Frontiers of Metamaterials for Remote Sensing

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Outline

• Briefly describe the types of metamaterials
• The NSF IUCRC Center for Metamaterials
• Applications of Metamaterials for Remote Sensing
  - Hyper lens/Perfect Lens
  - Complex filtering – Wavelength and Polarimetric
  - Light channeling, light trapping, superbeaming
  - Optical angular momentum modes via metamaterials
The term was coined in 1999 by Rodger M. Walser of the University of Texas at Austin. He defined metamaterials as:

macroscopic composites having a manmade, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to specific excitation.

Possible Properties: Negative index of refraction; slow or stopped light; light channeling, filtering in complex ways
Types of Metamaterials and CfM Projects

• Traditional Metamaterials: Array of Split Ring Resonators
• Photonic Crystals: Filters, photon sorting, light trapping
• Plasmonic Crystals: Filters, light trapping
• Frequency Selective Surface: Filters, photon sorting light trapping
• Transformational Optics: Cloaking materials
• Generalize Snell’s Law Structures: Beam steering
Metamaterials: **Fundamentally** New Electromagnetic Materials

Optical Index of Refraction:

\[ n = \sqrt{\frac{\varepsilon}{\mu}} \]

**\( \varepsilon \)** = Electric permittivity

**\( \mu \)** = Magnetic permeability

Left Handedness and Negative Index of Refraction


From Maxwell’s Equations

\[ \nabla \cdot D = 0 \quad \nabla \times E = -\frac{\partial B}{\partial t} \]

\[ \nabla \cdot B = 0 \quad \nabla \times B = \frac{\partial D}{\partial t} \]

\[ \beta \times E = \omega \mu H \]

\[ \beta \times H = -\omega \varepsilon E \]

Boundary Conditions at an interface

\[ E_{1,t} = E_{2,t} \quad E_{1,n} = \frac{\varepsilon_1}{\varepsilon_2} E_{2,n} \]

\[ H_{1,t} = H_{2,t} \quad H_{1,n} = \frac{\mu_1}{\mu_2} H_{2,n} \]

If both \( m \) and \( e \) are negative, then the beam can propagate
Metamaterials: Fundamentally New Electromagnetic Materials

If we can find a material with:
\[ \varepsilon < 0 \quad \text{and} \quad \mu < 0 \]
then:
\[ n = -\sqrt{\varepsilon \mu} \]
Passage of Rays through Veselago’s Left-Handed substance with Negative Index of Refraction

The plane-wave refraction with no reflected wave:

\[ \theta_1 > 0 \]
\[ \theta_2 = -\theta_1 \]
\[ \theta_2 = -\theta_1 \]

ESTF 2018
Veselago’s Left-Handed Material with Negative Index of Refraction

Pendry’s Perfect Lens cancels the amplitude decay of evanescence waves:
Meta-atoms of Metamaterials

- Intrinsic properties
- Described by a few parameters
- $a_0 << a << \ldots$
- Material scale and resonance properties determine bulk index

Atomic scale | Atomic homogenization | Meta-atomic scale | Effective medium (second homogenization)

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Split Ring Resonator (SSR)

- First introduced by Smith et al.,
- Ring resonances excited by the incident field produce unusual E&M fields
- Can produce negative index of refraction

Meta “Atoms”
Are we there yet?
The past and the future of metamaterials

Stealth technology & FSSs
Microwave metamaterials
THz & photonic metamaterials
Dynamic & quantum metamaterial device & systems

Past: 2000
Present: 2011
Future

Materials & fabrication technologies

Top-down metalworking: Cu, Au, Ag & Al
PCB lithography copper etch
E-beam lithography, FIB, nanoimprint

- Noble metals are replaced by structured alloys, CNT & graphene, oxides, superconductors
- Hybridization with functional materials (nanocarbon, organics, nanosemiconductors, phase change media)
- NEMS structures
- Close-to-molecular level top-down fabrication, self-organization, DNA & protein scaffolding, stereo lithography, casting around organic frameworks

Technology development curve

- First Recognition
- Quantum MM
- Switchable MM
- Nonlinear MM
- Transformation Optics MM
- Designer Dispersion MM
- Negative index MM
- Artificial Magnetism MM
- Sober assessment
- Enthusiasm & Excitement
- MM for energy & sensor appl.

Hard work: applications, devices, systems

Research and development effort

Time
The Center for Metamaterials

Mission: The Center provides a collaborative, multi-university facility to research, design, fabricate and test a wide range of metamaterials for use in high-performing optical, electronic, and acoustic devices.

Research projects focus on market relevant topics that are jointly identified by university and industry participants.
Structure of the Center for Metamaterials

Member Companies
- Raytheon
- Corning
- Xerox
- USAF
- Army, USAF
- Phoebus
- US Connect
- +10 more

City University of New York
Clarkson University
University of North Carolina
Western Carolina University
Member Benefits

• Industry relevant research: members guide research;
• Broad range of physical resources, facilities, and equipment;
• Members interact with highly qualified students who have in-depth knowledge of metamaterials;
• Prepublication access to technical papers;
• Networking with industry peers; and
• Low-cost R&D channel (low even by university standards: CfM overhead only 10% vs. 50%).
• Umbrella agreement allows rapid continuing research
• Significant funding opportunities
• Networking with program managers at government agencies and large companies
• Can perform research that needs to adhere to ITAR
Members – Collaborations and Directed Research

Industry members

University scientists

ARL Designs

CORNING

COBHAM

xerox

Raytheon

US CONEC

Ball

PHOEBUS OPTOELECTRONICS LLC

MIT Lincoln Laboratory

UTC Aerospace Systems
Projects at the CfM

Website: www.centerformetamaterials.org

• Rapid Prototyping and Printing of Tunable Metamaterials
• Photon Sorting and Multi-Wavelength Detection
• Active Metasurfaces
• Optical Superresolution
• Conformal Metamaterial Antennas
• Gain Enhancement to Vivaldi Antenna using Metamaterials
• Conformal Artificial Magnetic Conductor Backed Antenna Structures
• Design and Fabrication of Low-Loss Low-Index Optical Metamaterials
• Optical Composite Materials
• Slow and Fast Light Using Metamaterials
• Self-Assembly of Split-Ring Resonators
• Self-Assembly of Functional Coatings: Superomniphobic Coatings
• Marking Technologies
Applications in the different spectral ranges

- Microwave and Radar: Active beam steering, directional antennas, low-profile antennas, flat lens
- Infrared: Polarimetric focal plane arrays, chem/bio toxin sensors, optical angular momentum, Hyperbolic Metamaterials in Bragg Stacks
- Visible: Solar cells and hydrogen/methanol generation via solar
- Ultraviolet: Solar blind photodetectors – detectors that are insensitive to light outside the UV spectrum
Tools in the Metamaterials Tool Chest

- Array of Split Ring Resonators
- Photonic Crystals
- Plasmonic Crystals
- Frequency Selective Surface
- Transformational Optics
- Generalize Snell’s Law Structures
Split-Ring Resonator
Metamaterials - Projects

• Metamaterial Ground plane of UHF/VHF Low Profile Systems
• Metamaterial Enhanced Vivaldi Antennas
• Actively Tunable Microwave Beam Steering
Metamaterial Ground plane of UHF/VHF Low Profile Systems

- Antenna sizes are directly related to the wavelength of operation
- Planar antennas are placed a distance of $\lambda/4$ away from the ground plane to improve the gain

Phase Delay = $2\times\pi/2$

Metal Phase-shift = $\pi$

Total phase accumulation: $2\times\pi/2 + \pi = 2\pi$
Objective

• Develop an Artificial Magnetic Conductor (AMC) which would mimic a Perfect H boundary
• The AMC would consist of an array of Split Ring Resonators (SRRs)
Polarization Independence

- The rings were designed to be polarization independent
- Performance should be identical for all polarizations including circular polarization
Antenna

• The Antenna maintained performance characteristics when it was placed closed to the AMC

• The AMC was simulated with an impedance boundary
Actively Tunable Beam Steering

New concepts in metasurfaces, Generalized Snells Law structures, are being used in phased array structures for beam steering.
Physical Structure and Performance
The choice of available infrared (IR) detectors is the key element of civilian, military, and scientific fields:

- Thermal imaging
- Environmental and chemical process monitoring
- Night vision systems
- Surveillance and the nation’s space-based intelligence
- Wavelength division and multi-detection

Yet, most multi-color IR detection systems involve costly and complicated vertically stacked semiconductor structures.
Photon Sorting in the Microwave

Waveguide-Cavity-Mode Photon Sorters

Waveguide Cavity Mode Sorters

Subwavelength patterning can filter, slow, channel, focus light in ways that naturally occurring materials cannot

1. Practical to manufacture
2. Lower loss
3. Great variability in characteristics
Pixelated Filters: Polarimetric, Multiwavelength, Hyperspectral and Superbeaming

- Pixelated filters of many types are used for remote sensing of aerosols.
- Cross-talk is a problem for many of these filters.
- Plasmonic structures within the polarizers can reduce cross talk and to enhance light collection.
Metamaterial based narrow bandwidth angle-of-incidence independent transmission filters for hyperspectral imaging

- Narrow bandwidth, high transmission optical filters allow a wide range of applications
  - Remote sensing
  - Hyperspectral imaging spectroscopy
  - LIDAR
  - Astronomy
  - Environmental monitoring

- Tunable filters allow for use in a variety of remote sensing applications

- Polarization dependency is being increasingly used in remote sensing
  - Offers reduction in instrument error
  - Sensitive to certain atmospheric parameters more-so than intensity
Conventional Bragg Stack designs have to much dispersion, namely the dependence on the wavelength of the transmission peak on the angle of incidence of the light.

Therefore, focusing optics cannot be used, or require bulky optical systems.

**Thickness Calculation**

\[ 2tk\sqrt{\varepsilon} = \pi \]

\[ 2t(2\pi/\lambda)\cos\theta\sqrt{\varepsilon} = \pi \]

\[ t\lambda_0 = \lambda_0 / 4\sqrt{\varepsilon} \]

\[ \lambda(\theta) = \lambda_0 \cos\theta \]

**Solid line:** The transmittance of a 19 layer Ge/ZnS Bragg stack (with the 5th Ge layer removed) for normal incident radiation. **Dashed line:** The transmittance for the modified Bragg stack for an incident angle of 30°.
Hyperbolic Metamaterial Enabled Structure

We will combine two optical materials/structures:

A. Bragg Stack
B. Hyperbolic Metamaterial – the wire mesh

The purpose of introducing a hyperbolic metamaterial (i.e., wire mesh) is to eliminate the dispersion of the Bragg Stack’s filtering properties.
A wire mesh arrayed in the $x$-$y$ plane (with the wires oriented in $z$ direction) has a dispersion relation for TM polarized incident light:

$$k\downarrow x^2 /\varepsilon \downarrow zz + k\downarrow z^2 /\varepsilon \downarrow xy = \varepsilon \downarrow xy k\downarrow o^2$$

$$\varepsilon = (\varepsilon \downarrow xy \& 0 \& 0 \& 0 \& \varepsilon \downarrow xy \& 0 \& 0 \& \varepsilon \downarrow zz )$$

$$\varepsilon \downarrow xy = (1+N)\varepsilon \downarrow out \varepsilon \downarrow in + (1-N)\varepsilon \downarrow out k\downarrow o^2 / (1+1)$$

$$\varepsilon \downarrow zz = N\varepsilon \downarrow in + (1-N)\varepsilon \downarrow out$$

$$k\downarrow z (\theta) = \sqrt{\varepsilon \downarrow xy k\downarrow o^2 - \varepsilon \downarrow xy /\varepsilon \downarrow zz} k\downarrow x^2 (\theta)$$

$\rightarrow |\varepsilon \downarrow zz| >> |\varepsilon \downarrow xy| \rightarrow \sqrt{\varepsilon \downarrow xy} k\downarrow o = k\downarrow z (\theta=0)$

Mitigates the dependence of $k\downarrow z$ on $\theta$, therefore largely eliminates the dependence of transmission on $\theta$
Ge/ZnS Bragg stack for 9 mm center wavelength

The transmittance of an 18 layer Ge/ZnS Bragg stack for normal incident radiation (solid line) and for 30° off-normal (dashed line). There is only a 4 nm change in the center wavelength.

<table>
<thead>
<tr>
<th></th>
<th>ε↓xy</th>
<th>ε↓zz</th>
<th>Thickness</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>20+i1.2×10¹⁻²</td>
<td>-381+i130</td>
<td>503 nm</td>
<td>Material: Gold Period= 800nm Diameter=300nm</td>
</tr>
<tr>
<td>ZnS</td>
<td>6.3+i1.2×10⁻³</td>
<td>-391+i130</td>
<td>895 nm</td>
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Si/ZnS Bragg stack for 4mm center wavelength

The transmittance of an 18 layer Si/ZnS Bragg stack for normal incident radiation (solid line) and for 30° off-normal (dashed line). There is only a 6 nm change in the center wavelength.

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon_{\perp xy}$</th>
<th>$\varepsilon_{\perp zz}$</th>
<th>Thickness</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>$14.5 + i1.5 \times 10^6$</td>
<td>$-74.3 + i12.4$</td>
<td>262 nm</td>
<td>Material: Gold Period= 300nm Diameter=113nm</td>
</tr>
<tr>
<td></td>
<td>$-2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZnS</td>
<td>$6.3 + i2.7 \times 10^{-3}$</td>
<td>$-80.2 + i12.4$</td>
<td>397 nm</td>
<td></td>
</tr>
</tbody>
</table>
NASA ACT Hyperspectral Filter: a spectrometer on a chip

- While the MS technology reduces the demands on several subsystems through its selectable spectral channels, the most dramatic effect is the elimination of the spectrometer subsystem itself.

- Greatly reduces the size and mass of the spectral instrument and eliminates the most thermally-sensitive subsystem.
Configuration and Operational Concept

Monolithic Integration

The spectral imager can operate either as a nadir-viewing pushbroom or a crosstrack-scanning whiskbroom sensor.

- In pushbroom mode, the spectral channels are measured in quick succession as the scene scans across rows of individual filters at the ground track speed.

- In whiskbroom mode, the fast optical system and quick detector readout speeds enable faster spectral scanning, with a latency between adjacent spectral channels below 10 ms while maintaining performance levels needed for atmospheric sounding and trace gas retrievals. widths.

Intermediate Image Filtering
The Metamaterial Spectrometer

1. Tunable transmission band (both the CWL and its bandwidth).
2. Any number of transmission bands can be engineered into the structure.
3. Broad Aol enables, focusing onto filter, eliminates optics which in turn reduces in SWaP.
4. An all dielectric system without optical losses increases the signal-to-noise.
5. Straightforward fabrication allows for hundreds of spectral channels.

Figure 3. Spectral channels defined by pixel-scale unit cells in the metamaterial offer spectral sensing with minimal latency between spectral channels and spectral channels with passbands matched to the spectral signature of the target gas.
Filter Performance
Conclusion

• The light controlling properties of engineered materials are many and powerful
• Hard and good engineering and materials science needs to be done to realize their potential
• Many applications to remote sensing can be realized
• SWaP benefits, but the –C can still be problematic for some applications