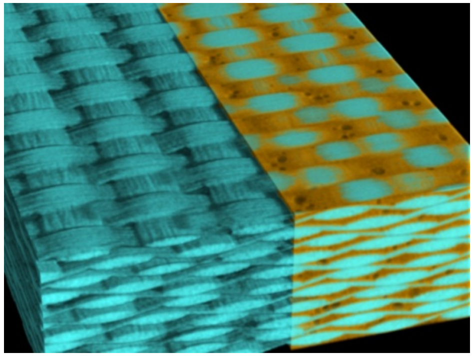
Multifunctional Structural Composites
"Engineering the EM Properties of Structures"



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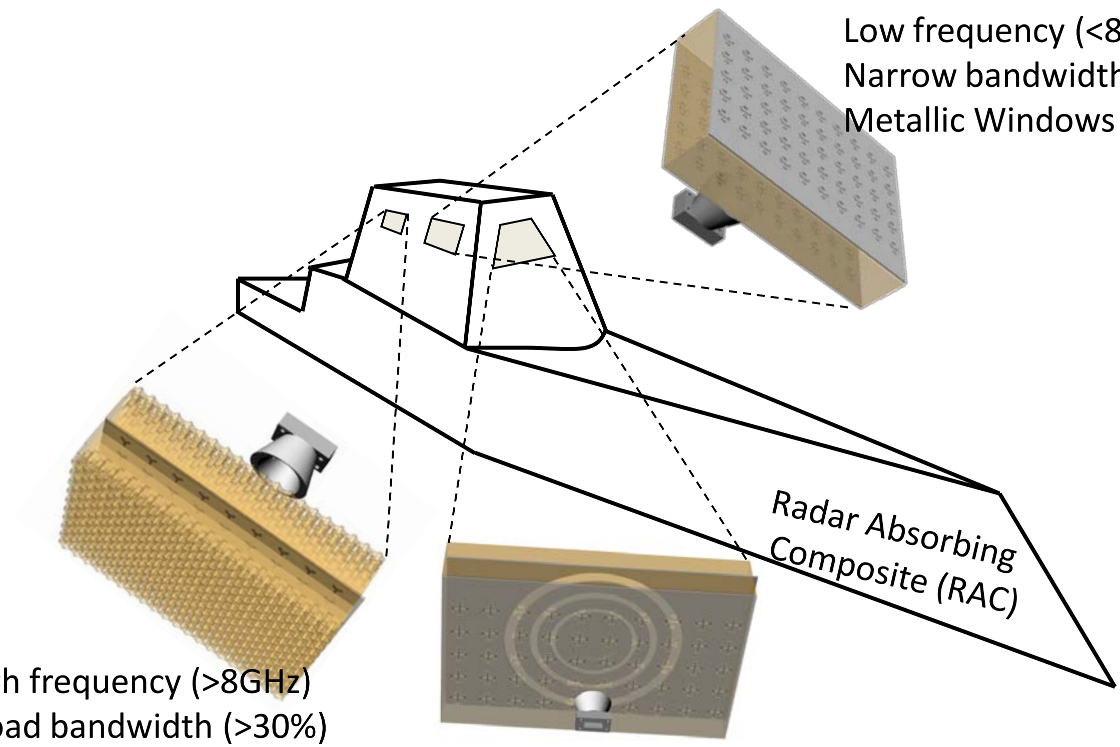
Electromagnetically functionalized structural composites: Long term vision

In my laboratory we work in the area of multifunctional materials.

More specifically on methods to integrate electromagnetic functionality into structural composites



Presentation Outline

- Motivation for "engineering" the EM properties of structural composites
- Who we are (some shameless self-promotion)
- Structural Composites: A brief overview
- Engineering structural composites with attractive EM properties
- Applications
  - (1) Progress towards a broadband structural radome design
    - Traditional approach
    - Motheye approach

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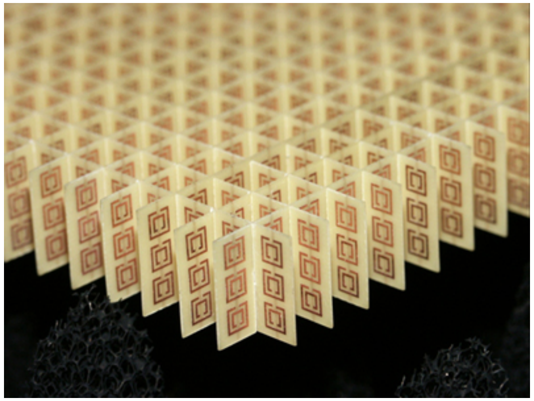
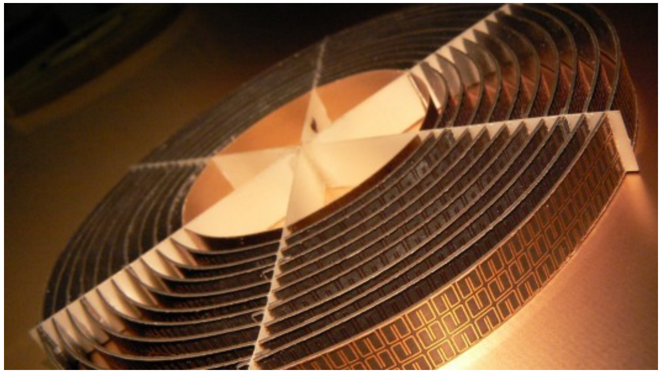
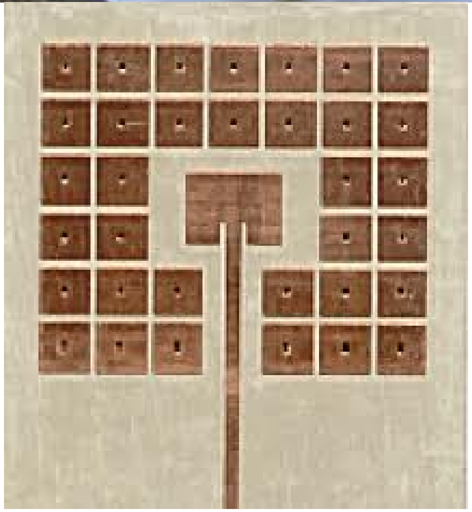
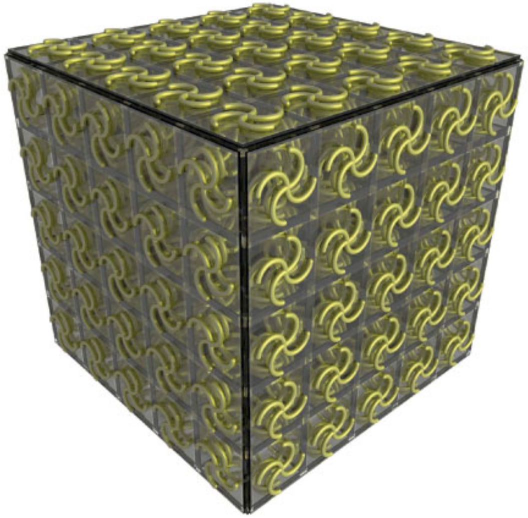
Motivation

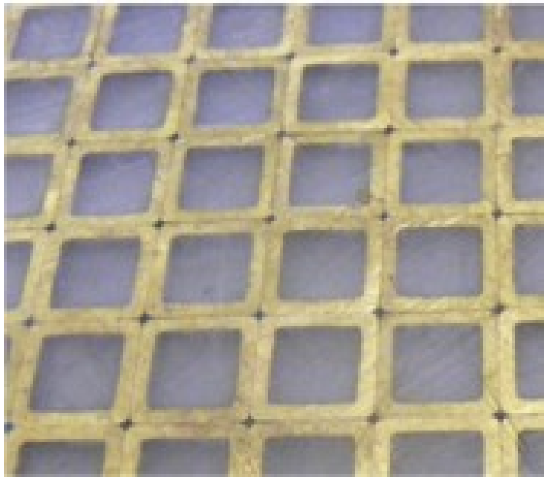
Over the last decade a great deal of progress has been made in the development of artificial materials with unusual and potentially useful EM properties.





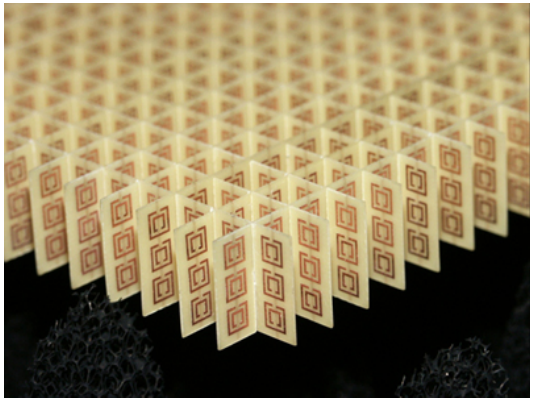
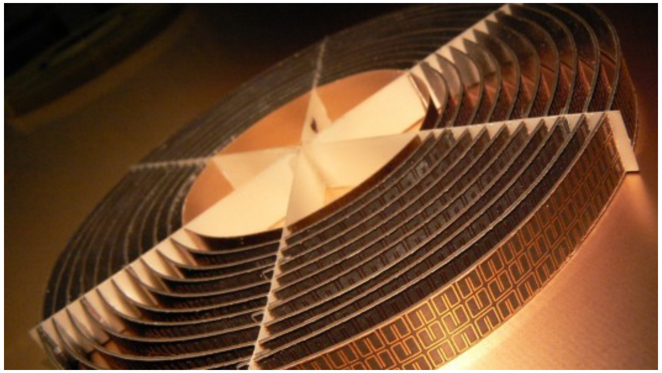
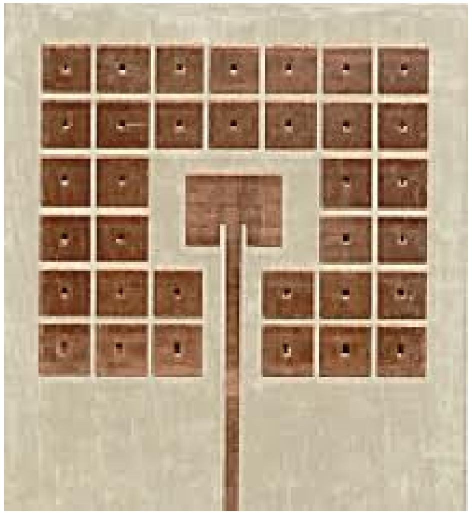
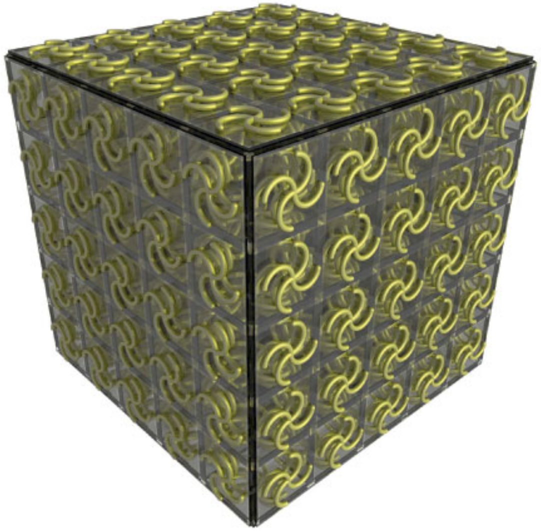
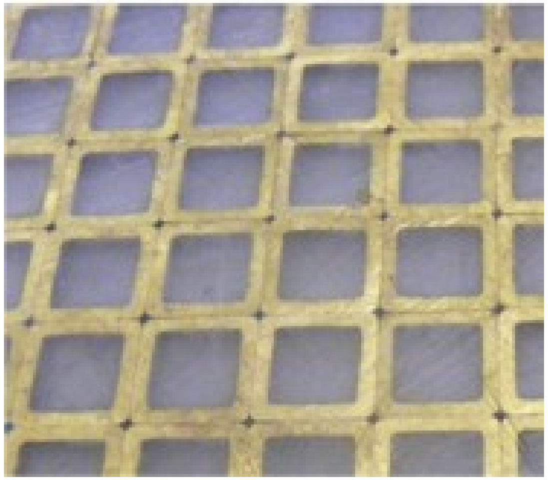






Motivation

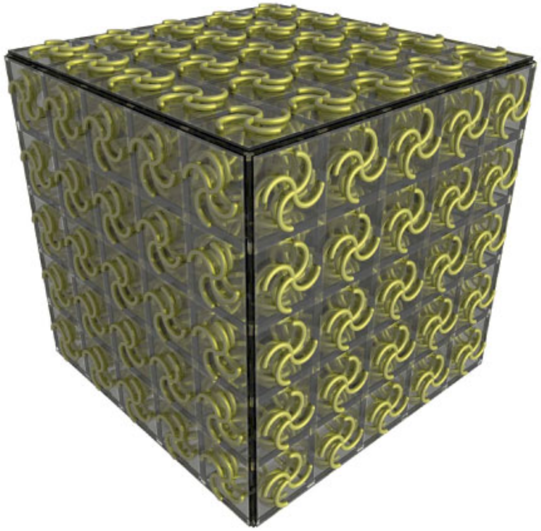
Unfortunately little of this work has transitioned from the laboratory to the field. Why?

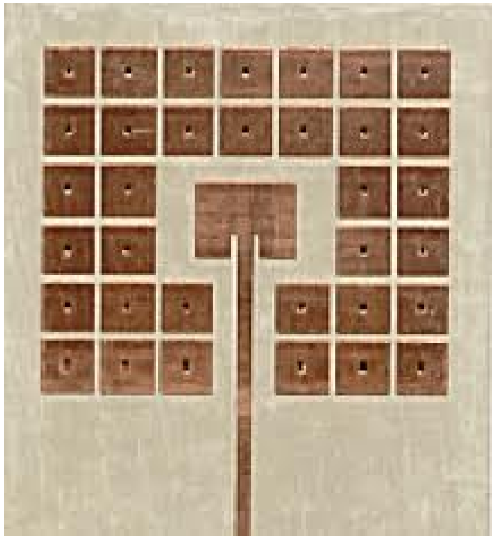







Motivation

Little of this work has transitioned from the laboratory to real platforms. Why?

My answer: It has not yet been worked out how to integrate these structures using (1) conventional materials that have other attractive properties, (2) scalable manufacturing methods, (3) cost effective material processing methods.

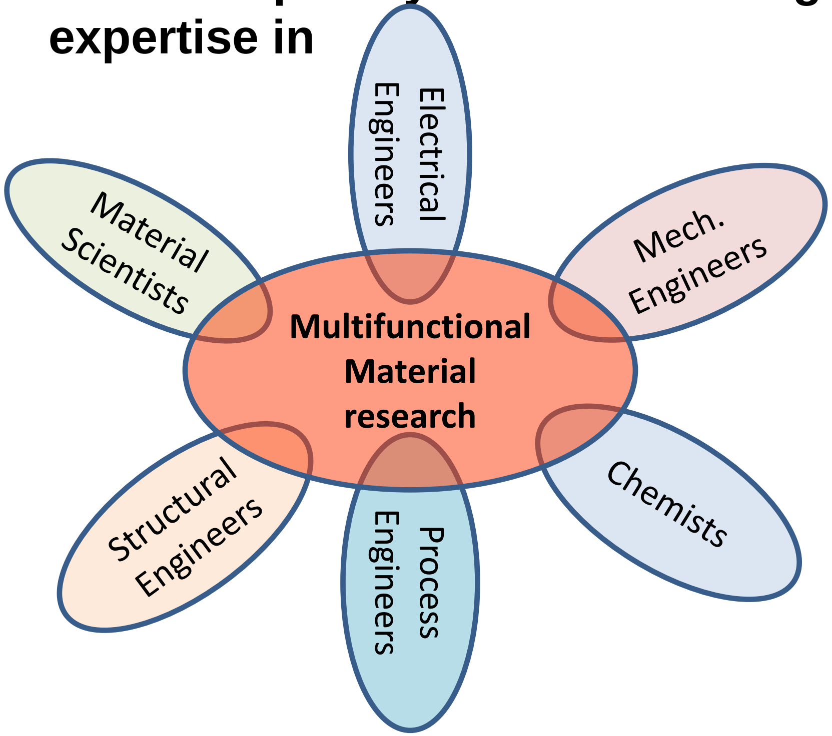




Multifunctional Composite Research

We believe that multifunctional structural composites are an attractive platform to integrate the unique EM properties of metamaterials within real commercial and military platforms.

- **Multifunctional material design will be critical for the development new military platforms with reduced size, weight , power (SWAP) and cost.**
- **To develop good multifunctional materials is not easy! It requires a true multidisciplinary effort combining expertise in**



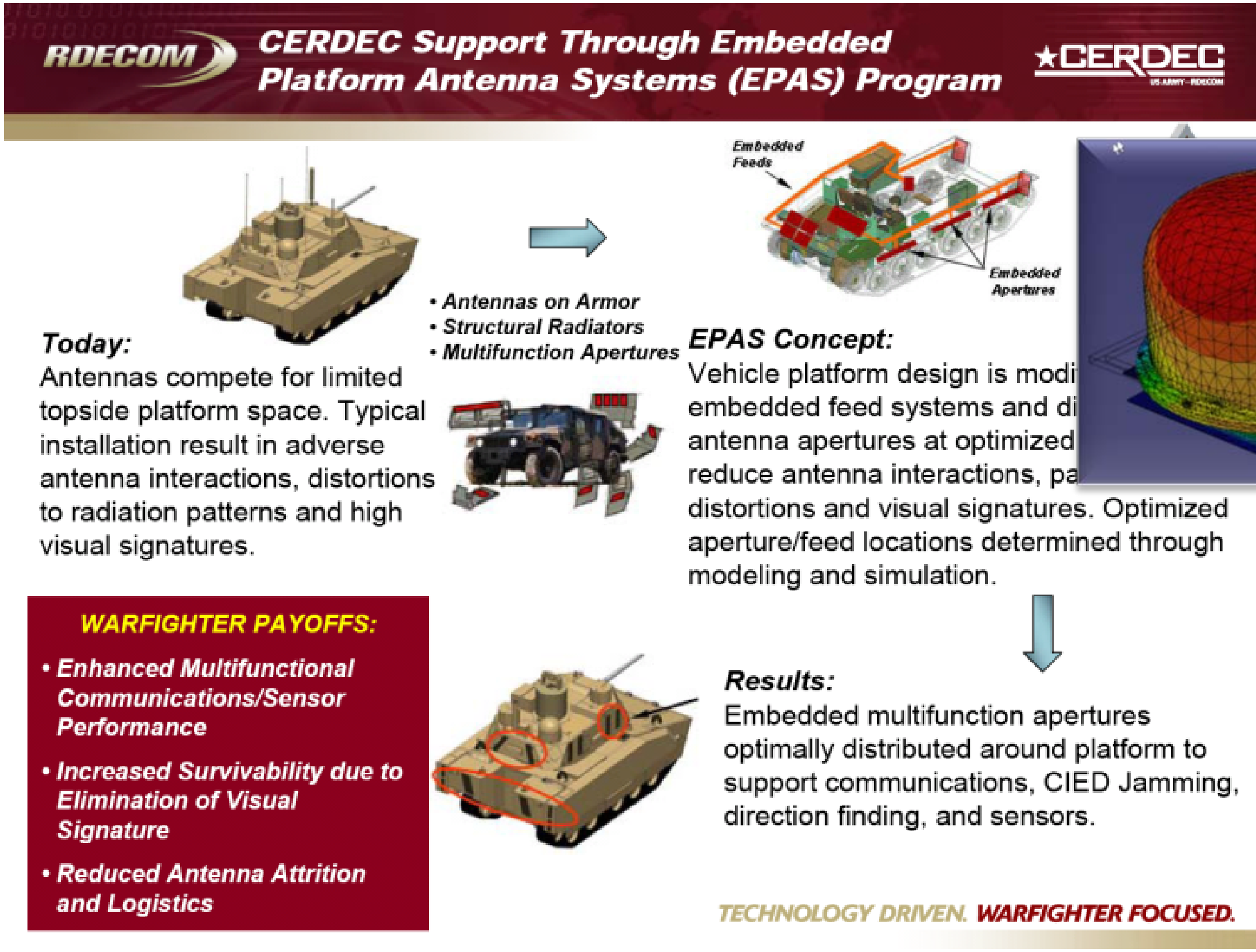
Conformal Load-Bearing Antenna Structure (CLAS)

AFRL CLAS project

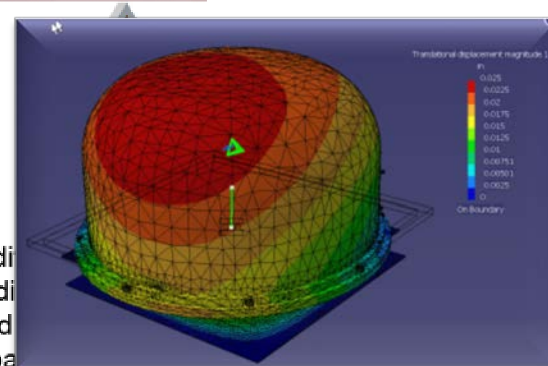
- ❑ **Antenna function is integrated directly into the load-bearing structure**
- ❑ **Lightweight and cost-effective solution since no additional support structure is needed**
- ❑ **Enhanced performance by reducing weight, drag and RCS**
- ❑ **Concept demands integrated development from normally independent technologies such as structures, electronics, materials and manufacturing**

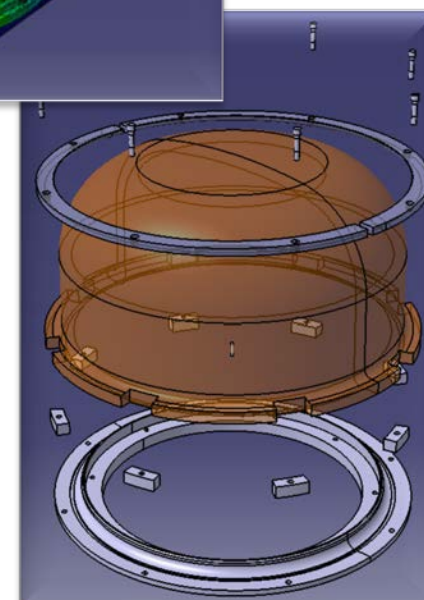
1. “Novel Concepts for Conformal Load-bearing Antenna Structure”, Paul J. Callus, Technical Report (DSTO-TR-2096), Feb. 2008
2. “Antenna Integration with Composite Sandwich Structures using Gain Enhancement Methods”, C. You and W. Hwang, Journal of Composite Materials, 2007
3. “E-Textile Conductors and Polymer Composites for Conformal Lightweight Antennas”, Y. Bayram, Y. Zhou, B. Shim, S. Xu, J. Zhu, N. Kotov and J. Volakis, IEEE Transactions on Antennas and Propagation, 2010
4. “Polymer-Carbon Nanotube Sheets for Conformal Load Bearing Antennas”, Y. Zhou, Y. Bayram, F. Du, L. Dai and J. Volakis, IEEE Transactions on Antennas and Propagation, 2010

Embedded Antennas in Armor



Ballistic Radome Design and Prototyping

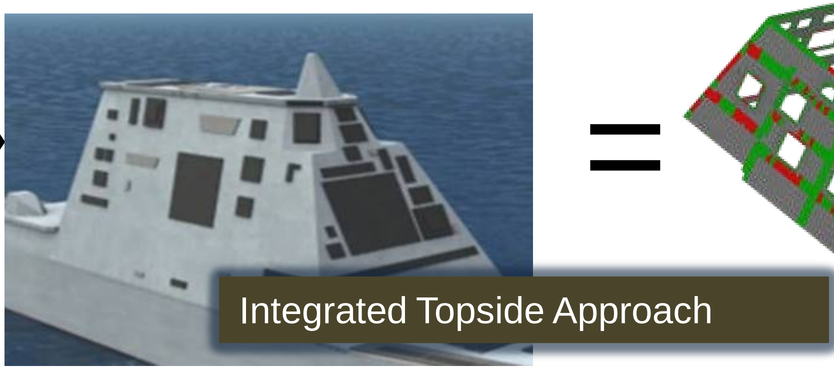


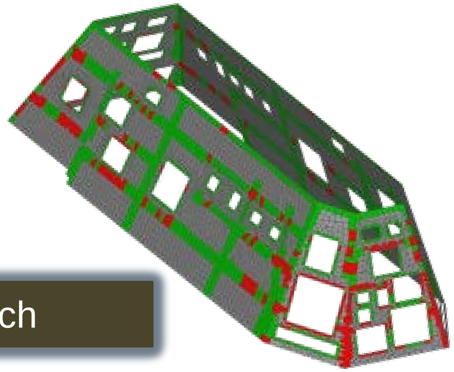


*Manufacturing technology briefing on Future Combat Systems in March 2005

Aperstructures

- The Navy has taken advantage of new antenna concepts that has enabled the development of integrated topside designs for numerous platforms.
- An integrated topside provides multi-functionality (balancing structural and antenna properties)
  - Integrating the structural regime and antenna functionality positively impacts: Structural Efficiency, EM Control, and densely spaced apertures
  - Integrated topside approach resulted in reduced structural integrity, decreased stiffness, increased weight due to structural reinforcements, and most importantly increased cost





Develop advance composite materials that enable the integrated topside approach with minimal impact to cost and mechanical/structural properties

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- Broadband EM properties of woven fabric composites
- Applications

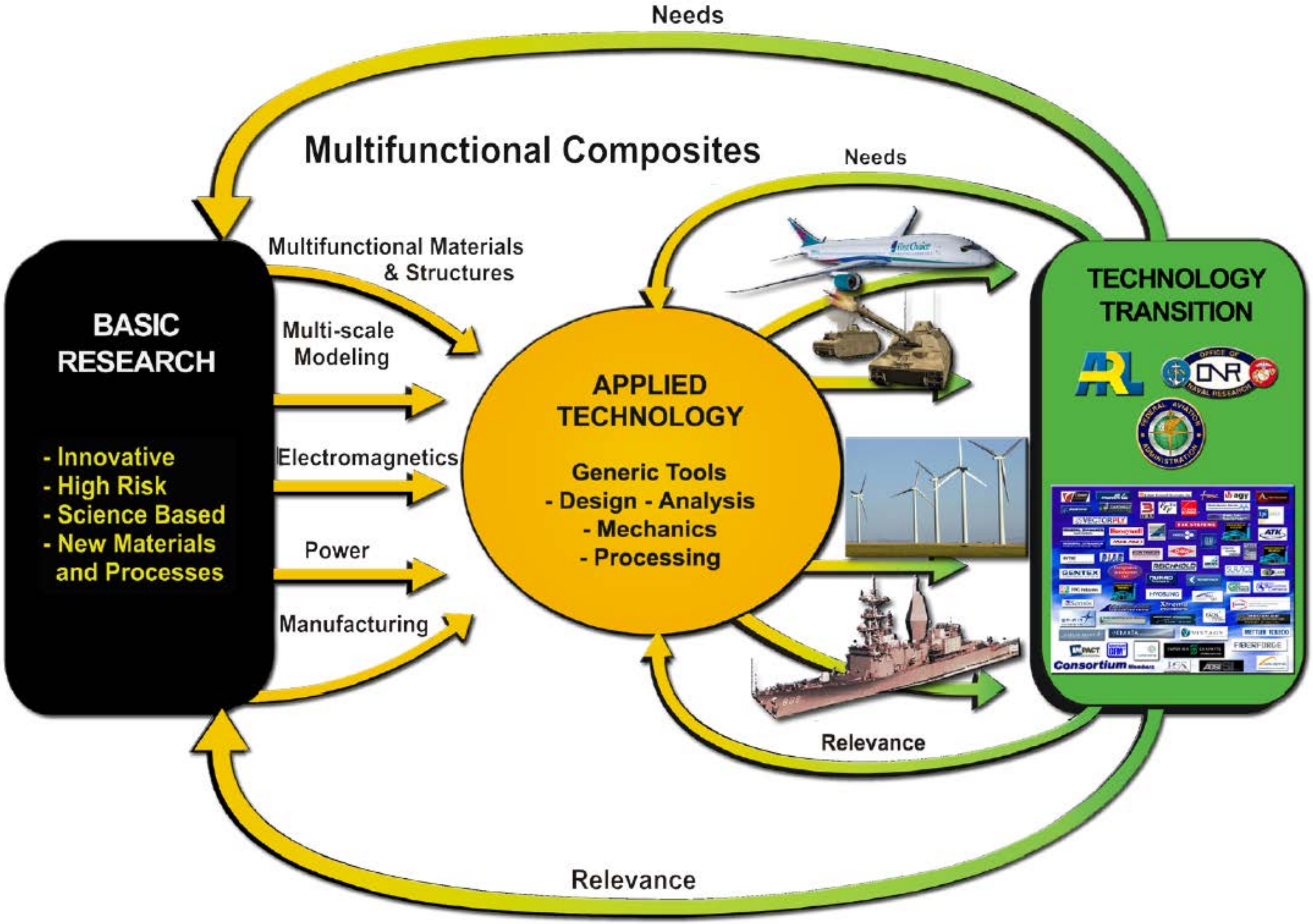
  (1) Progress towards a broadband structural radome design

    - Traditional approach
    - Motheye approach

University of Delaware
Center for Composite Materials

- Founded in 1974
- NSF and DoD Center of Excellence for 25 years
- Over 350 people
  - 35 affiliated faculty representing 11 different academic departments
  - 39 research professionals
  - 11 postdoctoral researchers
  - 35 visiting scholars
  - 83 graduate students
  - 138 undergraduate research assistants
  - 15-member administrative team
- 64 members of the University-Industry Consortium
- More than 2000 alumni!

UD-CCM's Multidisciplinary Research Philosophy



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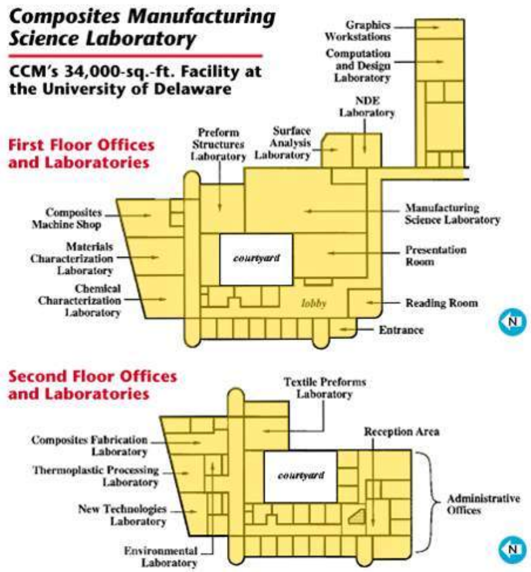
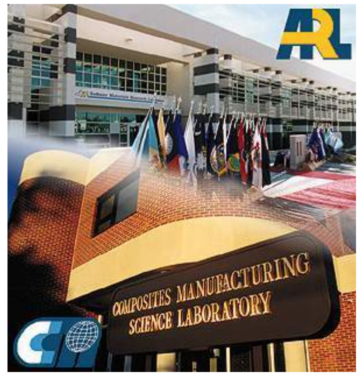
FACILITIES





- Composites Manufacturing Science Laboratory (34,000 sq ft)
  - Basic/Applied Research
  - Open/Shared Facility
- Applications and Technology Transfer Laboratory (18,000 sq ft)
  - Off Campus
  - Access Controlled, Export/ITAR compliant
  - Prototyping Integration Facility for Advanced Multifunctional Platforms
  - Full-Time Staff US Citizens – 15 people located at ATTL
- UD Departmental Facilities and Equipment
- Access to ARL Rodman Materials Lab as part of MCoE

Examples of Technology Transition to Full Scale Prototypes

Ballistic Hardtops for HMMWV

Medical Mission Module

HEMTT A3 Armor Ready Cab

EMI Shelter for HMMWV

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- ❑ Engineering structural composites with attractive EM properties
- ❑ Broadband EM properties of woven fabric composites
- ❑ Applications

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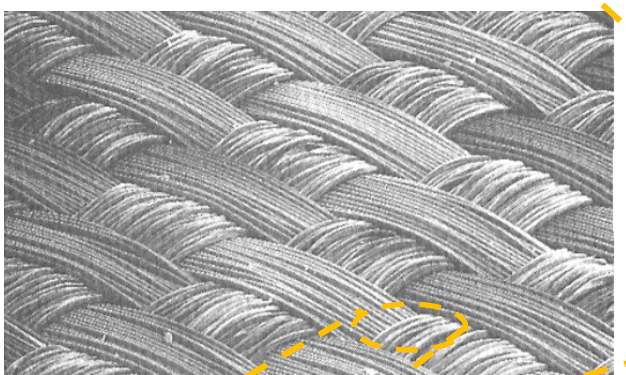
WHAT ARE COMPOSITE MATERIALS?

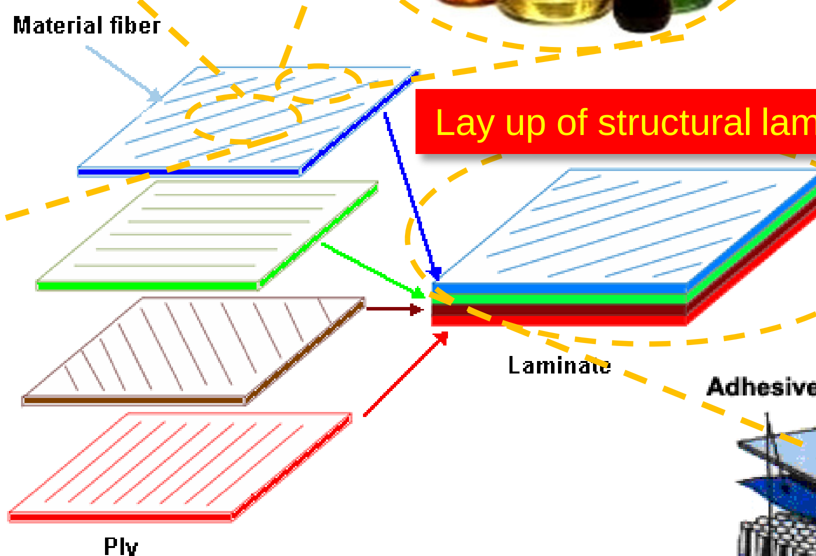
Composites are made from two or more distinct materials that when combined are better (stronger, tougher, and/or more durable) than each would be separately.

Woven Fabric Composites (Fiber Reinforced Composites)

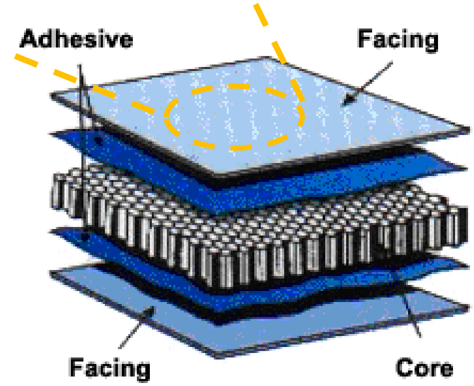
Fabric weave architecture



Bulk properties of polymer matrix



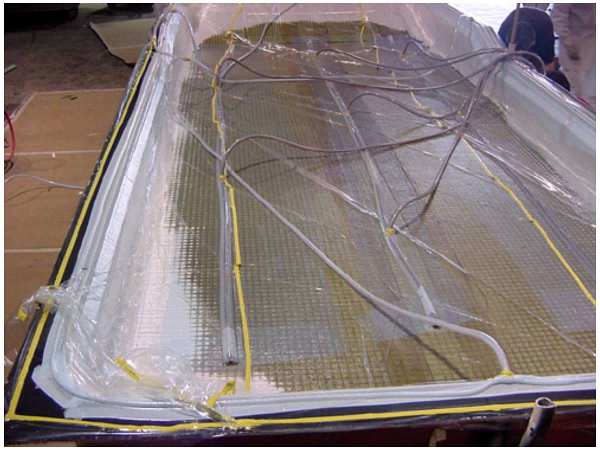
Lay up of structural laminate

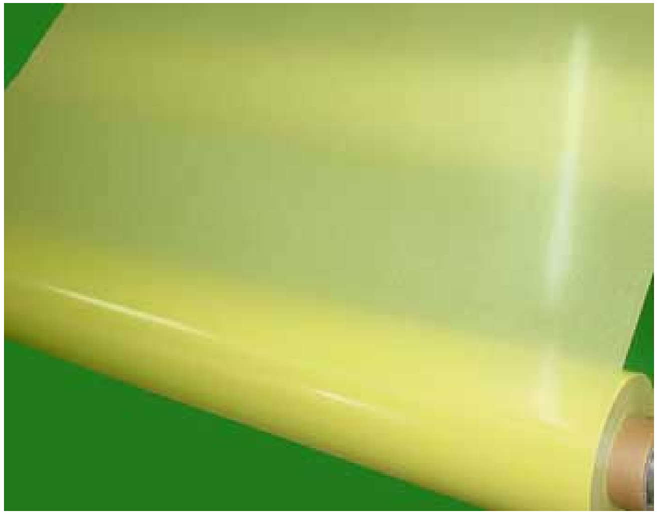


Composite structure

Glass, carbon, aramid or polymer

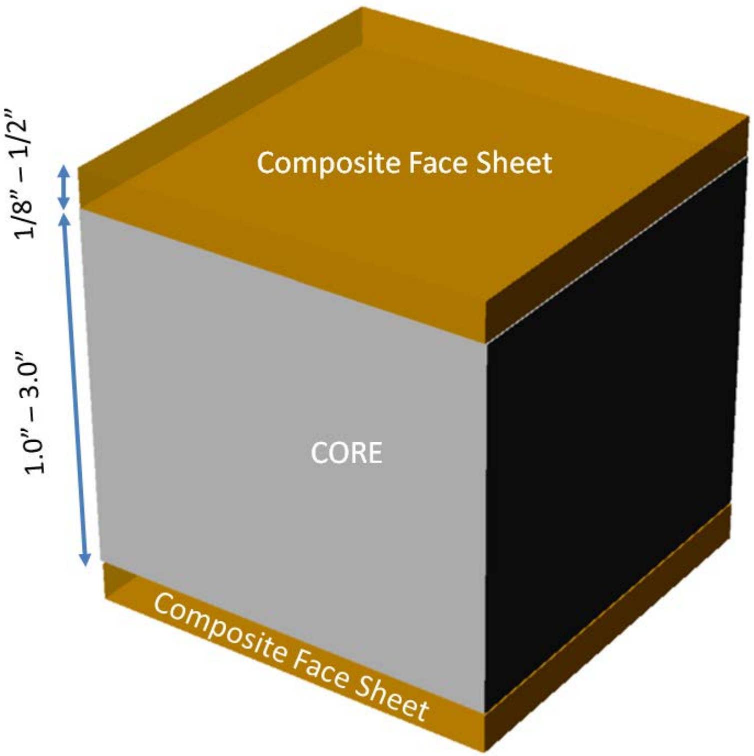
Continuous Fiber Composites





Polymer matrix is infused throughout the fabric layers and cured to create the final structural composite panel

Composite Structures
"Typical Sandwich Composite Panel"

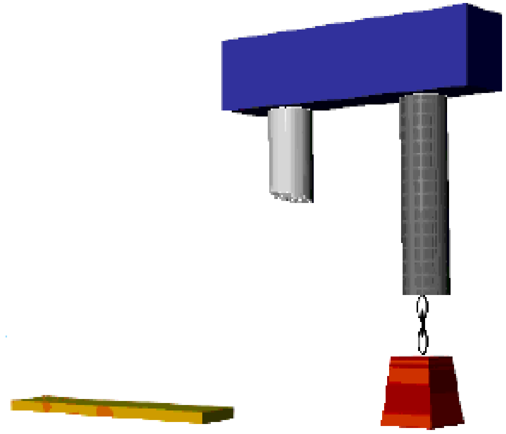


Honeycomb Core (Hexel)

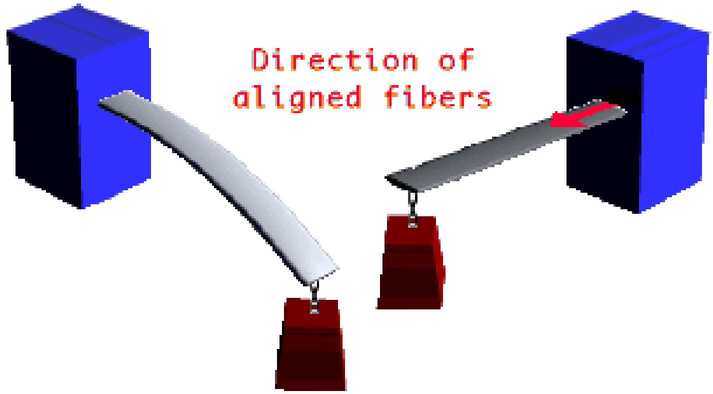
Balsa Wood Core

Foam Core

WHY USE FIBER REINFORCED COMPOSITES ?



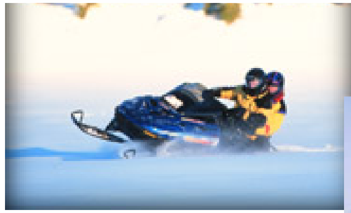
Composites have higher strength than traditional materials due to aligned fibers carrying the load



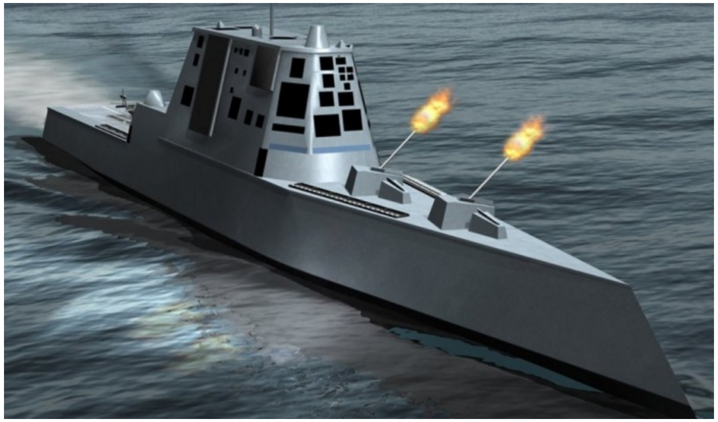
Composites are stiffer than conventional materials of the same weight due to their adaptive nature one can align fibers in the direction to carry the load

Composites are lighter than traditional materials due to their tailorability they can be designed to minimize weight without sacrificing strength

Commercial Applications



Military Applications



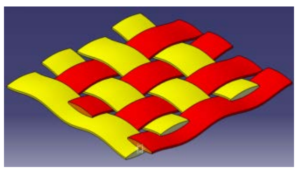
Multifunctional Composites

- Composite structures can be designed to improve
  - Strength
  - Stiffness
  - Weight
  - Fatigue
  - Corrosion
  - Wear
  - Thermal behavior
  - Acoustic
  - Optical
  - RF Properties

- Improve more than one property?
  - Multifunctional Composite Materials

"The Electromagnetic and Mechanical Properties of Structural Composites: Overall Technical Vision and Approach"

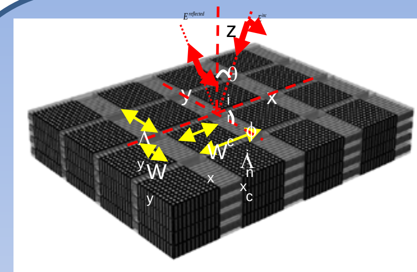
Reinforcement Architecture



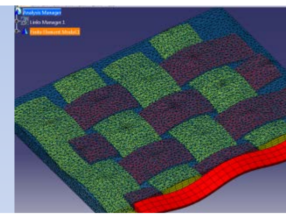
Fabric CAD Model Database

Polymer

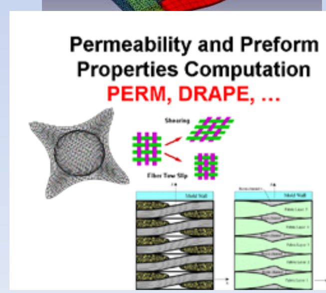
"Additives"



Electromagnetic Performance



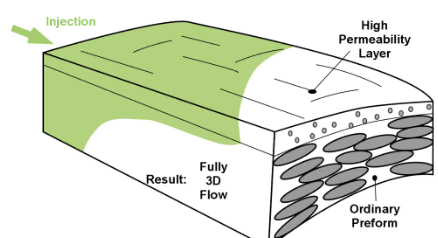
Structural Performance



Manufacturability

Model-based Design & Optimization

Optimal Reinforcement Prototyping



Composite fabrication Experimental Validation

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Engineering the EM properties of a Structural Composite

We have been specifically working in two main areas:

(1) How do we integrate 3D conductor networks within a structural composite

Applications:

- ❑ Antenna integration
- ❑ Metamaterial integration (meta-composite)
- ❑ Frequency selective surfaces
- ❑ Integrated electronics

(2) How do we create favorable EM properties by varying the dielectric and magnetic properties of the composite

Applications:

- ❑ Radomes
- ❑ Integrated lenses
- ❑ Low observables (e.g. radar absorbing composites)
- ❑ Integrated beam forming

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Engineering structural composites with attractive EM properties

What do we mean "attractive EM properties"?

Depends on the application but some examples include

- Antenna integration
  - Low material losses
  - Integrated impedance matching
  - Spatially varying dielectric properties
  - High impedance ground planes

- Structural radomes, ballistic radomes …
  - Low material losses
  - Integrated impedance matching
  - Integrated frequency selective surfaces

- Radar absorbing composite (RAC)
  - Graded conductivities
  - Wideband impedance matching

Bottom line: We would like the ability to control ε, μ and σ in x, y and z

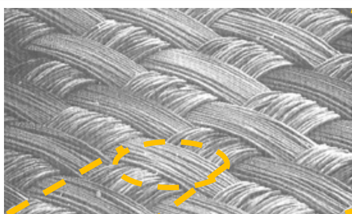
Broadband EM Properties of Woven Fabric Composites

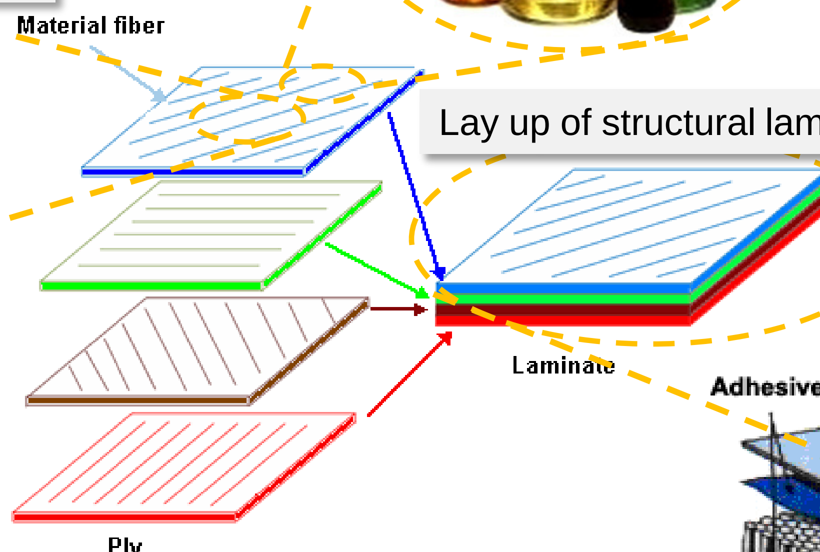
There are five main variables that determine the broadband EM response of a woven fabric composite

1. The bulk EM properties of the fibers
2. The bulk EM properties of the polymer matrix
3. The weave architecture of the fabrics
4. The lay up geometry of the structural laminate
5. The geometry of the structure

Bulk properties of polymer matrix

Fabric weave architecture

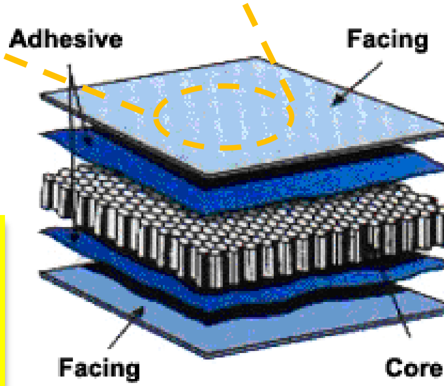




Lay up of structural laminate

Bulk properties of glass

What determines the EM properties of a structural composite?



Composite structure

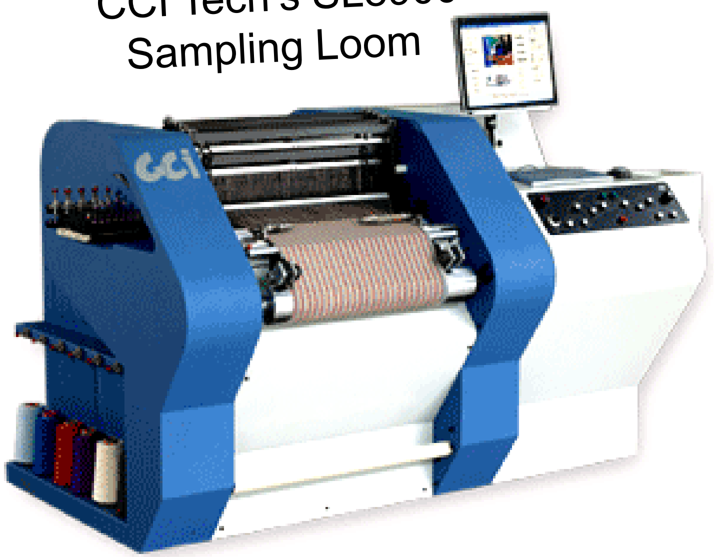
Engineering structural composites with attractive EM properties

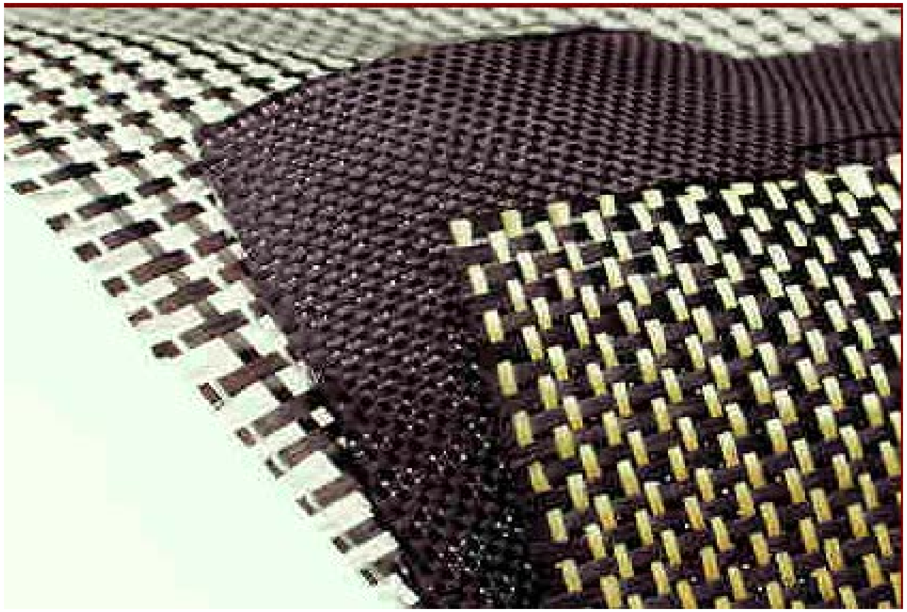
How can we "engineer" attractive EM properties without sacrificing mechanical properties?

1. Fabric Level

- Engineer hybrid fiber bundles or hybrid fabrics that combine fiber types (e.g. glass/polymer or glass/carbon)

CCI Tech's SL8900 Sampling Loom

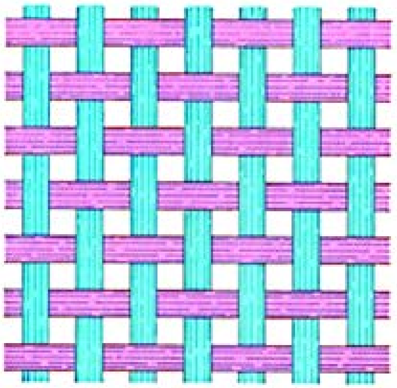




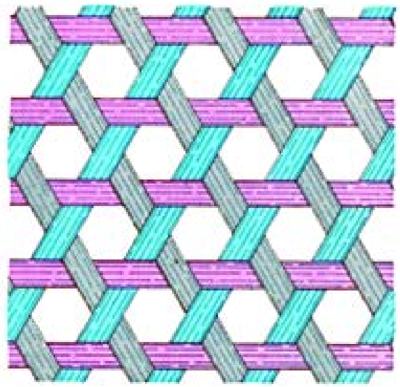
Dielectric Properties of Standard Fiber Types

	Glass			Carbon	Polymer
	E-glass	S-glass	Quartz		Kevlar, Vectran, PE
Mechanical	Good	Good	Good	Very Good	Very poor in compression
Dielectric Constant	6.0 – 6.3*	5.1 - 5.3	3.7	NA	2.3 - Topaz
Loss Tangent	0.002-0.003* (@18 - 40 GHz)	0.003 - 0.004 (@18 - 40 GHz)	0.0001-0.0003 (@18 - 40 GHz)	Very High σ = 50,000 – 70,000 S/m	0.0003***- Topaz
Cost	Low 0.68-1.81 $/lb	Medium ~10$/lb	Very High ~100 $/lb	High 10-50 $/lb	High 10-50 $/lb

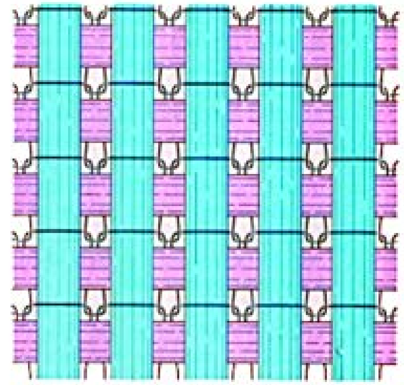
EXAMPLES OF FIBER REINFORCEMENT



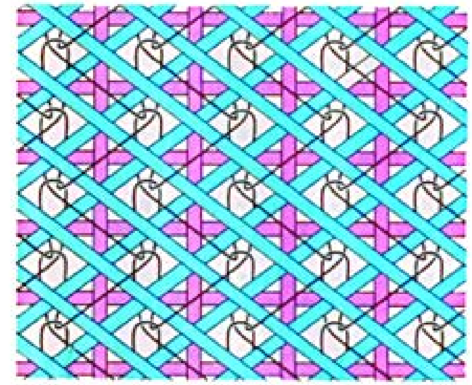
Biaxial Weave



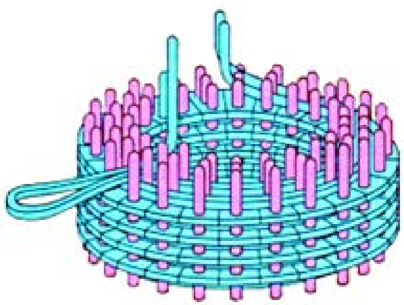
Triaxial Weave



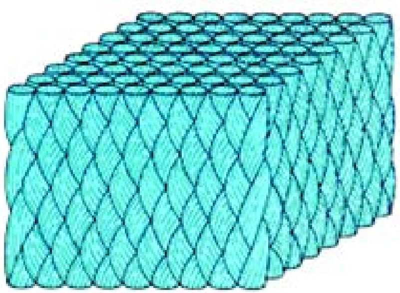
Knit



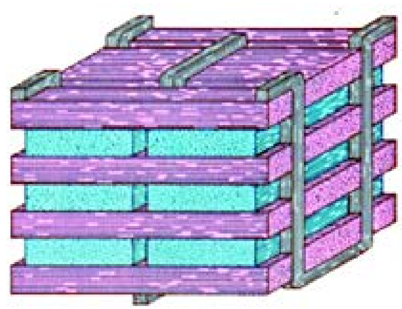
Warp Knit



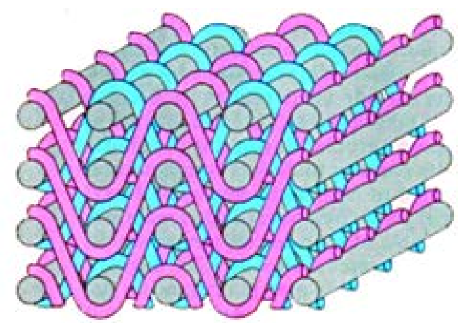
3-D Cylindrical Construction



3-D Braiding



3-D Orthogonal Fabric



Angle-Interlock Construction

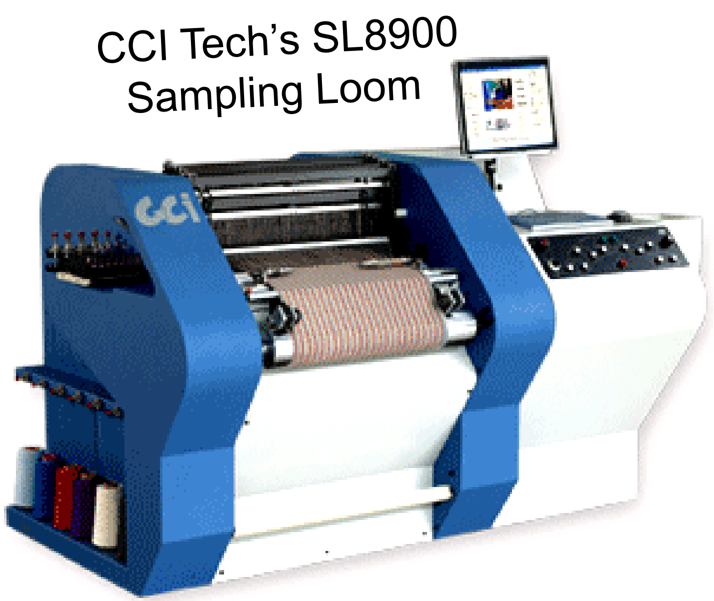
illustrations—Scientific American

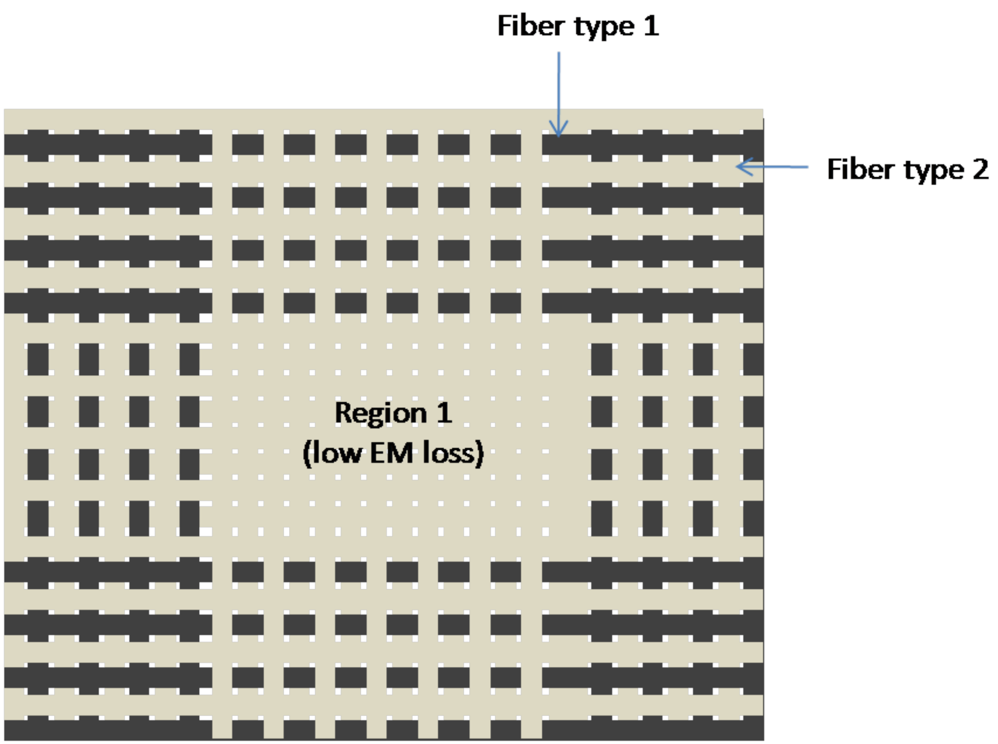
Engineering structural composites with attractive EM properties

How can we "engineer" attractive EM properties without sacrificing mechanical properties?

1. Fabric Level

- ❑ Large scale heterogeneities at the fabric level



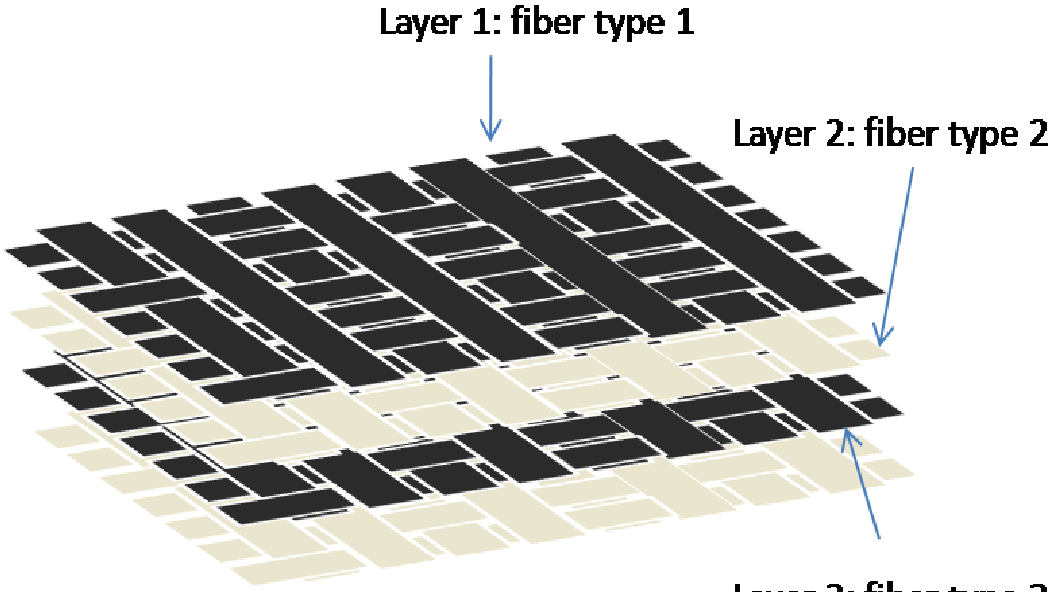


Engineering structural composites with attractive EM properties

How can we "engineer" attractive EM properties without sacrificing mechanical properties?

1. Fabric Level

- Engineer heterogeneous panels in which fabrics vary layer by layer

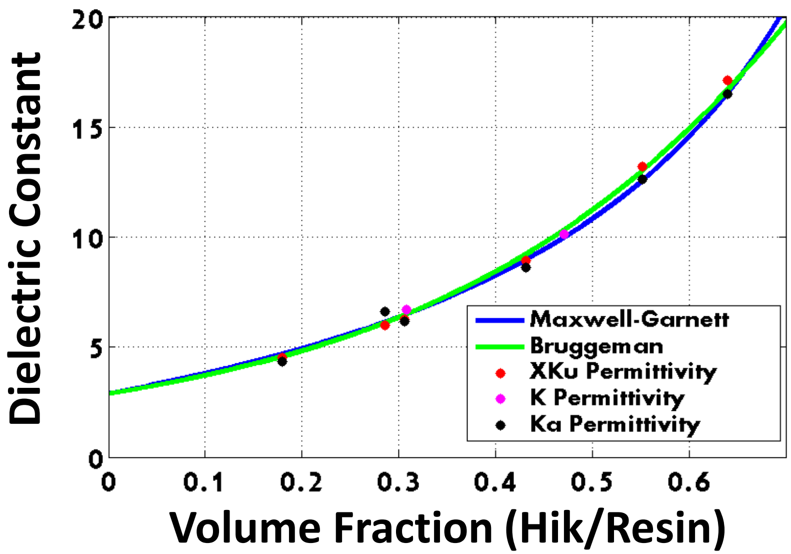


Engineering structural composites with attractive EM properties

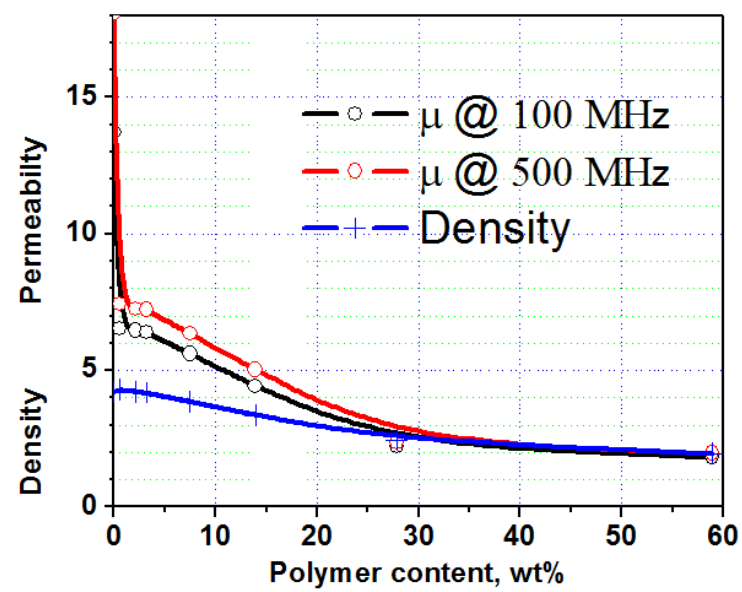
How can we "engineer" attractive EM properties without sacrificing mechanical properties?

2. Dielectrically loaded resins

- Polymer resin loaded with dielectric, conductive and magnetic particles



Mixture of vinyl ester polymer resin (510 A) with HiK powder (Emerson and Cuming)



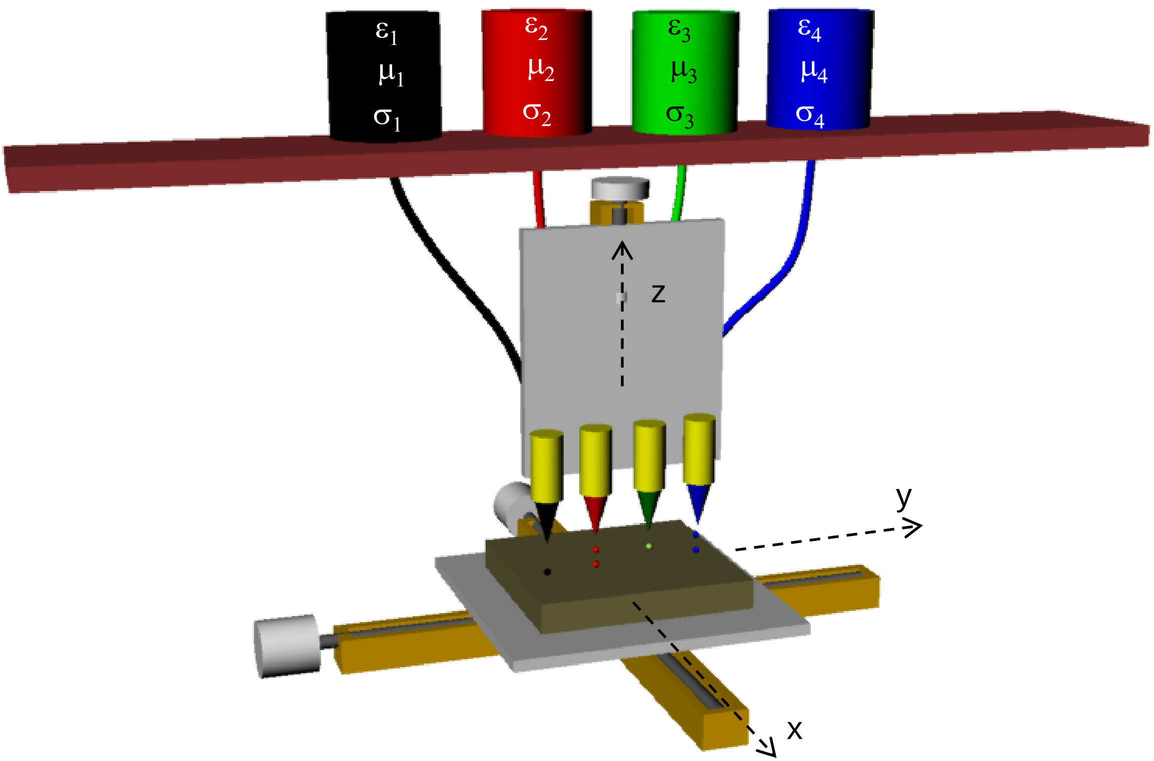
Polymer mixed with magnetic nano-particles (Spectrum Magnetics LLC)

Engineering structural composites with attractive EM properties

How can we "engineer" attractive EM properties without sacrificing mechanical properties?

2. Dielectrically loaded resins

3D Printing of Electromagnetically Loaded Resins



Three major types of polymer matrix materials

- **Thermoset**

A **thermosetting plastic**, also known as a **thermoset**, is polymer material that **irreversibly** cures. The cure may be done through heat, through a chemical reaction (two-part epoxy, for example), through a photo-initiator (UV) or irradiation such as electron beam processing.

- **Thermoplastic**

Thermoplastic is a polymer that turns to a liquid when heated and freezes to a very glassy state when cooled sufficiently. Thermoplastic polymers differ from thermosetting polymers in that they can be remelted and remolded.

- **Elastomer**

An **elastomer** is a polymer with the property of viscoelasticity. The term, which is derived from *elastic polymer*, is often used interchangeably with the term rubber.

Dielectric Properties of Standard Resin Types

	Epoxies (low temp. thermosetting polymer resin)	Cyanate Ester (high temp. thermosetting polymer resin)	Vinyl Ester (low temp. thermosetting polymer resin)	Thermoplastics (Teflon, PP, PE, PEEK, PEI)
Dielectric Constant	3.0 – 4.0*	2.7-2.9	3.0 – 4.0*	2.0-3.0
Loss Tangent	0.03-0.05* (@18 - 40 GHz)	0.003** (@18 - 40 GHz)	0.03-0.05* (@18 - 40 GHz)	~0.0004*** (@18 - 40 GHz)
Cost	Low	High	Low	Medium
Processing	Simple mature process	Medium	Simple mature process	More Difficult (High Temp)

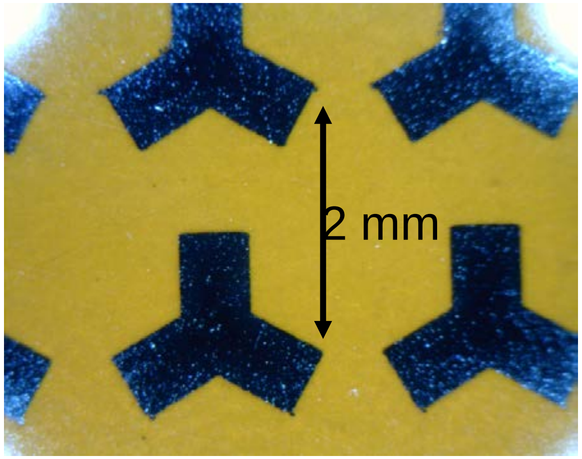
* - 510A vinyl ester resin
** - TenCate BTCy-1 cyanate ester resin
*** - Topaz thermoplastic resin

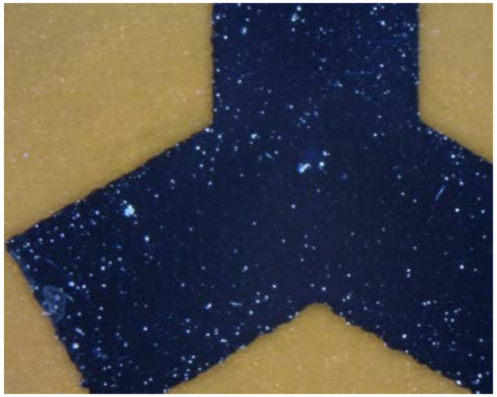
Engineering structural composites with attractive EM properties

How can we "engineer" attractive EM properties without sacrificing mechanical properties?

3. Direct write or conductive inks

Inkjet printing of conductive inks



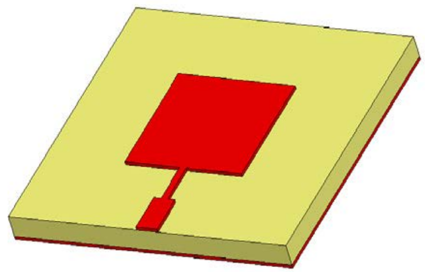


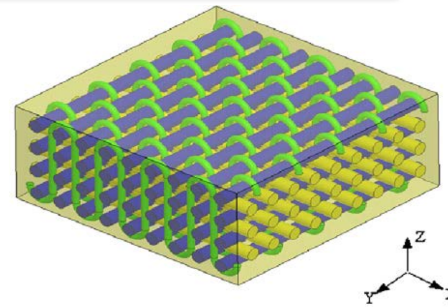
Inkjet printing system, Dr. Kate Duncan, Army CERDEC

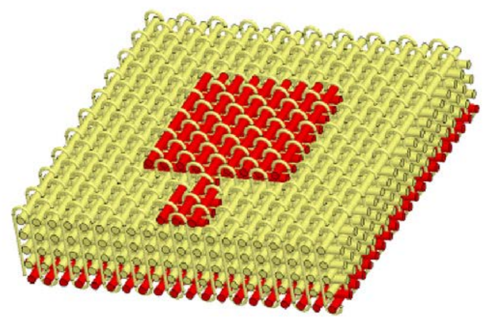
Engineering structural composites with attractive EM properties

How can we "engineer" attractive EM properties without sacrificing mechanical properties?

4. Embroidery of conductive threads and yarns





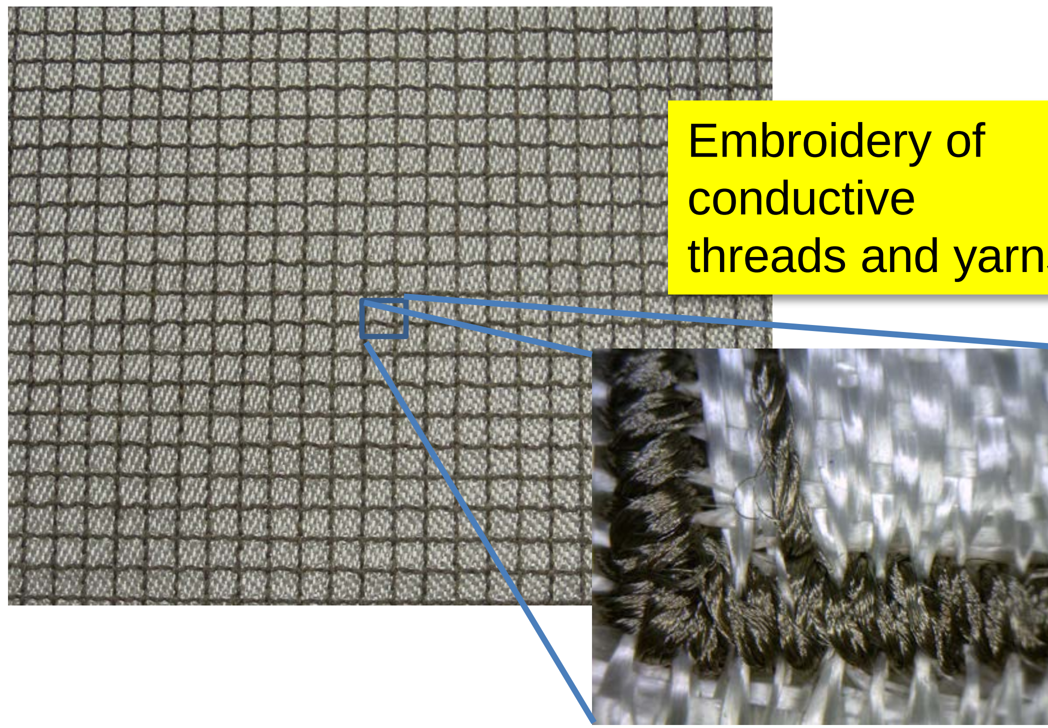


L. Yao, M. Jiang, D. Zhou, F. Xu, D. Zhao, W. Zhang, N. Zhao, Q, Jiang and Y. Qiu, "Fabrication and characterization of microstrip array antennas integrated in the three dimensional orthogonal woven composite", Composites: Part B 42 (2011) 885–890

Engineering structural composites with attractive EM properties

How can we "engineer" attractive EM properties without sacrificing mechanical properties?

4. Embroidery of conductive threads and yarns



Embroidery of conductive threads and yarns

Engineering structural composites with attractive EM properties

How can we "engineer" attractive EM properties without sacrificing mechanical properties?

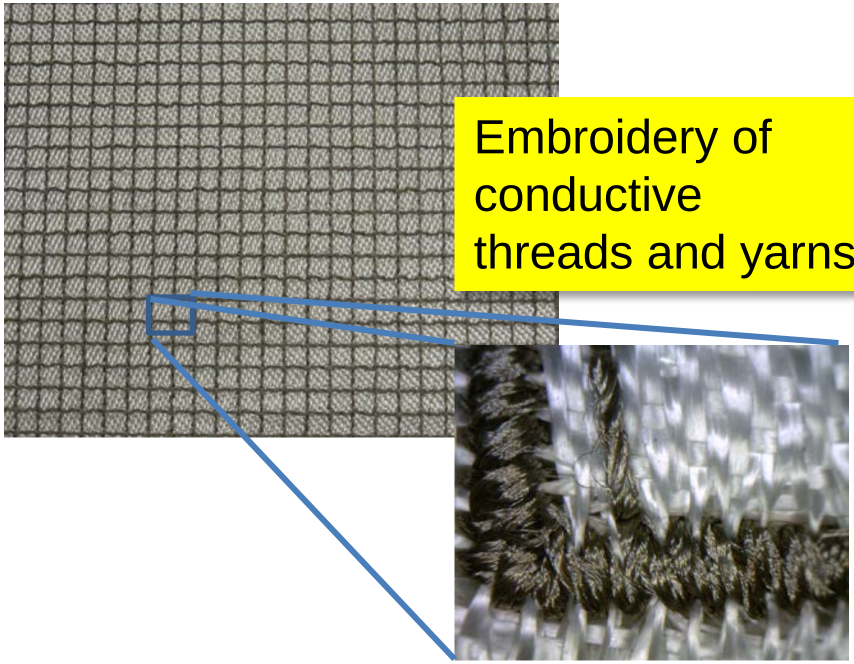
4. Embroidery of conductive threads and yarns

Shieldex 117/17/17

Shieldex 234/23

Tibtech Conductib

Tibtech Thermotech



Embroidery of conductive threads and yarns

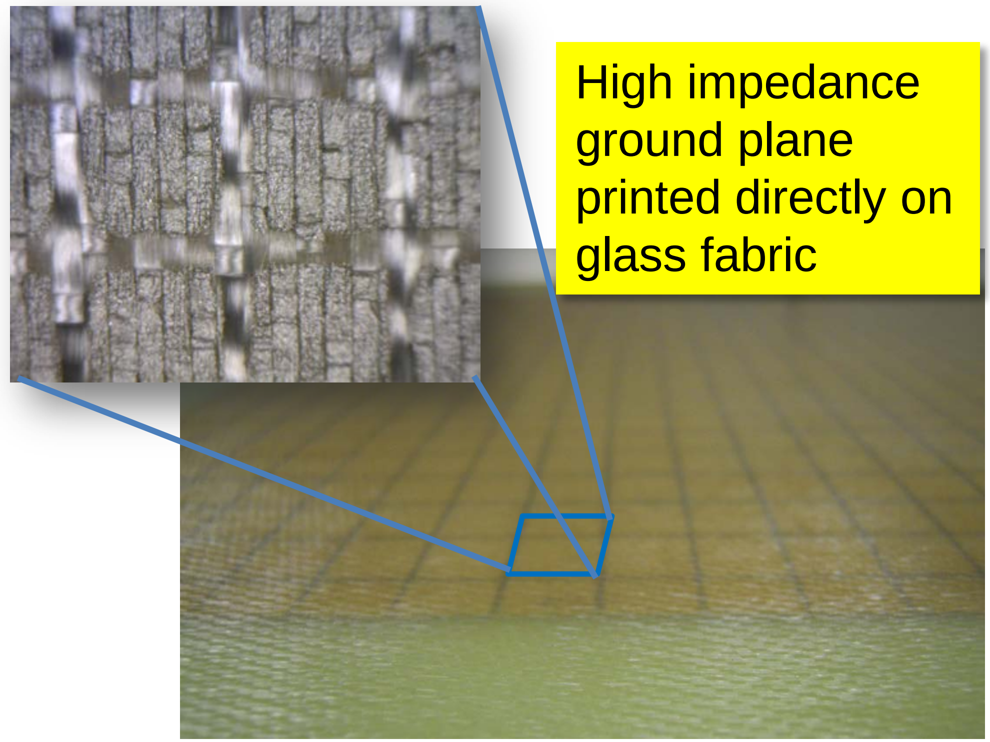
DC resistivity's varied from ~0.1 to ~10 Ohms/cm

Engineering structural composites with attractive EM properties

How can we "engineer" attractive EM properties without sacrificing mechanical properties?

5. Direct write or conductive inks

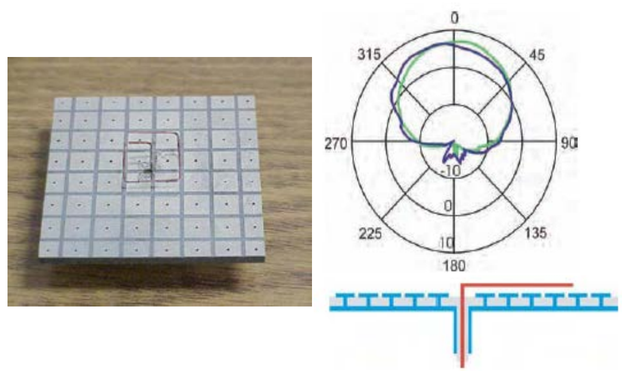
- ❑ **Integrated Conductors in Structural Composites: <u>Screen Printing</u>**



Engineering structural composites with attractive EM properties

- **Artificial impedance surfaces are typically periodic arrangements of conductors and/or dielectrics that are used to create a specific impedance condition for a band of frequencies.**
- **The surface impedance affects the complex transmission and reflection coefficients.**
- **These structures can be used for**
    - **FSS passbands/stopbands (e.g. for aircraft radar radomes)**
    - **Zero-degree reflection phase (e.g. for an antenna close to a ground plane)**
    - **Surface wave suppression (e.g. for closely spaced antennas on the same ground plane)**

FSS used in an aircraft radar radome.



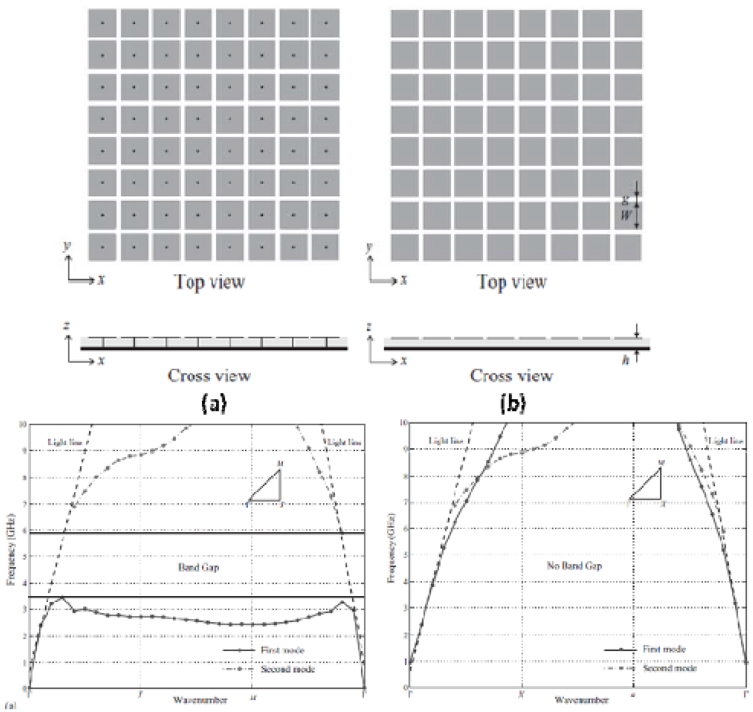
Zero-degree reflection phase for an antenna close to ground plane

Surface wave suppression for closely spaced antennas – good for 4G cell phones

Engineering structural composites with attractive EM properties

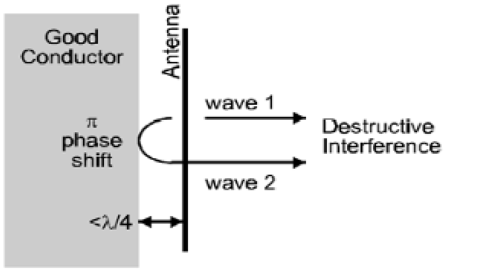
Patch loaded grounded dielectric slab – The capacitive reactance of the patches in parallel with the inductive reactance of the grounded dielectric layer causes a high impedance condition at a resonant frequency. This high impedance causes a zero-degree reflection phase at the resonant frequency.

Mushroom-type EBG – The periodic vertical posts (vias) create a stopband for TM waves. EBG's exhibit surface wave suppression in addition to a zero-degree reflection phase.

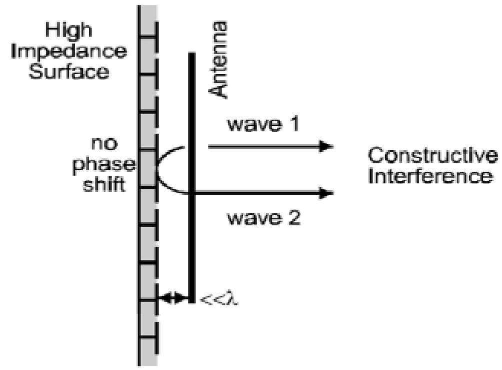


Mushroom-type EBG

Patch loaded grounded dielectric slab



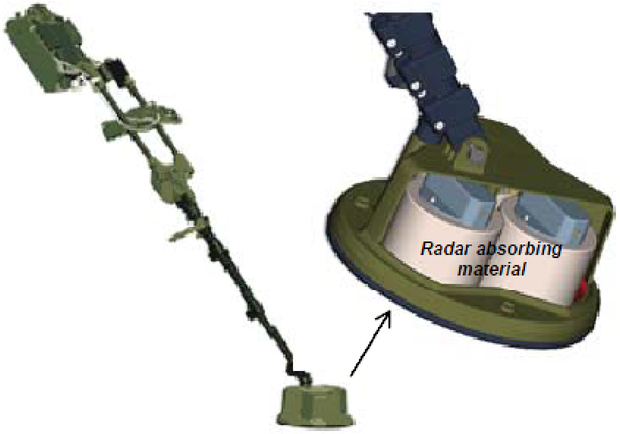
***Traditional Approach**: Reflection from electrical conductor causes 180º phase shift*



***Reflection from EBG:** "magnetic conductor" causes no phase shift upon reflection*

Engineering structural composites with attractive EM properties

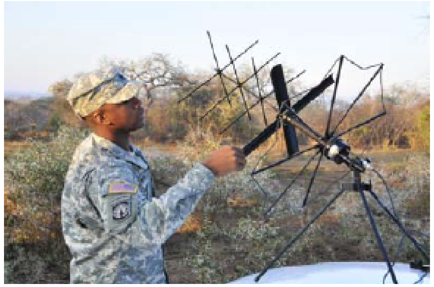
Potential DoD applications for low profile, broadband antennas



Landmine detection sensor requires small, lightweight, low power components

Airborne detection and surveillance systems require conformal antennas

Forward looking ground penetrating radar systems require smaller antenna arrays

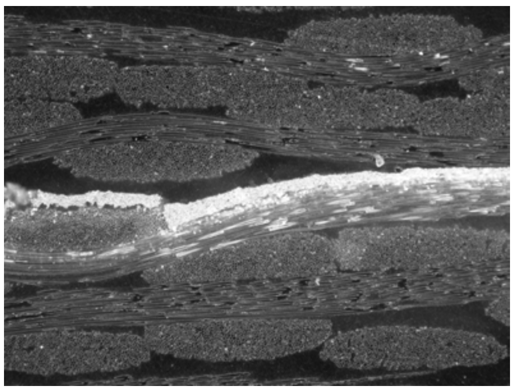


Directional communications antennas could be more compact

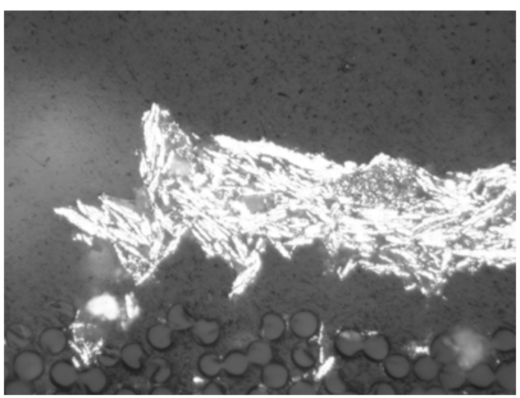
Engineering structural composites with attractive EM properties

How can we "engineer" attractive EM properties without sacrificing mechanical properties?

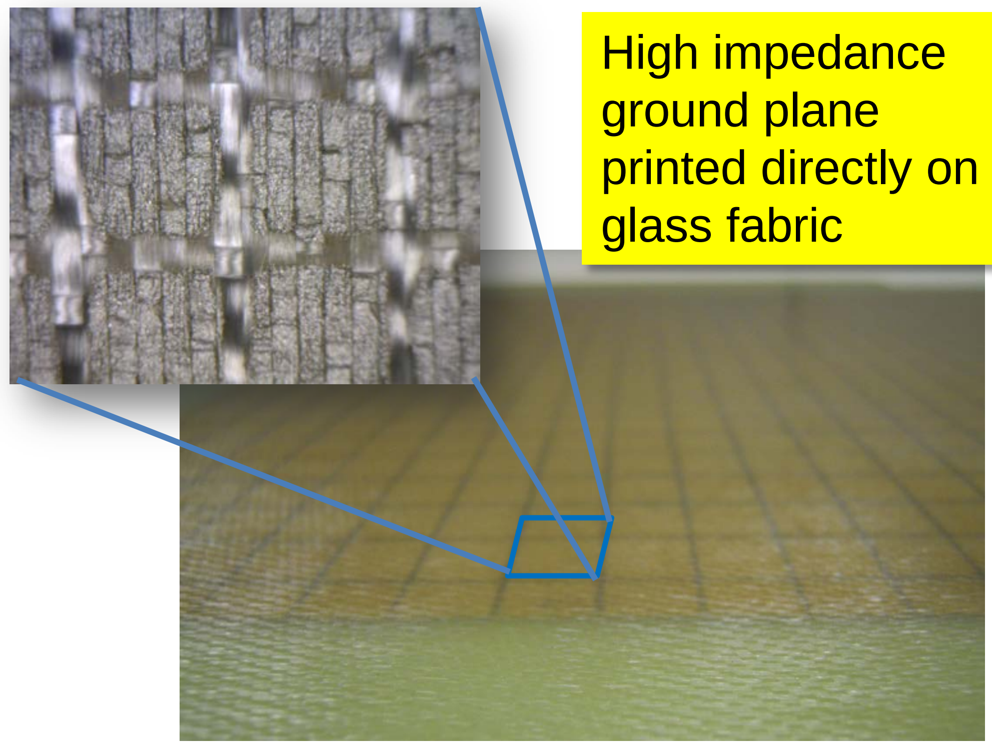
Embedded Silver Ink 10x



Embedded Silver Ink 100x



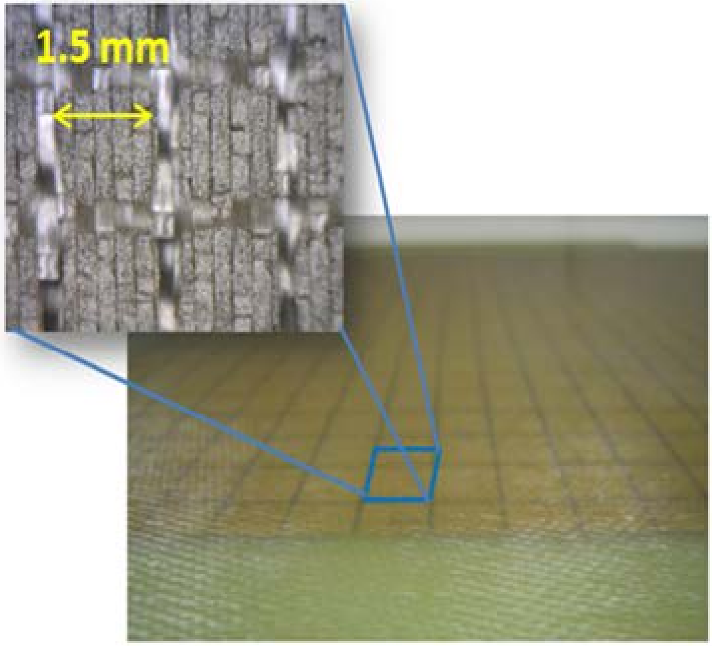
- ❑ **Integrated Conductors in Structural Composites: <u>Screen Printing</u>**



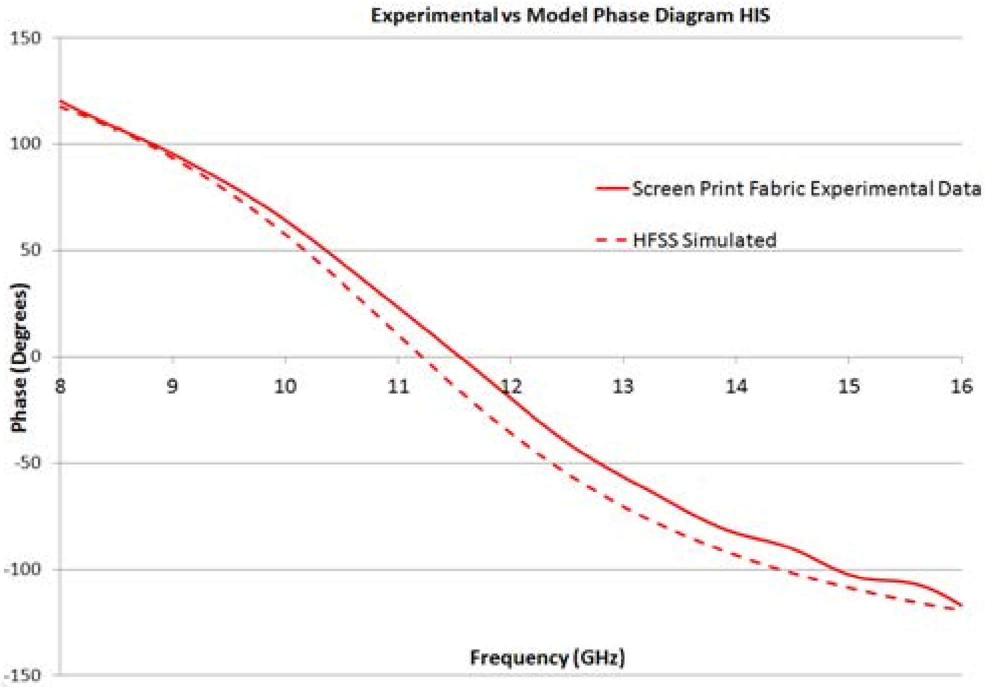
Engineering structural composites with attractive EM properties

How can we "engineer" attractive EM properties without sacrificing mechanical properties?

High impedance ground plane printed directly on glass fabric



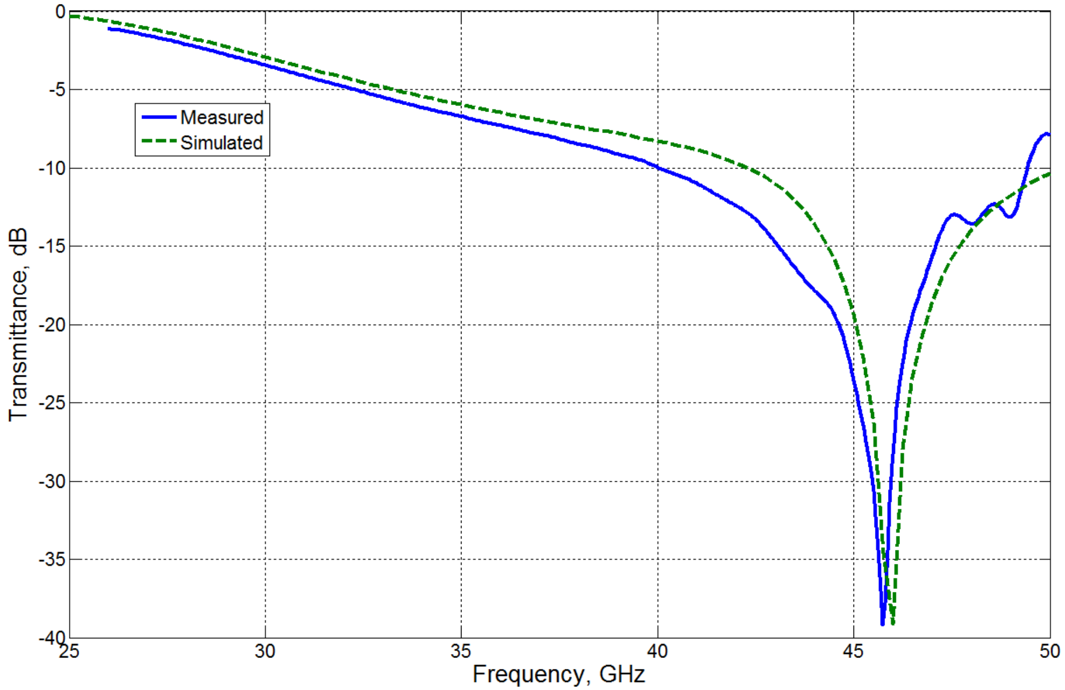
- **Integrated Conductors in Structural Composites: Screen Printing**

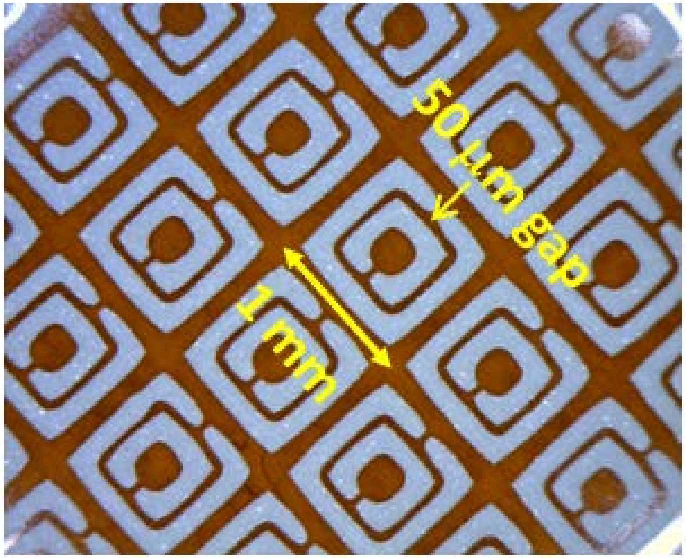


Engineering structural composites with attractive EM properties

How can we "engineer" attractive EM properties without sacrificing mechanical properties?

- ❑ **Integrated Conductors in Structural Composites: <u>Screen Printing</u>**



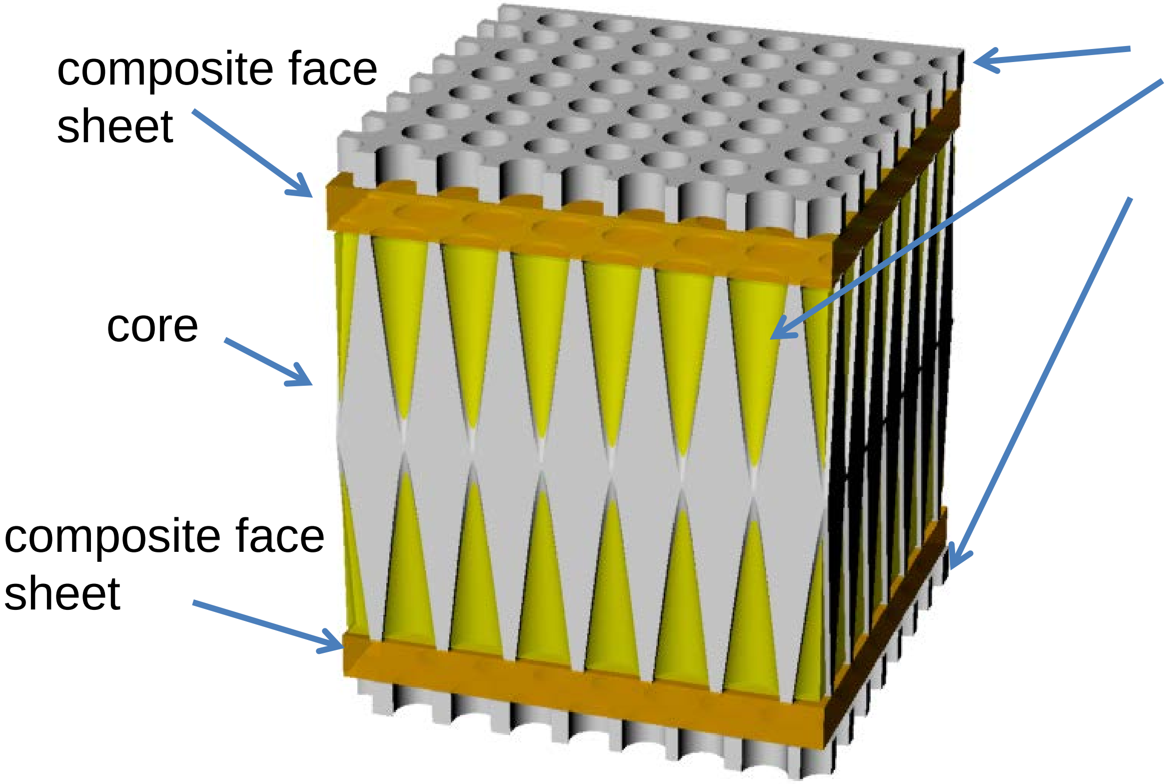


Split ring resonators screen printed on a Kapton. Total sample size 20"x20"

Engineering structural composites with attractive EM properties

How can we "engineer" attractive EM properties without sacrificing mechanical properties?

6. Subwavelength surface texturing



Impedance matching is accomplished on the surface and within the core using a subwavelength moth-eye approach

Presentation Outline

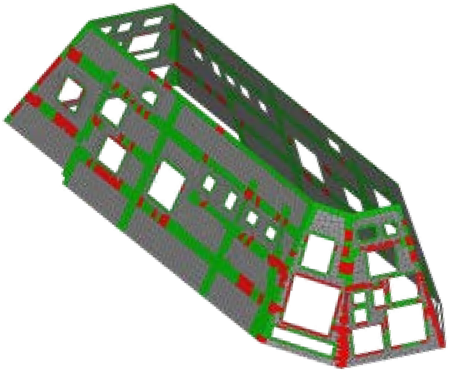
- ❑ Motivation for "engineering" the EM properties of structural composites
- ❑ Who we are (some shameless self-promotion)
- ❑ Structural Composites: A brief overview
- ❑ Engineering structural composites with attractive EM properties
- ❑ **Application**

  (1) Progress towards a broadband structural radome design

  - **Traditional approach**
  - **Motheye approach**

Motivation

- The Navy has taken advantage of new antenna concepts that has enabled the development of integrated topside designs for numerous platforms.
- An integrated topside provides multi-functionality (balancing structural and antenna properties)
  - Integrating the structural regime and antenna functionality positively impacts: Structural Efficiency, EM Control, and densely spaced apertures
  - Integrated topside approach resulted in reduced structural integrity, decreased stiffness, increased weight due to structural reinforcements, and most importantly increased cost



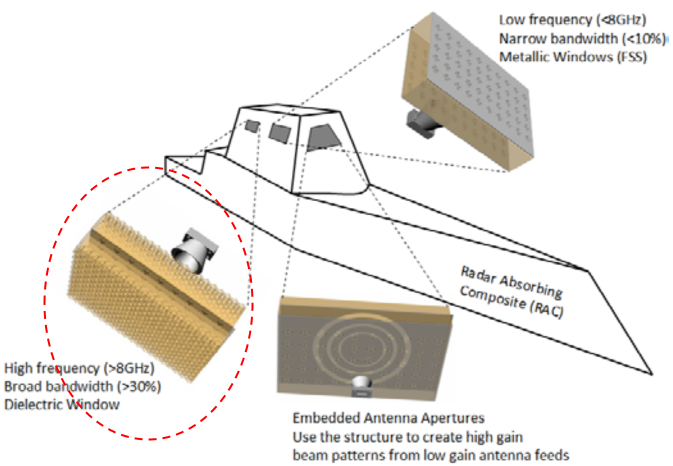
Develop advance composite materials that enable the integrated topside approach with minimal impact to cost and mechanical/structural properties

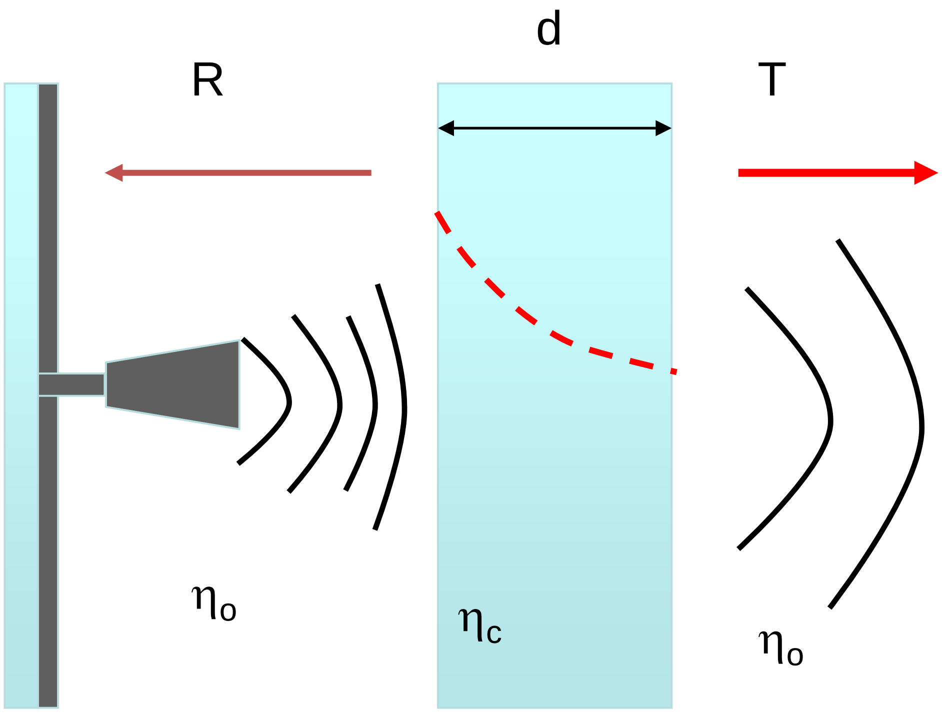
Radomes

Idea: RF transparent windows formed within a composite skin would allow radiating elements to be placed behind the structure, maintaining the structural integrity of the composite and protecting the antennas.

Q: Why can't we just do that now?
A: Two main reasons:

(1) Fresnel reflection
(2) Material loss



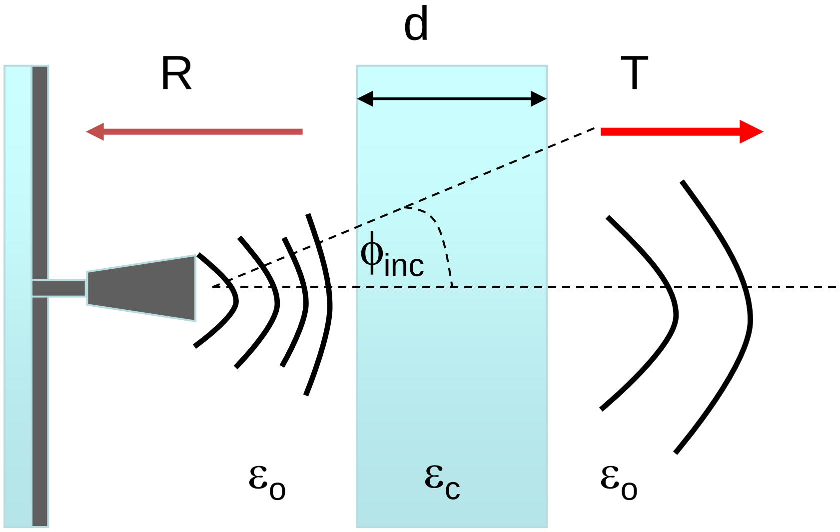


Dielectric Windows

Fresnel reflections

$$T_{\perp} = 1 - \left[\frac{\dfrac{1-\sqrt{\varepsilon_c}\cos(\theta_{inc})}{1+\sqrt{\varepsilon_c}\cos(\theta_{inc})}\left(1-e^{-2j\frac{2\pi}{\lambda}\sqrt{\varepsilon_c}\,d\cos(\theta_{inc})}\right)}{1-\left(\dfrac{1-\sqrt{\varepsilon_c}\cos(\theta_{inc})}{1+\sqrt{\varepsilon_c}\cos(\theta_{inc})}\right)^2 e^{-2j\frac{2\pi}{\lambda}\sqrt{\varepsilon_c}\,d\cos(\theta_{inc})}} \right]^2$$

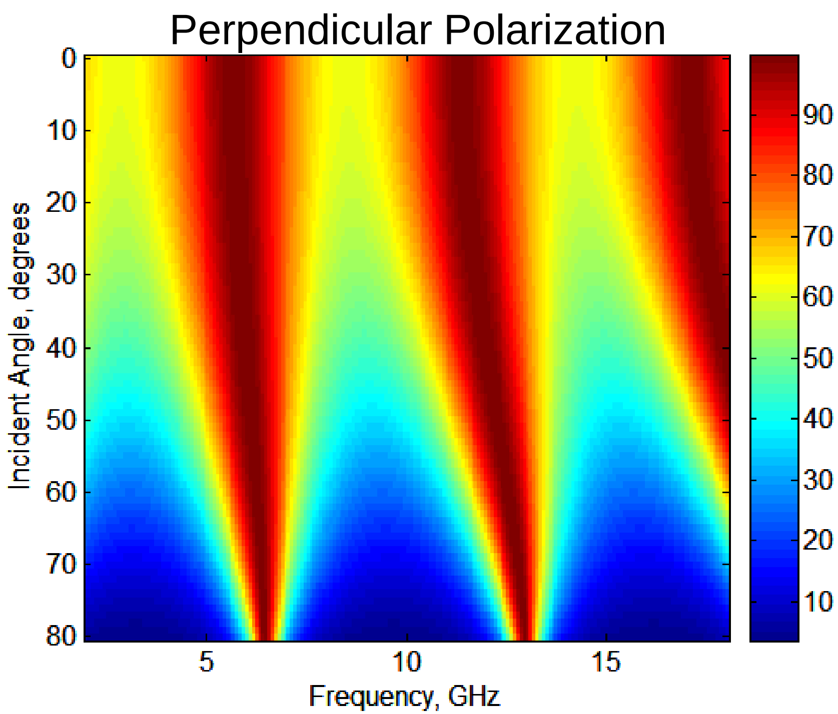
$$T_{\parallel} = 1 - \left[\frac{\dfrac{1-\sqrt{\varepsilon_c}/\cos(\theta_{inc})}{1+\sqrt{\varepsilon_c}/\cos(\theta_{inc})}\left(1-e^{-2j\frac{2\pi}{\lambda}\sqrt{\varepsilon_c}\,d\cos(\theta_{inc})}\right)}{1-\left(\dfrac{1-\sqrt{\varepsilon_c}/\cos(\theta_{inc})}{1+\sqrt{\varepsilon_c}/\cos(\theta_{inc})}\right)^2 e^{-2j\frac{2\pi}{\lambda}\sqrt{\varepsilon_c}\,d\cos(\theta_{inc})}} \right]^2$$

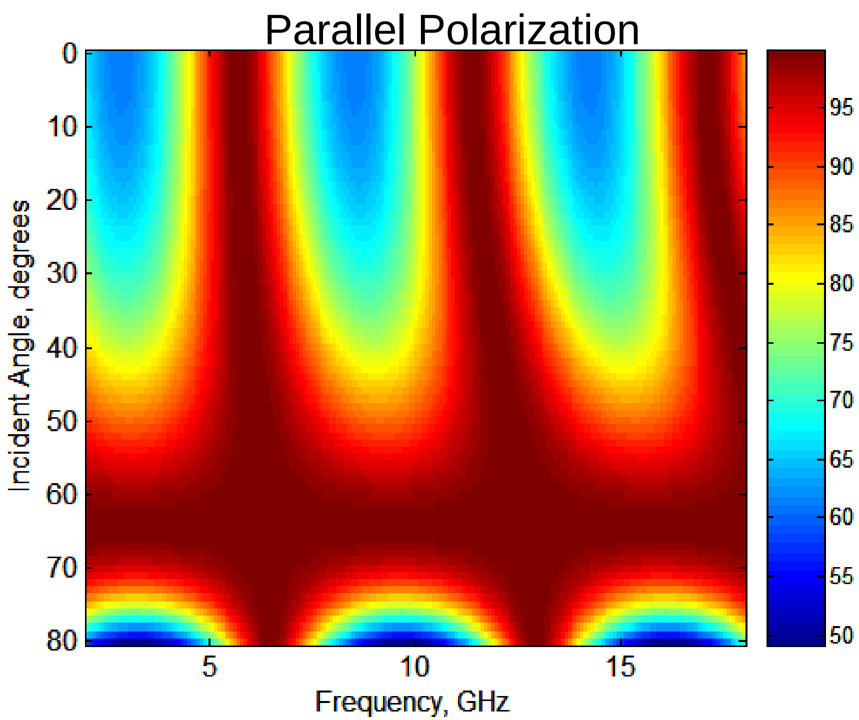


Dielectric Windows: Fresnel reflections

% Transmitted Energy

d=0.5 inch, ε_c=4.3



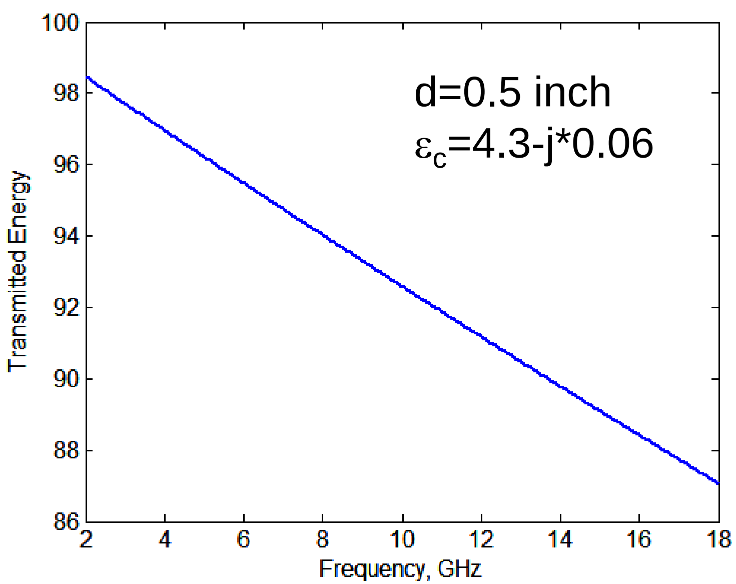


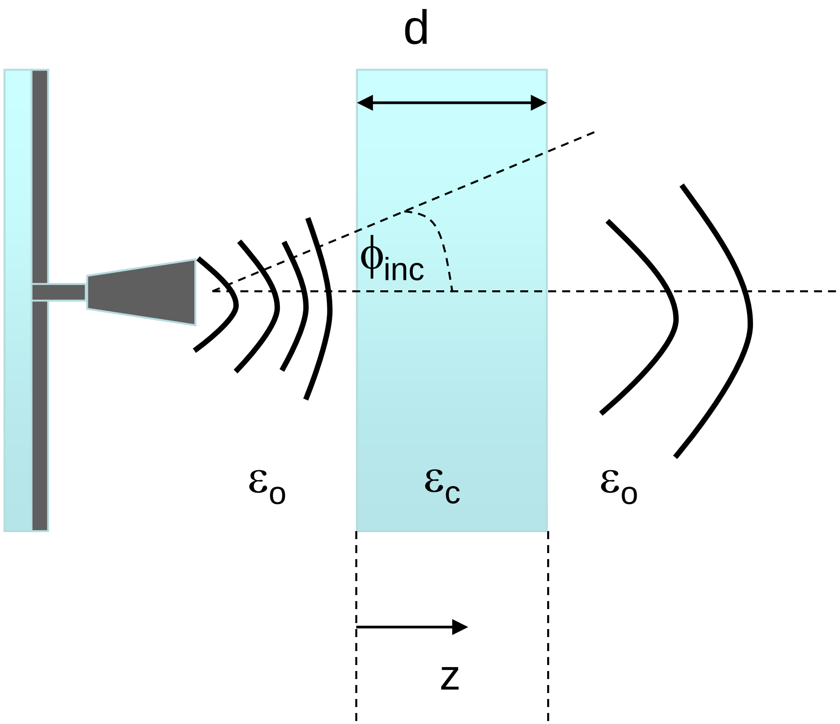
Dielectric Windows: Material Loss

(ignore all Fresnel reflections)

$$\varepsilon_c = \varepsilon' - j\varepsilon'' = \varepsilon'\left(1 - j\frac{\varepsilon''}{\varepsilon'}\right)$$

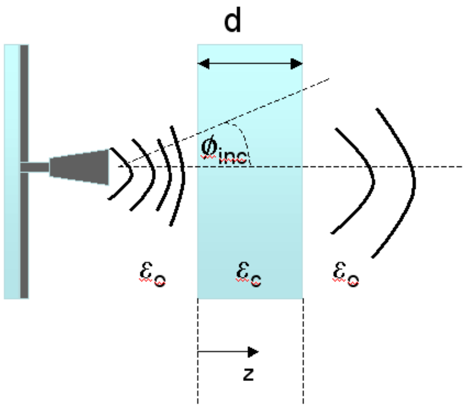
$$T(d) = \left| e^{\frac{j\omega}{c} d \sqrt{\varepsilon'} \sqrt{1 - j\left(\frac{\varepsilon''}{\varepsilon'}\right)}} \right|^2$$

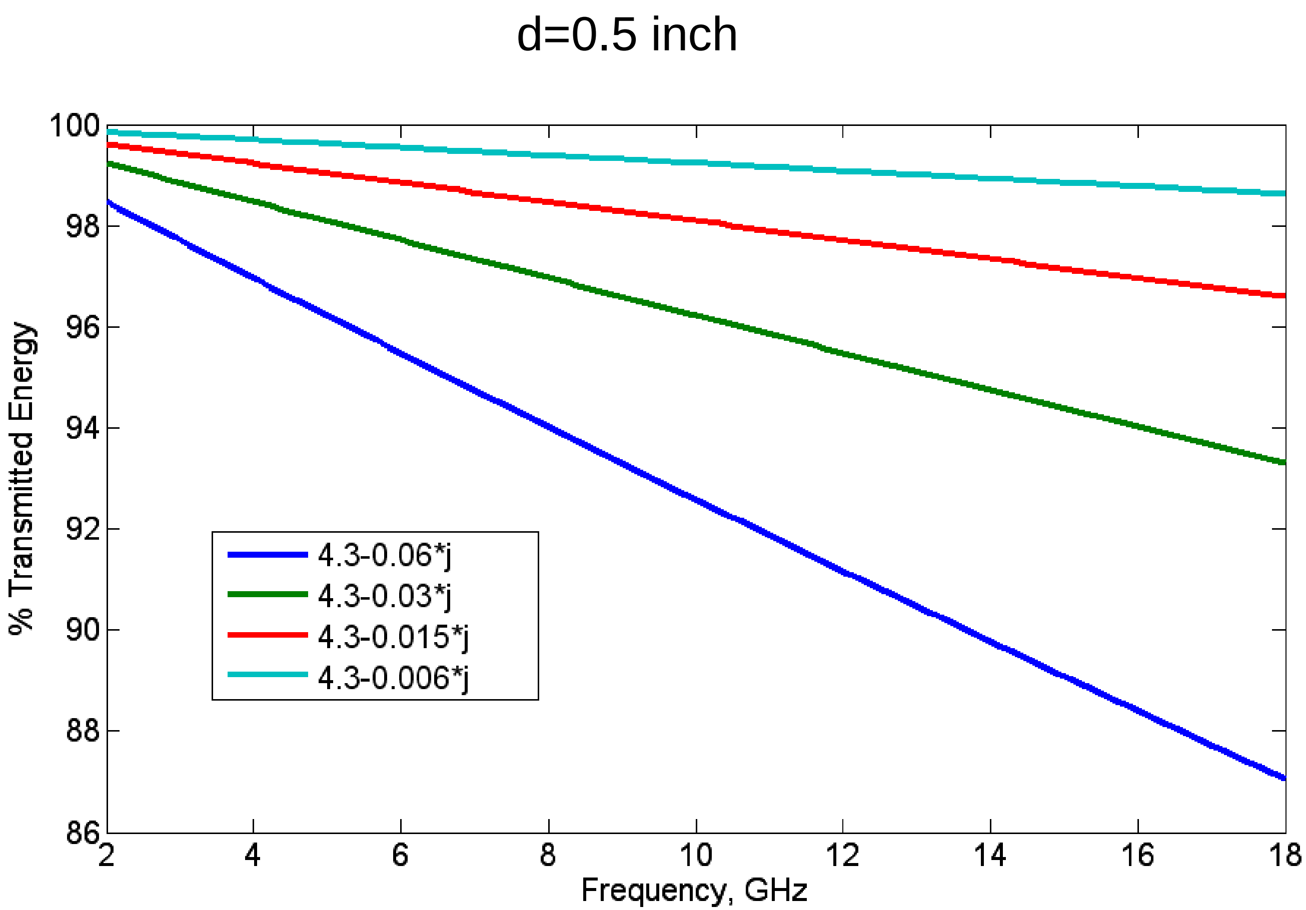




Dielectric Windows: Material Loss

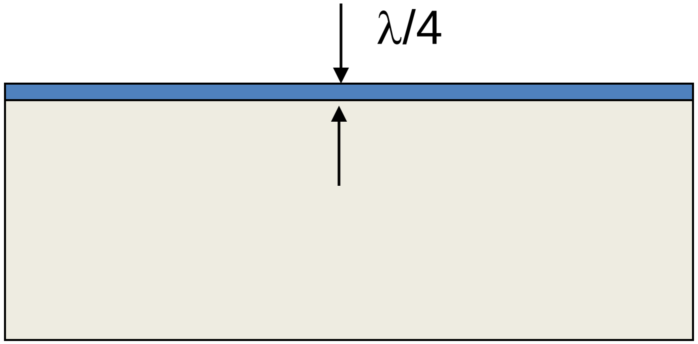
$$T(d) = \left| e^{\frac{j\omega}{c} d \sqrt{\varepsilon'} \sqrt{1 - j\left(\frac{\varepsilon''}{\varepsilon'}\right)}} \right|^2$$



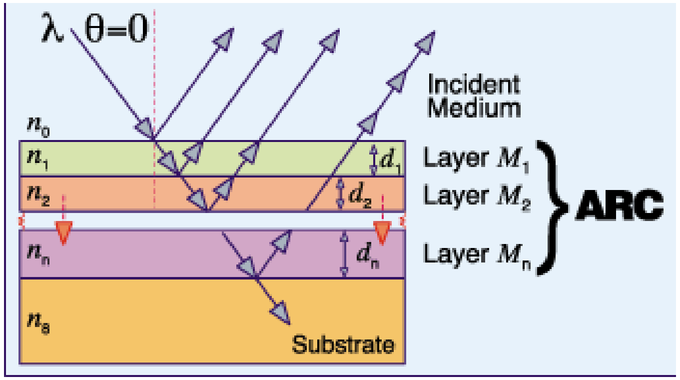


Common Types of Antireflective (AR) Surface Coatings

1. Single layer -The simplest interference AR coating consists of a single quarter-wave layer of transparent material whose refractive index is the square root of the substrate's refractive index. This theoretically gives zero reflectance at the center wavelength and decreased reflectance for wavelengths in a broad band around the center.

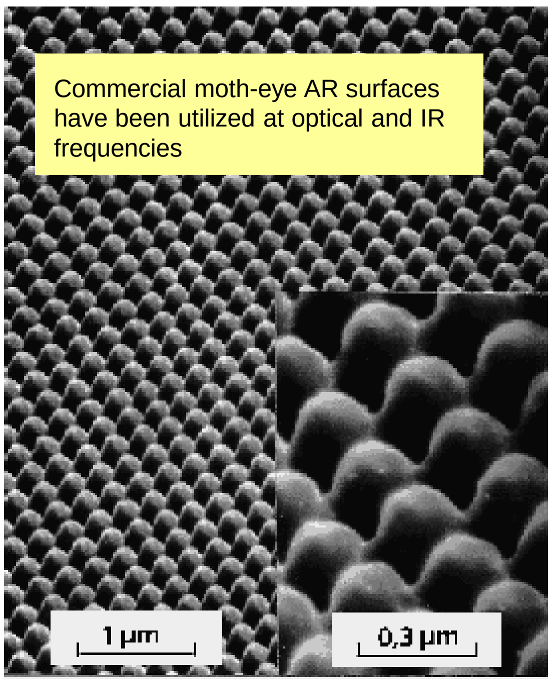


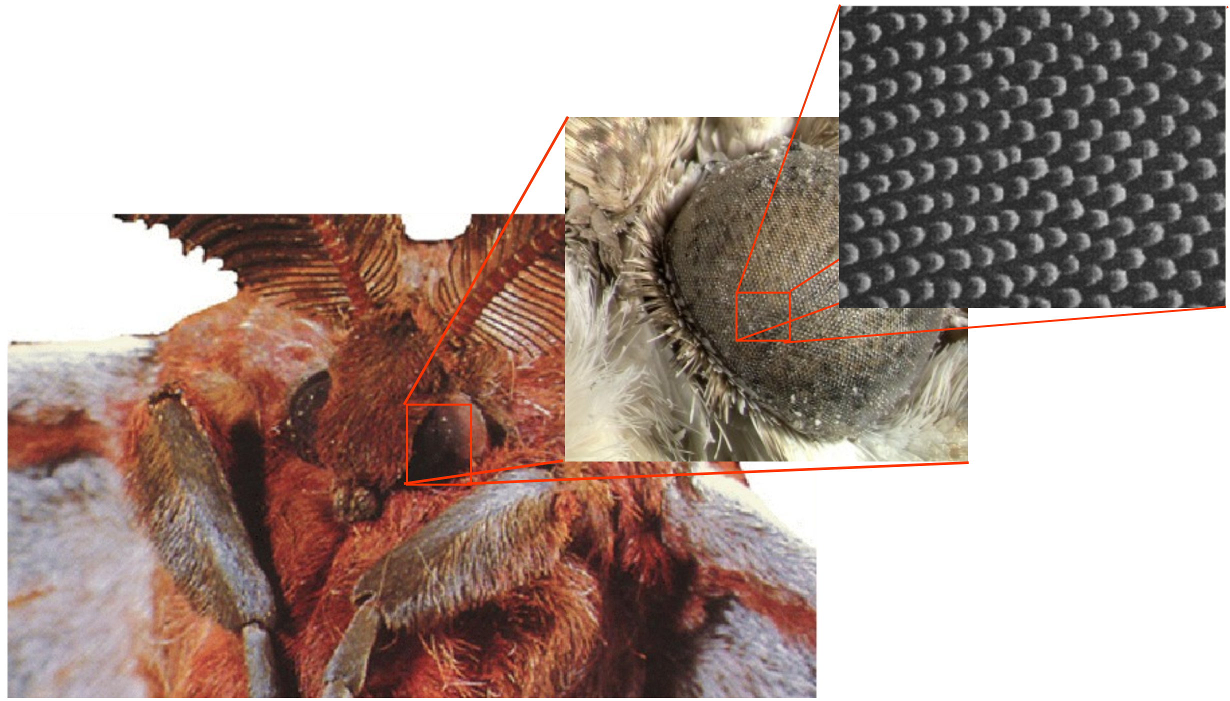
2. Multiple layers -By using multiple λ/4 layers of materials with precise dielectric properties, it is possible to design AR coatings much more broadband than a single layer.



Moth-eye Antireflective (AR) Surface Coatings

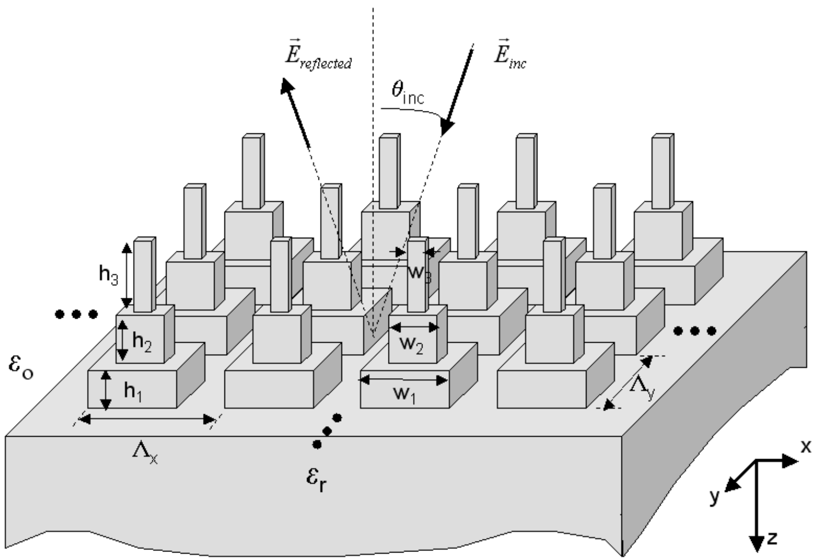
3. Moth eye AR coatings - By using sub-wavelength periodic structures it is possible to design AR surfaces over relatively large bandwidths and incident angles.

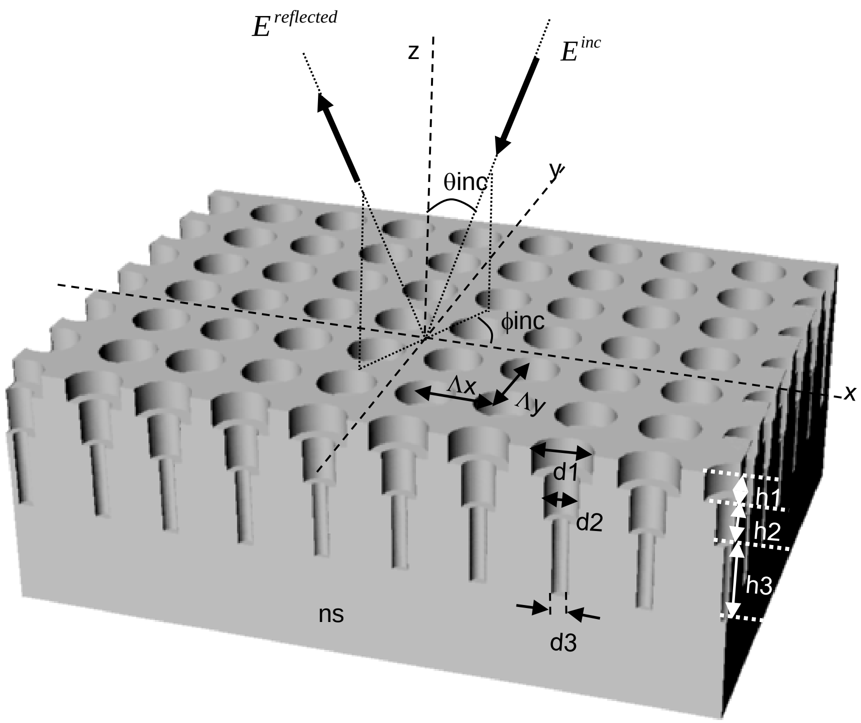




Mark Mirotznik, Brandon Good, Paul Ransom, David Wikner and Joseph Mait, "Broadband Antireflective Properties of Inverse Motheye Surfaces", IEEE Antennas and Propagation, Vol. 58 (September 2010).

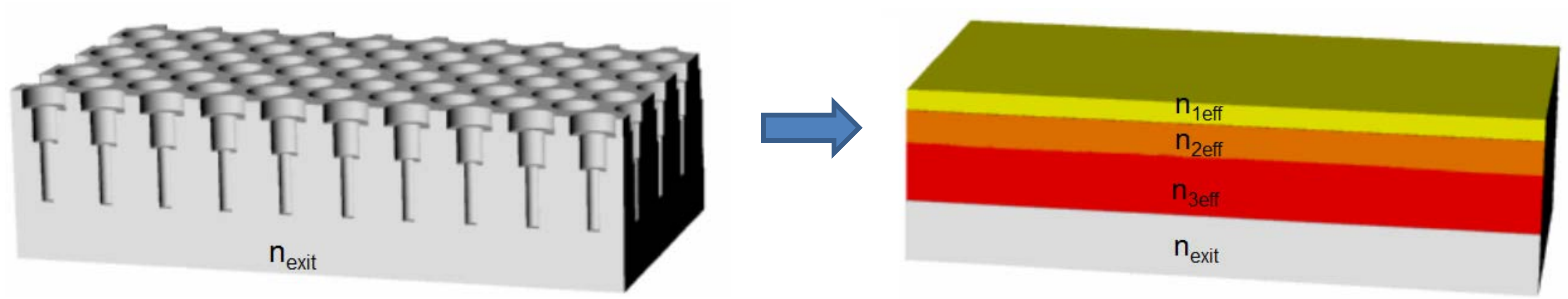
Design of Antireflective coating using “Moth-eye” subwavelength surfaces





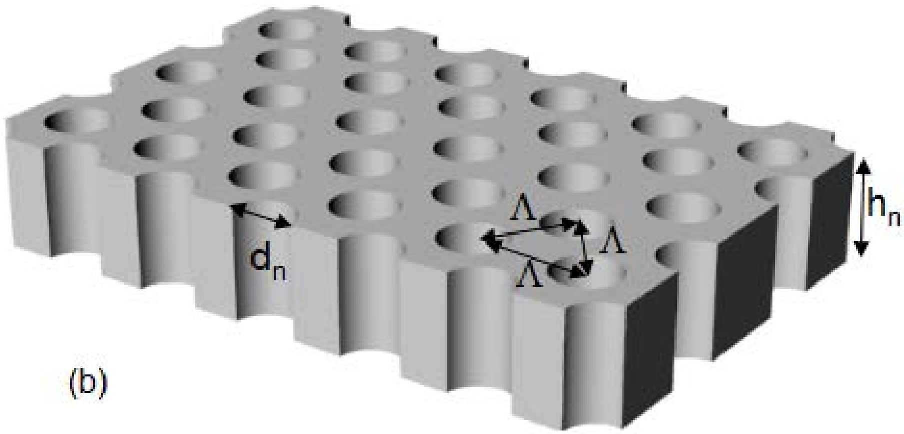
AR coating is formed by machining a multi-level subwavelength grating pattern on a lossless dielectric substrate. The period of the grating must be smaller than the material wavelength to ensure only the zeroth diffractive order propagates.

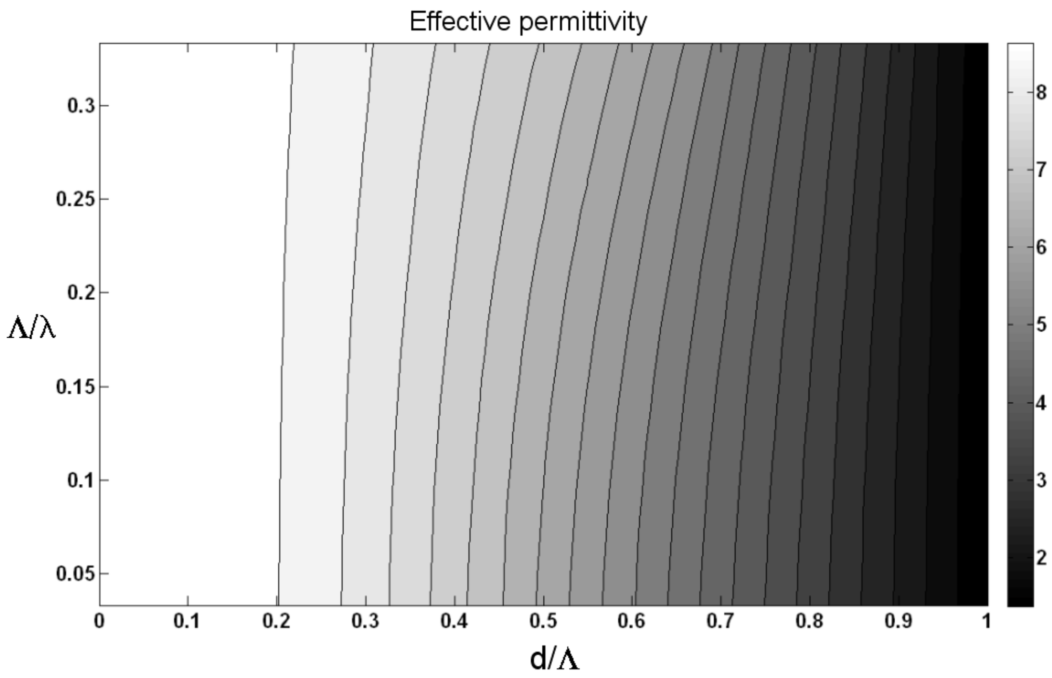
Design Algorithm of Antireflective coating using "Moth-eye" subwavelength gratings



One way of looking at the moth-eye AR surface is that they act "effectively" as an equivalent thin film stack of dielectrics.

Design Algorithm of Antireflective coating using "Moth-eye" subwavelength gratings

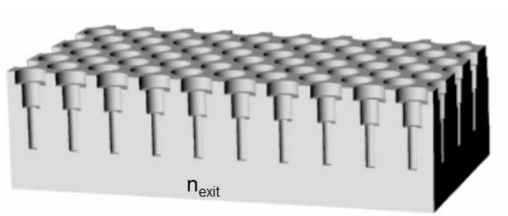


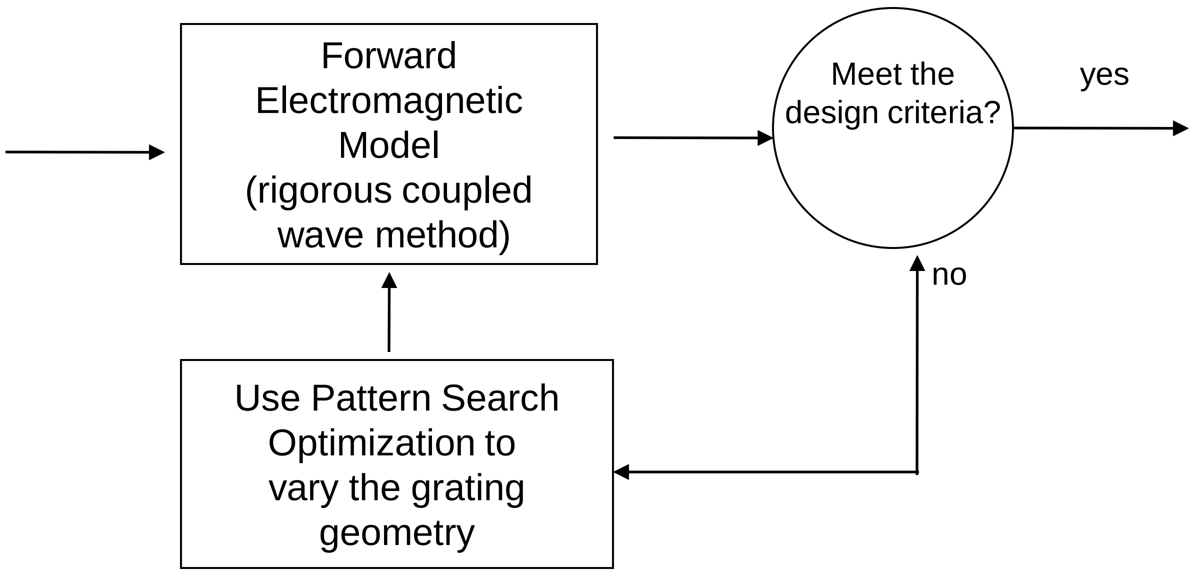


Iterative Design Algorithm

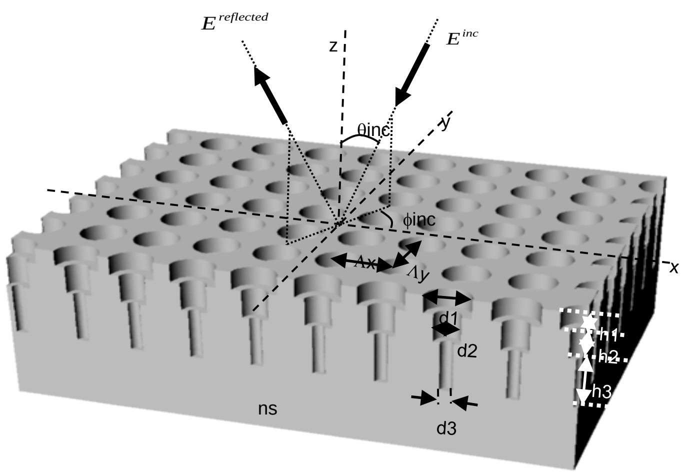
AR moth-eye surfaces were designed using an optimization algorithm, for use at practical radar bands (X, Ka and W).

Initial Design Based on ¼ wavelength stack





Solve 4-Region Model using Rigorous Coupled Wave Method



A rigorous coupled wave (RCW) code was developed to compute the reflection and transmission coefficients all diffractive orders.

Main Attributes of the RCW Method

1. Representation of periodically varying permittivity in each layer of the grating structure using Fourier series expansion:

$$\varepsilon(x,y)=\varepsilon(x+\Lambda_x,y+\Lambda_y)=\sum_m\sum_n\varepsilon_{m,n}\exp\left(j\left(\frac{2\pi mx}{\Lambda_x}+\frac{2\pi ny}{\Lambda_y}\right)\right)$$

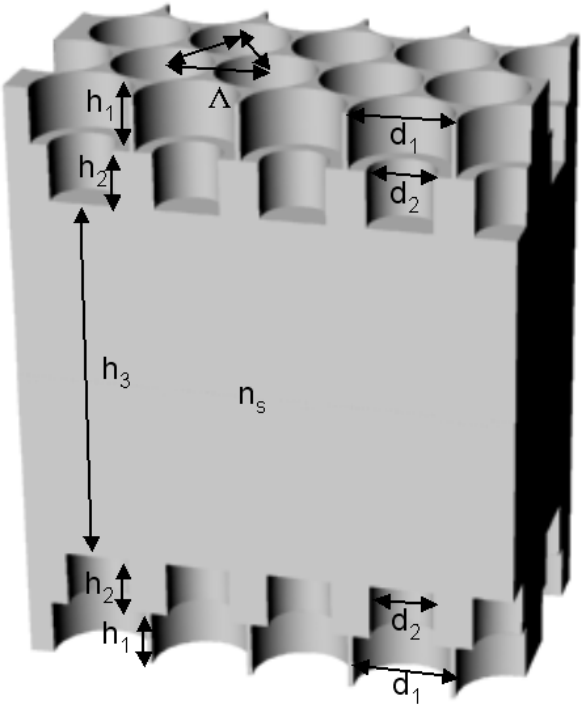
2. Represent the electric and magnetic field distributions within each layer using spatial harmonics

$$H(x,y,z)=\sum_{i=-\infty}^{\infty}U_i(z)\exp\left(-j\left(k_{xi}x-k_{yi}y\right)\right)$$

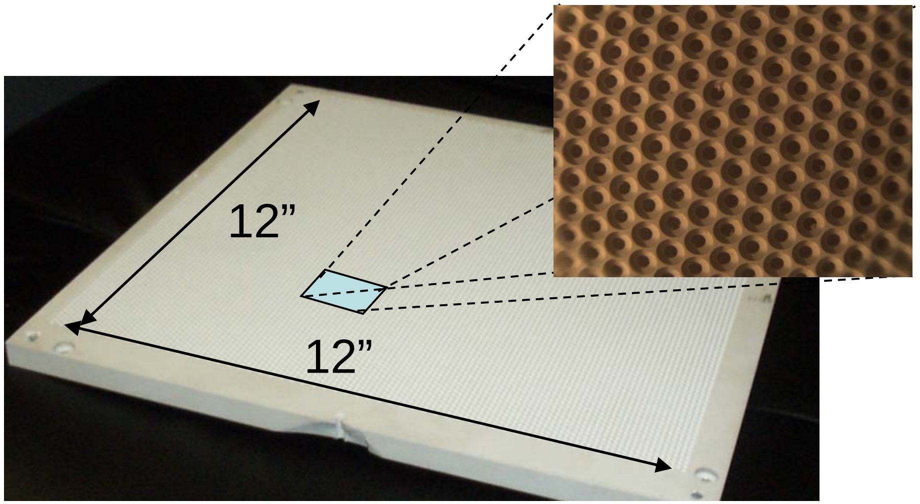
3. From continuity considerations of the electromagnetic field at the boundary of the grating, the Fourier harmonics may be matched to the Rayleigh expansion of the fields beyond the grating region to determine all propagating orders.

Design Example: Ka-band

Goal: Design an antireflective coating for Ka-band (30-40 GHz) for normal incidence and that the substrate material is the high dielectric constant material HiK (n=3.0).



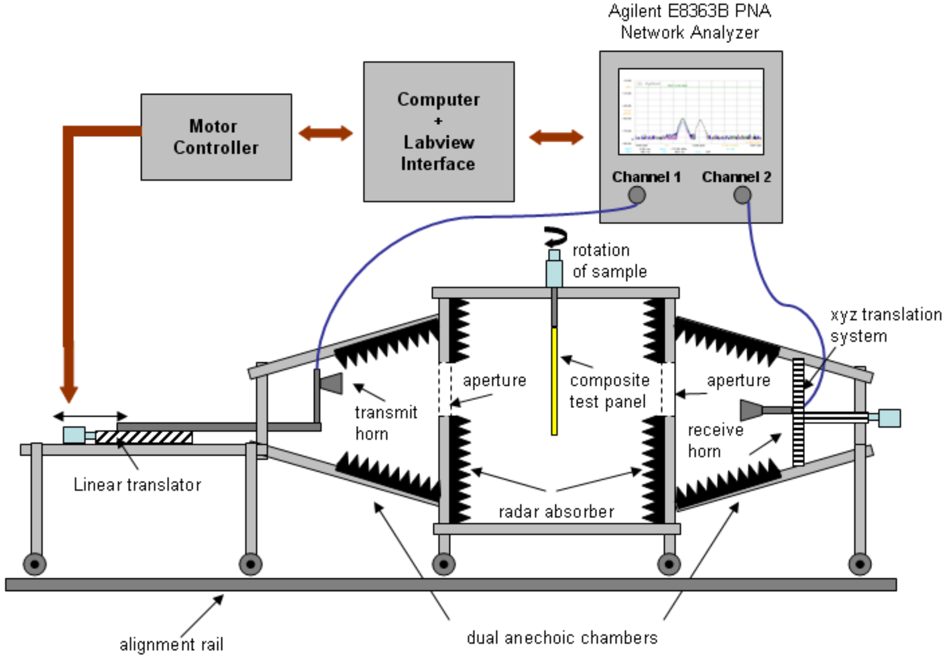
Λ= 2.8 mm
h_1=1.33 mm
h_2=2.26 mm
h_3=6.0 mm
d_1=2.54 mm
d_2=1.27 mm
ε_r=9.0-0.02j

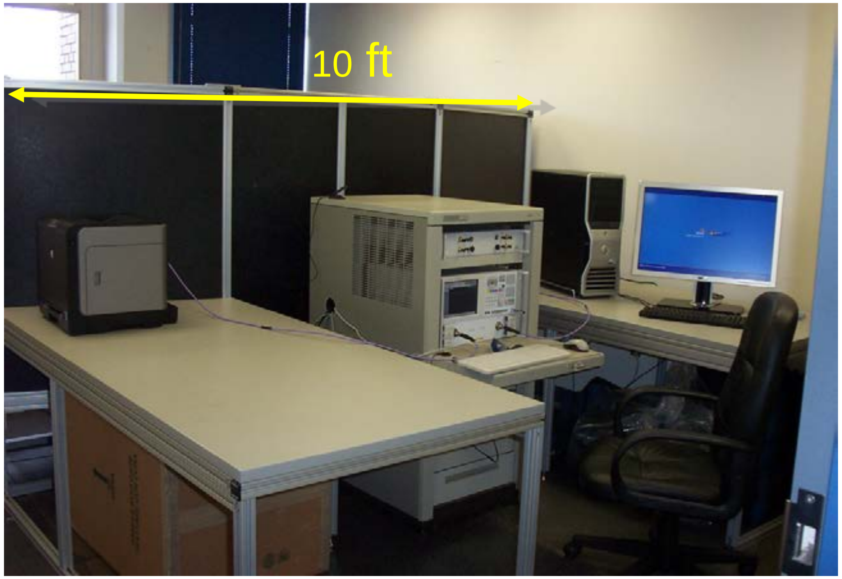


Fabricated using CNC milling

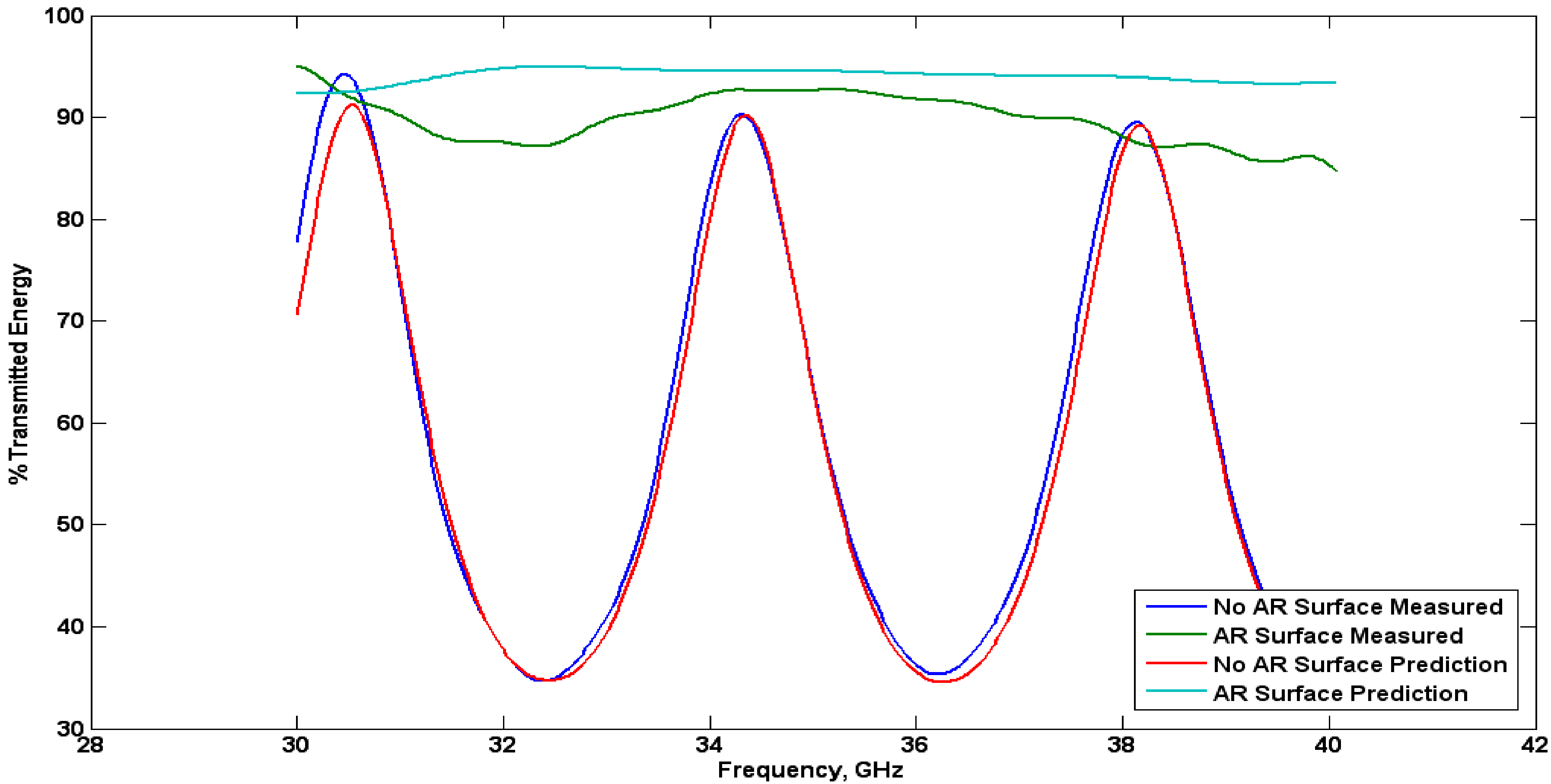
Transmission Measurements

• A material measurement system was used to measure transmission throughout the Ka-band

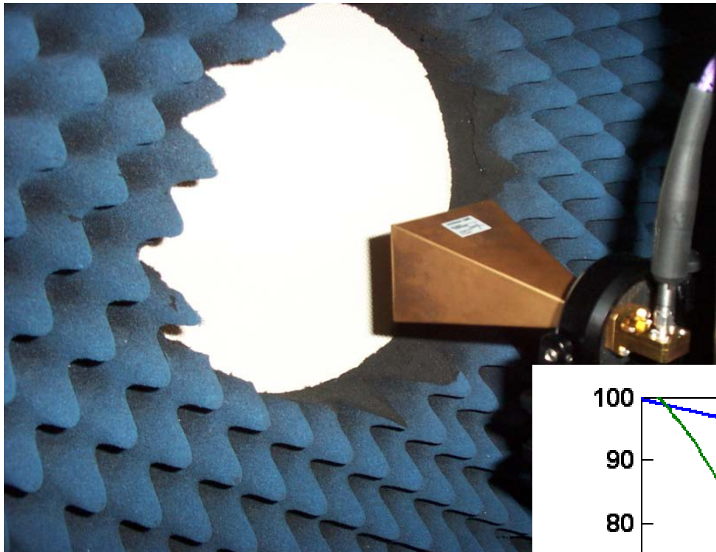


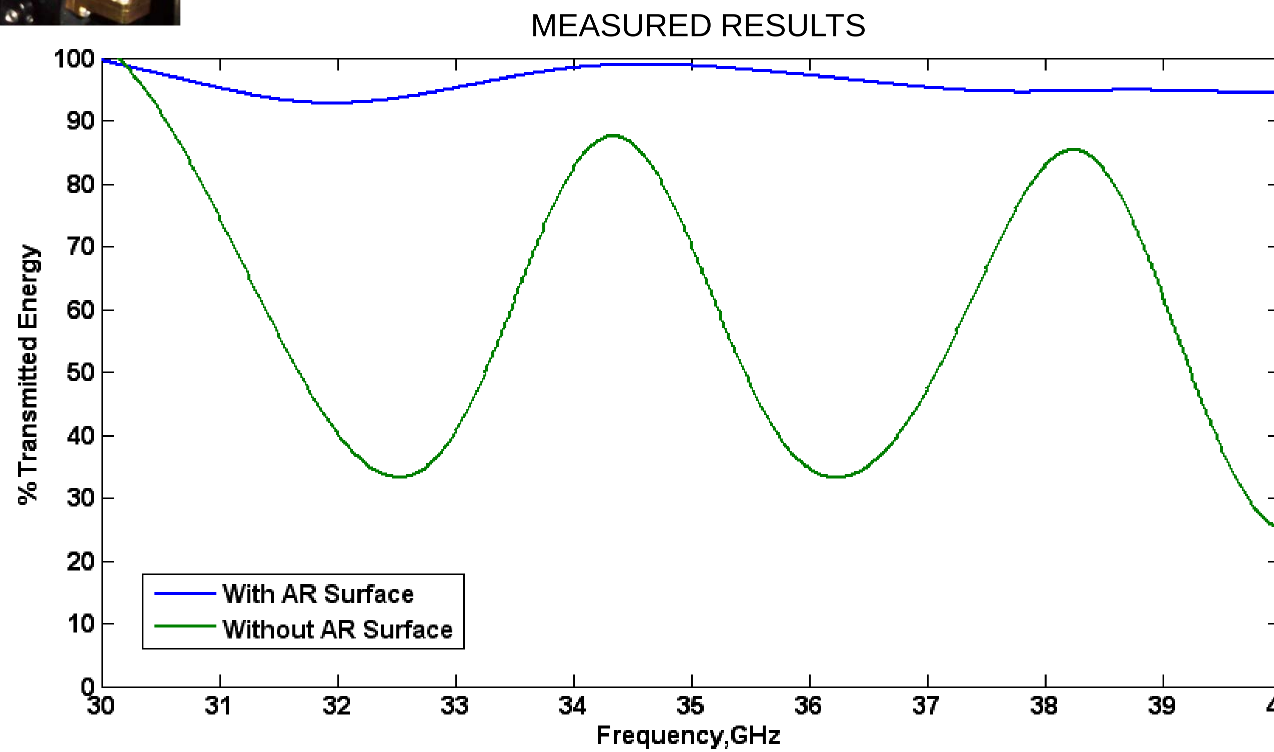


Transmission Results

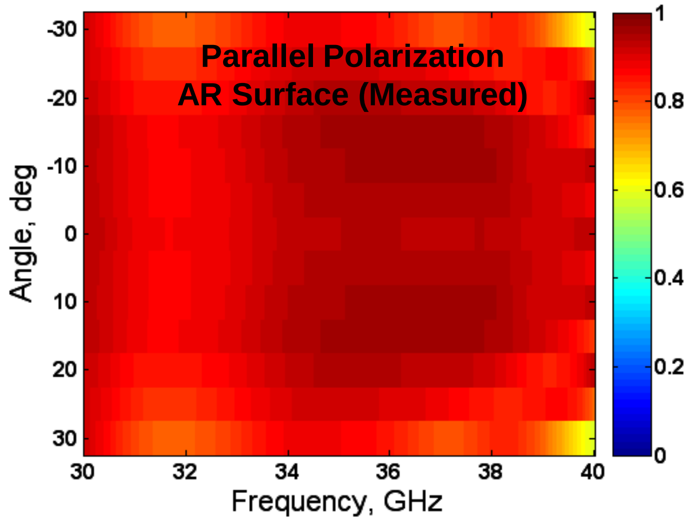


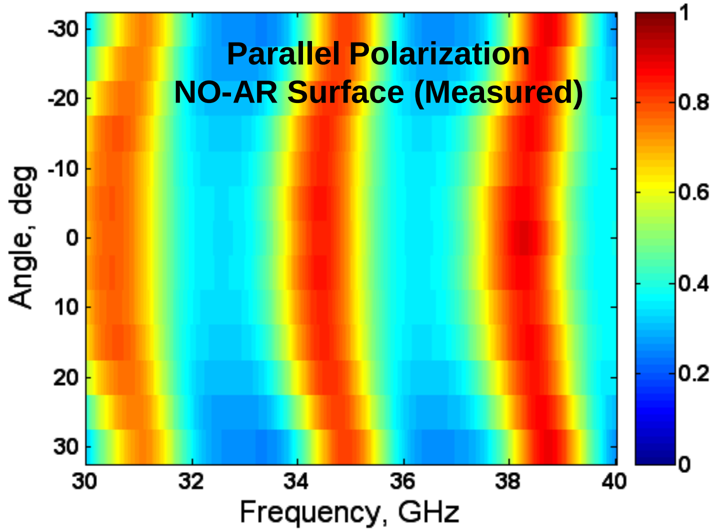
Transmission Results: Normal Incidence

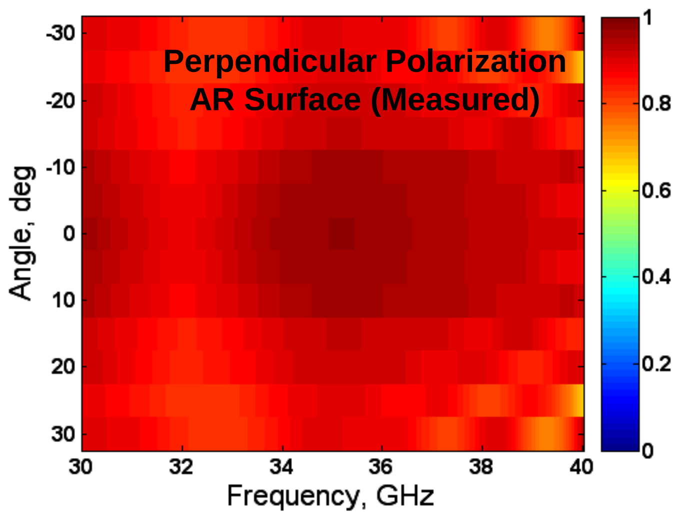


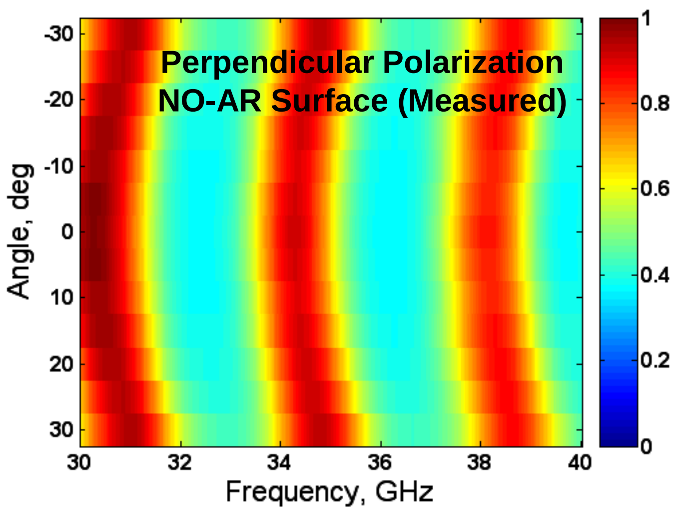


Transmission Results: Off-Axis

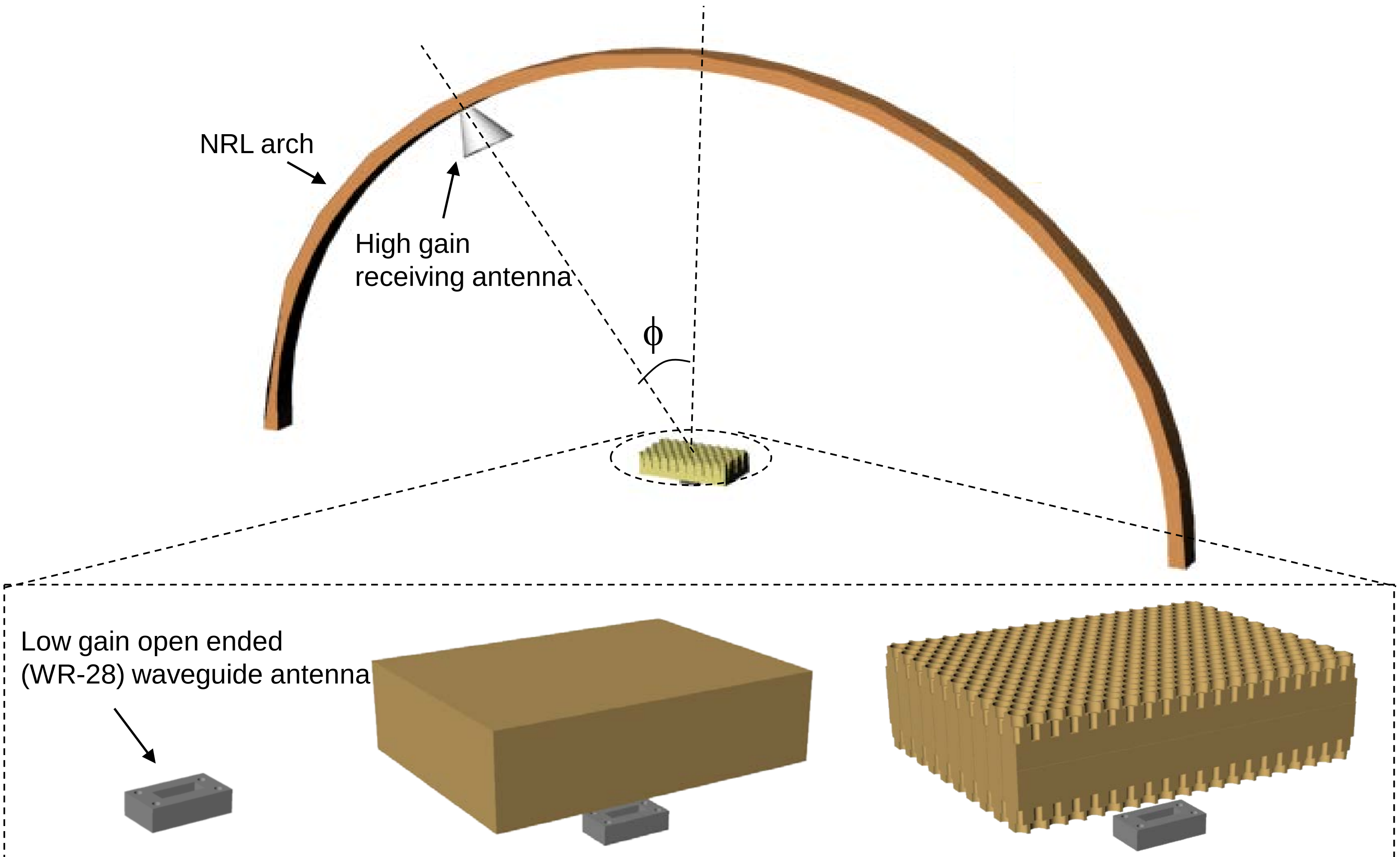








NRL Arch Measurements

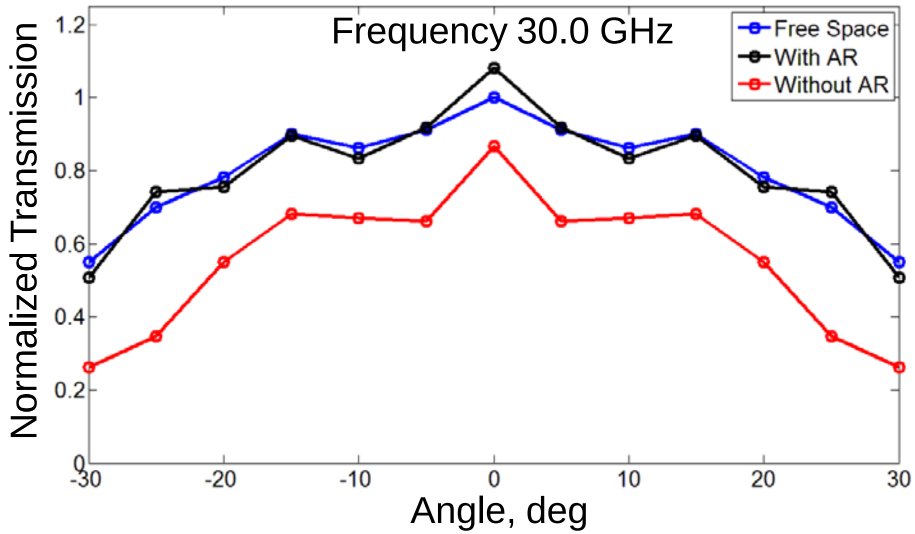


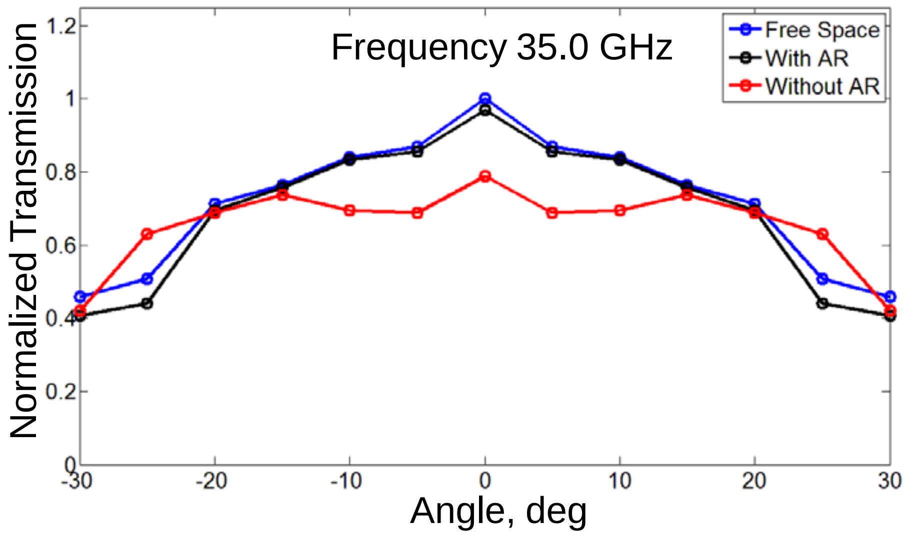
Case 1. Free-space

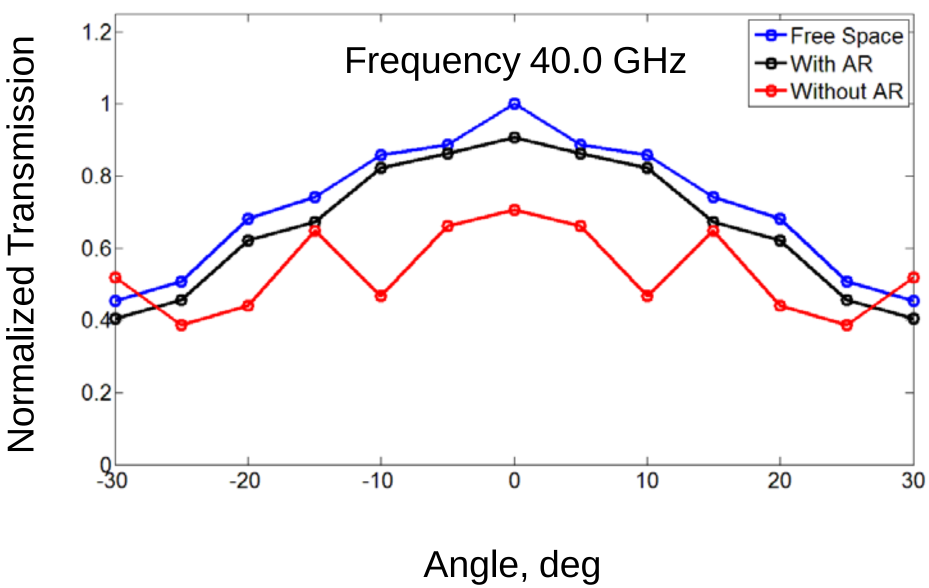
Case 2. 12” x 12” x 0.5” dielectric slab without antireflective surfaces. Dielectric constant ε_r=9.0

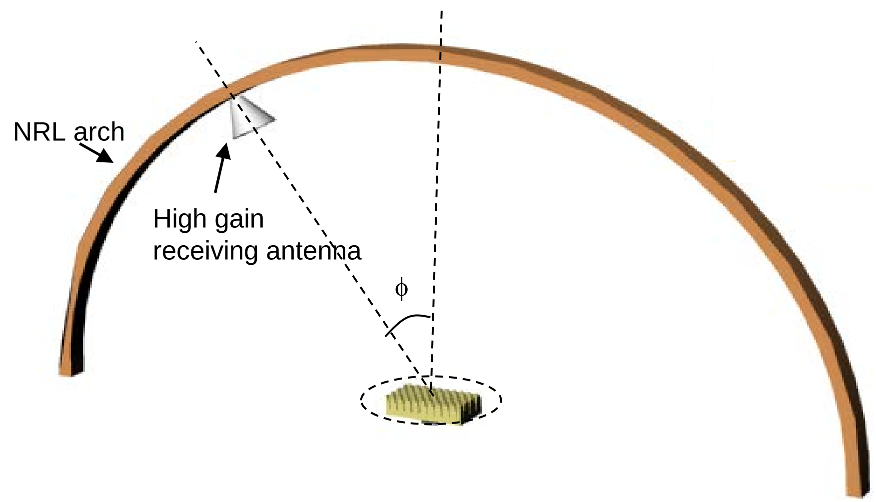
Case 3. 12” x 12” x 0.5” dielectric slab with antireflective surfaces. Dielectric constant ε_r=9.0.

NRL Arch Results



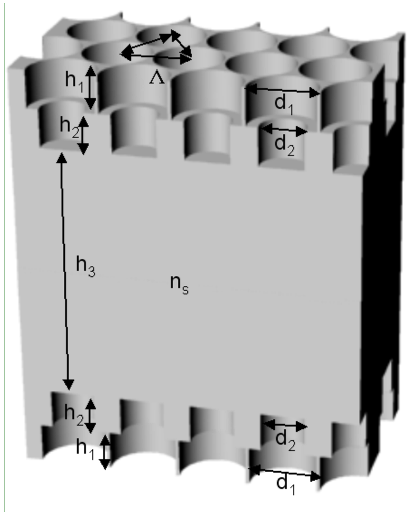




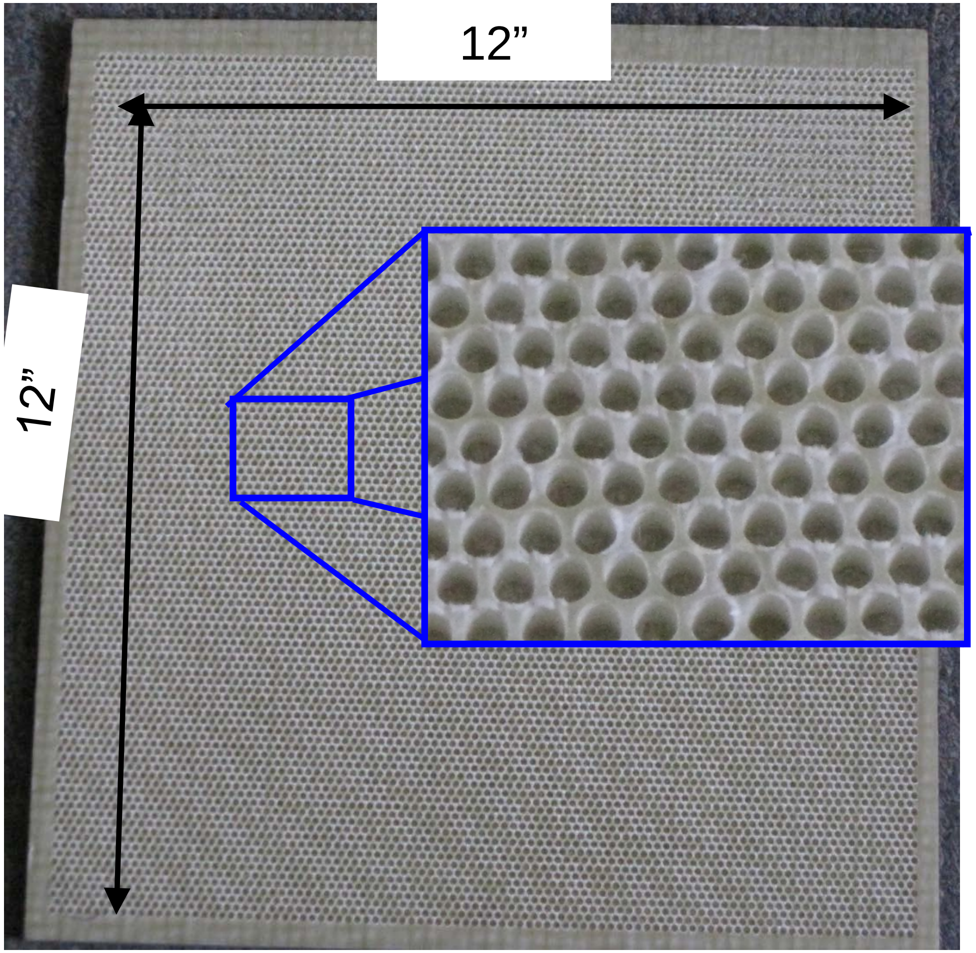


Design Example: Ku-band in composites

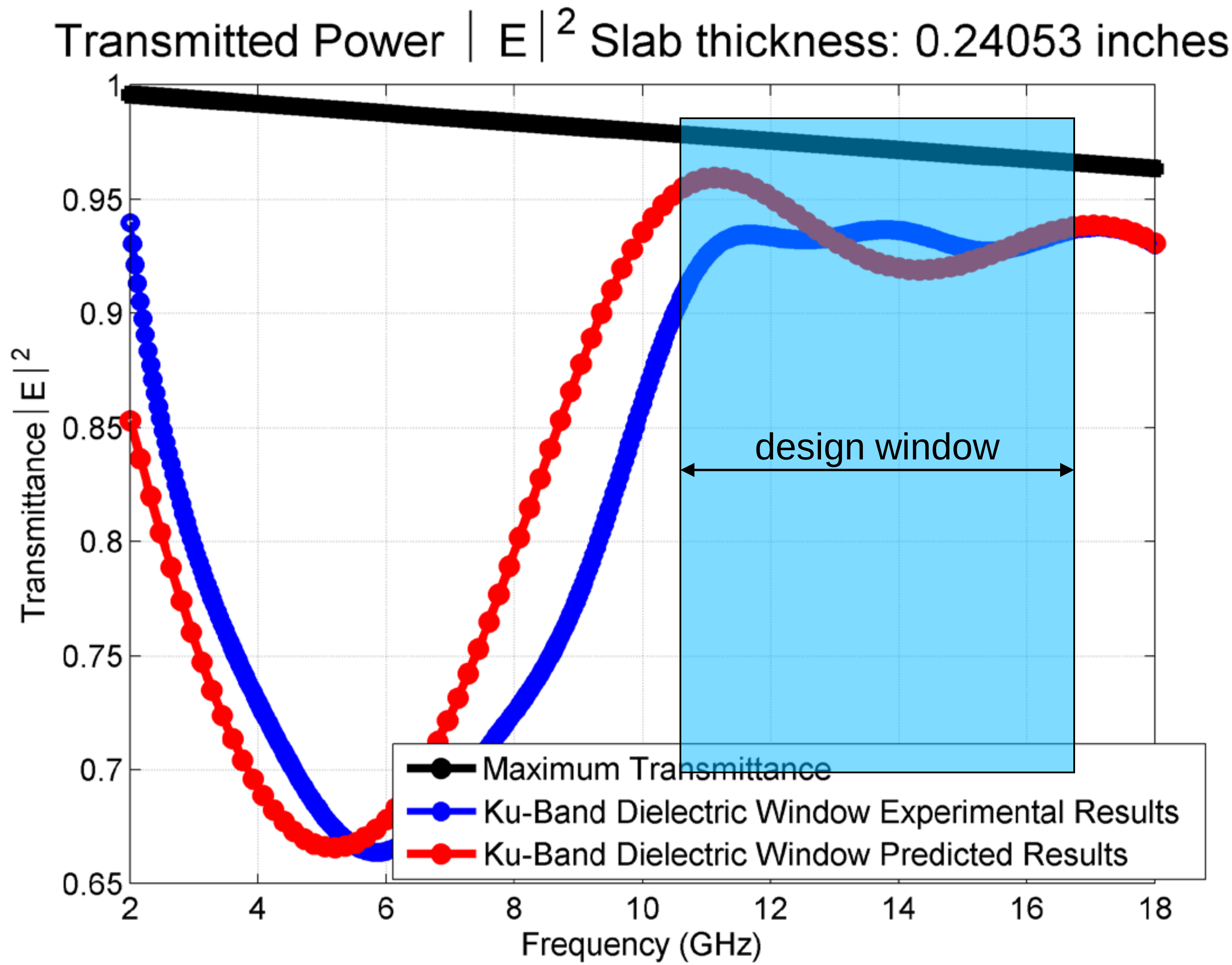
Goal: Design an antireflective surface structure for fiberglass composite skins at Ku-band (12-18 GHz) for normal incidence



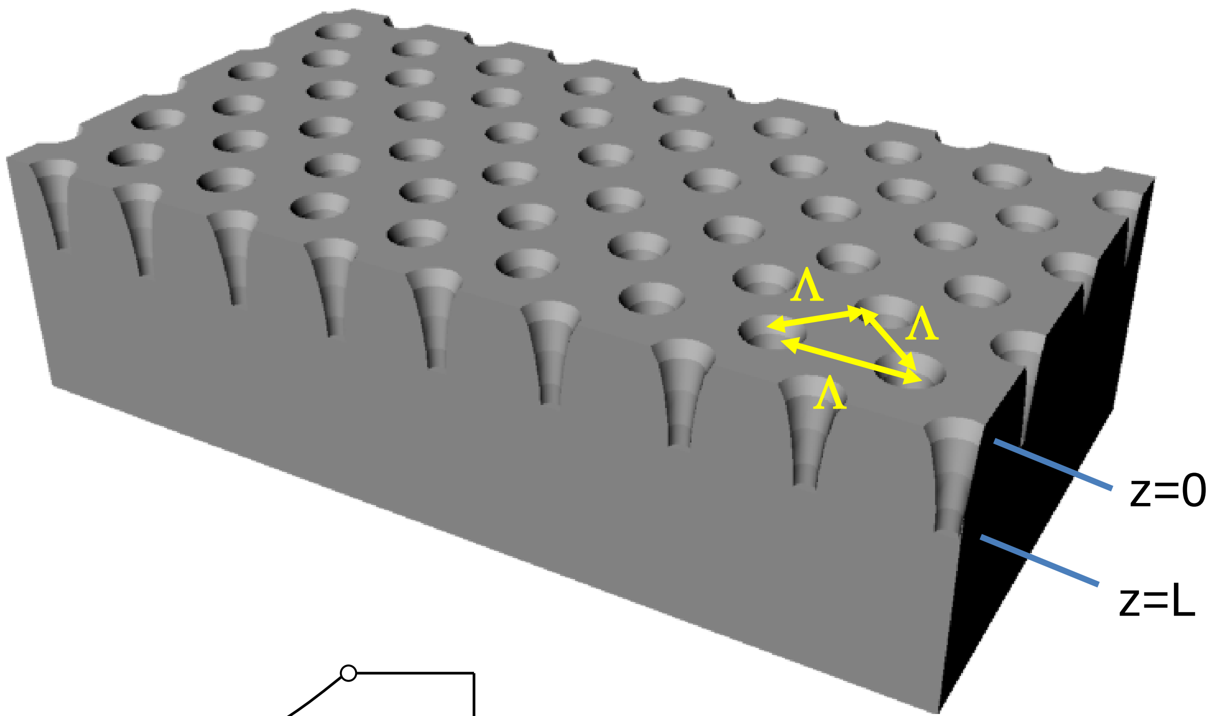
Λ= 3 mm
h_1= 3.13 mm
h_2= 0 mm
h_3= 3.4 mm
d_1=1.9 mm
d_2=0 mm
ε_r=4.5 - .05j

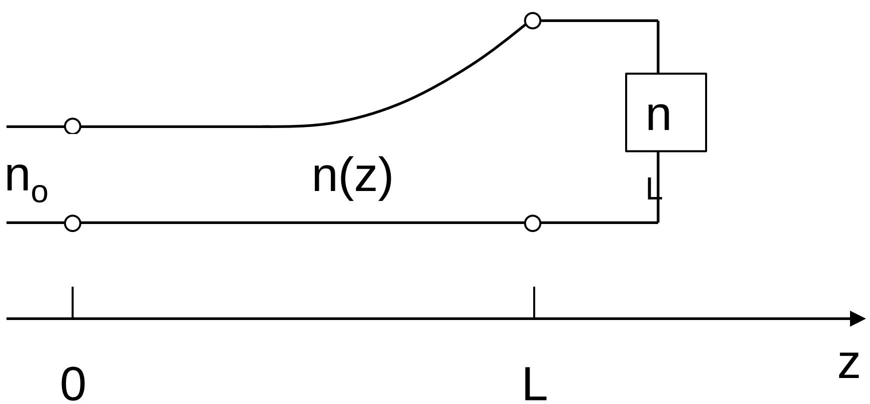


Composite Dielectric Window Results



Wider Bandwidths using Continuous Tapered Holes

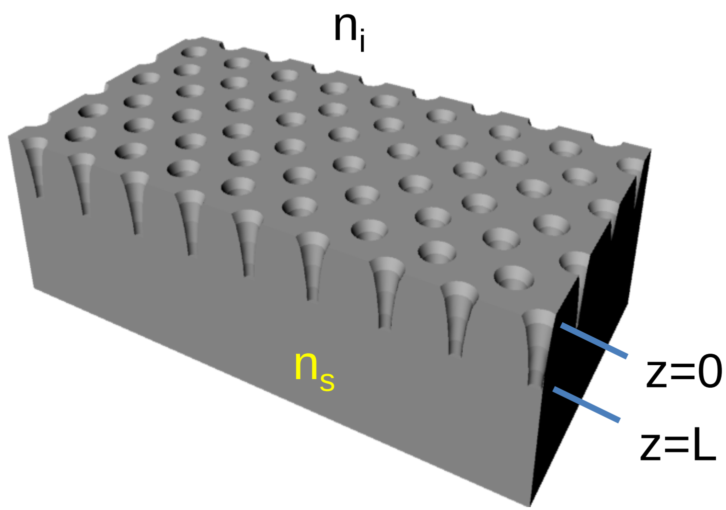


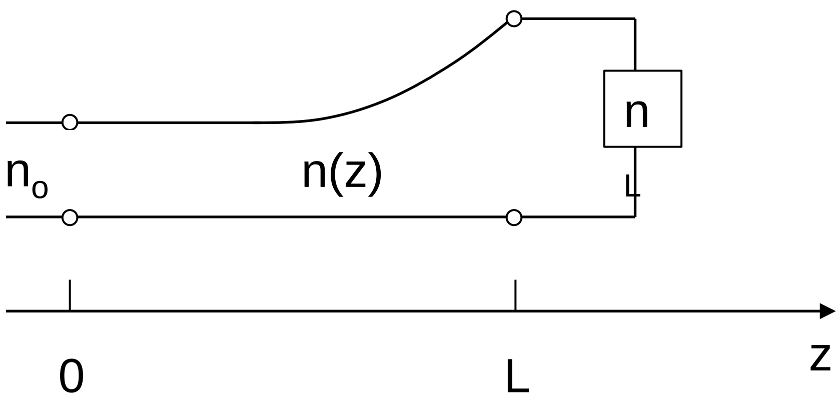


$$\Lambda < \frac{\lambda_{\min}}{n_o\left(1 - \sin(\theta_{inc})\cos(\phi_{inc})\right)}$$

$$L \approx \frac{\lambda_{max}}{4}$$

Wider Bandwidths using Continuous Tapered Holes





Gaussian Taper

$$n(z)=\begin{cases} n_i \exp\left[2\left(\frac{z}{L}\right)^2 \ln\left(\frac{n_s}{n_i}\right)\right] & 0 \le z \le \frac{L}{2} \\ n_i \exp\left[2\left[0.5-\left(1-\frac{z}{L}\right)^2\right] \ln\left(\frac{n_s}{n_i}\right)\right] & \frac{L}{2} \le z \le L \end{cases}$$

Exponential Taper

$$n(z)=n_i \exp\left[\frac{z}{L}\ln\left(\frac{n_s}{n_i}\right)\right]$$

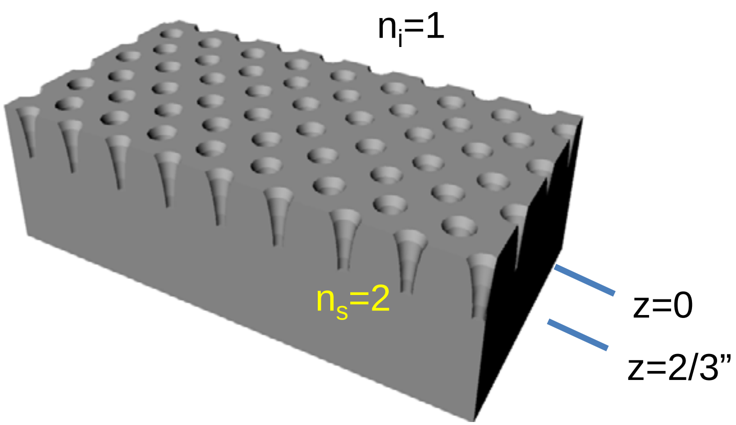
Klopfenstein Taper

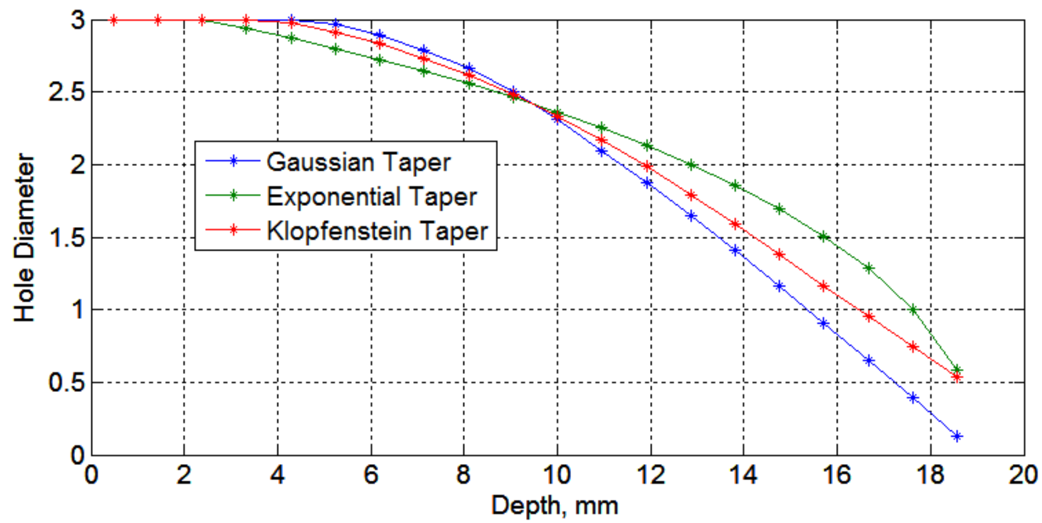
$$n(z)=\sqrt{n_i n_s}\,\exp\left[\Gamma_m A^2 \phi\left(2\frac{z}{L}-1, A\right)\right]$$

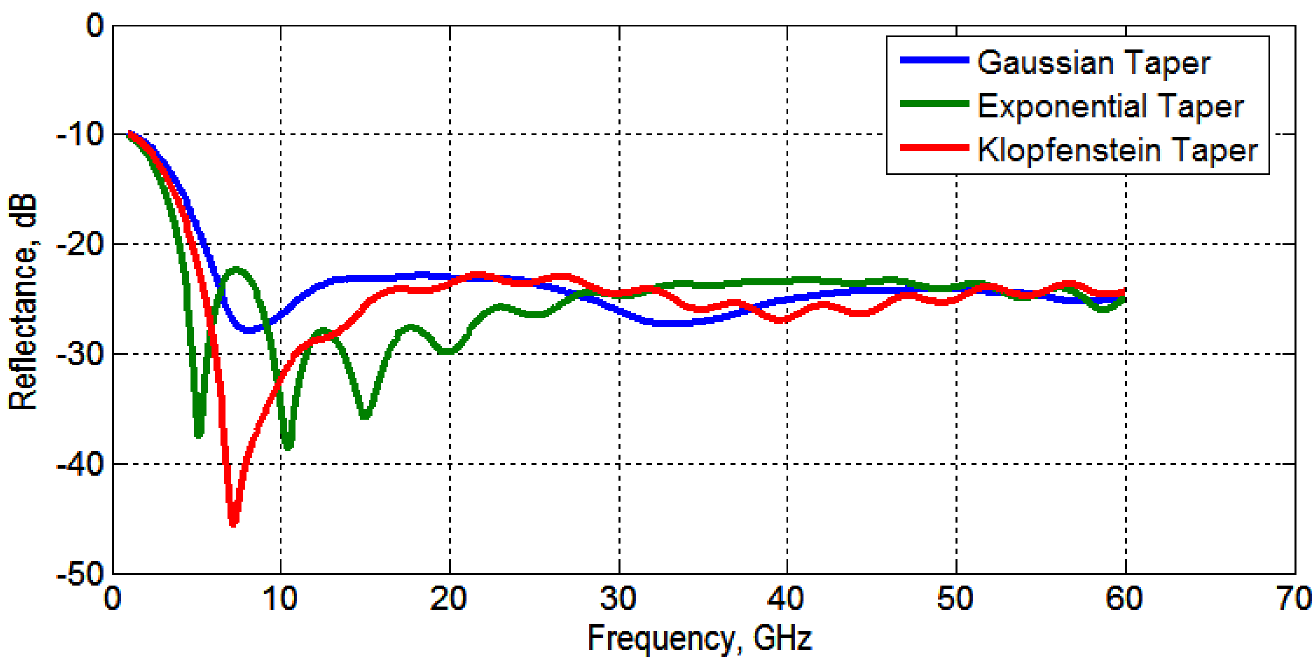
$$\phi(x,A)=\int_0^x \frac{I_1\left(A\sqrt{1-y^2}\right)}{A\sqrt{1-y^2}}\,dy$$

$$A=\cosh^{-1}\left[\frac{1}{2\Gamma_m}\ln\left(\frac{n_s}{n_i}\right)\right]$$

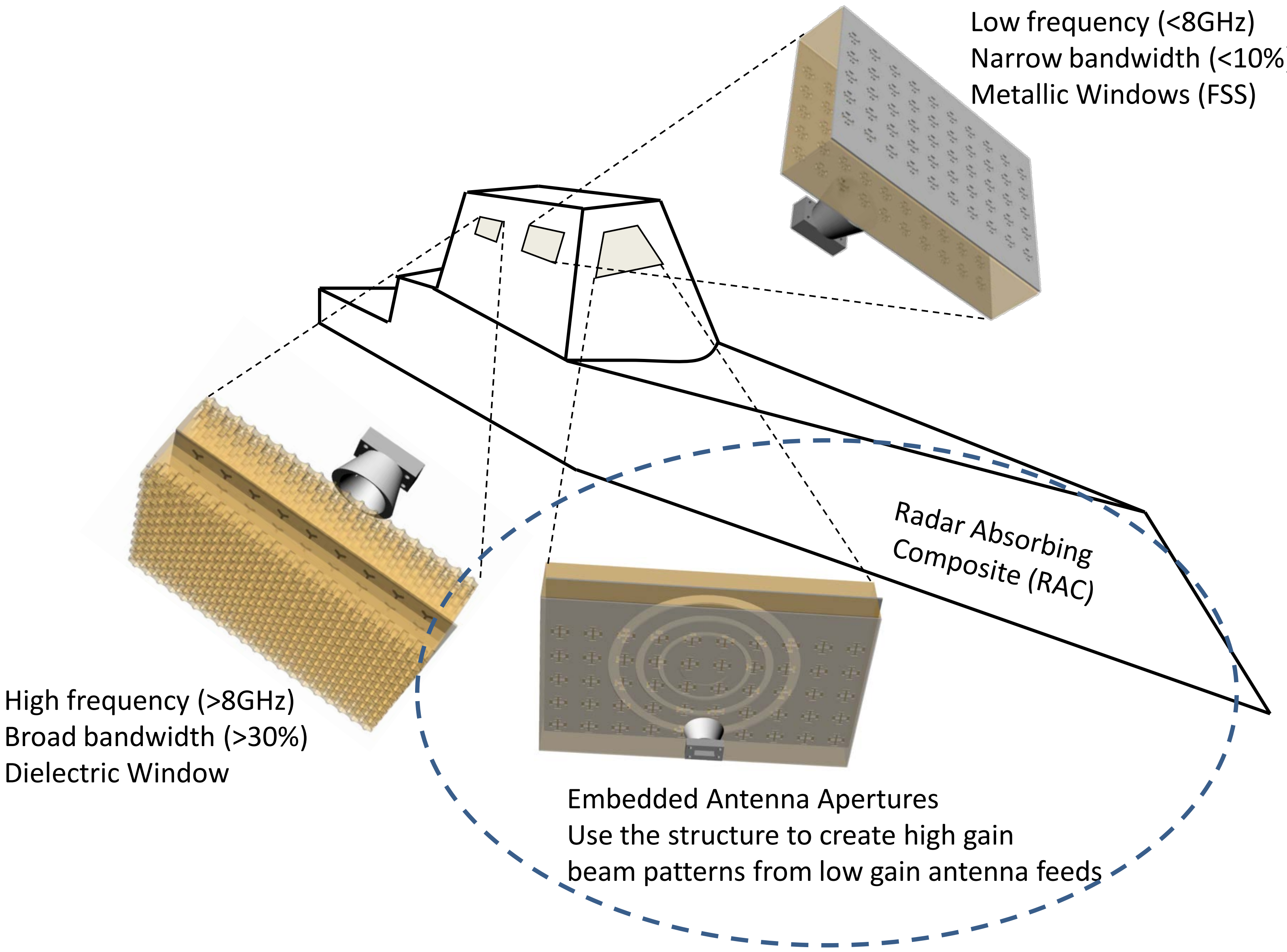
Wider Bandwidths using Continuous Tapered Holes



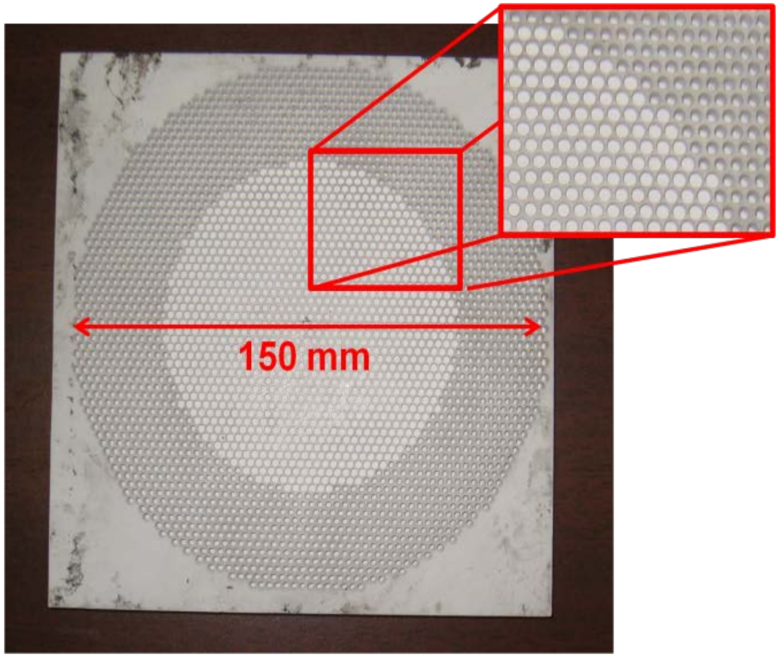


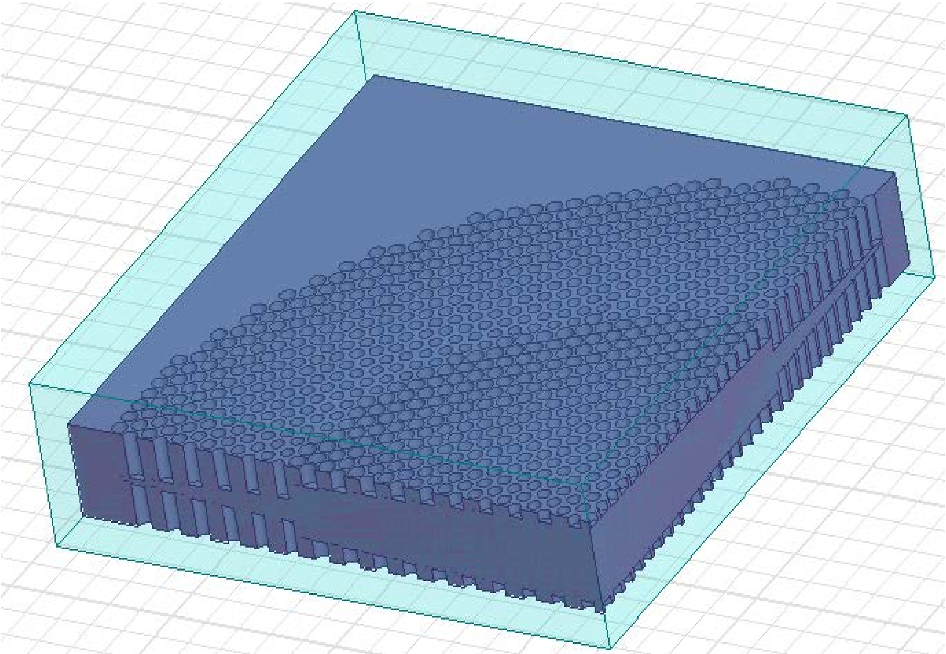


Microwave Lens Integration



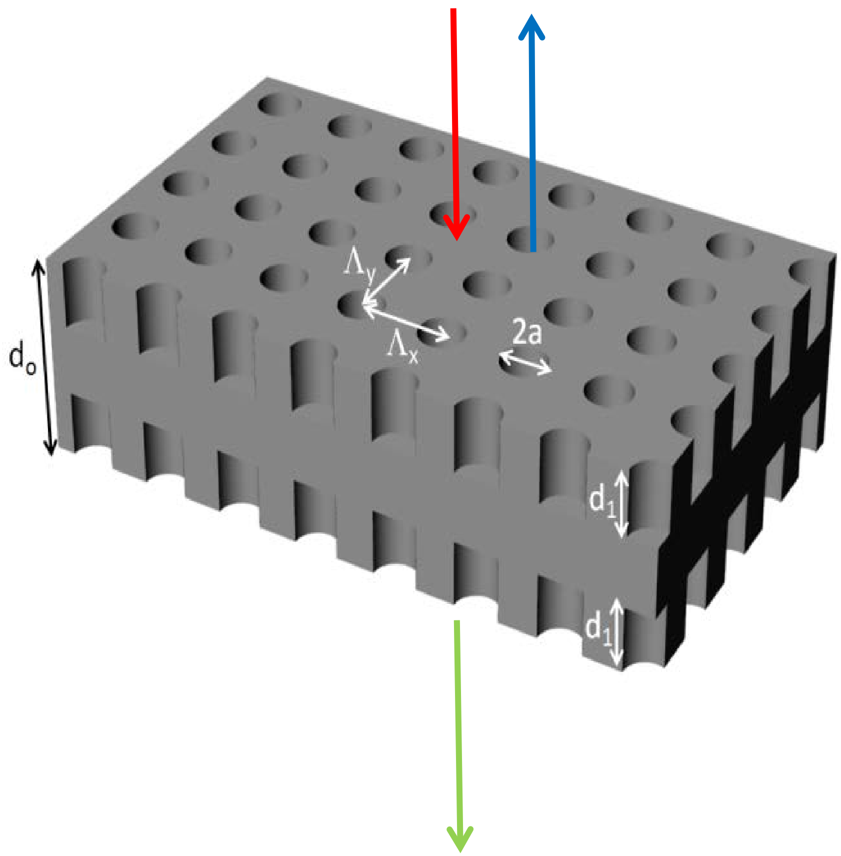
Microwave Lens Integration

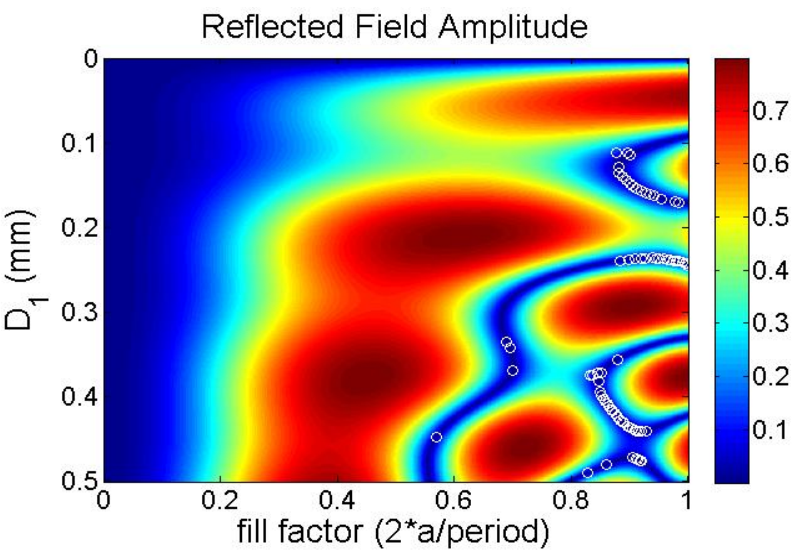


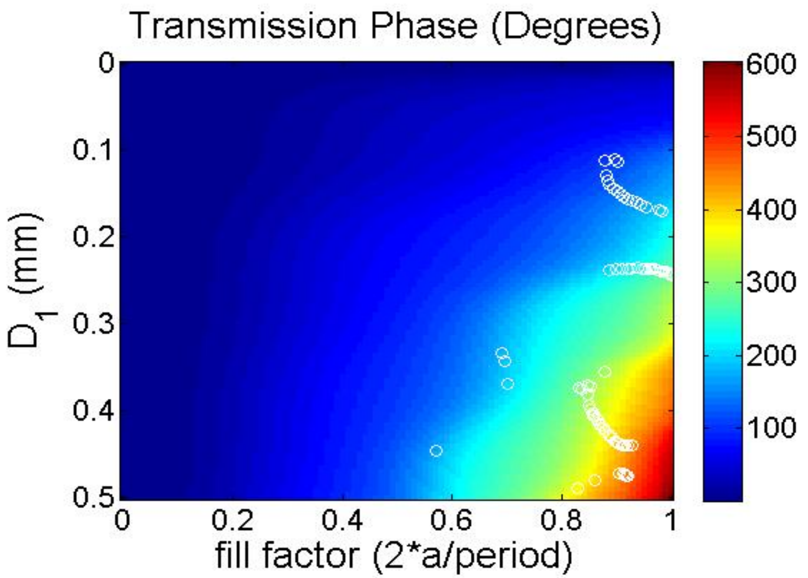


Using aperiodic subwavelength hole arrays we can create lenses with integrated antireflective properties

Microwave Lens Integration

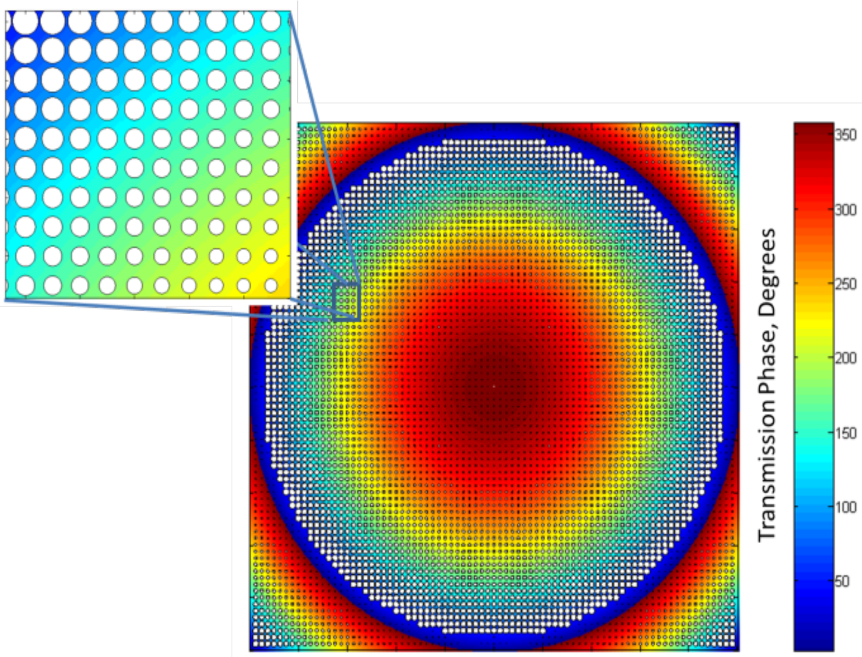


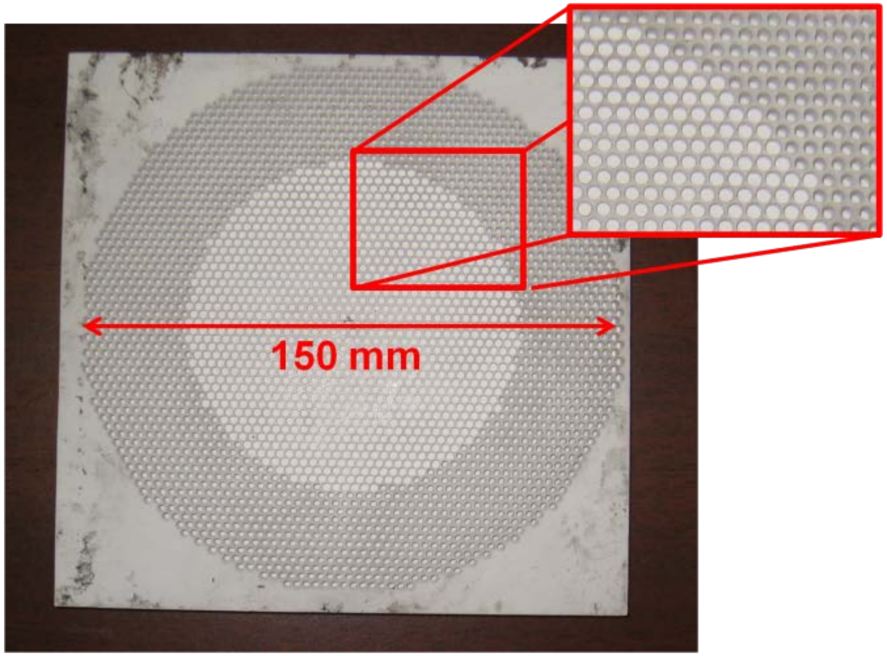




How does it work?
Find grating structures with small reflection coefficients but variable transmission phase. Create look-up table

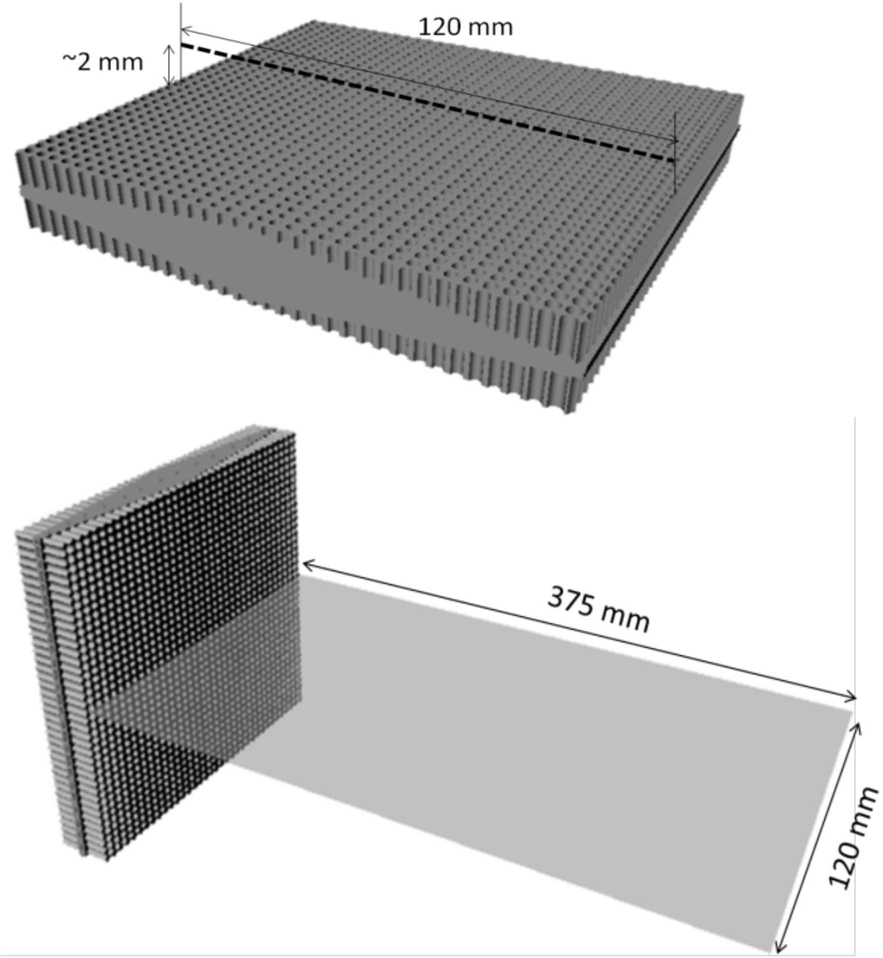
Microwave Lens Integration

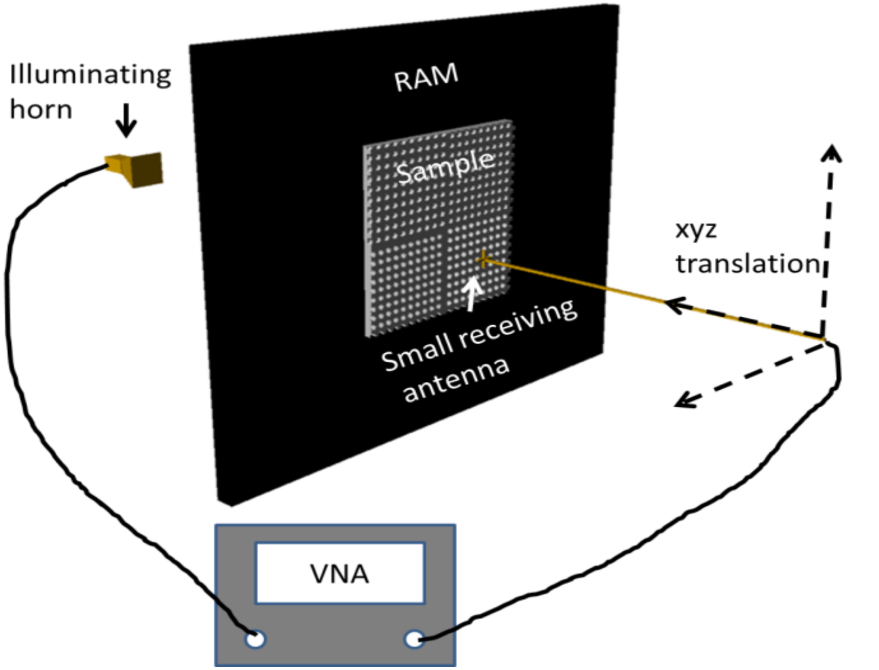




How does it work?
Using look-up table of allowable grating structures we spatially map a desired phase distribution to a local aperiodic subwavelength array.

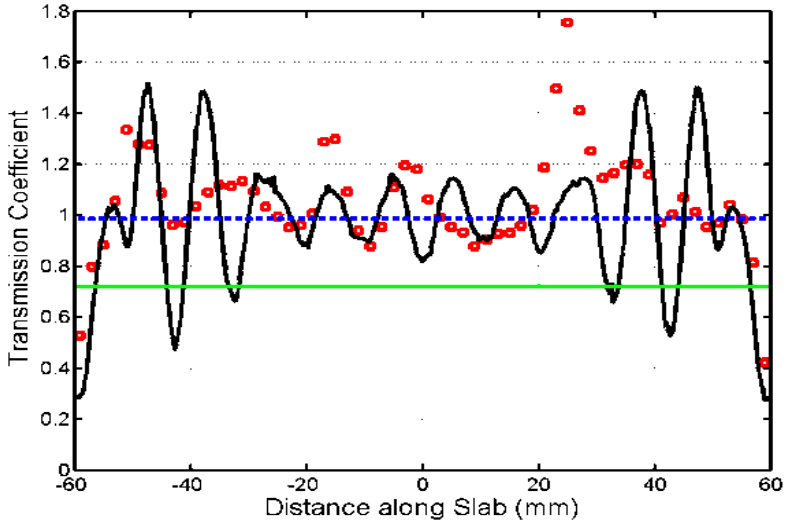
Microwave Lens Integration

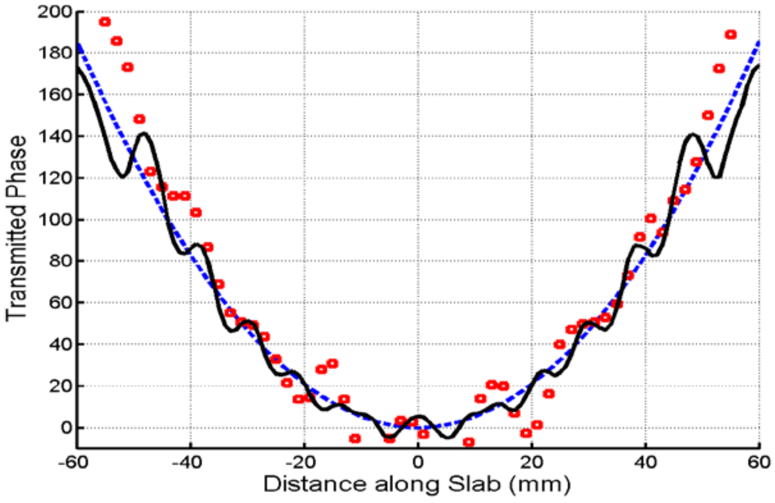




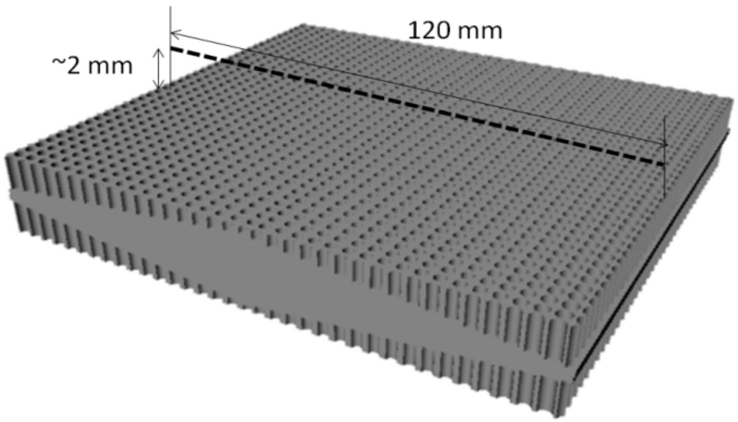
We used this experimental setup to scan the transmitted field.

Microwave Lens Integration



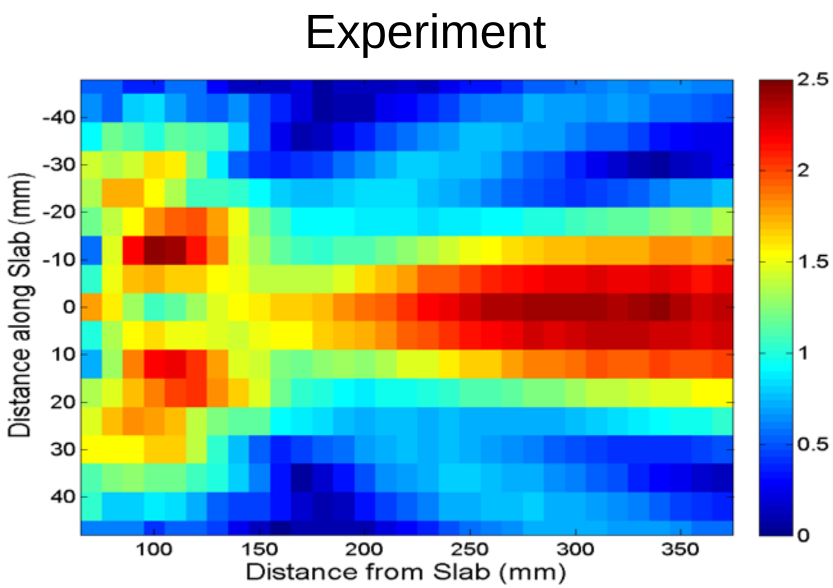


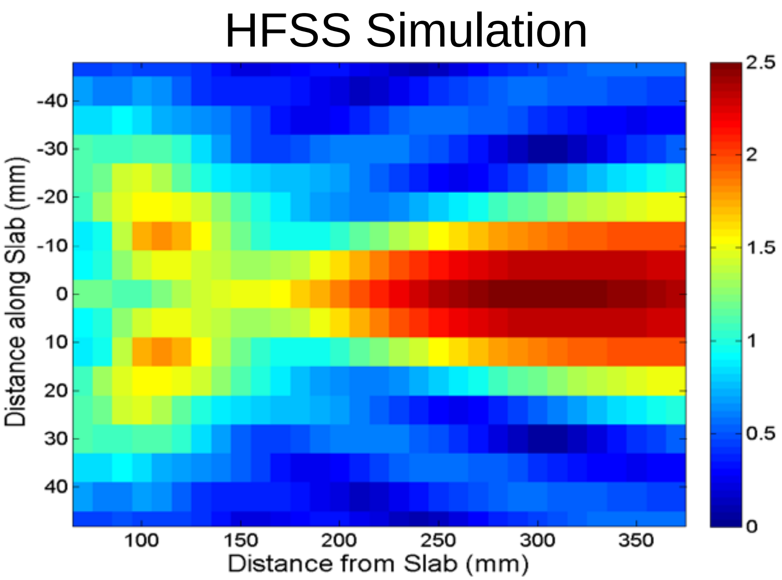
Experimental data (-o-), desired magnitude (----), 12.7 mm dielectric slab of $e_r = 6$ (——), and HFSS near field (——) for the spherical flat lens.

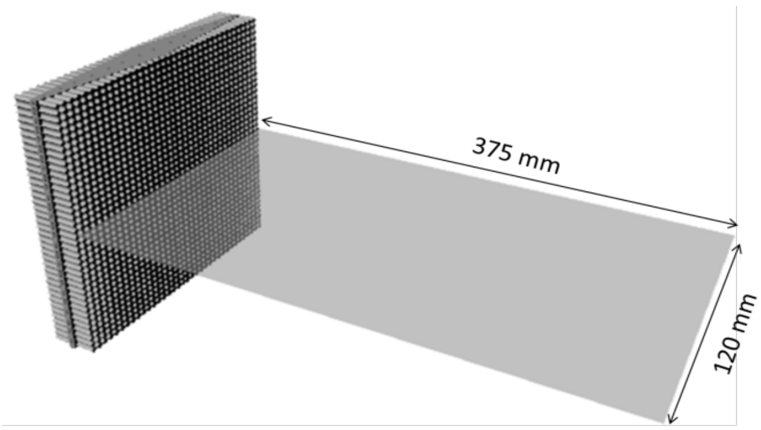


Results: Transmission along line scan close to lens surface (26 GHz)

Microwave Lens Integration







Results: Transmission in plane that includes focal spot (26 GHz)

Acknowledgements

UD Center of Composite Materials
Dr. Shridhar Yarlagadda
Prof. Jack Gillespie
Raymond McCauley
Dave Roseman

UD Department of Electrical Engineering
Peter Pa
Jared Smith
David Calhoun
Austin Good
Sarah Jensen

Naval Surface Warfare Center
Paul Ransom
Brandon Good
Shawn Simmons
Wayne Jones

Army Research Laboratory
Dr. Joseph Mait
David Wikner

Office of Naval Research
Dr. Steven Russell

Thank you!

Questions??