Multifunctional Structural Composites
“Engineering the EM Properties of Structures”

Mark S. Mirotznik, Ph.D., Jared Smith and Peter Pa
Department of Electrical Engineering
University of Delaware

Shridhar Yarlagadda, Ph.D.
Center for Composite Materials
University of Delaware

Paul Ransom and Brandon Good
Naval Surface Warfare Center
Carderock Division
In my laboratory we work in the area of multifunctional materials. More specifically on methods to integrate electromagnetic functionality into structural composites.

- High frequency (>8GHz)
  - Broad bandwidth (>30%)
  - Dielectric Window

- Low frequency (<8GHz)
  - Narrow bandwidth (<10%)
  - Metallic Windows (FSS)

- Radar Absorbing Composite (RAC)

- Embedded Antenna Apertures
  Use the structure to create high gain beam patterns from low gain antenna feeds
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
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
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?
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.
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 of 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

  - Electrical Engineers
  - Process Engineers
  - Mech. Engineers
  - Chemists
  - Material Scientists
  - Structural Engineers
Conformal Load-Bearing Antenna Structure (CLAS)

- 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

AFRL CLAS project

Embedded Antennas in Armor

**Today:**
Antennas compete for limited topside platform space. Typical installation result in adverse antenna interactions, distortions to radiation patterns and high visual signatures.

**WARFIGHTER PAYOFFS:**
- Enhanced Multifunctional Communications/Sensor Performance
- Increased Survivability due to Elimination of Visual Signature
- Reduced Antenna Attrition and Logistics

**EPAS Concept:**
Vehicle platform design is modified to accommodate embedded feed systems and distribute antenna apertures at optimized locations to reduce antenna interactions, parasitic distortions and visual signatures. Optimized aperture/feed locations determined through modeling and simulation.

**Results:**
Embedded multifunction apertures optimally distributed around platform to support communications, CIED Jamming, direction finding, and sensors.

*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
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
- 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!
University of Delaware
Center for Composite Materials

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

EMI Shelter for HMMWV

HEMTT A3 Armor Ready Cab
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
  - Broadband EM properties of woven fabric composites

Applications
  (1) Progress towards a broadband structural radome design
      - Traditional approach
      - Motheye approach
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
- Glass, carbon, aramid or polymer
- Composite structure

Material fiber
Ply
Laminate
Adhesive
Facing
Core
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)
- Foam Core
- Balsa Wood 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

- Skiing equipment
- Snowmobile
- Tractor
- Commercial airplane
- Road bicycle
- Car
- Truck
- Bridge
Military Applications
Multifunctional Composites

• Composite structures can be designed to improve
  – Strength
  – Stiffness
  – Weight
  – Fatigue
  – Corrosion
  – Wear
  – Thermal behavior

• Improve more than one property?
  – **Multifunctional Composite Materials**

  – Acoustic
  – Optical
  – RF Properties
“The Electromagnetic and Mechanical Properties of Structural Composites: Overall Technical Vision and Approach”

Electromagnetic Performance

Structural Performance

Manufacturability

Reinforcement Architecture

Fabric CAD Model Database

“Additives”

Model-based Design & Optimization

Optimal Reinforcement Prototyping

Composite fabrication

Experimental Validation
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
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
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
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 $\varepsilon$, $\mu$, and $\sigma$ in x, y and z
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

What determines the EM properties of a structural composite?
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)
### Dielectric Properties of Standard Fiber Types

<table>
<thead>
<tr>
<th></th>
<th>Glass</th>
<th>Carbon</th>
<th>Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical</strong></td>
<td>E-glass</td>
<td>S-glass</td>
<td>Quartz</td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Dielectric Constant</strong></td>
<td>6.0 – 6.3*</td>
<td>5.1 - 5.3</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Loss Tangent</strong></td>
<td>0.002 - 0.003* (@18 - 40 GHz)</td>
<td>0.003 - 0.004 (@18 - 40 GHz)</td>
<td>0.0001 - 0.0003 (@18 - 40 GHz)</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Low 0.68-1.81 $/lb</td>
<td>Medium ~10$/lb</td>
<td>Very High ~100 $/lb</td>
</tr>
</tbody>
</table>
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
How can we “engineer” attractive EM properties without sacrificing mechanical properties?

1. Fabric Level

- Large scale heterogeneities at the fabric level

CCI Tech’s SL8900 Sampling Loom

Fiber type 1

Fiber type 2

Region 1 (low EM loss)
How can we “engineer” attractive EM properties without sacrificing mechanical properties?

1. Fabric Level

- Engineer heterogeneous panels in which fabrics vary layer by layer

Layer 1: fiber type 1
Layer 2: fiber type 2
Layer 3: fiber type 3
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 Å) with HiK powder (Emerson and Cuming)

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

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

* - 510A vinyl ester resin  
** - TenCate BTCy-1 cyanate ester resin  
*** - Topaz thermoplastic resin
How can we “engineer” attractive EM properties without sacrificing mechanical properties?

3. Direct write or 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

How can we “engineer” attractive EM properties without sacrificing mechanical properties?

4. 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: Screen Printing

High impedance ground plane printed directly on glass fabric
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)
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.

*Traditional Approach:* Reflection from electrical conductor causes 180° 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
How can we “engineer” attractive EM properties without sacrificing mechanical properties?

- Embedded Silver Ink 10x
- Embedded Silver Ink 100x
- Integrated Conductors in Structural Composites: Screen Printing

High impedance ground plane printed directly on glass fabric
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
How can we “engineer” attractive EM properties without sacrificing mechanical properties?

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

![Graph showing transmittance vs. frequency with measured and simulated data compared.](image)

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.
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

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

\[
T_\parallel = 1 - \left[ \frac{1 - \sqrt{\varepsilon_c} \cos(\theta_{inc})}{1 + \sqrt{\varepsilon_c} \cos(\theta_{inc})} \right] \left( 1 - e^{-2 j \frac{2\pi}{\lambda} \sqrt{\varepsilon_c} d \cos(\theta_{inc})} \right)^2
\]
Dielectric Windows: Fresnel reflections

% Transmitted Energy

d=0.5 inch, $\varepsilon_c=4.3$

Perpendicular Polarization

Parallel Polarization
Dielectric Windows: Material Loss

(ignoring all Fresnel reflections)

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

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

\[ d = 0.5 \text{ inch} \]
\[ \varepsilon_c = 4.3 - j \times 0.06 \]

Graph showing transmitted energy as a function of frequency, with data points indicating a decrease in energy with increasing frequency.
Dielectric Windows: Material Loss

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

\[ d = 0.5 \text{ inch} \]

Graph showing the percentage of transmitted energy against frequency for different values of \( \varepsilon'' \) and \( \varepsilon''' \).
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 $\frac{\lambda}{4}$ layers of materials with precise dielectric properties, it is possible to design AR coatings much more broadband than a single layer.
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.

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

Initial Design Based on \( \frac{1}{4} \) wavelength stack

Forward Electromagnetic Model (rigorous coupled wave method)

Use Pattern Search Optimization to vary the grating geometry

Meet the design criteria?

yes

no
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.
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).

\[ \Lambda = 2.8 \text{ mm} \]
\[ h_1 = 1.33 \text{ mm} \]
\[ h_2 = 2.26 \text{ mm} \]
\[ h_3 = 6.0 \text{ mm} \]
\[ d_1 = 2.54 \text{ mm} \]
\[ d_2 = 1.27 \text{ mm} \]
\[ \varepsilon_r = 9.0 - 0.02j \]

Fabricated using CNC milling
Transmission Measurements

- A material measurement system was used to measure transmission throughout the Ka-band.
Transmission Results

![Graph showing transmission results.](graph.png)
Transmission Results: Normal Incidence

MEASURED RESULTS

![Graph showing transmission results with and without AR surface.](image-url)
Transmission Results: Off-Axis

Parallel Polarization
AR Surface (Measured)

Frequency, GHz

Parallel Polarization
NO-AR Surface (Measured)

Frequency, GHz

Perpendicular Polarization
AR Surface (Measured)

Frequency, GHz

Perpendicular Polarization
NO-AR Surface (Measured)

Frequency, GHz
Case 1. Free-space

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

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

Low gain open ended (WR-28) waveguide antenna
**Goal:** Design an antireflective surface structure for fiberglass composite skins at Ku-band (12-18 GHz) for normal incidence

\[
\begin{align*}
\Lambda &= 3 \text{ mm} \\
h_1 &= 3.13 \text{ mm} \\
h_2 &= 0 \text{ mm} \\
h_3 &= 3.4 \text{ mm} \\
d_1 &= 1.9 \text{ mm} \\
d_2 &= 0 \text{ mm} \\
\varepsilon_r &= 4.5 - .05j
\end{align*}
\]
Composite Dielectric Window Results

Transmitted Power $|E|^2$ Slab thickness: 0.24053 inches
Wider Bandwidths using Continuous Tapered Holes

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

\[ L \approx \frac{\lambda_{\text{max}}}{4} \]
Wider Bandwidths using Continuous Tapered Holes

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

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

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

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

\[ A = \cosh^{-1} \left( \frac{1}{2 \Gamma_m \ln \left( \frac{n_s}{n_i} \right)} \right) \]
Wider Bandwidths using Continuous Tapered Holes

\[ n_t = 1 \]
\[ n_s = 2 \]
\[ z = 0 \]
\[ z = 2/3" \]

Graphs showing hole diameter vs. depth (mm) and reflectance vs. frequency (GHz) for different tapers.
Microwave Lens Integration

High frequency (>8GHz)
Broad bandwidth (>30%)
Dielectric Window

Low frequency (<8GHz)
Narrow bandwidth (<10%)
Metallic Windows (FSS)

Radar Absorbing Composite (RAC)

Embedded Antenna Apertures
Use the structure to create high gain beam patterns from low gain antenna feeds
Using aperiodic subwavelength hole arrays we can create lenses with integrated antireflective properties.
How does it work?
Find grating structures with small reflection coefficients but variable transmission phase. Create look-up table.
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

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

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

Experiment

HFSS Simulation

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

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

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

Army Research Laboratory
Dr. Joseph Mait
David Wikner

Office of Naval Research
Dr. Steven Russell
Thank you!

Questions??