Metamaterials, Metasurfaces, and Nanotechnology, and their Applications to Antennas, Sensors, and Cognitive Radar

Amir I. Zaghloul

ECE Department, Virginia Tech and U.S. Army Research Laboratory, Adelphi, MD 20783

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• Introduction

• Metamaterials
  • Negative Refractive Index
  • Periodic and Random Material
  • Application to Enhanced Dipole Antenna
  • Application to Rotman lens

• Metasurfaces
  • Electromagnetic Band-Gap Surfaces
  • Wideband EBG Surfaces
  • Adaptive and Active Reflection Phase Surfaces
  • Application to Spiral Antennas
  • Application to Cognitive Radar

• Nanotechnology
  • Carbon Nano-Tubes
  • CNT Patches
  • Application to Gas Sensors
  • Application to Polarization-Selective Patches

• Conclusions
Academia, Defense Laboratories, and Industry are ideal for an efficient, effective, and agile research system.
Open Campus

- Campus-like environment with collaborative space
- Ready access for all partners including foreign nationals
- Expansion of academic programs & collaboration
- Access to world-renown facilities and resources
- Synergistic with MD and DC metro area entrepreneur community
  - Better focus of small business innovative research (SBIR) investments
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Metamaterials

**A Definition:** A class of engineered materials that exhibit highly beneficial electromagnetic properties, which are not naturally occurring or common synthetic materials.

![Diagram showing different types of metamaterials](image)
Some Specific Metamaterials
Design Goals

- Metamaterials present themselves as an additional "tool set" for designing and enhancing antenna performance
  - Investigate metamaterial magnetic ground planes to reduce planar antenna sizes
    - Applicable to conformal platform applications
  - Investigate metamaterials to impedance match embedded antennas in platform thus improving bandwidth
  - Investigate metamaterials to reduce mutual coupling between antennas operating at different frequencies
    - Mitigate co-site interference
    - Improve array performance
Metamaterials Realizations

• Printed elements/circuits on dielectric material in a periodic structure

A split ring structure etched into copper circuit board plus copper wires to give negative $\mu$ and negative $\epsilon$ (courtesy David Smith and Shelly Schultz, UCSD).

Smith, et al., @ Duke Univ., 2006
**Metamaterial Antennas** - ones made from ideal homogenized metamaterials where the behavior of the unit cells gives effective macroscopic parameters.

**Metamaterial inspired** - designs that are realized from understanding metamaterial concepts, but cannot be called metamaterials (e.g., an antenna constructed with one “unit cell.”) Often the designs are realized by a few metallic inclusions (e.g., split ring resonators,) but could have been realized using well-known traditional methods.
Victor Veselago writes a theoretical paper discussing the implications of double negative materials.

ARL fabricates a class of metamaterial at RF for optimization of antenna performance.

ARL fabricates double negative test structures for proof of feasibility.

ARL measures University of Michigan/CERDEC metamaterial structure to validate performance enhancement.

ARL develops Volumetric Randomly Oriented Unit Cells for isotropic performance.

ARL is contracting agent with MetaMaterials, Inc for Metaferrite antenna development.

ARL identifies significant modeling issues and defines needs for the MSME.

ARL field tests metamaterial antennas on Army platforms.

Prototype antennas fabricated and measured.

Metamaterials can be used to broadband (impedance match) antennas.

Metamaterials can be used to mitigate “hot spots”.

Metamaterials can integrate antennas into armor.

Duke Univ. Metamaterial Rotman lens.

General Atomics/Metamaterial belt antenna for the soldier.

Analytical and numerical tools for general metamaterial configurations.

Accurate analytical and numerical tool for periodic-metal-insert metamaterials.

Random-metal-insert metamaterials for broadband applications.
OBJECTIVES
• Investigate metamaterial structures for insertion in Army platforms to accomplish:
  • Size reduction, lower profile, and improved performance/higher gains of antennas
  • Wideband operation

APPROACH
• Use negative refractive index materials for new optics with smaller overall dimensions
• Use random metamaterials for possible wideband operation and lower losses
• Use metaferrites with high permeability to reduce profile of planar antennas
• Develop generalized analytical tools to deduce the parameters of multilayer metamaterials
• Use progressive dimensions and stacked EBG surfaces for low profile antennas

ACCOMPLISHMENTS
• Light-weight, thin metaferrite material was built and low-profile, wide bandwidth antenna was demonstrated
• Rigorous formulation of anisotropic multilayer metamaterial was used to calculate bulk constitutive parameters
• Wideband (>4:1 ratio) EBG surface was shown to improve the performance of broadband antennas, e.g. spiral antenna
• Prove through simulation and measurements refractive focusing using NRI metamaterials

• Show near-isotropic NRI behavior in a Capacitively Loaded Loop plus Probe (CLL-P) slab
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 with Metamaterial

Simulated S-Parameters without Metamaterial

Frequency, GHz

-30.0 -25.0 -20.0 -15.0 -10.0 -5.0 0.0

dB

S11
S21
S31
Refractive Focusing Using Negative-Refractive-Index Index Metamaterials

Measured S-Parameters

- **S11 with metamaterial**
- **S21 with metamaterial**
- **S31 with metamaterial**
- **S21 without metamaterial**
Realization of Negative-Refractive-Index in a Parallel Slab

- Full-wave simulation of parallel slab
- Unit cell is a Capacitively Loaded Loop + Probe (CLL-P)
- Refractive index is calculated using Snell’s Law and S-parameters
  => agreement
- Uniform negative refractive index at wide inclined angles => isotropic
CLL-P Configurations

**Parallel CLL-P Configuration:** Couples to longitudinal component of magnetic field

**Vertical CLL-P Configuration:** Couples to lateral component of magnetic field

**Cross CLL-P Configuration:** Couples to both components of magnetic fields for isotropic characteristics
Calculation of Simulated Refractive Index
Isotropic negative refractive index in cross-arranged CLL slab
Fabricated Metamaterials

Periodic metamaterial configuration

Random metamaterial configuration
• Develop wideband control of metamaterial transmission and reflection properties as an alternative to adaptive narrowband tuning

• Application-specific metamaterials: band-pass, band-stop, reflection-enhanced surfaces

• Explore the characteristics of randomly oriented cells in metamaterials:
  − Broader transmission/reflection bandwidth
  − Applied to fabrication disorders in otherwise periodic metamaterials
  − Study orthogonal incidences and polarization properties
TABLE I. HFSS SIMULATION RESULTS FOR STRUCTURES BASED ON # OF CLL FINS.

<table>
<thead>
<tr>
<th># of CLL Fins</th>
<th>Max Gain (dB)</th>
<th>Gain Improvement (dB)</th>
<th>3-dB Beamwidth (degrees)</th>
<th>Frequency of Max Gain (GHz)</th>
<th>Front-to-Back Ratio (dB)</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>2.2</td>
<td>0</td>
<td>360°</td>
<td>15.3</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>5.4</td>
<td>3.2</td>
<td>165.1°</td>
<td>19.3</td>
<td>9.3</td>
</tr>
<tr>
<td>4</td>
<td>6.9</td>
<td>4.7</td>
<td>95.7°</td>
<td>19.7</td>
<td>3.2</td>
</tr>
<tr>
<td>8</td>
<td>7.8</td>
<td>5.7</td>
<td>88.9°</td>
<td>20.8</td>
<td>10.7</td>
</tr>
<tr>
<td>12</td>
<td>9.7</td>
<td>7.5</td>
<td>48.3°</td>
<td>20.5</td>
<td>12.4</td>
</tr>
</tbody>
</table>
Improved Gain and Radiation Pattern of Enhanced Dipole

Radiation Pattern of Planar, 2-Fin Structure

Radiation Pattern of 12-Fin Structure
A Metamaterial-Loaded Rotman Lens

- Use negative refractive index medium
- New optics pattern
- Reduced size
- Single ray path

AIZ/EA 072209
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  • Adaptive and Active Reflection Phase Surfaces
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• **Nanotechnology**
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  • CNT Patches
  • Application to Gas Sensors
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• **Conclusions**
EBG structures are usually periodic

High surface impedance

Do not support surface waves

Useful when mounting an antenna close to a ground plane

EBG structures are compact in size, have low loss, and can be integrated into an antenna
• In phase reflection of the wave
• Band Gap is the frequencies where the reflected phase is between +90° and -90°
• Usually narrowband

![Graph and formulae related to EBG structures]
Reflection Phase off EBG Surfaces

Mushroom EBG Configuration and Reflection Phase*

Variation of Frequency Response of Reflection Phase with Patch Dimensions**

*Sievenpiper et al., IEEE Trans MT&T, Nov 1999
Frequency response of reflection phase for uniform (fast) and progressive (slow) EBG*

*Zaghloul, Palreddy. Weiss, EuCAP 2011

Frequency response of reflection phase for uniform (fast) and stacked (slow) EBG**

** Palreddy, Zaghloul, Lee, EuCAP 2012
Tunable EBG surface using varactor diodes
Dual Band Tunable EBG

EBG surface independently tuned over two separate frequency bands using dual layer with varactor diodes

Tunable Surface Using Distributed MEMS

Schematic of unit EBG cell

S21-Parameter for unit EBG cell

Top view of tunable structure

*Zhang et al., IEEE Nano/Micro Engineered, 2009*
EBG-Backed Spiral Antenna

- Formed by cascading Uniform EBGs of same height
- Resonate close to one another
- Has a wider band gap than regular EBG
• Computed using FEKO

• Reflection phase computed just above the EBG surface

• Notice that the Progressive EBG structure has wider band gap.
Gain patterns of the spiral antenna in free space
Gain patterns of the spiral antenna near uniform EBG
Gain patterns of the spiral antenna near progressive EBG
Return Loss comparison of the spiral antenna under different loading conditions
Boresight gain comparison of the spiral antenna under different loading conditions
Boresight axial ratio comparison of the spiral antenna under different loading conditions
• Higher gain and higher front-to-back ratio with progressive EBG

• Better boresight axial ratio performance with progressive EBG than Uniform EBG

• Uniform height progressive EBG structure has a wider band gap, compared to the regular EBG structure

• Accomplished with low profile that is afforded by the reflection phase characteristics of the broadband EBG

• This low profile is in contrast with the higher profile design that uses PEC-backed or absorber-backed cavities

• Gain patterns of the antenna near progressive EBG are cleaner & smoother, like the case in free space, compared to the case near uniform EBG
• Cognitive Radar is based on learning through interactions of the radar with the environment

• Information is facilitated by feedback from the receiver to the transmitter

• Information on target is deduced through processing of radar returns

• Environment or channel data include reflection phase and resonance frequencies of surfaces, which constitute part of the feedback from the receiver to the transmitter

• Adaptive reflection phase control can be a key function
Block diagram of cognitive radar viewed as a dynamic closed-loop feedback system*

• For the radar to be cognitive, adaptivity has to be extended to the transmitter too

• The function of the radar-scan analyzer is to provide the receiver with information on the environment

• The selection of waveforms to be used for adaptive radar transmission is application dependent

• There is much that we can learn from the echo-location system of a bat

• An echo-locating bat can pursue and capture its target with a facility and success rate that would be the envy of a radar engineer
Adaptive Reflection Phase

- Adaptively control the environment, primarily reflection function

- Function of phase variation can be controlled by transmitter and shared by receiver

- Narrow-band fast phase change or wide-band slow phase change versus frequency

- Introduces false target information in radar jamming systems

- Can be effective in Digital Radio Frequency Memory (DRFM) techniques
Outline

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Carbon Nanotube Background

- Carbon nanotubes (CNTs) are sheets of graphene rolled up as hollow cylinders
  - Typical diameter range of 1 – 2 nm for single wall CNTs (SWCNT) and 2 – 25 nm with 0.4 nm spacing (van der Waals gap) between concentric shells for multi wall CNTs (MWCNT)
  - Lengths > 1 cm have been achieved for single tubes
  - Threads of long CNTs can be woven together to increase length and overall diameter
- Chirality (orientation of rolled-up graphene sheets) determines metallic or semiconducting nature of SWCNTs
  - Zigzag – semiconducting, Armchair – metallic, Chiral – mostly semiconducting
  - MWCNTs are always metallic / MWCNT bundles exhibit multiple conducting channels in parallel and are better electrical conductors than SWCNT bundles
- CNTs have long mean free electron paths (on order of several μm vs. nm for Cu at room temperature)
  - Leads to low resistivity and possible ballistic transport over short lengths
- Electrons conduct through the π-bond of carbon atoms
  - Skin effect can be ignored up through the THz frequency range
Carbon Nanotube Thread
Conductivity Simulation

- Conductivity simulated for thin copper cylinder, double-wall carbon nanotube and 1-ply, 3-ply and 3x3 (9)-ply carbon nanotube thread
  - 3.4 Å van der Waals spacing between nanotubes in CNT thread
- CNT thread predicted to yield orders of magnitude higher conductivity above single carbon nanotube
- Simulations agree well with measured resistivity of CNT thread (1e-4 Ω-cm → σ\approx 1e6 S/m), and confirm known conductivity of copper (~5.96e7 S/m)
- Increasing CNT thread/rope ply (diameter and conductive paths) should yield improved conductivity

![Conductivity vs. Frequency](image)

\[ \sigma_{SWNT} = -j \frac{2e^2v_F}{\pi^2\hbar a(\omega - j\nu)} \]

Number of Carbon Nanotubes in Rectangular CNT Bundle

\[
N_w = \frac{2(R-a)}{x}; N_l = \frac{2(R-a)}{\sqrt{3}/2}x + 1
\]

\[ N_{total} = N_w \cdot N_l - \frac{N_l}{2}; N_{outer} = 2 \cdot (N_w + N_l) \]

Approximate Number of Carbon Nanotubes in Circular CNT Bundle / Thread

\[
A_{circle} = \frac{\pi R^2}{2R \cdot 2R} = \frac{\pi}{4}; N_{total} \approx \frac{\pi}{4} N_{total}
\]

Conductivity of Double-wall Nanotube

\[
\sigma_{MWNT} = \sum_{q=1}^{N} \sigma_{SWNT}^{(q)}
\]

\[
\sigma_{DWNT} \approx 2\sigma_{SWNT}
\]

Conductivity of CNT Bundle / Thread

\[
\sigma_{Bundle} \approx N_{total} \cdot \sigma_{DWNT}
\]

Physical Constants

- \( e = 1.602e-19 \) coulombs
- \( m_e = 9.11e-31 \) kg
- \( Ne = 8.46e28 \) electrons/m
- \( \nu = (2.47e-14) \)
- \( h = 1.0546e-34 \) m^2 kg/s
- \( vF = 9.71e5 \) m/s

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Radius (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double-wall CNT</td>
<td>0.005</td>
</tr>
<tr>
<td>1-ply CNT thread</td>
<td>12.5</td>
</tr>
<tr>
<td>3-ply CNT thread</td>
<td>37.5</td>
</tr>
<tr>
<td>3x3-ply CNT thread</td>
<td>112.5</td>
</tr>
<tr>
<td>30-gauge Cu wire</td>
<td>127.5</td>
</tr>
<tr>
<td>15-gauge Cu wire</td>
<td>725</td>
</tr>
</tbody>
</table>
Carbon Nanotube Gas Sensor
Background

- When subjected to certain oxidizing/reducing gases, $\varepsilon_r$ and $\sigma$ of CNTs are altered
  - Examples: He, Ar, N2, O2, NH3
- Charge transfer between the reacting gas molecules and the CNTs are the most likely mechanism for this occurrence
  - Gas molecules act as either electron donors or acceptors to CNTs
- Process is reversible ($\varepsilon_r$ and $\sigma$ return to original values over recovery time)
- CNT gas sensor achieved by coating a microwave cavity resonator with a thin layer of randomly scattered SWNTs and/or aligned MWNTs
  - Resonator frequency shifts by small, but measurable amount in direct response to the change in $\varepsilon_r$ and $\sigma$ caused by the presence of the reacting gas

Goal: Incorporate CNT gas sensing capabilities with RF properties to yield complete lightweight, durable wireless gas sensor
Microstrip Aperture-Coupled Patch Antenna

- Radiating slots produce broadside radiation pattern
  - When substrate thickness, $t$, is small, radiation is approximated by horizontal magnetic currents circulating the perimeter of the patch over a ground plane
- 50 Ω microstrip line (impedance matched to antenna feedpoint) provides RF energy to patch through aperture in ground plane

1) \[ W = \frac{1}{2 f_r \sqrt{\mu_0 \varepsilon_0}} \left[ \frac{2}{\varepsilon_r + 1} \right] = \frac{c}{2 f_r} \left[ \frac{2}{\varepsilon_r + 1} \right] \]

2) \[ \varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \frac{t}{W} \right]^{-1/2} \]

3) \[ \frac{\Delta L}{t} = 0.412 \frac{(\varepsilon_{\text{eff}} + 0.3)(\frac{W}{t} + 0.264)}{(\varepsilon_{\text{eff}} - 0.258)(\frac{W}{t} + 0.8)} \]

4) \[ \lambda_{\text{cm}} \approx \frac{30}{f_r \text{ (in GHz)}} \]

\[ L = \frac{\lambda}{2\sqrt{\varepsilon_{\text{eff}}}} - 2\Delta L \]
• Apply carbon nanotube thread/yarn to create meshed patch antenna structure

• Alternate thread in mesh with highly conductive MWNT thread (RF radiators) and semiconducting SWNT thread (dielectric buffer / “gas sensing” mechanism)
  - MWNT threads are main conductive elements for radiating meshed thread patch antenna
  - SWNT threads have high # of defects to limit their conductivity and serve as dielectric buffer threads
  - Defect sites on SWNT threads provide more locations for reactive gas molecules to donate or accept electrons → increases gas sensing mechanism

• In the presence of oxidizing/reducing gases, εr of SWNT dielectric buffer threads will change and resonant frequency of patch antenna will shift
Meshed Carbon Nanotube Thread Patch Antenna Design

- Ka-band antenna design (f₀ ≈ 30 GHz)
- 2.7 x 3.7 mm aperture-coupled meshed CNT thread patch antenna
- Patch constructed from 50 µm diameter CNT thread (alternating between high-conductivity MWNT threads and low-conductivity, high-defect dielectric buffer SWNT threads) spaced ~ λ/67 apart
- Conductive MWNT threads assigned approximate conductivity of σ = 1e6 S/m; defects in CNT walls (resistive barriers) and quantum level effects (CQ, LK) not accounted for in this simulation
- Semiconducting / dielectric buffer SWNT threads assigned dielectric constant, εᵣ = 5, based on measured data from literature
- RT/Duroid 6010 (εᵣ = 10.2, t = 10 mil) for feedline substrate, RT/Duroid 5870 (εᵣ = 2.33, t = 20 mil) for patch substrate
- Feedline (l = 1590 µm, w = 190 µm) and ground plane constructed from copper to reduce simulation complexity → future cases will explore effect of using CNT meshed thread
Simulated $S_{11}$ for Meshed CNT Thread vs. Solid Copper Patch Antenna

- **Meshed CNT thread patch** design yields center frequency shift ($f_0$) and bandwidth reduction when compared with traditional solid copper patch design
  - 2 GHz (7%) $f_0$ shift: from 29.6 GHz to 27.85 GHz
  - 400 MHz (~16%) bandwidth ($S11 = -10$ dB) reduction: from 2.5 GHz to 2.1 GHz
- Broadside radiation pattern maintained with CNT meshed patch antenna
- **Meshed CNT thread patch** design yields small gain reduction when compared with **traditional solid metal patch** design
  - 0.46 dB (~7 %) reduction: from 6.79 dBi to 6.33 dBi
  - Gain reduction likely from resonance shift observed in S11 simulation
From experimental observation, permittivity ($\varepsilon_r$) of a thin layer of semiconducting SWNTs increases linearly when in the presence of increasing concentrations of ammonia gas (NH$_3$).

Estimated change from $\varepsilon_r = 5$ to $\varepsilon_r = 5.15$ in presence of 1000 ppm of NH$_3$, then $\varepsilon_r = \varepsilon_r + 0.15$ with each additional 3000 ppm NH$_3$.

- Permittivity changes applied to SWNT thread model to simulate gas sensing for meshed thread patch antenna.

- Small, but measurable resonant frequency shift predicted to occur with increasing concentrations of NH$_3$ around the meshed CNT thread patch antenna.
  - 60 MHz shift in $f_0$, from 27.84 GHz to 27.78 GHz.

- Frequency shift is small enough to guarantee continuous bandwidth for TX/RX communications functionality.

- Adding PABS to SWNT will increase the sensitivity of gas detection with ability to sense very low, and more practical levels.
Polarization Selectivity
In CNT Patch Antennas

Return Loss for Co-Aligned CNT Patch

Return Loss for Cross-Aligned CNT Patch
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• Metamaterials and metasurfaces define structures that have been known by different names in the past

• Metamaterial structures may lead to more efficient, smaller antennas with new features not doable with natural materials

• Metasurfaces provide reflection phases that can reduce antenna profiles with potential application to cognitive radar

• Carbon nano-tubes have high tensile-strength and light weight, with high conductivity if used in multiple layers

• CNTs have potential applications in body-worn electronics, sensors, and polarization selective antennas