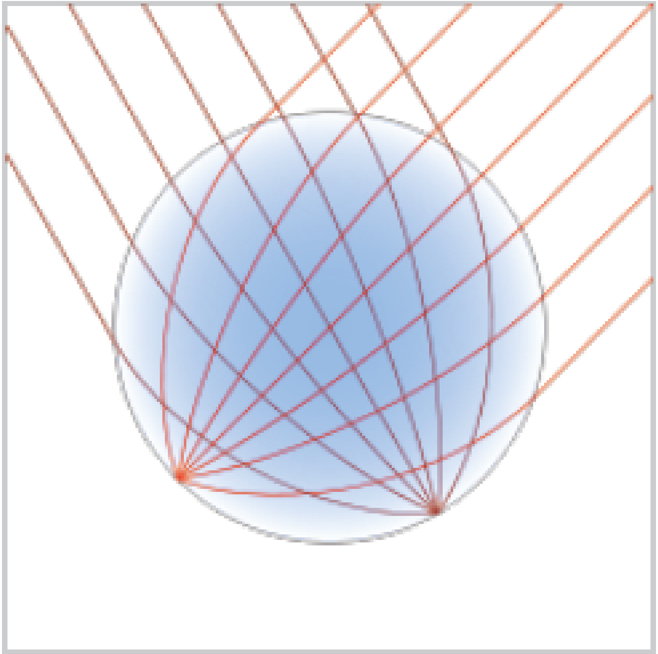
A Metamaterial-Loaded Rotman Lens



Luneburg Lens

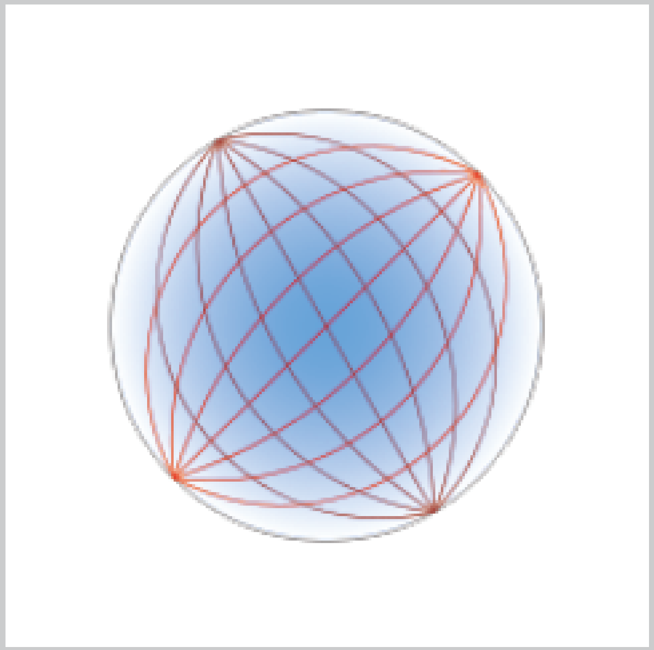
$$n = \sqrt{\epsilon_r} = \sqrt{2 - \left(\frac{r}{R}\right)^2}$$



Cross-section of the standard Luneburg lens, with blue shading proportional to the refractive index

Maxwell's Fish-Eye Lens

$$n = \sqrt{\epsilon_r} = \frac{n_0}{1 + \left(\frac{r}{R}\right)^2}.$$



Cross-section of Maxwell's fish-eye lens, with blue shading representing increasing refractive index

Metamaterial-Driven Luneburg Lens

- **Replace the progressively increasing or decreasing positive permittivity layers in the lens with negative permittivity materials**

- **Rays will continue to bend in symmetric manner**

- **Resulting beam will depend on the progression of negative permittivity in the lens, i.e. relationship of *n* and radius *r***

- **Isotropic radiators or formed beams may be produced from a feed horn in front of lens with the right refractive index function**

- **Details and possible designs are underway**

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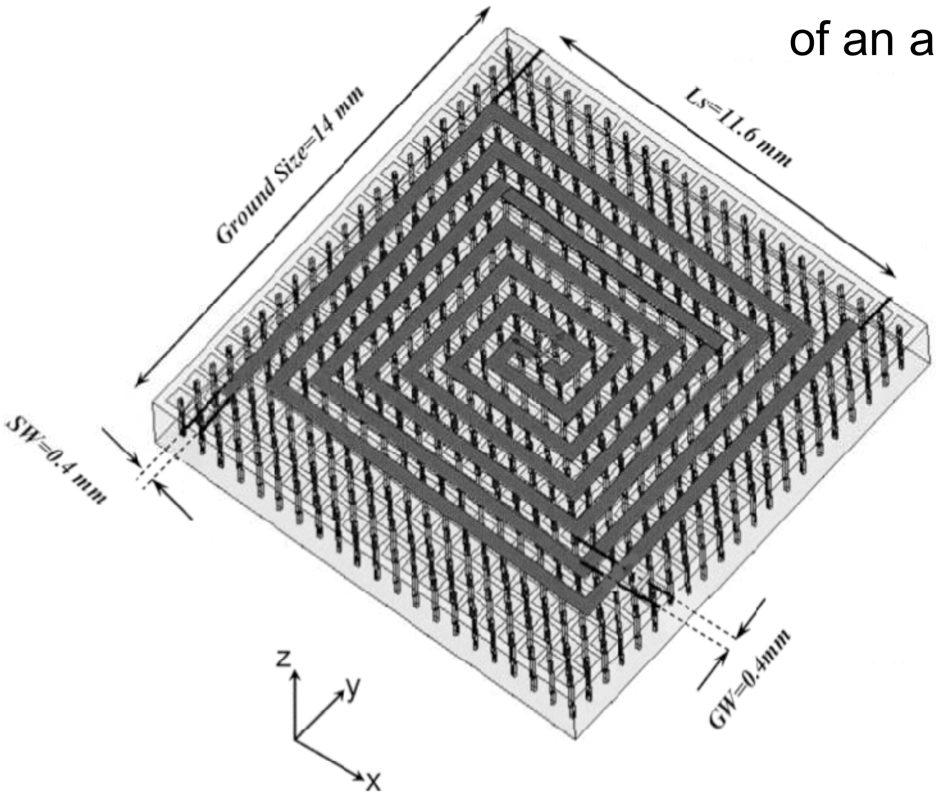
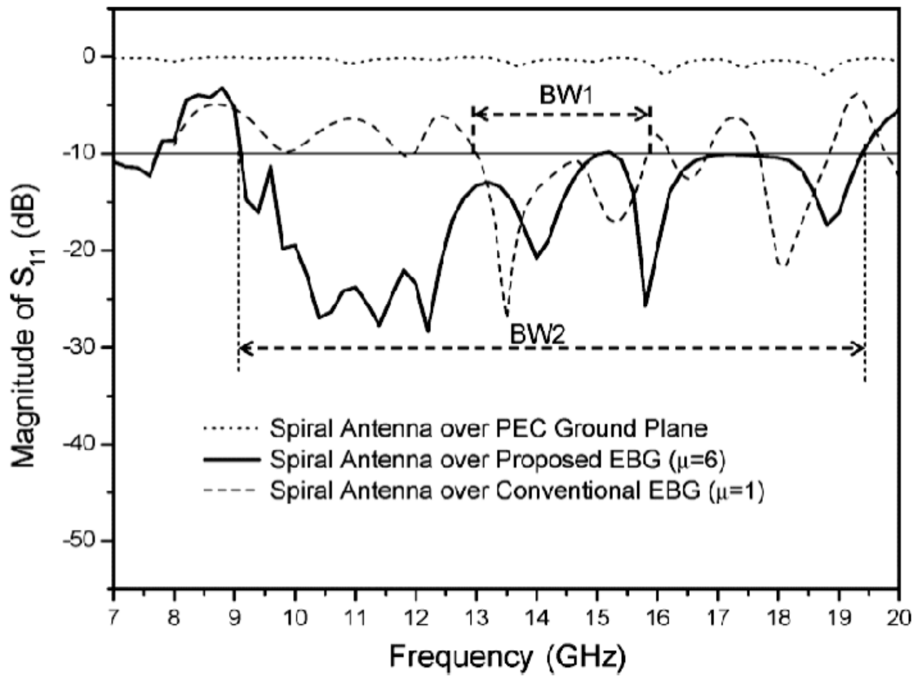
Wide-Banding of AMC

It is well known that increasing the permeability of EBG structures can help increase the bandwidth of an antenna.

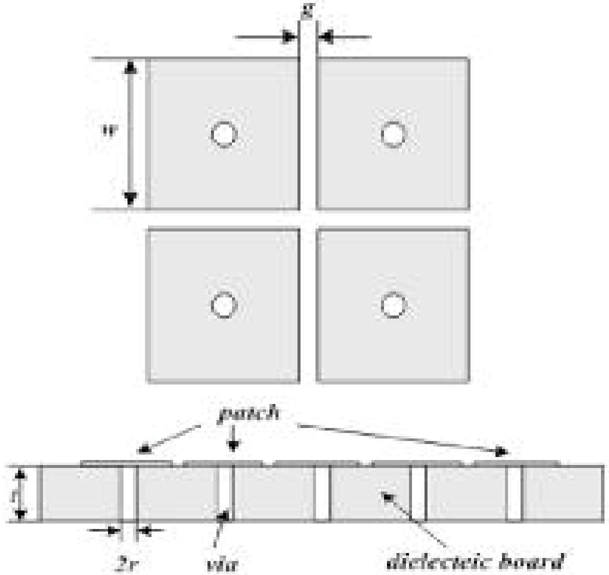




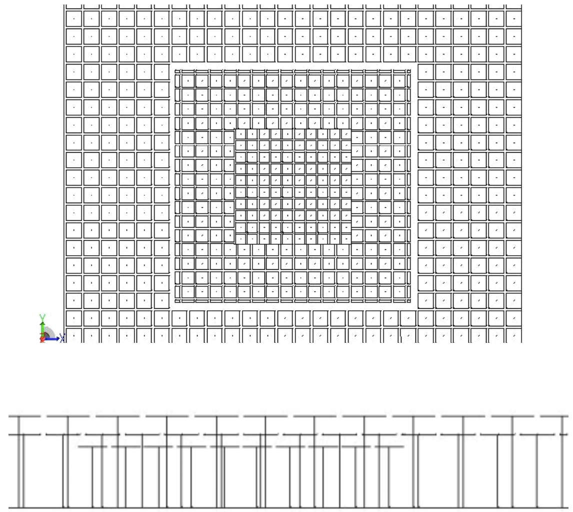
Enhanced Bandwidth Artificial Magnetic Ground Plane for Low-Profile Antennas, Yousefi, L.; Mohajer-Iravani, B.; Ramahi, O. M., Antennas and Wireless Propagation Letters, Volume 6, Issue , 2007 Page(s):289 – 292.

• Spiral antennas use the entire spiral at lower frequencies and less of the structure As the frequency of operation increases – essentially keeping the aperture size constant. This accounts for a reasonably stable gain over a wide bandwidth.

• Metamaterial "unit cells" can be made progressively smaller in with respect to this fact to enhance spiral antenna performance.

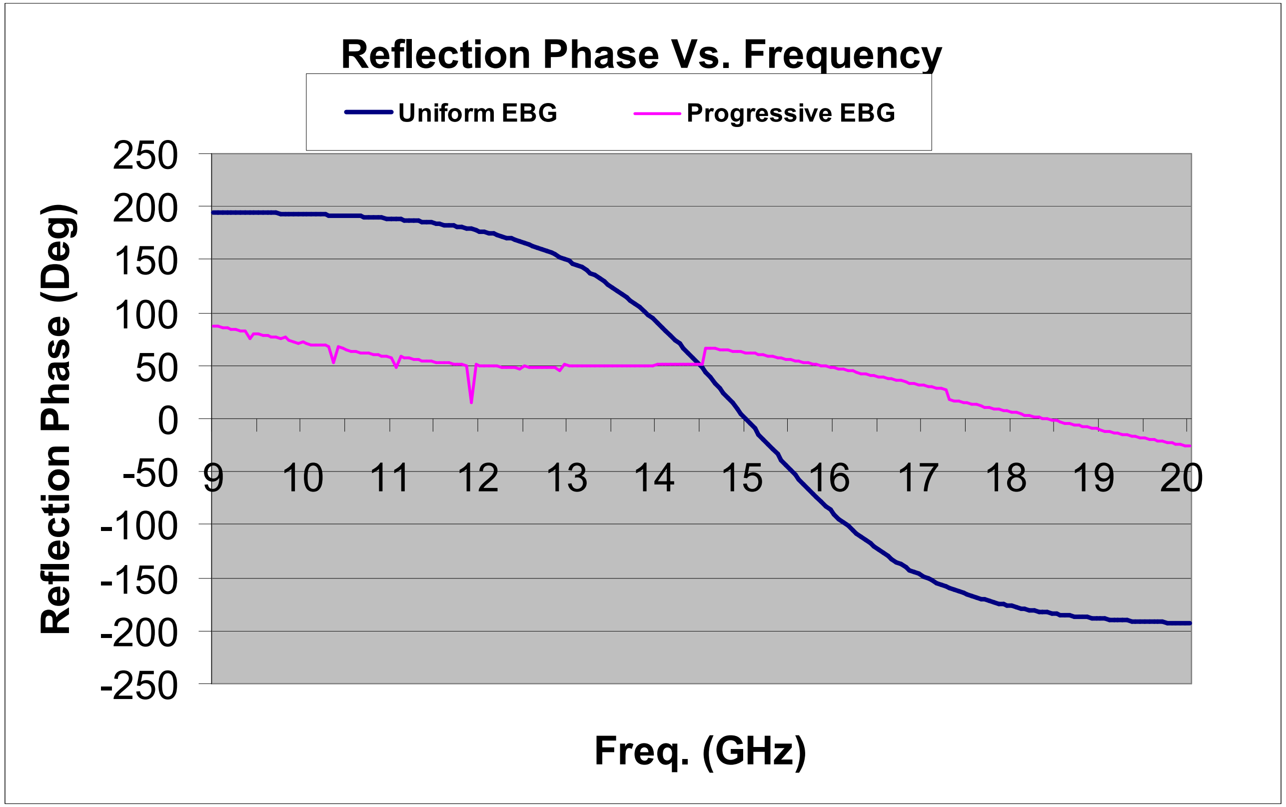


Uniform EBG
Narrow-Band EBG



Progressive EBG
Broad-Band EBG

Reflection Phase Comparison of Uniform and Progressive EBG - Computer Simulations



Uniform EBG has ±45º over narrow band
Progressive EBG has ±45º over broad band

Random-Oriented, Random-Spaced Negative Refractive Index Metamaterial

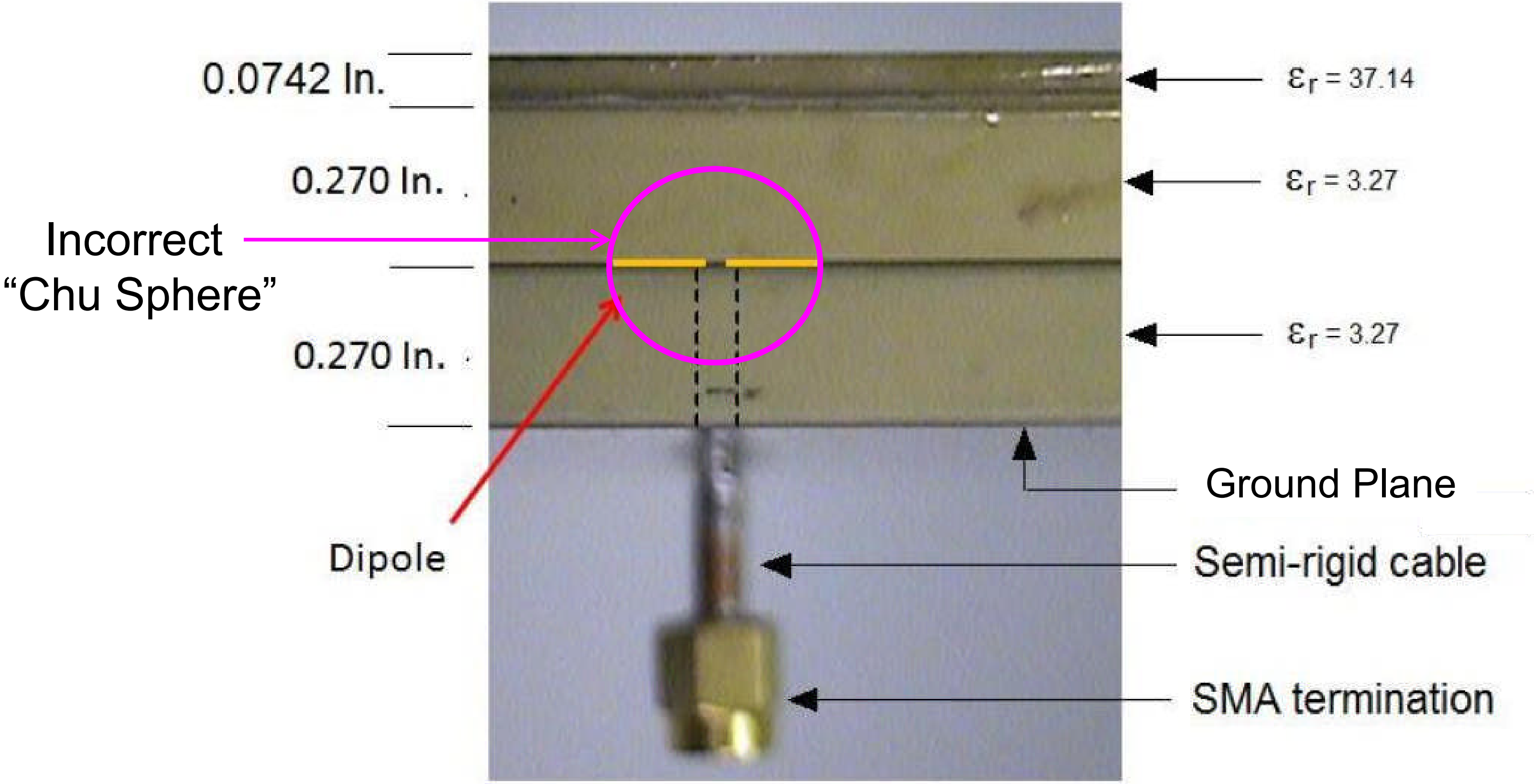
Basic Unit Cell

Randomly-Oriented, Randomly-Spaced

- Unit cell is a Capacitively Loaded Loop + Probe (CLL-P)
- Isotropic
- Uniform negative refractive index at wide inclined angles
- Wide-band operation
- Fabrication and measurements under way

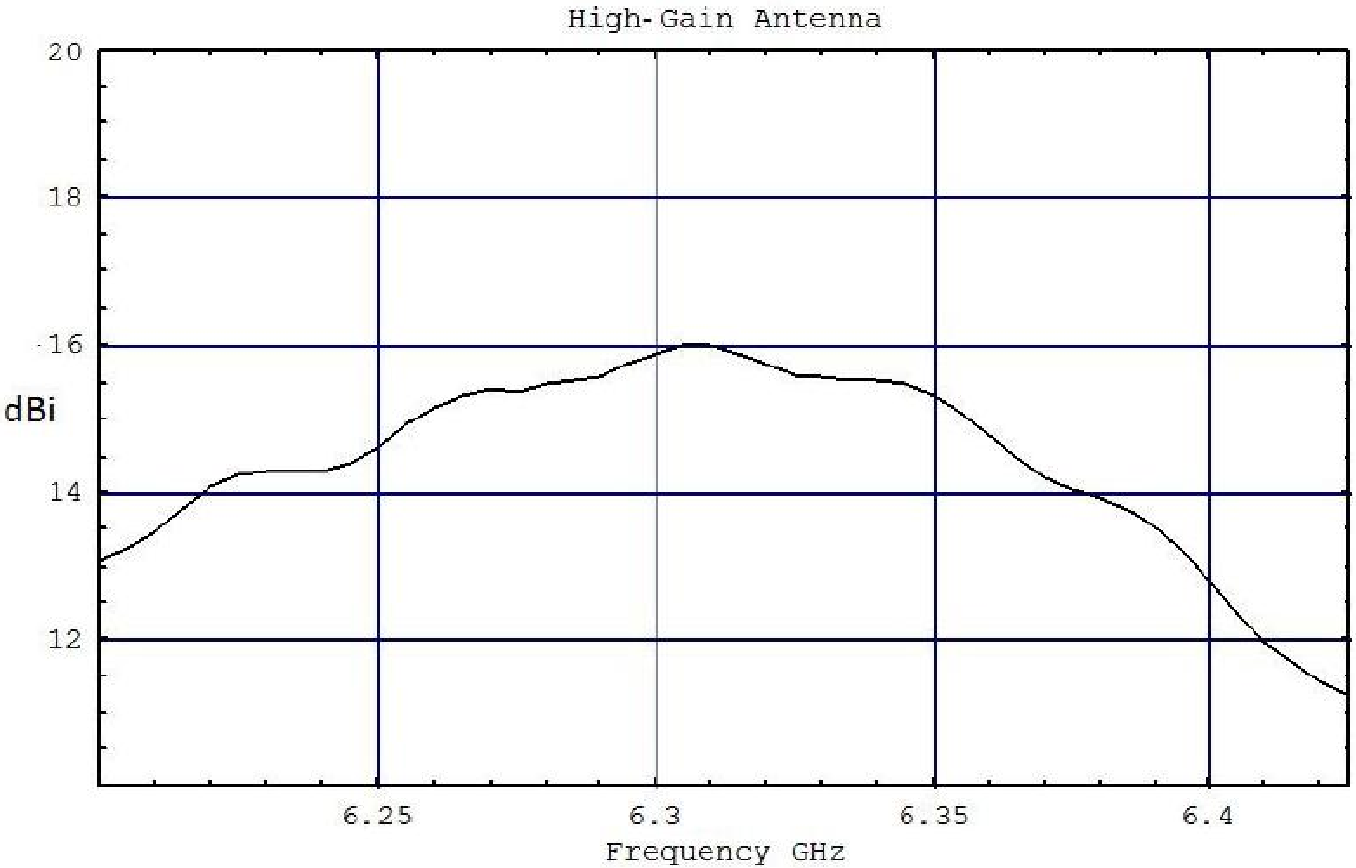
A High-Gain Antenna

With layered media, it is possible to achieve a high-gain configuration. This antenna was fabricated to measure the predicted simulations.



1. David R. Jackson, and Nicolaos G. Alexopoulos, "Gain Enhancement Methods for Printed Circuit Antennas," IEEE Transactions on Antennas and Propagation, Vol. AP-33, pp. 976-987, September 1985.

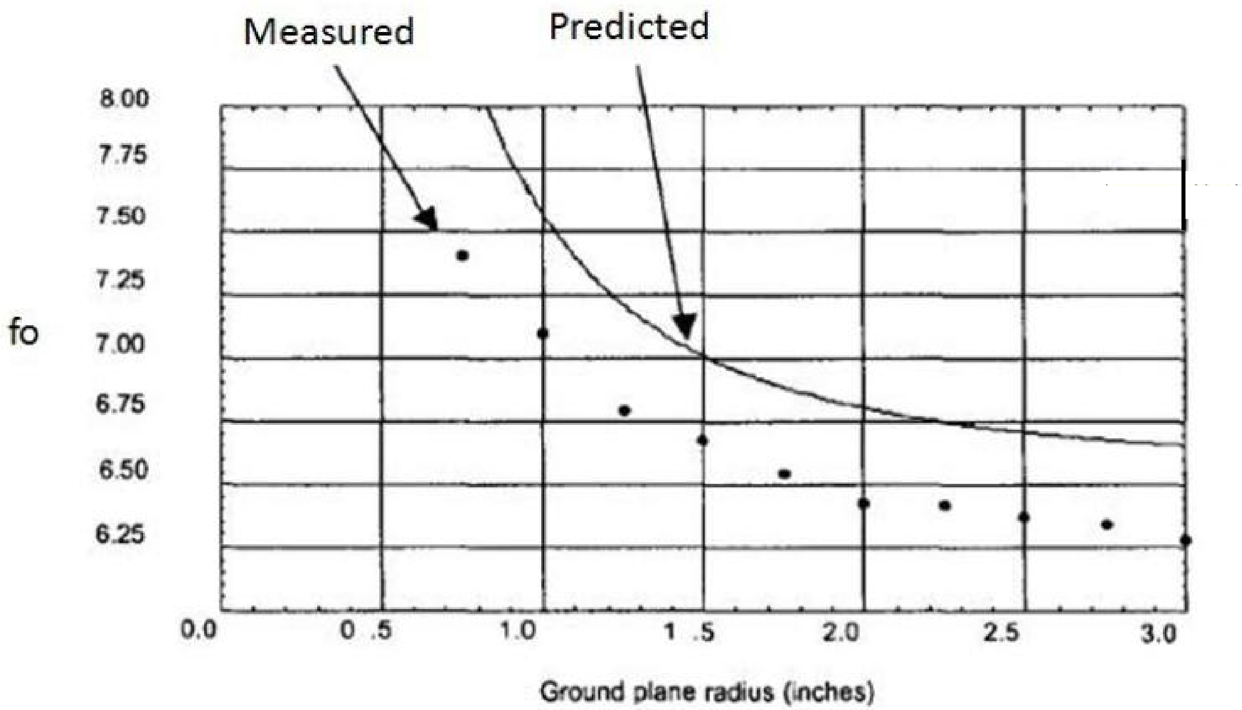
• The antenna was fabricated and the high-gain was measured.
• A remarkable 16 dBi for a "dipole."



Measured gain of Superstrate antenna.

Aperture Size – An Important Consideration

- A study was performed decreasing the radius of the structure
- The 16 dBi gain remained fairly constant, but occurred at higher and higher frequencies as the structure became smaller and smaller.
- The structure was acting like a cavity resonator with predictable modes.



Measure and predicted high-gain frequencies based versus radius of the structure.

Comments on "Supergain"

The large values of stored energy in the aperture region of a "supergain antenna" cause a number of engineering problems which are severe enough to make this type of antenna completely impractical. The first problem is that of extremely high Q's, which limit the operating bandwidth to extremely small values. For instance, it has been stated by Taylor[32] that an antenna designed within a sphere of 50 wavelengths diameter will have a beamwidth of approximately 1°. If the same beamwidth is to be maintained while the diameter of the sphere is reduced to 45 wavelengths, the Q will rise to a value of 500. If the diameter is reduced to 40 wavelengths, the Q will rise to a value of 5×10^{10}. For further reductions in diameter, the value of Q rises to astronomical values. Since the bandwidth is of the order of the inverse of Q, it can be seen that the bandwidth diminishes rapidly.

As a result of the high stored energy, large values of circulating current flow in the antenna structure and a point is very quickly reached at which the ohmic losses completely nullify any gain increase due to increased directivity.

Henry Jasic , "Antenna Engineering Handbook," McGraw Hill, 1961.

Metamaterials can Reduce Antenna size using "slow waves."

ABSTRACT*—MINIATURIZATION OF SLOW WAVE ANTENNAS EXPLOITING THE* SLOW WAVE ENHANCEMENT FACTOR IS PRESENTED. THE PRINTED ANTENNAS ARE PERIODICALLY LOADED WITH SHUNT CAPACITORS TO **SLOW DOWN THE GUIDED WAVE IN THE STRUCTURES**. IN THIS PAPER, THE LOADED UNIT CELL OF THE EQUIVALENT TRANSMISSION LINE MODEL IS UTILIZED TO EXTRACT THE SLOW WAVE ENHANCEMENT FACTOR, THE RATIO OF THE LOADED TO THE UNLOADED PROPAGATION CONSTANTS OF THE WAVE IN THE ANTENNAS. FROM THIS MODEL, THE SLOW WAVE ENHANCEMENT FACTOR OF A LOADED ANTENNA AGREES VERY WELL WITH THE MINIATURIZATION FACTOR, AND THEREFORE LOAD PARAMETERS IN THE CIRCUIT MODEL CAN BE READILY OBTAINED WHEN A SPECIFIC SIZE REDUCTION IS ATTEMPTED. THIS CLAIM WAS SUBSTANTIATED BY DEMONSTRATING TWO SMALL RADIATORS, A HIGH-FREQUENCY (HF) SLOTLOOP ANTENNA AND A PLANAR INVERTED F ANTENNA (PIFA), TO ACHIEVE THE DESIRED SIZE REDUCTIONS. EXPERIMENTAL RESULTS SHOW THAT BOTH OF THE ANTENNAS DEMONSTRATE GREATER THAN **TEN-TIMES SIZE REDUCTION FROM THEIR UNLOADED COUNTERPARTS AT THE EXPENSE OF THE DEGRADED GAINS AND IMPEDANCE BANDWIDTHS.** SPECIFICALLY, THE LOADED SLOT LOOP PRESENTS THE PREDICTED GAIN AND MEASURED BANDWIDTH ON THE ORDER OF **-39.5 DB AND 0.38%** FOR VSWR <2, RESPECTIVELY. THEREFORE, A MATCHING NETWORK DERIVED FROM FILTER DESIGN TECHNIQUES IS PROPOSED TO INCREASE THE ANTENNA BANDWIDTH SO THAT A MEASURED FRACTIONAL BANDWIDTH OF 1.78% IS ACHIEVED. THE SLOT LOOP COMBINED WITH THE IMPEDANCE MATCHING CIRCUIT OCCUPIES A FOOTPRINT SIZE OF 0.031 X 0.031 LAMBDA (FREE SPACE.) AT THE OPERATING FREQUENCY. ON THE OTHER HAND, THE MEASURED RADIATION GAIN AND BANDWIDTH OF THE LOADED PIFA ARE REDUCED TO **-22.5 DBI AND 0.15%** FOR VSWR <2, RESPECTIVELY, WITH A FOOTPRINT OF 0.013 X 0.018 LAMBDA AT THE OPERATING FREQUENCY.

Chi, P.-L.; Waterhouse, R.; Itoh, T.; "Antenna Miniaturization Using Slow Wave Enhancement Factor from Loaded Transmission Line Models." *IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION*, VOL. 59, NO. 1, JANUARY 2011

Conclusions For Metamaterials

- Metamaterial present exciting possibilities for enhanced antenna performance.

- This is particularly true for in-situ antenna performance.

- Electrically small antennas will always have limitations with respect to aperture size and the Chu limit, but improvements in realized gain have been shown.

- Innovative ideas for enhancement classical of wideband antenna structures (e.g., the spiral antenna) can further extend the operational bandwidth of the antenna.

- Military application where the antennas are closely located to each other on platforms require innovative strategies to de-conflict operational problems. Metamaterials offer possible solutions.

Beamformers

Next, we describe ARL efforts to realize antenna array beamformers for Army platforms – with particular attention to the Rotman Lens. Considerations such as size, weight, cost, and performance are examined for a number of different case studies. First, a conformal Rotman lens array for terrestrial communication applications is described. Next, a X-band antenna array, presently under development for a compact radar, will be introduced and analyzed. A Satellite On the Move (SOTM) demonstrator array (Ka-band) that achieves scanning through the use of MEMs phase shifters will be presented as will a Ka-band Rotman lens - developed to demonstrate the Multi-Function RF concept. Finally, a 75 GHz beamformer for use in collision avoidance will be examined.

Outline

- **Rotman Lens – An ARL legacy**
- A flexible Rotman lens for Terrestrial Communications
- A Satellite on the Move (SOTM) array with MEMs phase shifters
- A 76 GHz array for collision avoidance applications
- Conclusion

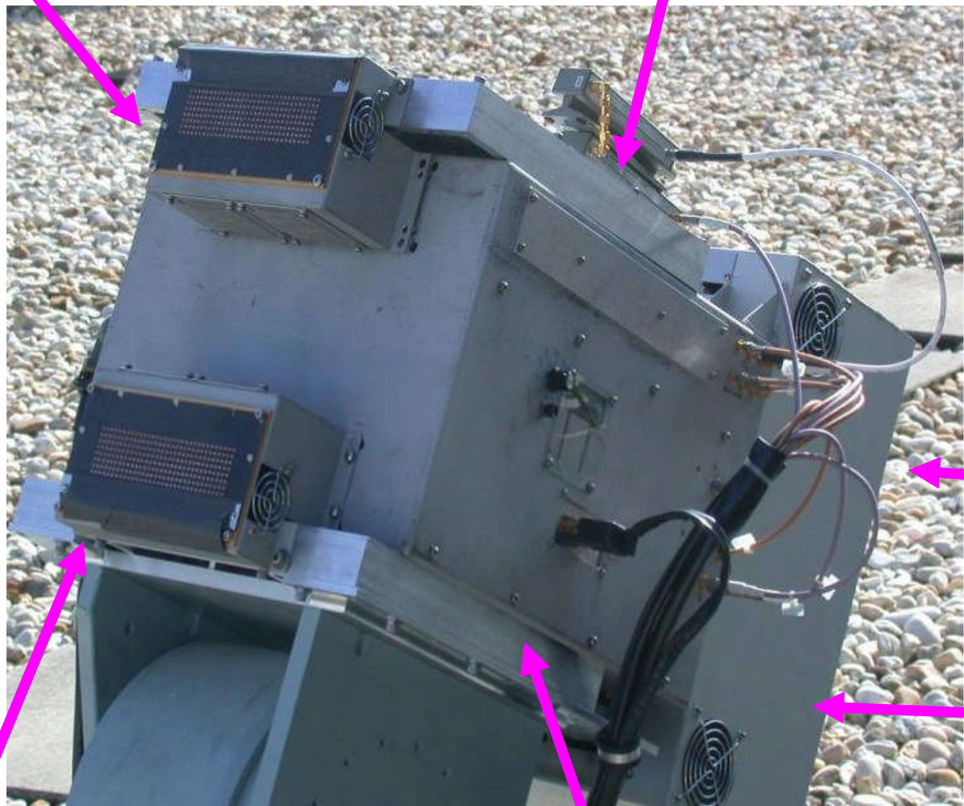
Why a Rotman Lens ?

- Allows multiple beam per antenna array aperture – they are wide bandwidth devices
- Insertion loss is low for some implementations
- A time-delay beamformer mitigates beam squint problems
- Photo etched versions are low cost
- Only allows discrete beam positions – a limitation
- Requires large switch array for electronic scanning

Rotman Lens in MFRF Architecture

Transmit Array (TX)
with Power MMICs

Transmit Rotman



2x16 TX
Switch
Matrix

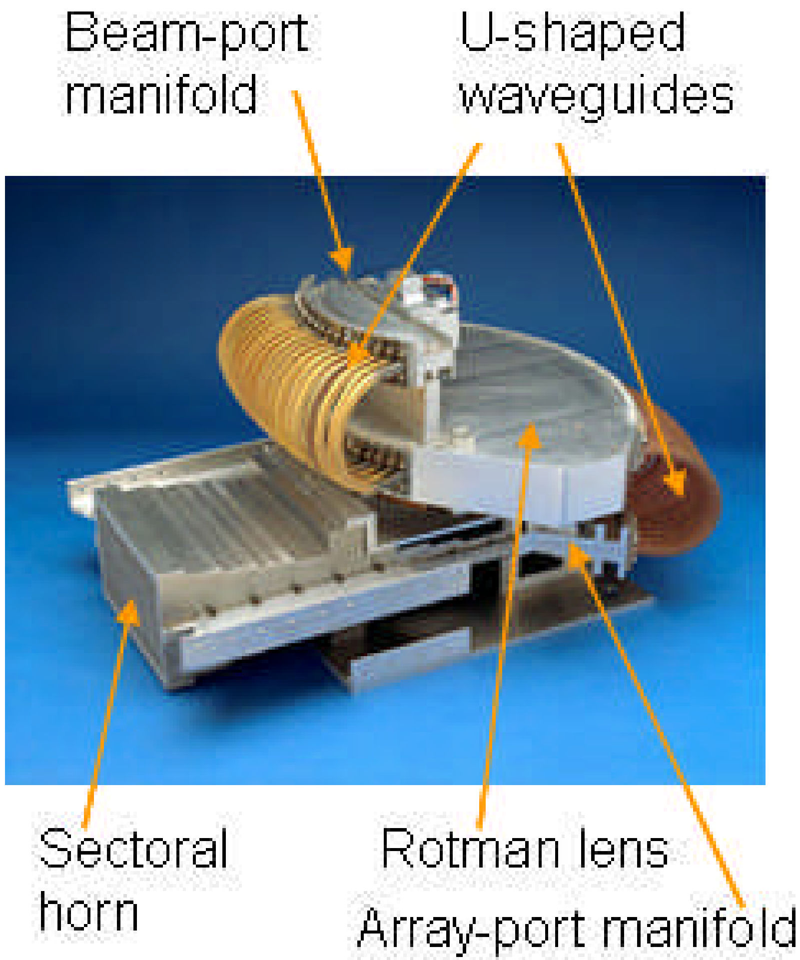
2x16 RX
Switch
Matrix

Receive Array (RX)
with LNA MMICs

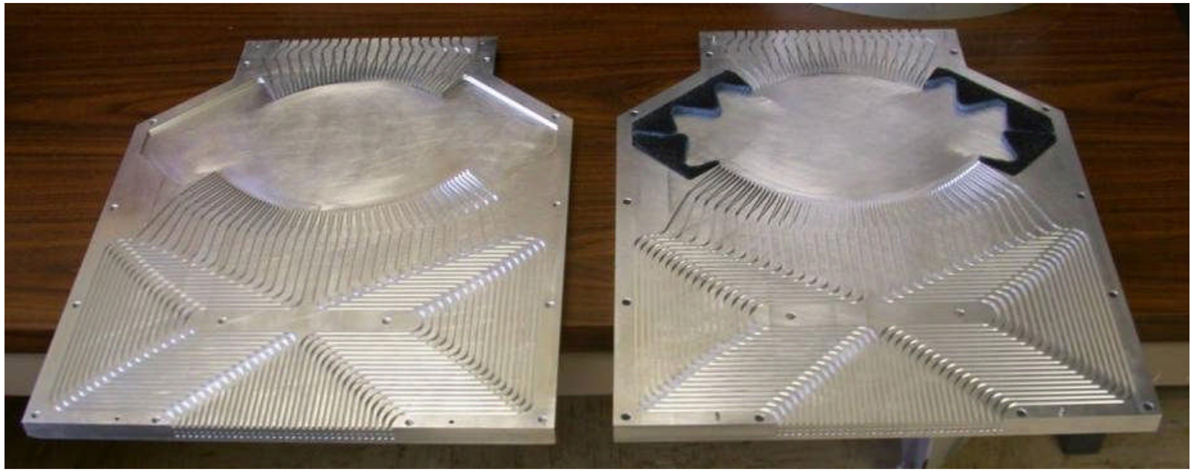
Receive Rotman

Early Rotman Lens Prototype (Georgia Tech)

- Beam-port manifold mounted on top
- 19 Beam ports connected with U-shaped waveguides
- 34 Array ports connected to a 34-element sectoral horn array.



Aluminum Rotman Lens

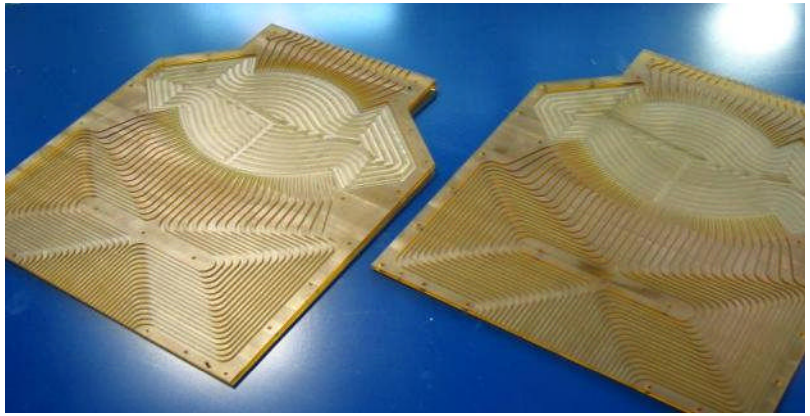


Fabrication tolerances: +/- 0.003” side-to-side
+/- 0.005” top-to-bottom

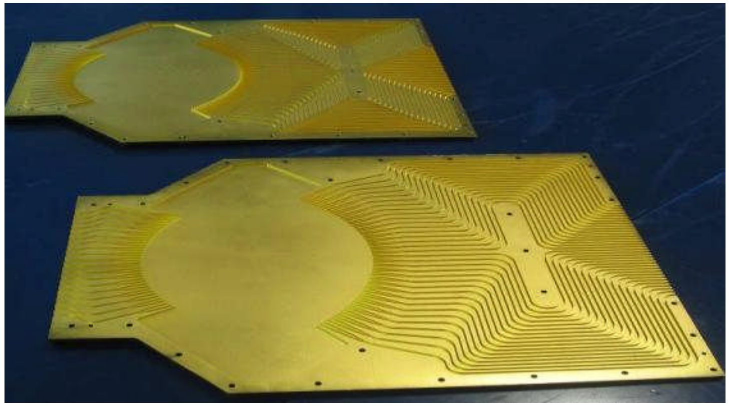
Plastic Rotman Lens with Conductive Plating

Machining performed at ARL, Adelphi

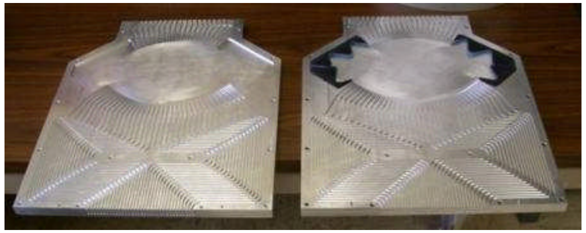
Metallization performed under contract to WMRD



Rotman lens machined in Ultem 1000.

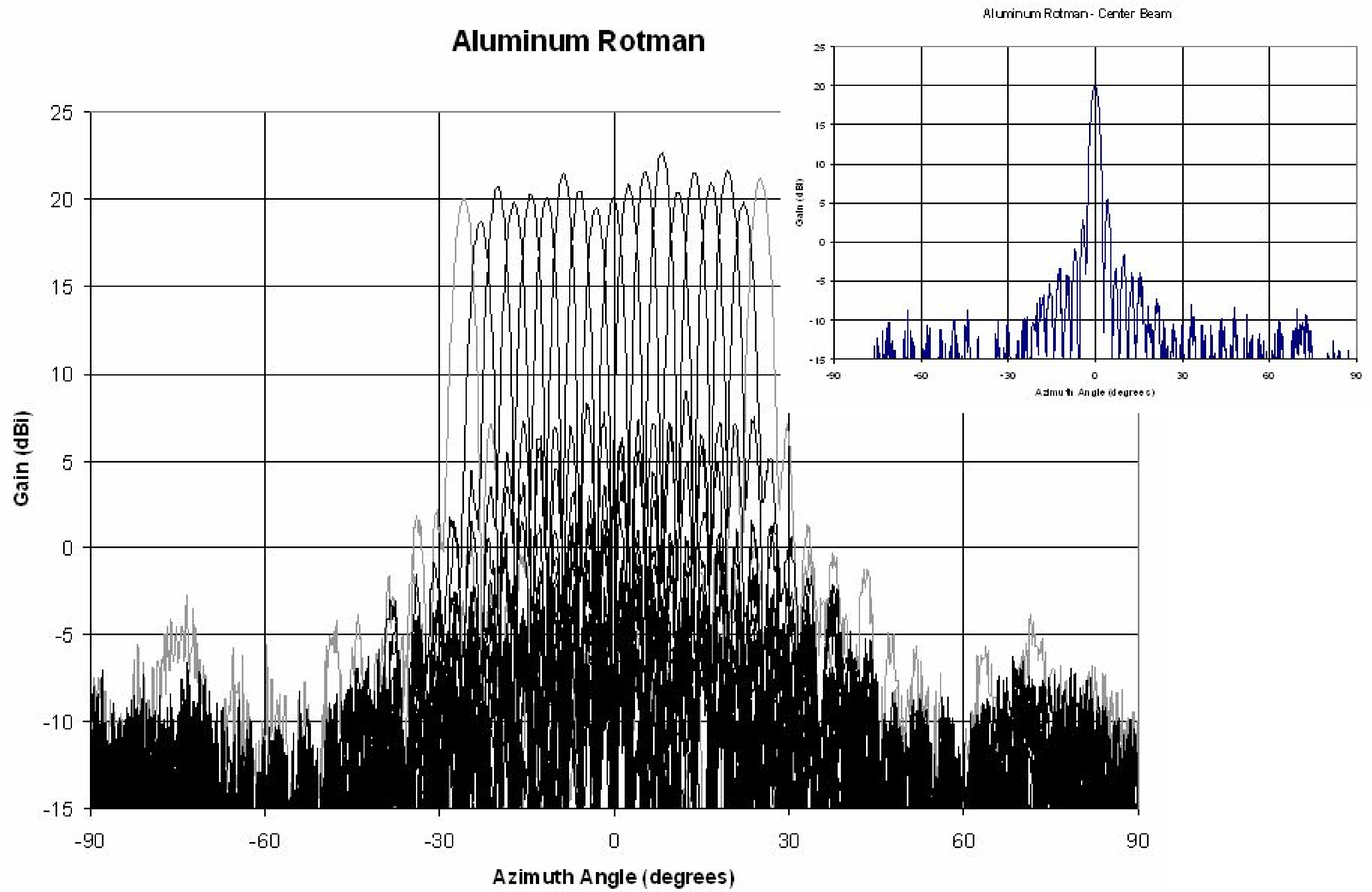


After metallization with gold as the final layer.

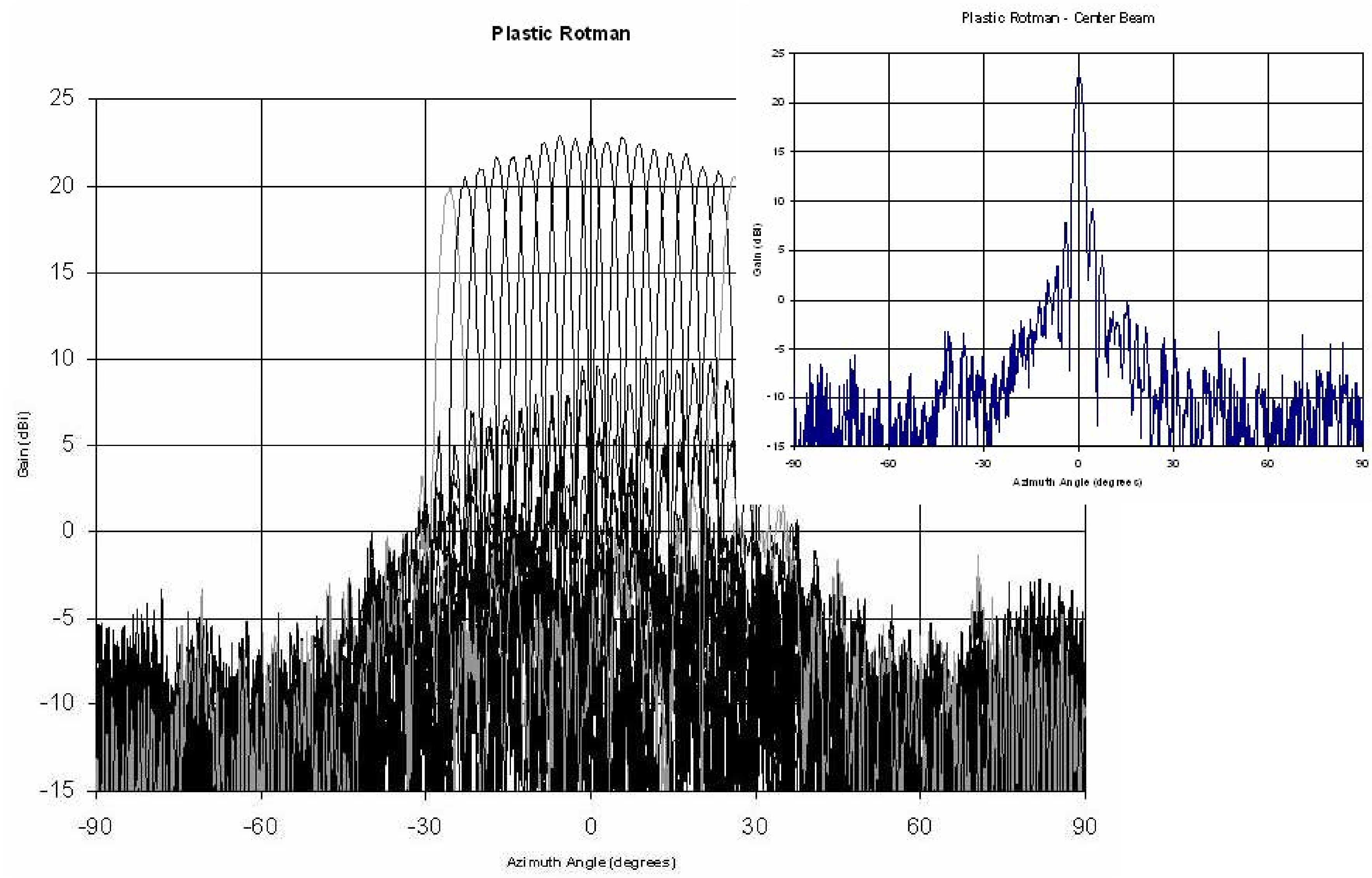


Aluminum: 14.65 pounds
Ultem: 6.05 pounds
60% Weight Reduction

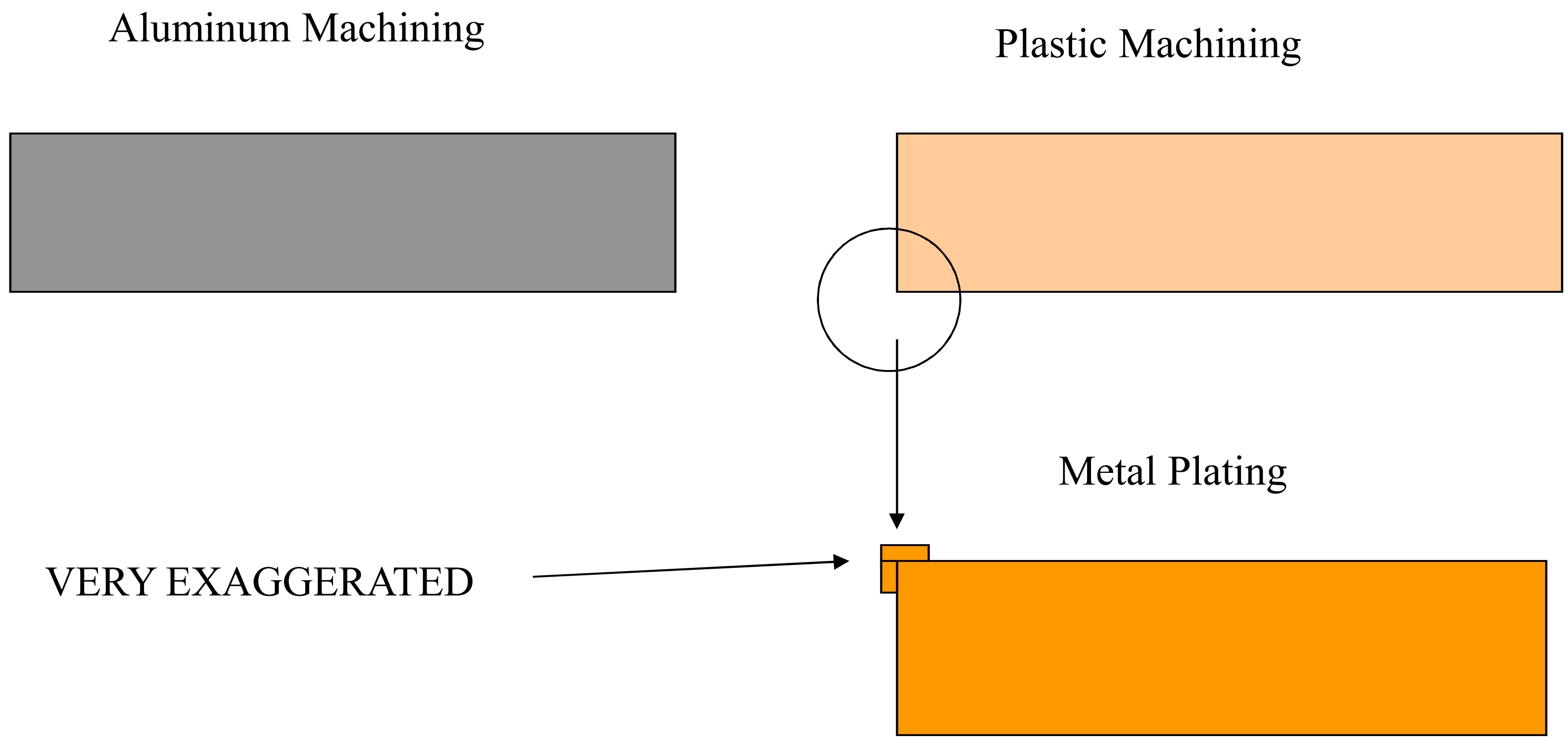
Aluminum Rotman Lens



Plastic Rotman Lens



Why the Improvement?

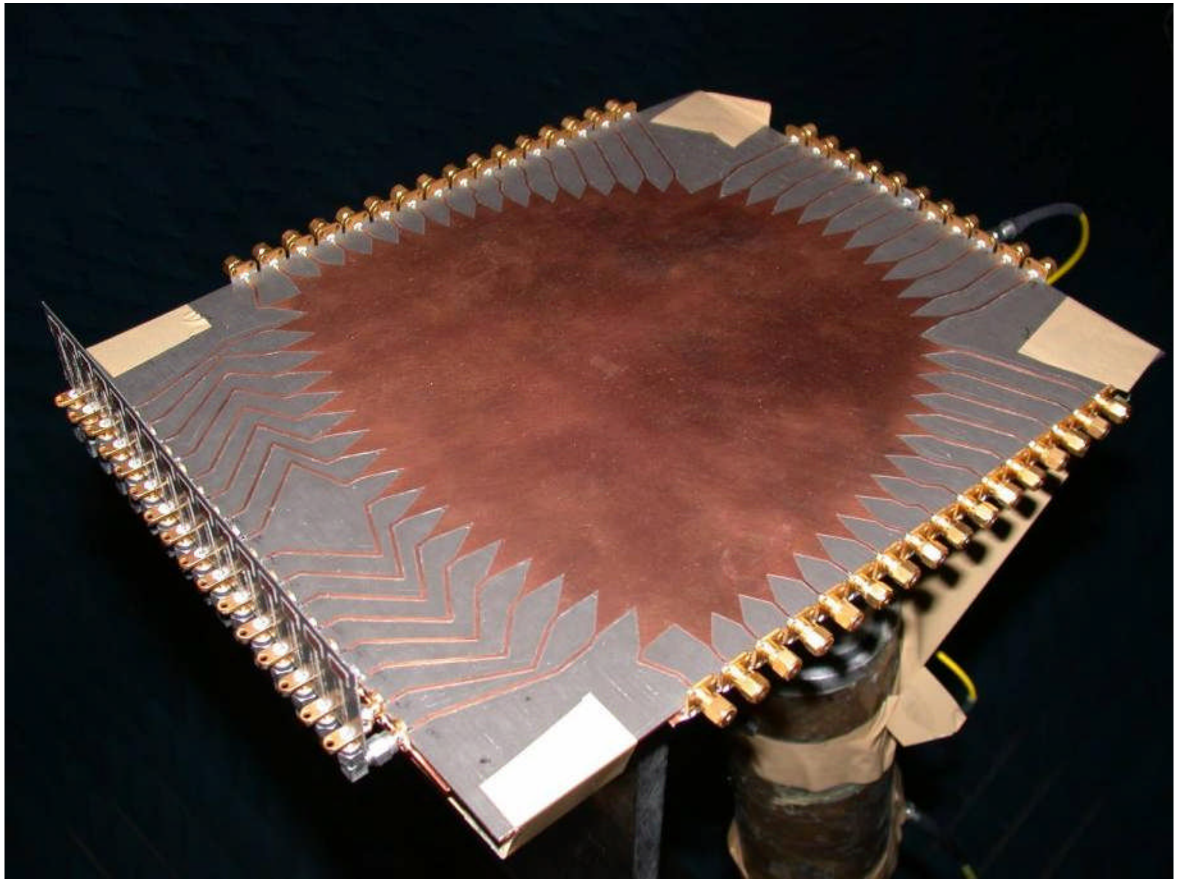


- Plating causes small build-up at machined edges possibly increasing performance due to better waveguide realization when both halves are pressed together

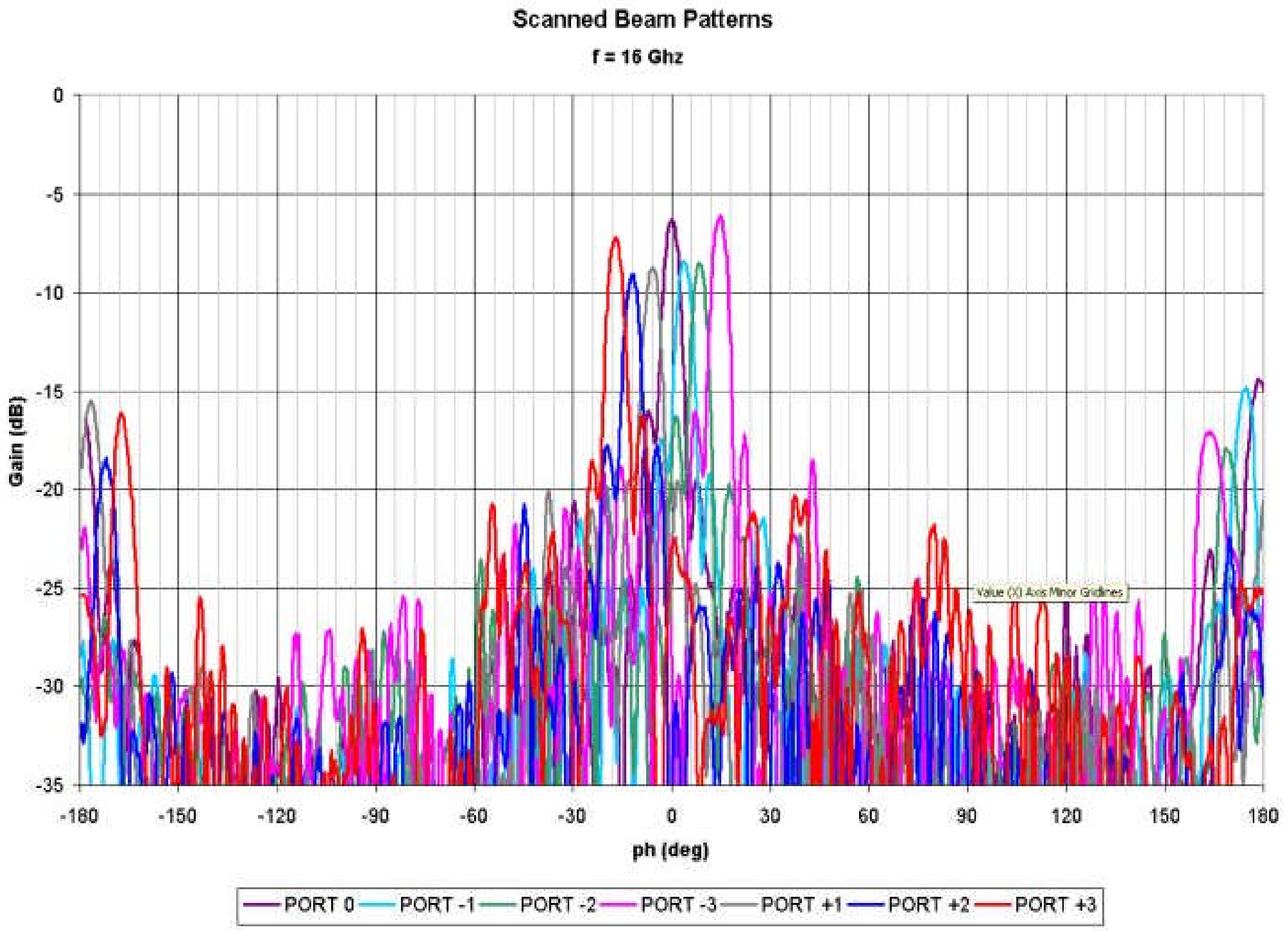
Microstrip Rotman Lens

Measured Gain ~ 12 dBi

Measured Insertion loss ~ 9.5 dB

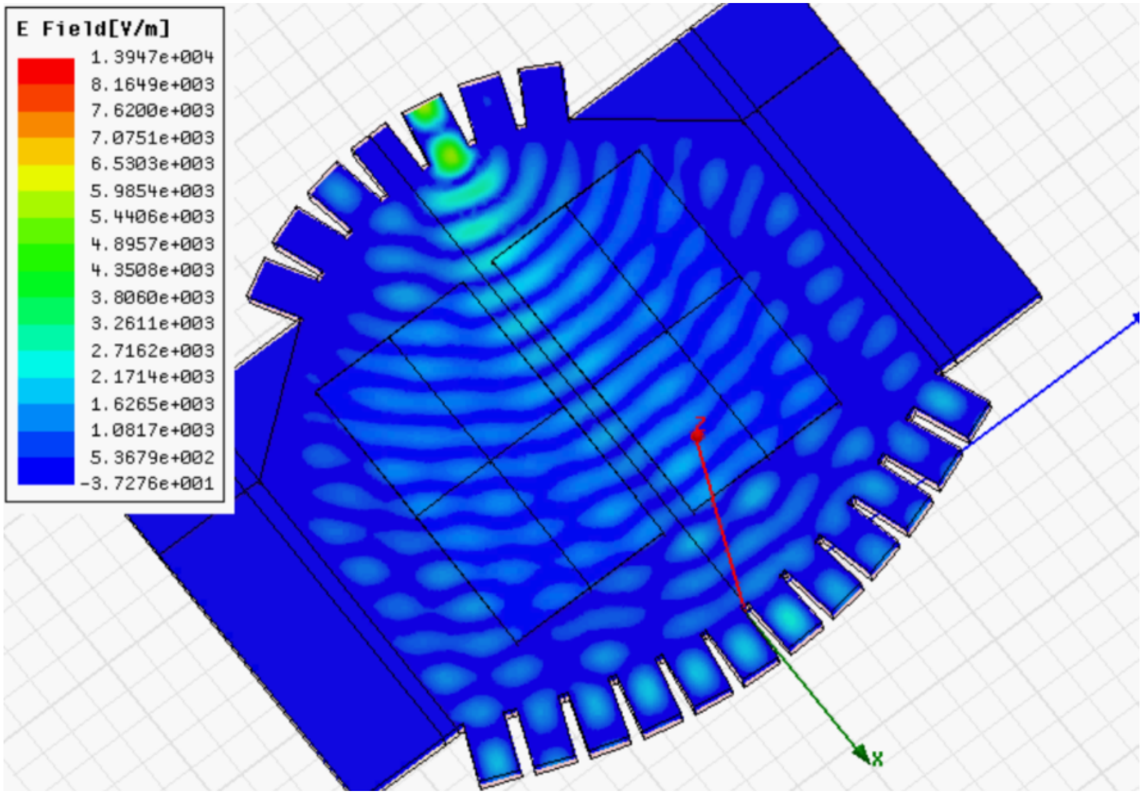


Measured Patterns of Microstrip Rotman Lens

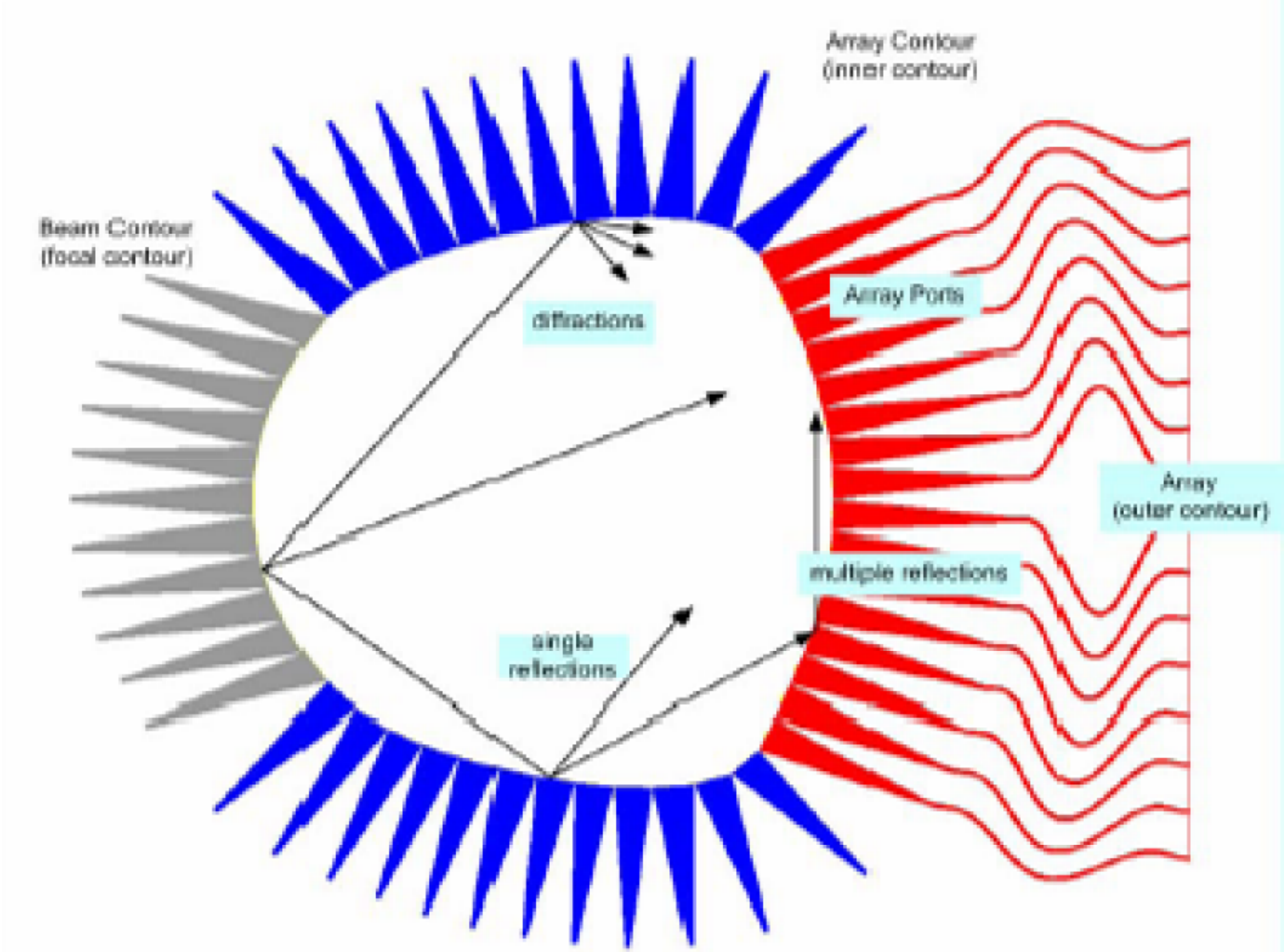


Rotman Lens Software Development - Ansoft Effort

- Collaboration with Ohio State University
- Hybridize HFSS FEM code with Domain Decomposition Method (DDM)

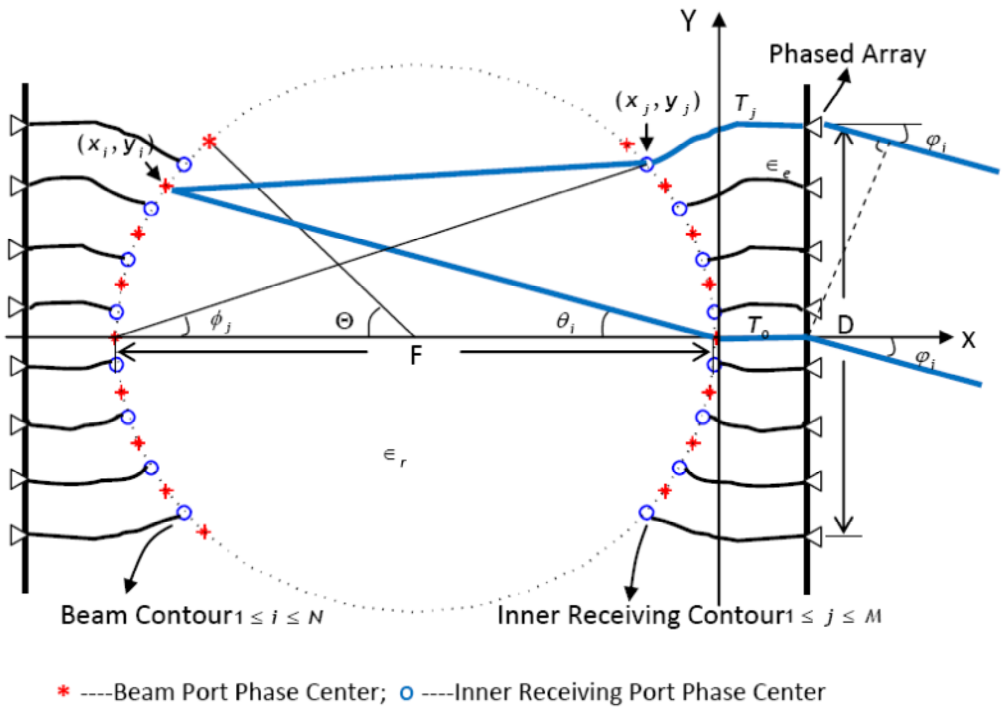


Rotman Lens Software Development - Remcom Effort

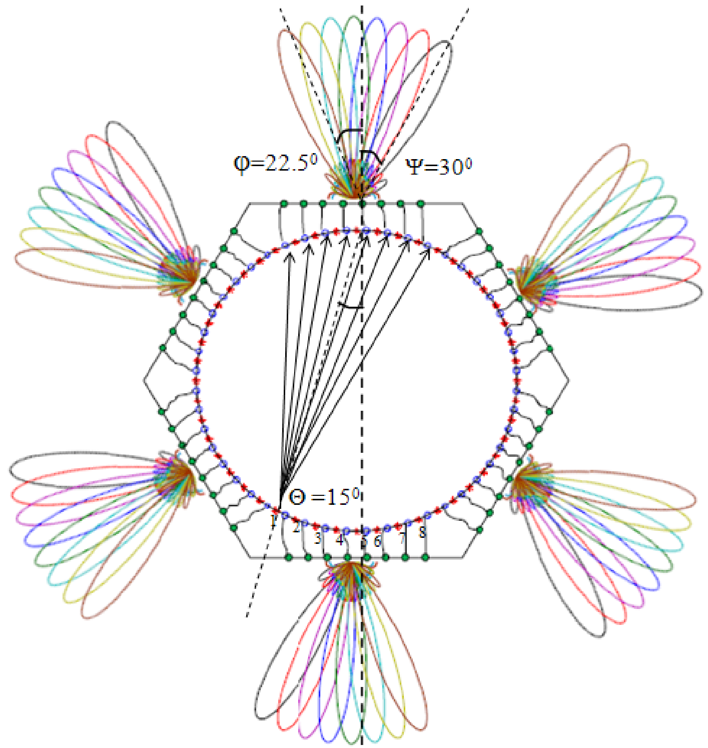


- Hybridize XFDTD code with ray tracing techniques (GO, UTD)

Recent Developments – 360-degree Lens



Parameters in One Sector of the Microwave Lens



Hexagonal Microwave Lens for 360-Degree Scanning

Beamformer Outline

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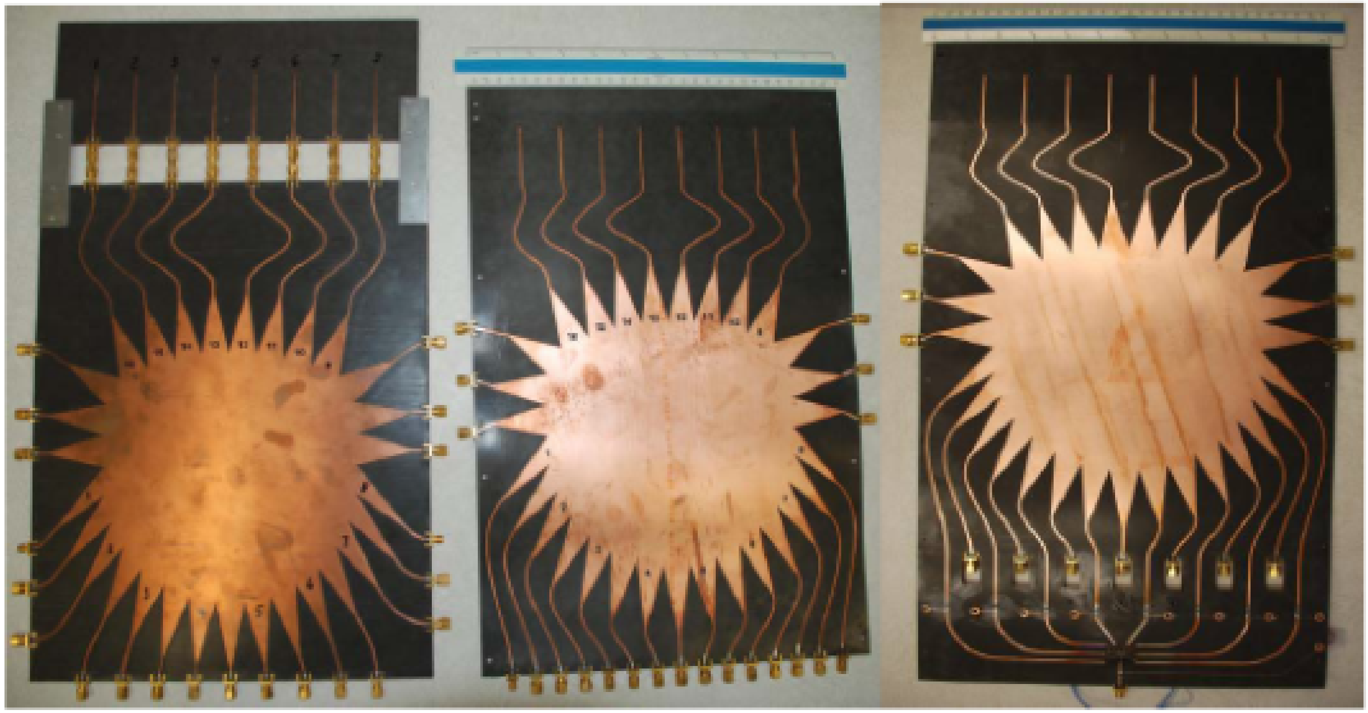
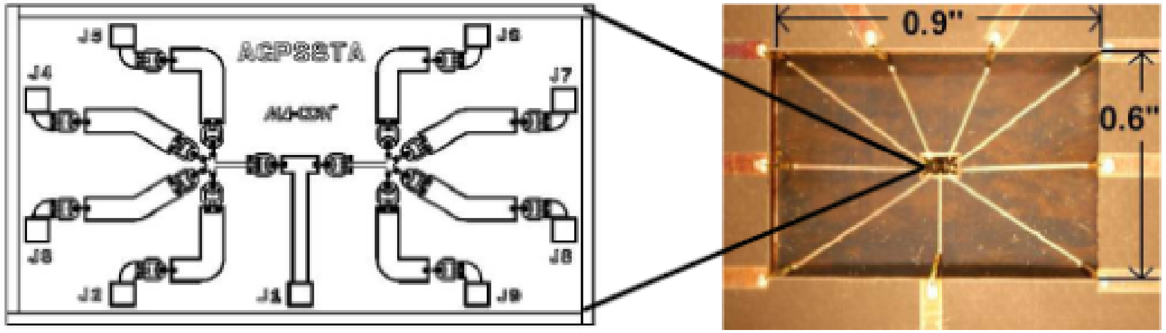
Integrated Microstrip Rotman Lens/Array

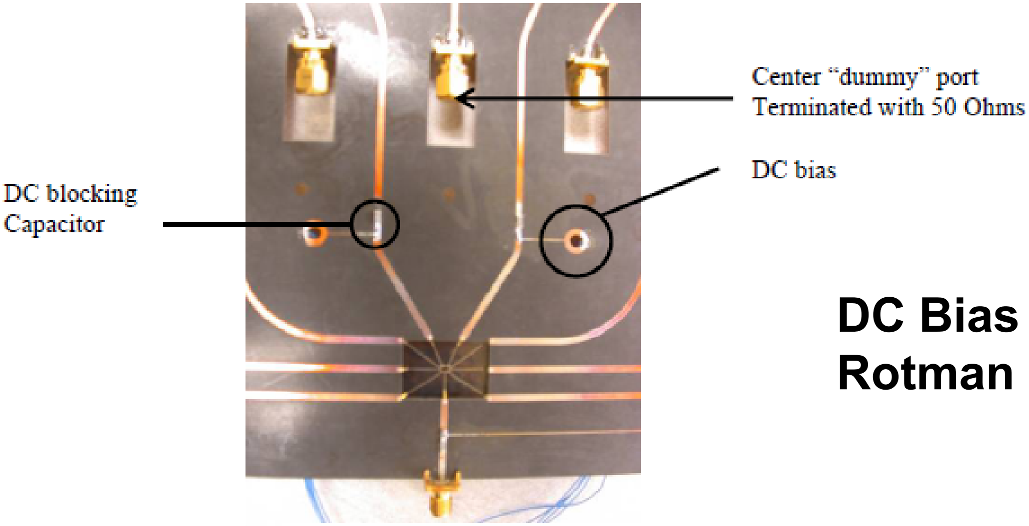


Modular (left) and Integrated Rotman Lens/Array

Switch Integration in Rotman Lens

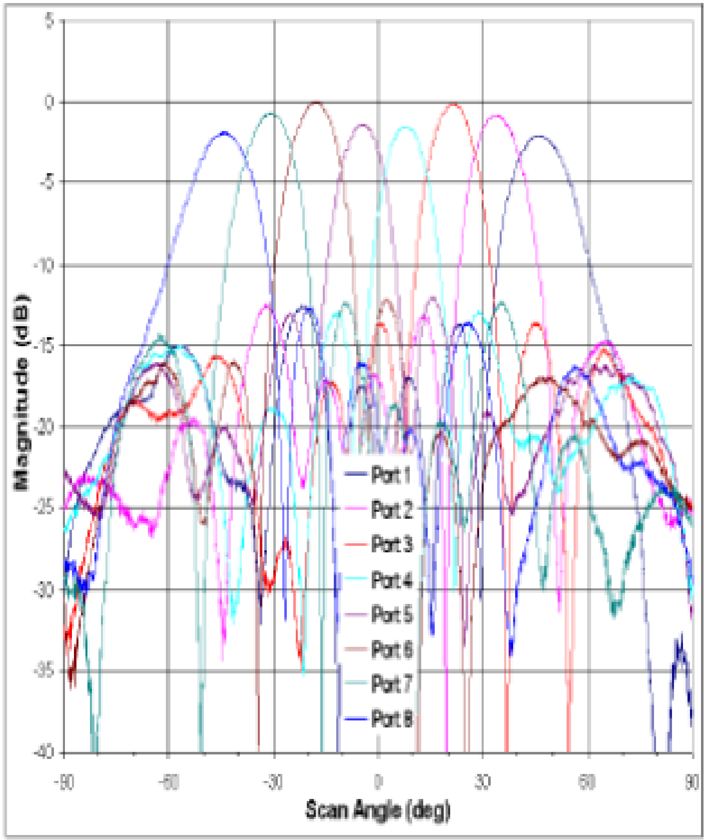


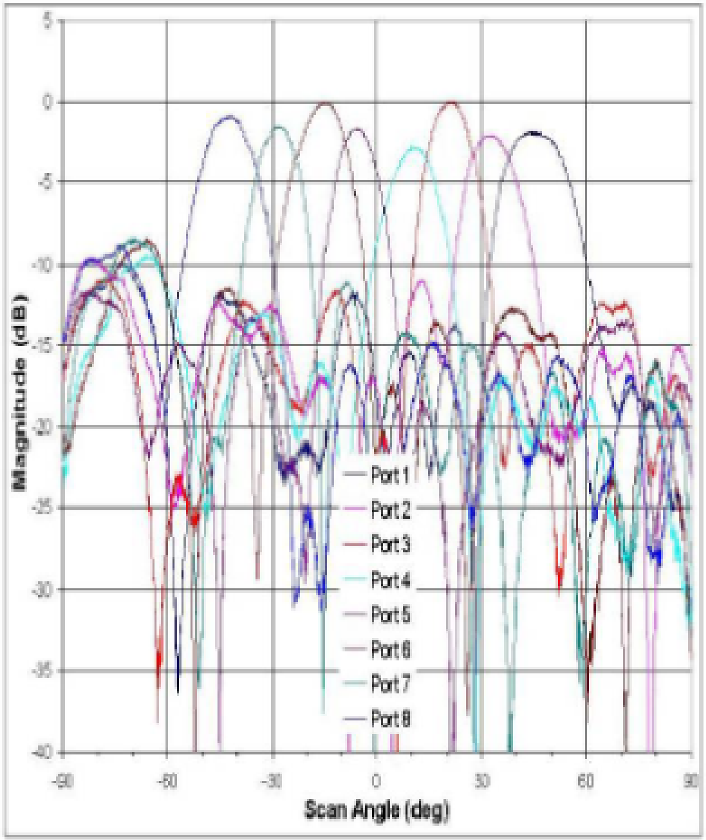
Single-Pole-8-Throw Switch for Beam Scanning Control



DC Bias Line for the SP8T Switch of Rotman Lens

Measured Radiation Pattern for Integrated Lens/Array



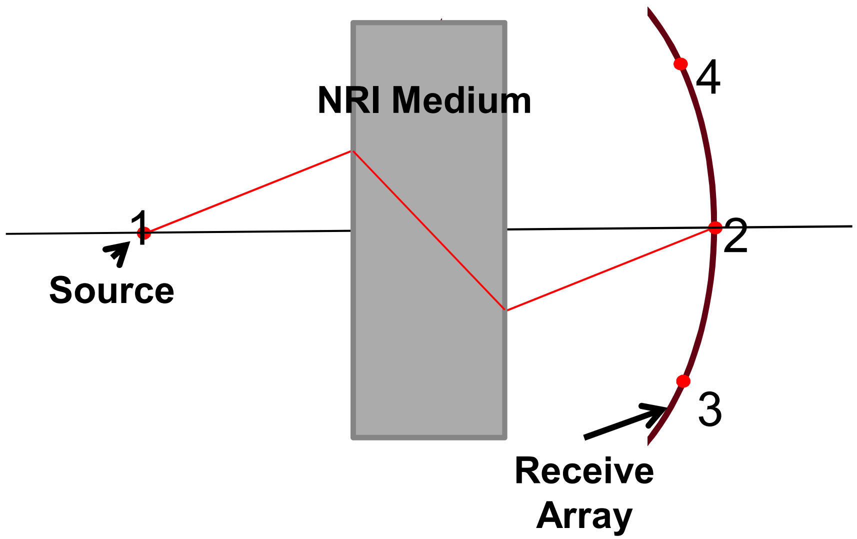


Comparison of Rotman Lens Integrated without Switches (left), & Integrated
with Switches (right)

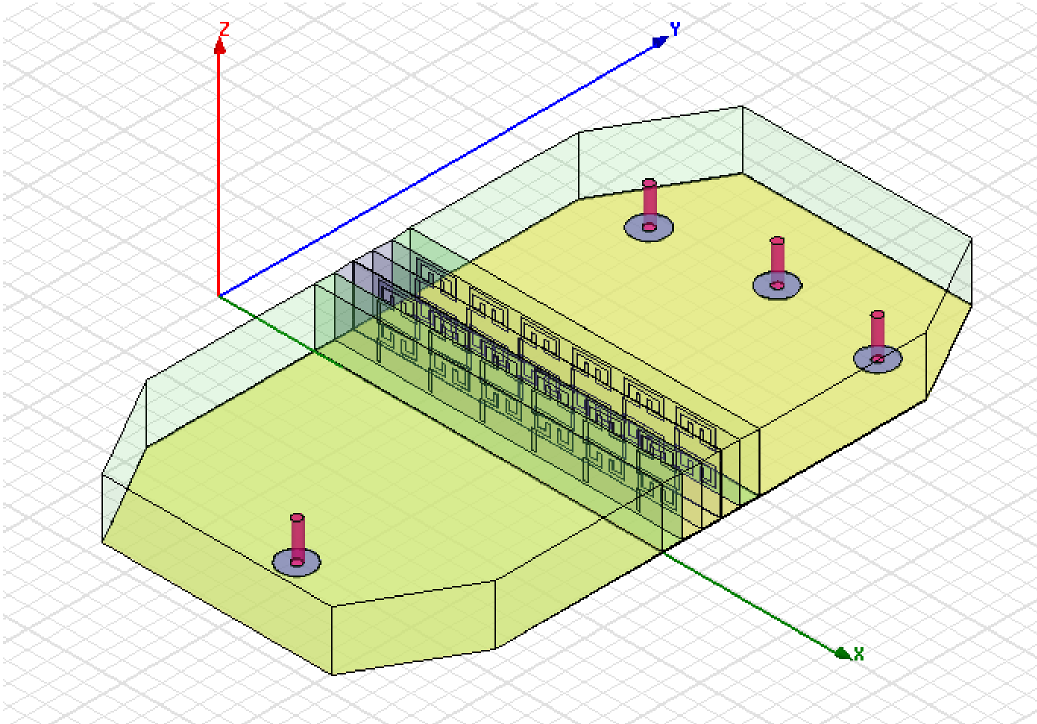
Refractive Focusing Using Negative-Refractive-Index Metamaterials

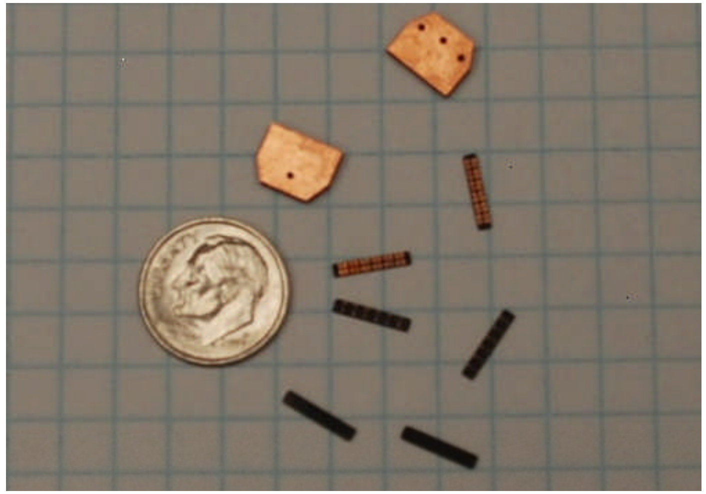
Objectives

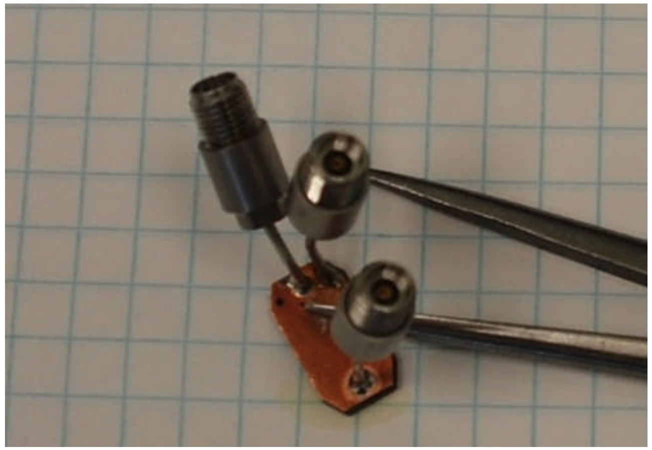
- Show through simulation and measurements focusing using NRI metamaterials
- Use metamaterials for size reduction of large electromagnetic structures



Refractive Focusing Using Negative-Refractive-Index Metamaterials

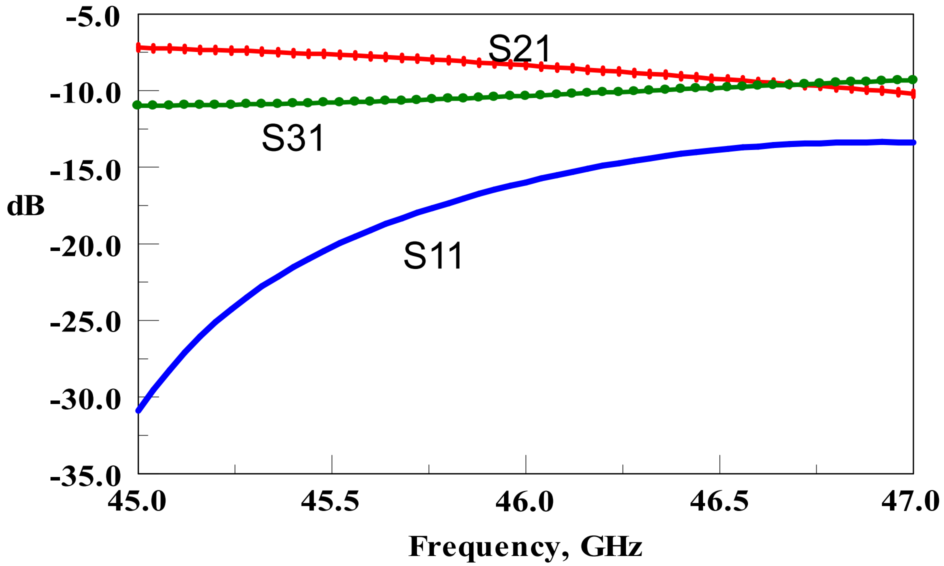




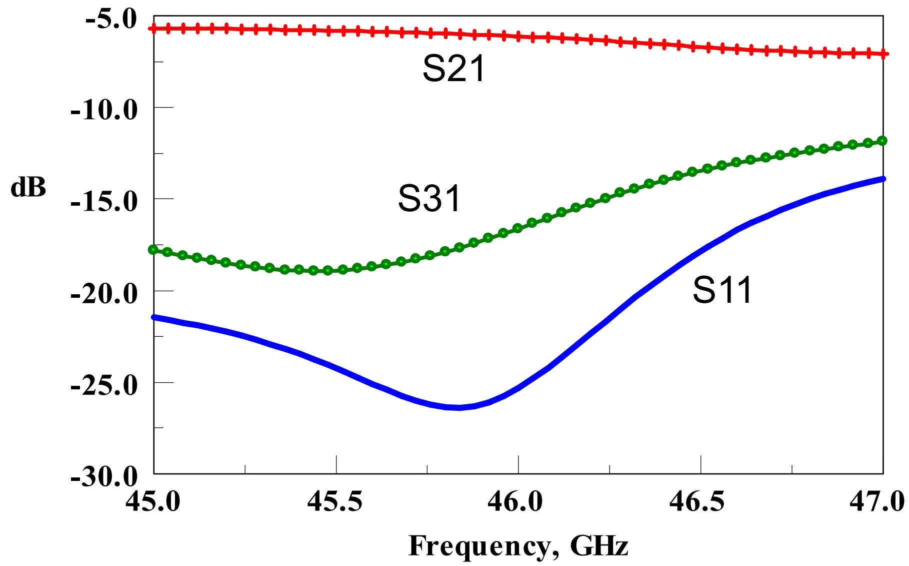


- 3D view of problem setup
- Height of dielectric 61 mil
- Dielectric constant 2.3
- Frequency range 45 – 47 GHz
- Wavelength at 46 GHz: 6.52 mm, 257 mil

Refractive Focusing Using Negative-Refractive-Index Metamaterials

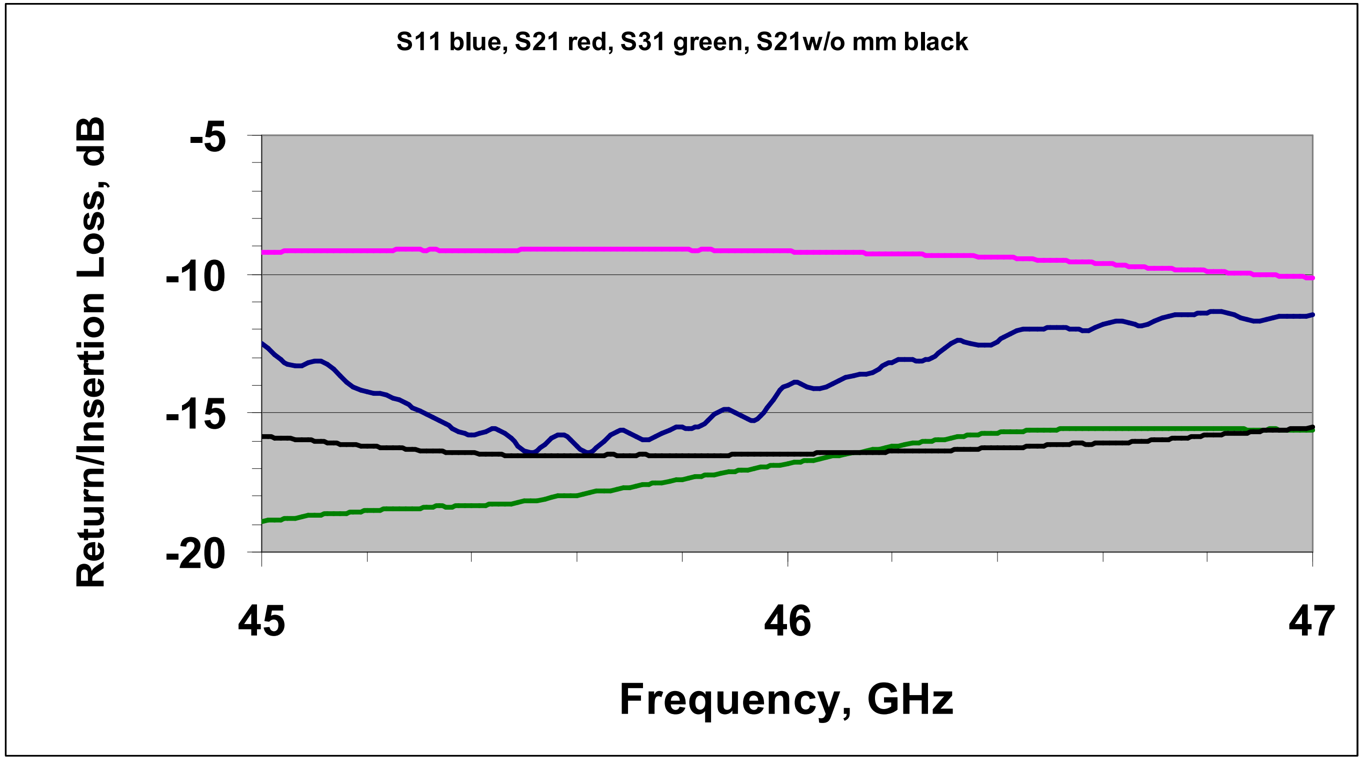


Simulated S-Parameters without Metamaterial



Simulated S-Parameters with Metamaterial

Refractive Focusing Using Negative-Refractive-Index Metamaterials



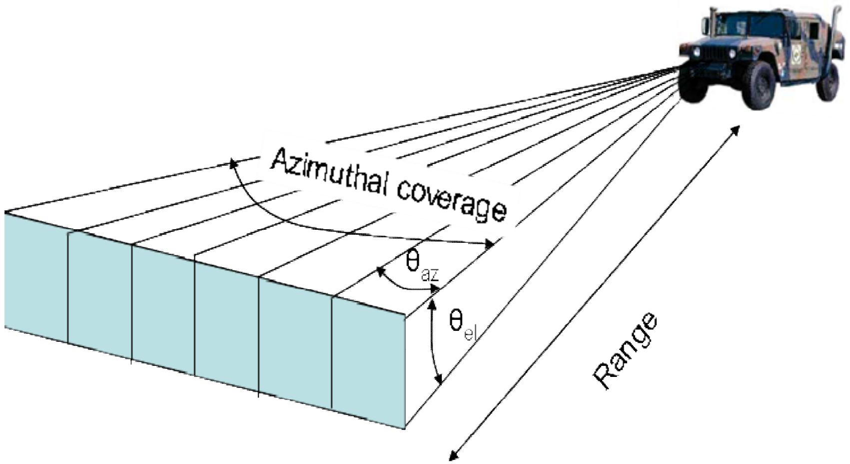
Measured S-Parameters

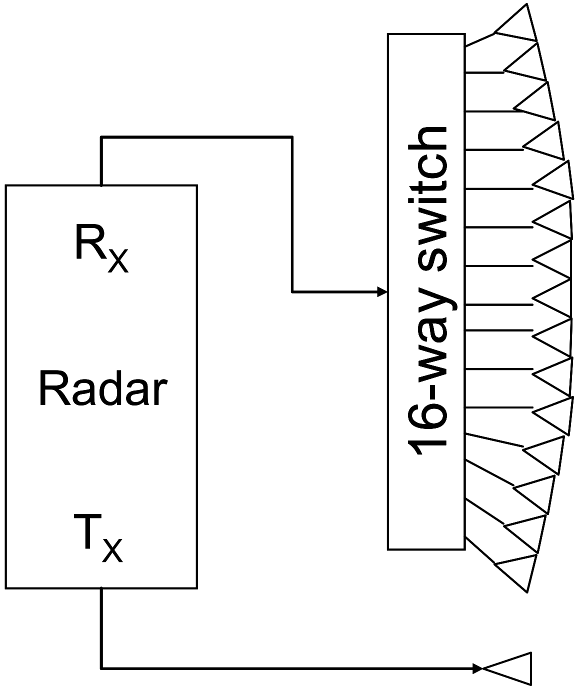
- S11 with metamaterial
- S21 with metamaterial
- S31 with metamaterial
- S21 without metamaterial

Outline

- Rotman Lens – An ARL legacy
- A flexible Rotman lens for Terrestrial Communications
- **A 76 GHz array for collision avoidance applications**
- Conclusion

Requirements





- Low profile

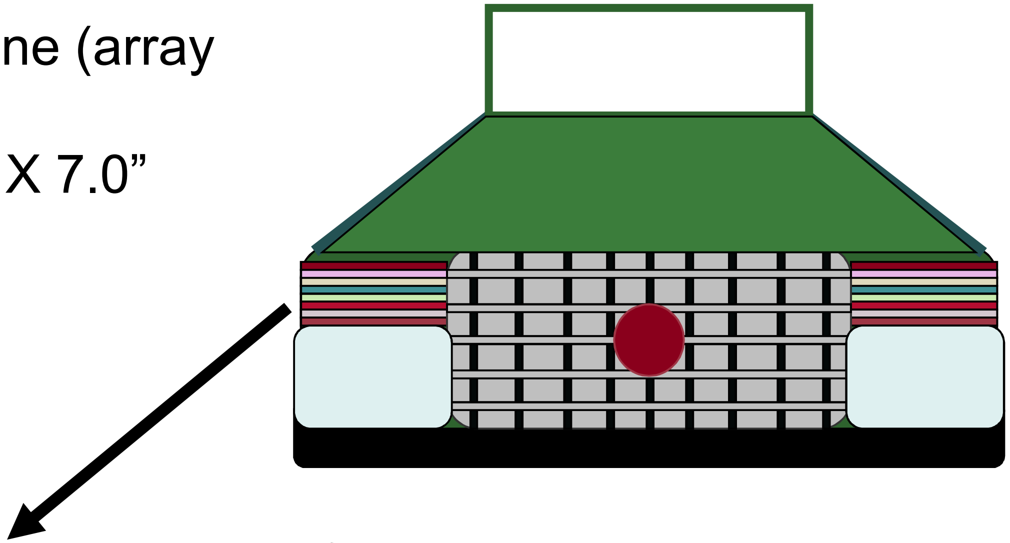
- 16 narrow beams in azimuth switchable at fast rate in nanoseconds range

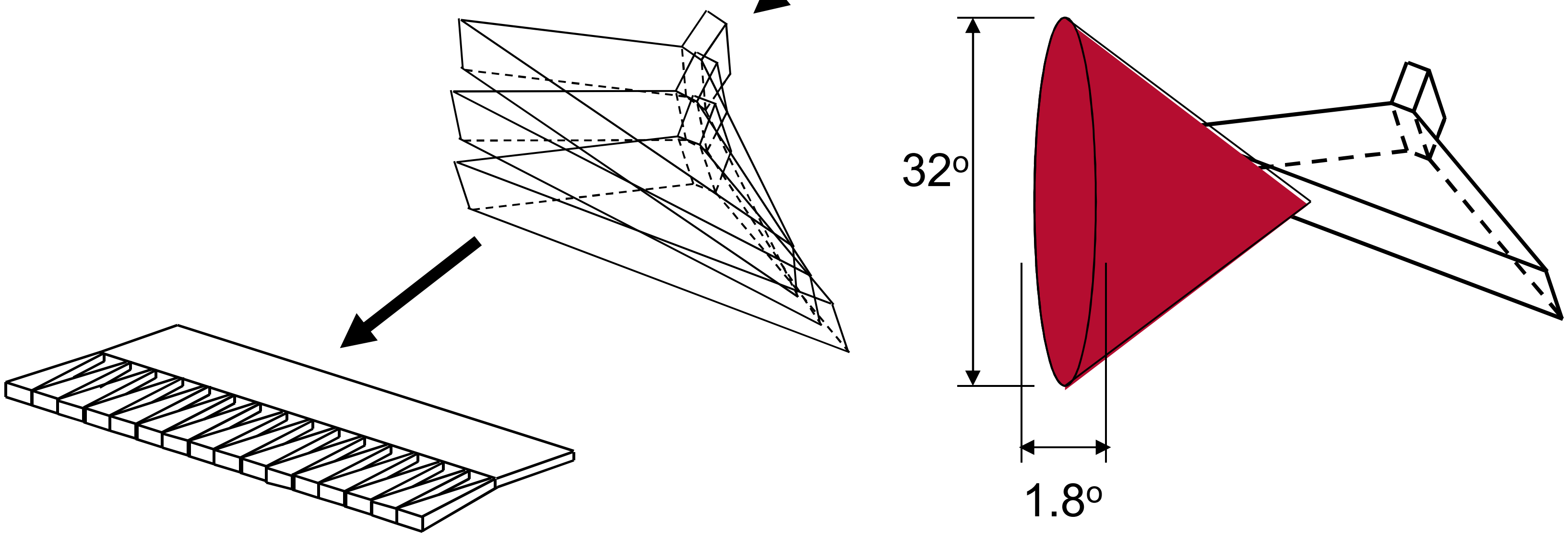
- Broad beam in elevation

Multiple Array Concept

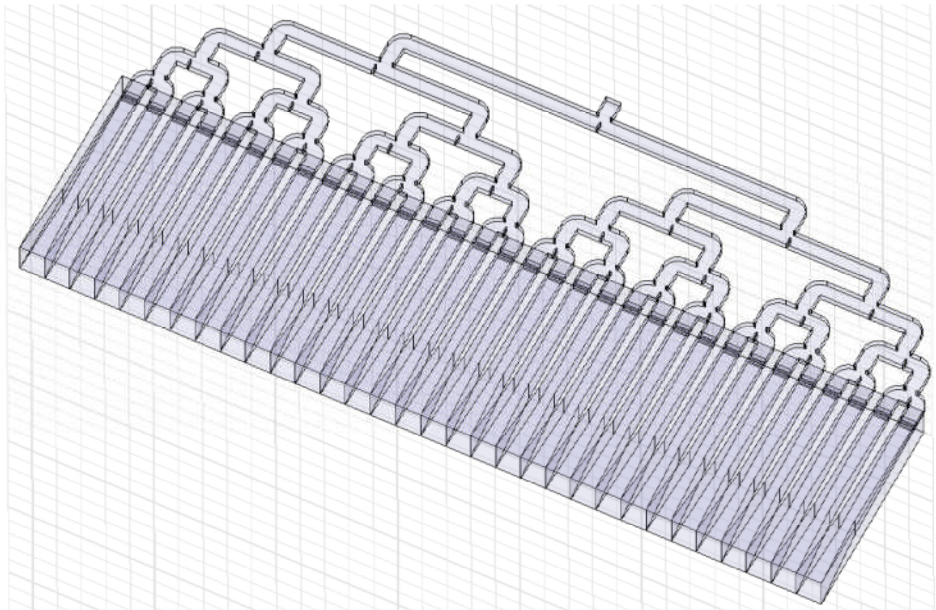
Antenna for Collision Avoidance

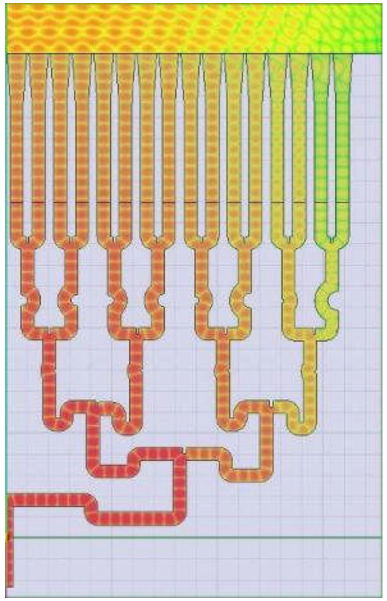
- Optimized horn array
- Horn dimensions: 1.3λ in the H-plane (array plane) and 2.0λ in the E-plane
- Overall aperture size: 0.5” (height) X 7.0” (width) X 5.0” (depth)
- Position on vehicle depends on coverage requirements

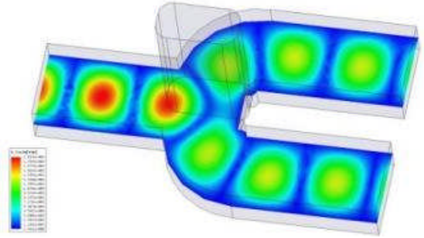


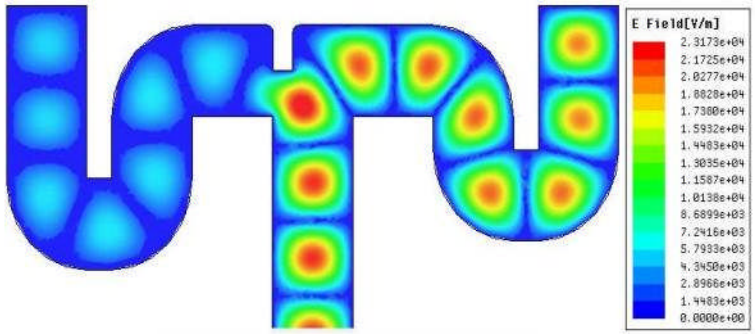


Pyramidal Horn Array



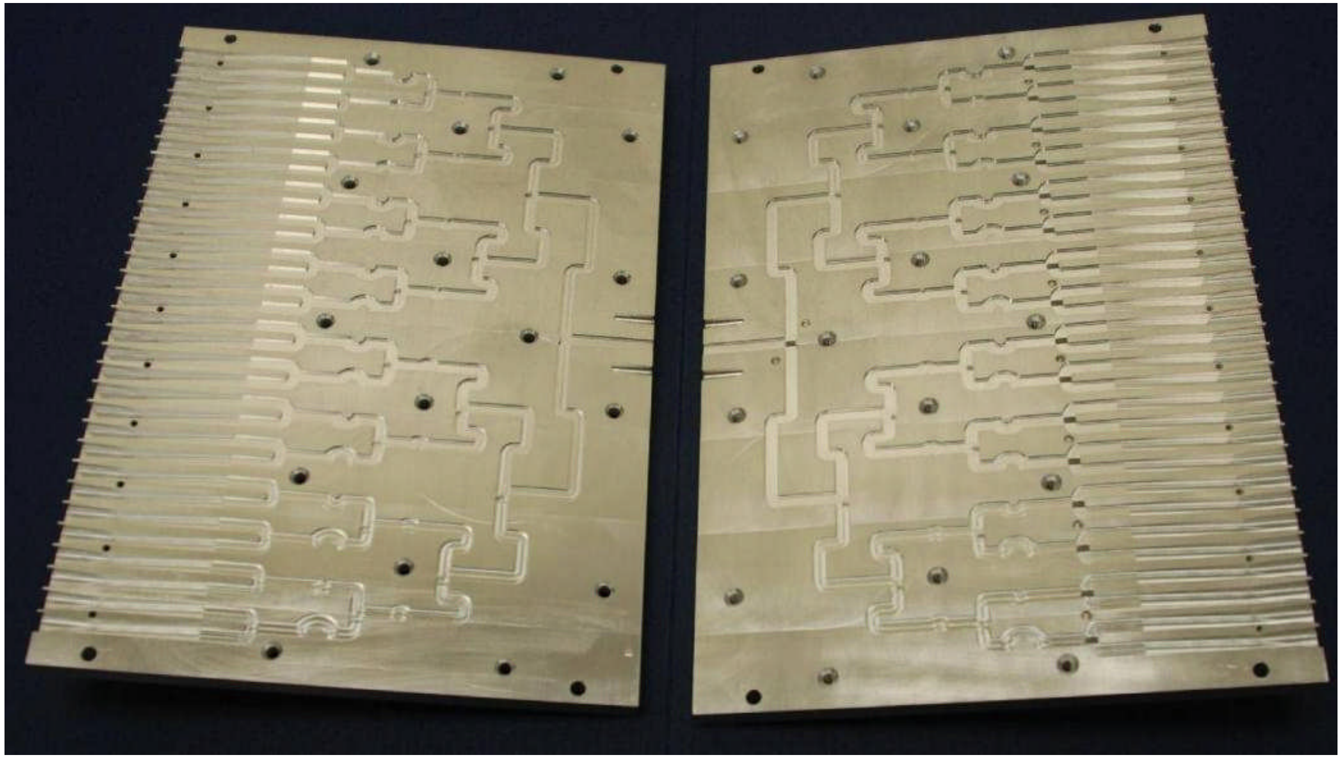




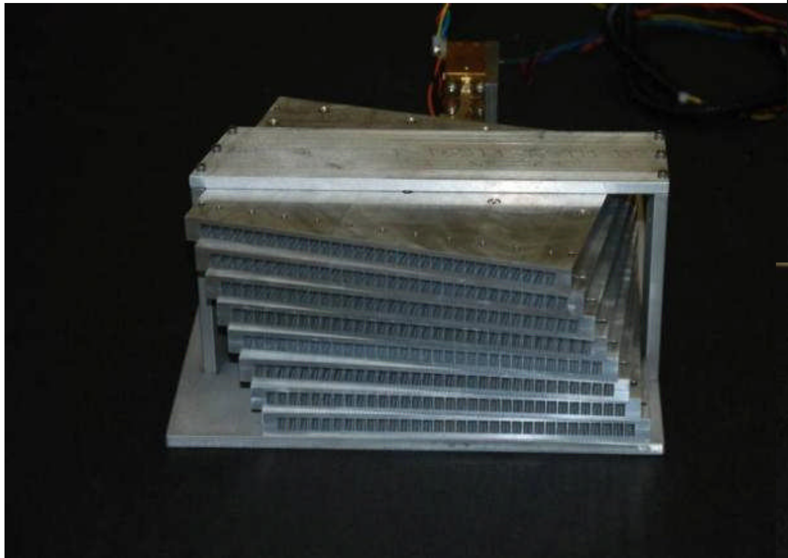


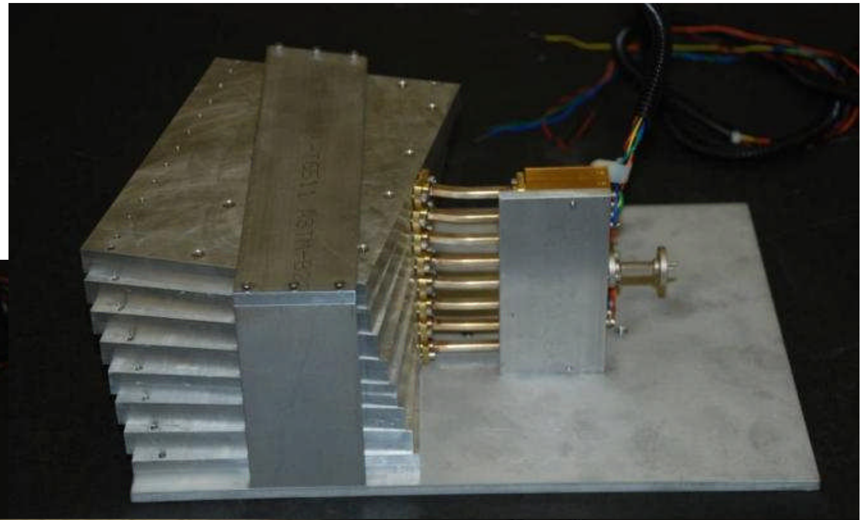
- 32-element array
- 40-dB Taylor aperture distribution
- 5-stage waveguide power divider
- Waveguide lengths are adjusted for equal phase
- Last stage contains equal power division in every pair
- First and last stages contain fourth port for matching (magic T)

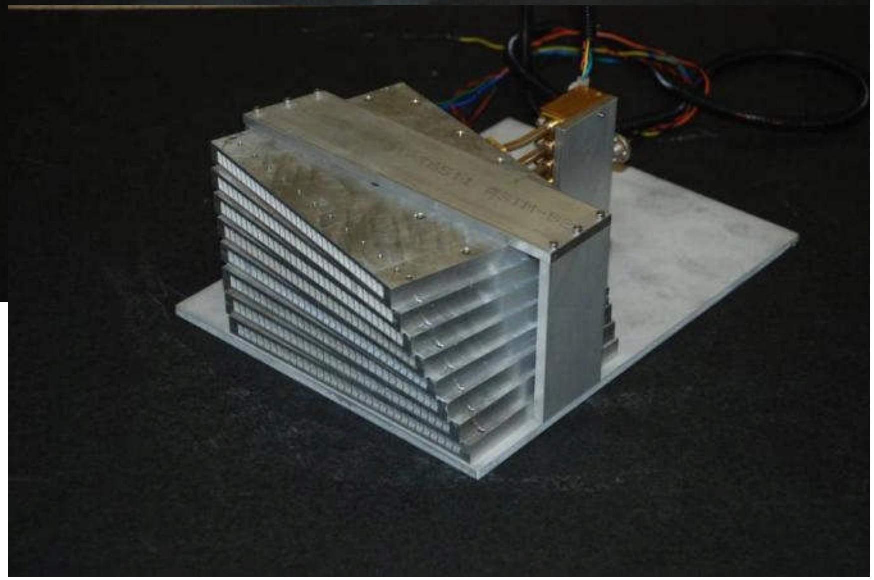
Fabricated Array



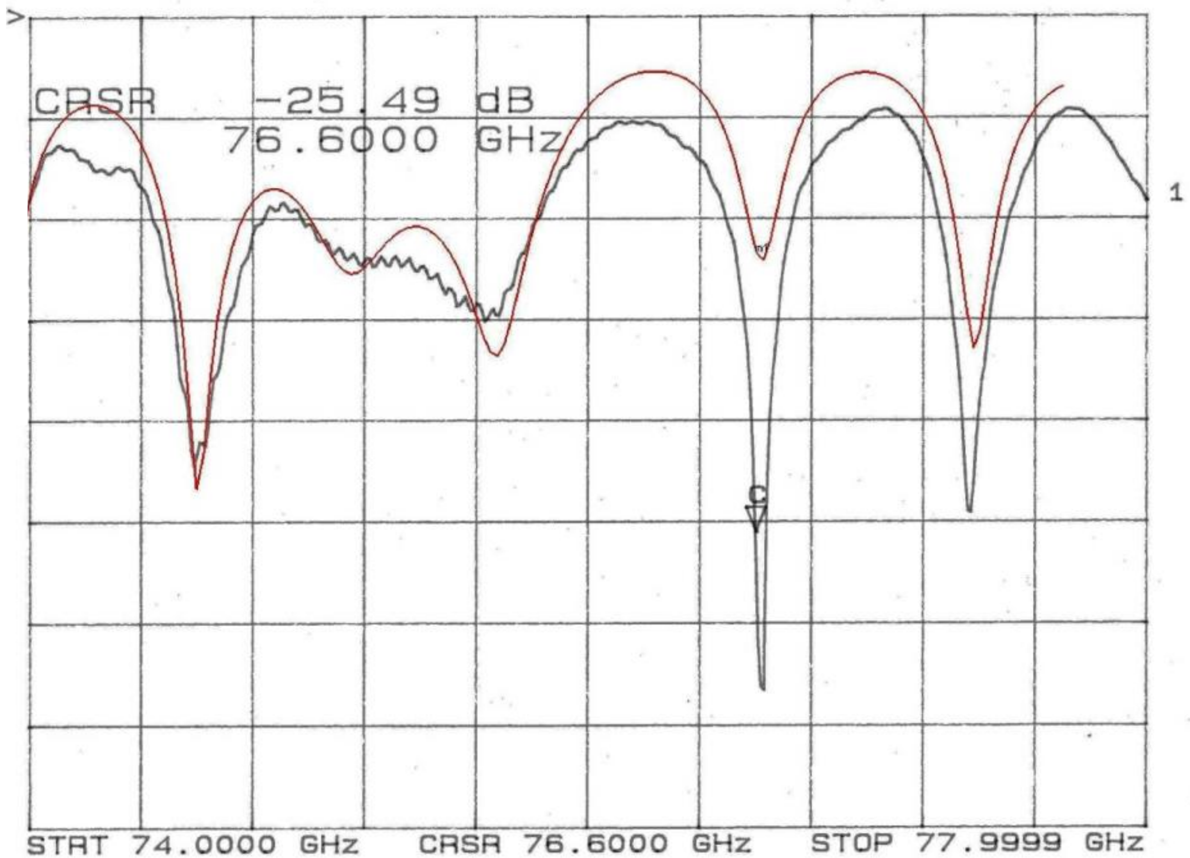
Array Stacking



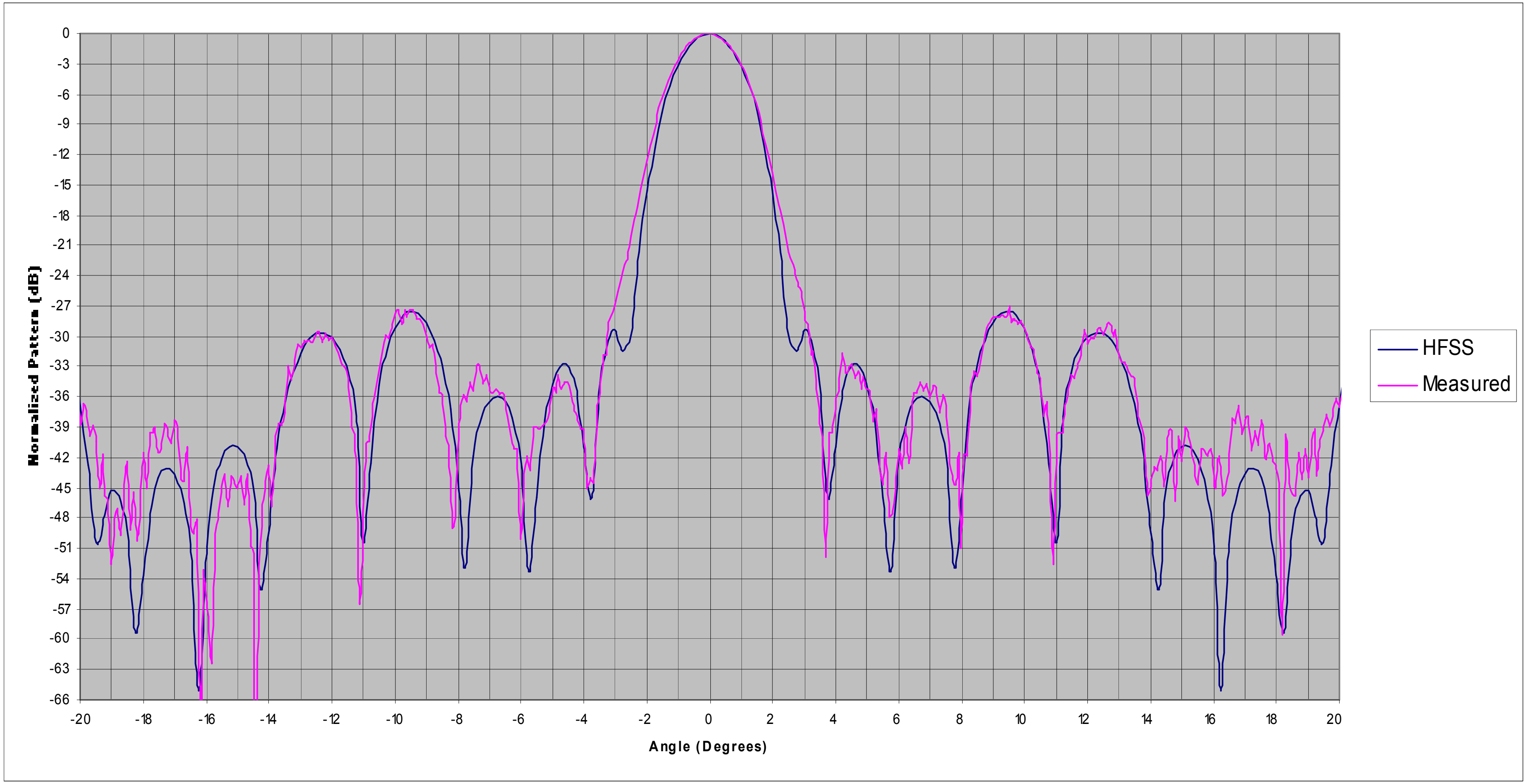




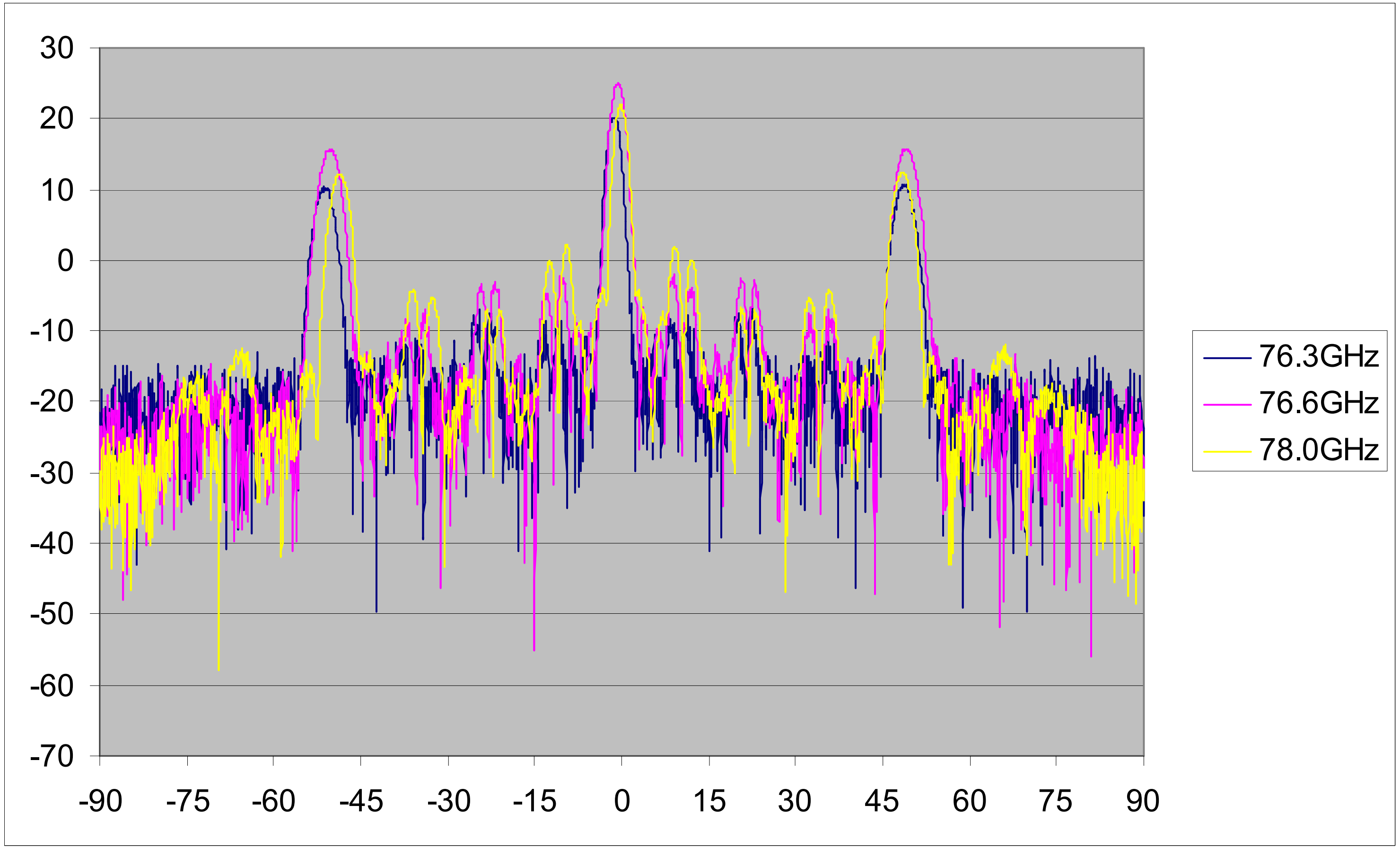
Measured vs. Simulate Return Loss



Measured vs. Simulated Patterns



Measured Patterns at Different Frequencies



Outline

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- A 76 GHz array for collision avoidance applications
- **Conclusion**

Conclusions

- Antenna development for military applications is a collaborative process that involves DoD labs, universities and industry
- Antenna has to be designed with platform and environment in mind
- In-situ antenna design & analysis are essential to successful development

Conclusions

- New simulation tools are still needed for new frontiers, such as metamaterials and nano-designs
- Fully integrated, adaptive designs have been at the forefront of antenna research and development
- Wideband, low profile, high efficiency, polarization diversity and low cost are still requirements