Frontiers of Metamaterials for Remote Sensing

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The National Science Foundation

Clarkson University

ESTF 2018

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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

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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

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Types of Metamaterials and CfM Projects

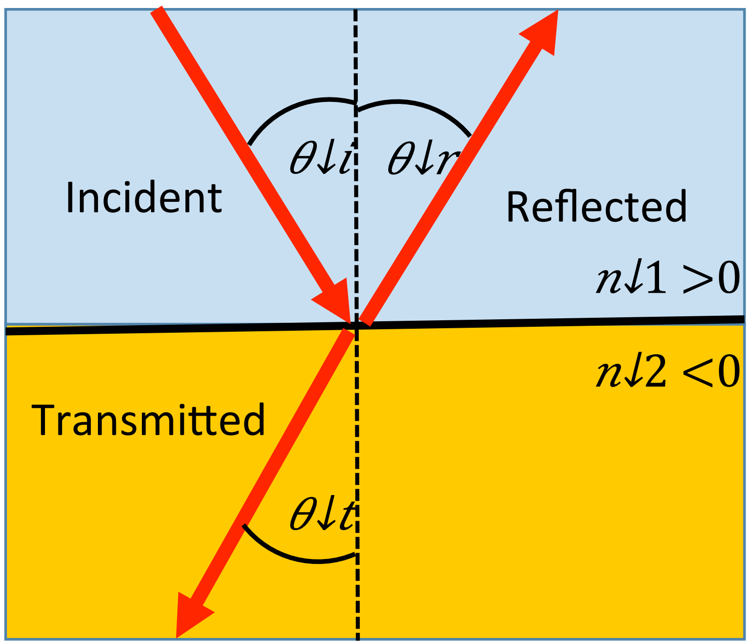
- Traditional Metamaterials: Array of Split Ring Resonators
- Photonic Crystals: Filters, photon sorting, light trapping
- Plasmonic Crystals: Filters, light trapping
- Frequency Selective Surface: Filters, photon sorting light trapping
- Transformational Optics: Cloaking materials
- Generalize Snell's Law Structures: Beam steering

Metamaterials: Fundamentally New Electromagnetic Materials

Optical Index of Refraction: $n=\pm\sqrt{\varepsilon\mu}$

$\varepsilon=$ Electric permittivity

$\mu=$ Magnetic permeability



V.G. Veselago, Sov. Phys. Usp. **10**, 509-514 (1968).

Left Handedness and Negative Index of Refraction

Victor Veselago, Sov. Phys. Usp. **10**, 509-514 (1968)

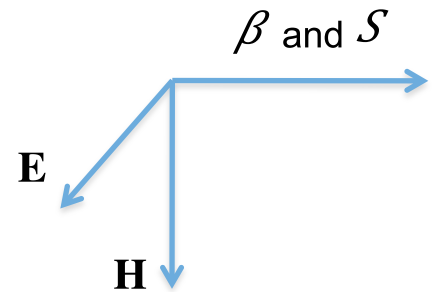
From Maxwell's Equations

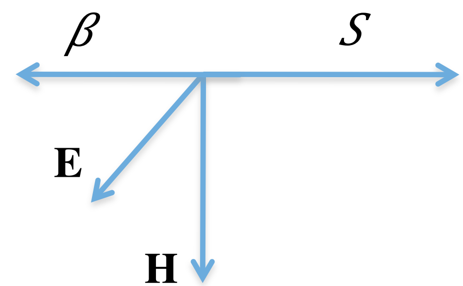
$$\nabla \cdot \mathbf{D} = 0 \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \nabla \times \mathbf{B} = \frac{\partial \mathbf{D}}{\partial t}$$

$$\beta \times E = \omega \mu H$$

$$\beta \times H = -\omega \varepsilon \mathbf{E}$$

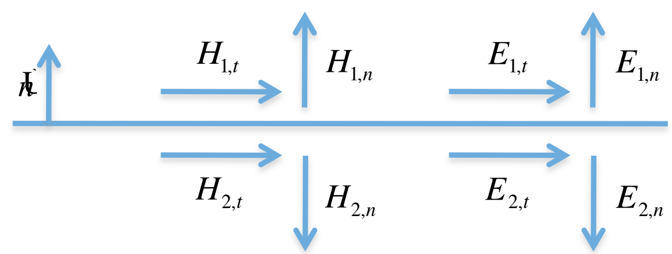


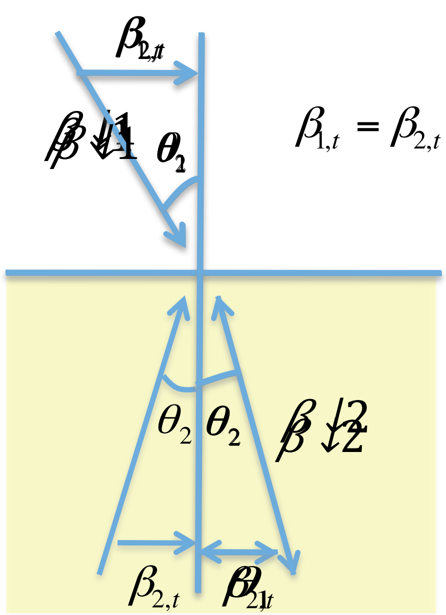


Boundary Conditions at an interface

$$E_{1,t} = E_{2,t} \qquad E_{1,n} = \frac{\varepsilon_1}{\varepsilon_2} E_{2,n}$$

$$H_{1,t} = H_{2,t} \qquad H_{1,n} = \frac{\mu_1}{\mu_2} H_{2,n}$$





$$\beta_{1,t} = \beta_{2,t}$$

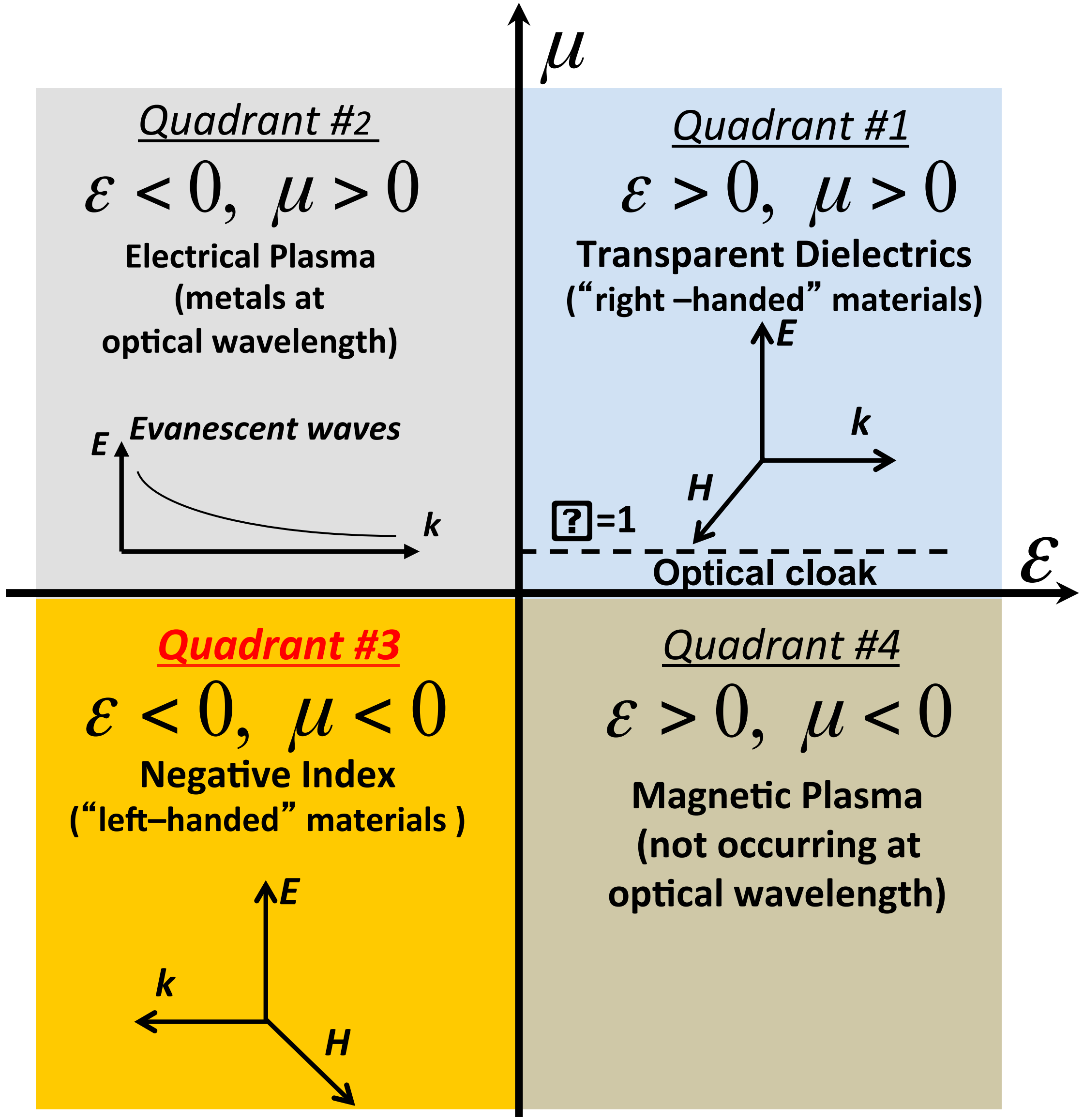
If *both* m and e are negative, then the beam can propagate

Metamaterials: Fundamentally New Electromagnetic Materials

If we can find a material with:

$\varepsilon<0$ and $\mu<0$

then: $n=-\sqrt{\varepsilon\mu}$



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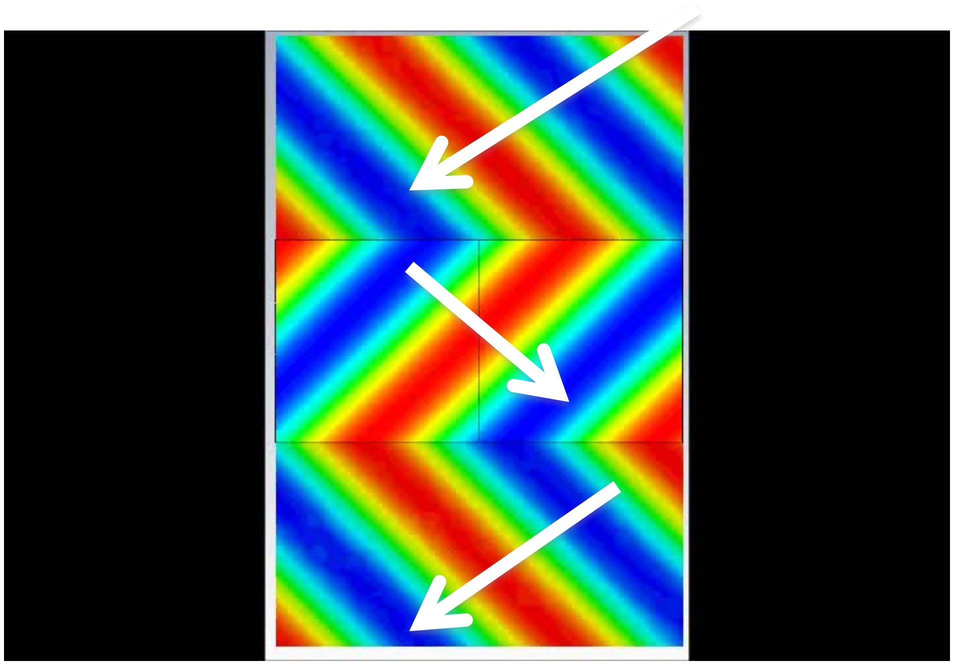
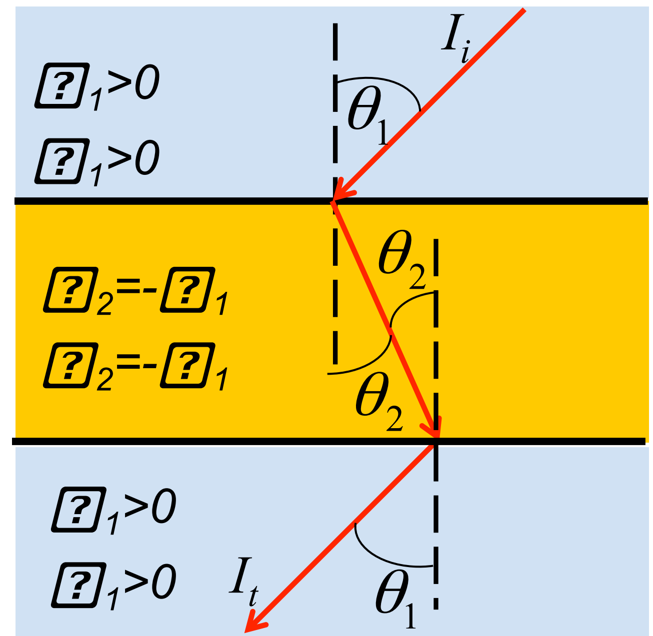
Passage of Rays through Veselago's Left-Handed substance with Negative Index of Refraction

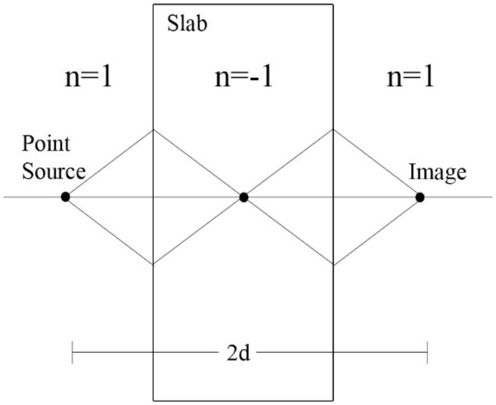
The plane-wave refraction with no reflected wave:

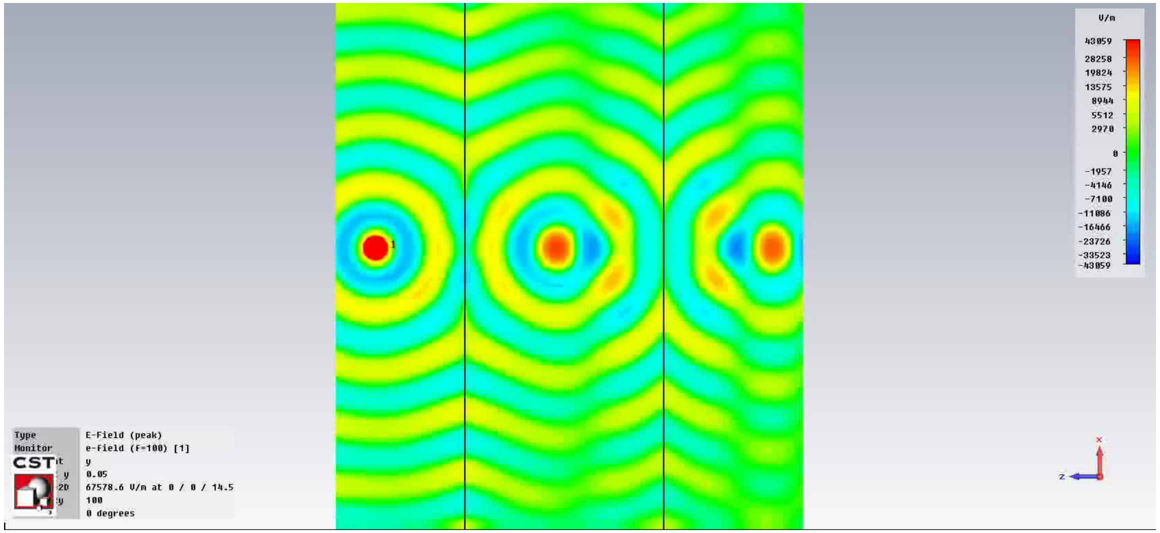




Veselago's Left-Handed Material with Negative Index of Refraction

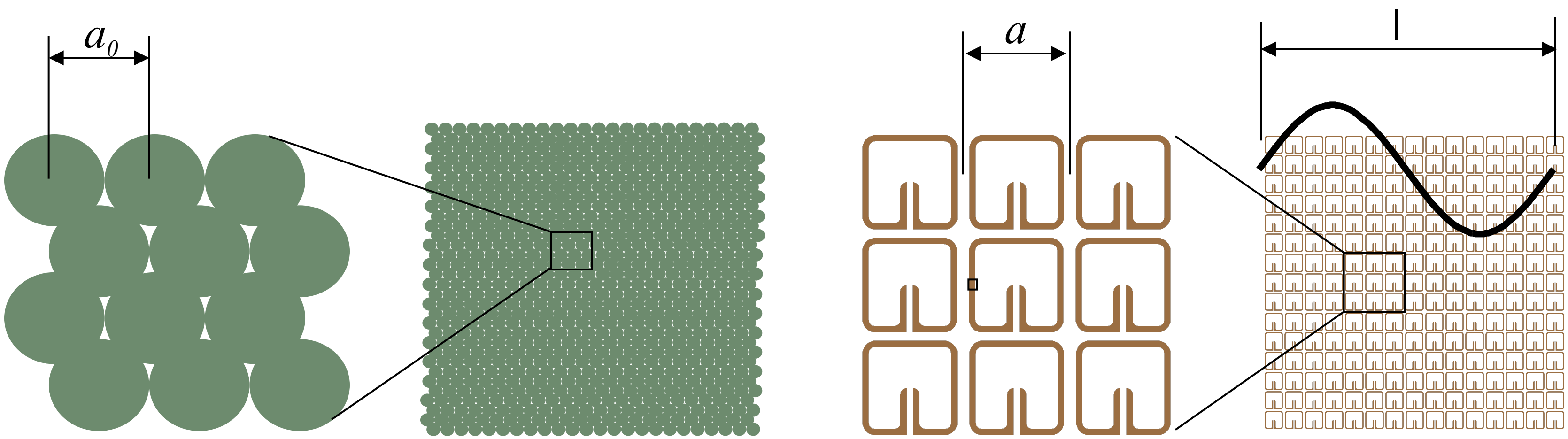
Pendry's Perfect Lens cancels the amplitude decay of evanescence waves:





Meta-atoms of Metamaterials

- Intrinsic properties
- Described by a few parameters
- $a_0 << a << \boxed{?}$
- Material scale and resonance properties determine bulk index



Atomic scale

Atomic homogenization

Meta-atomic scale

Effective medium (second homogenization)

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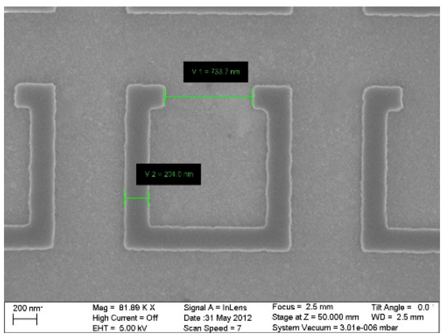
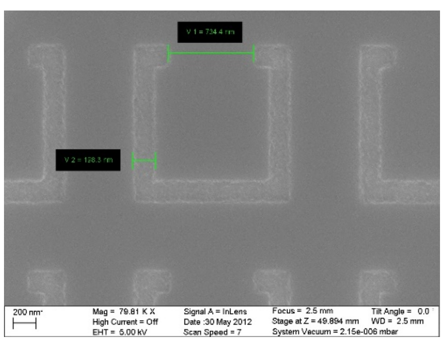
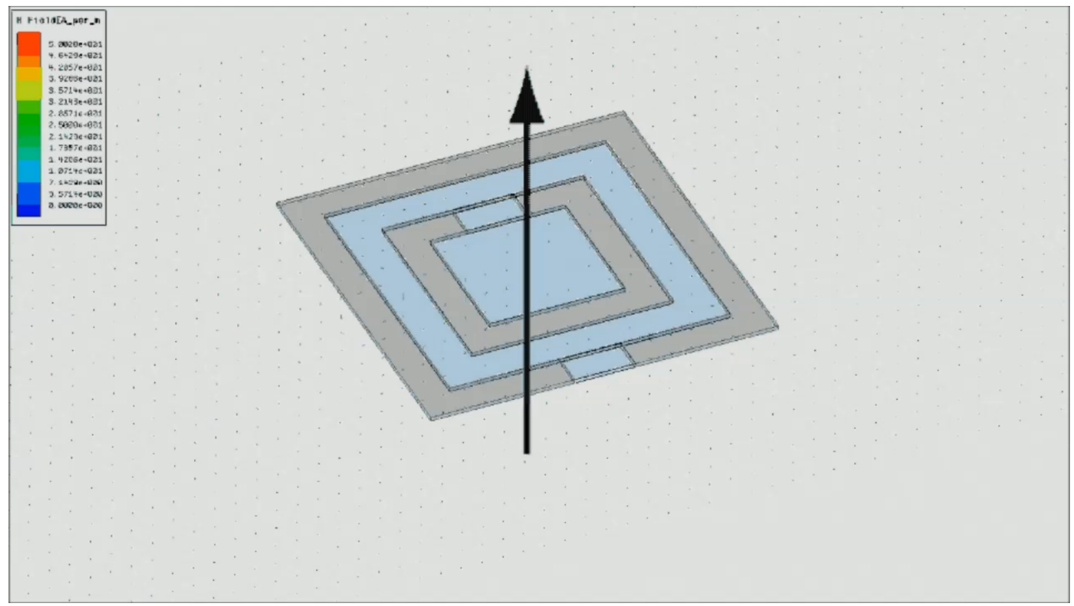
Split Ring Resonator (SSR)

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



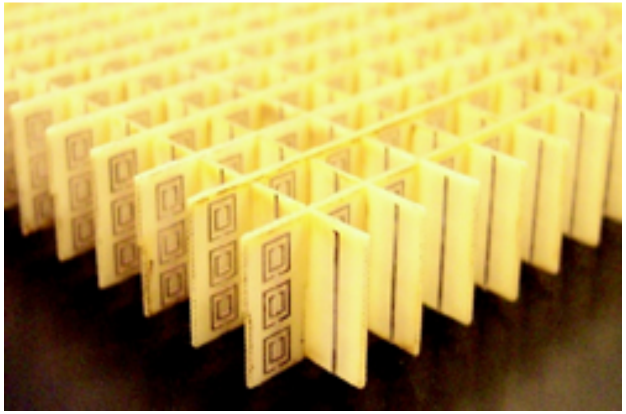


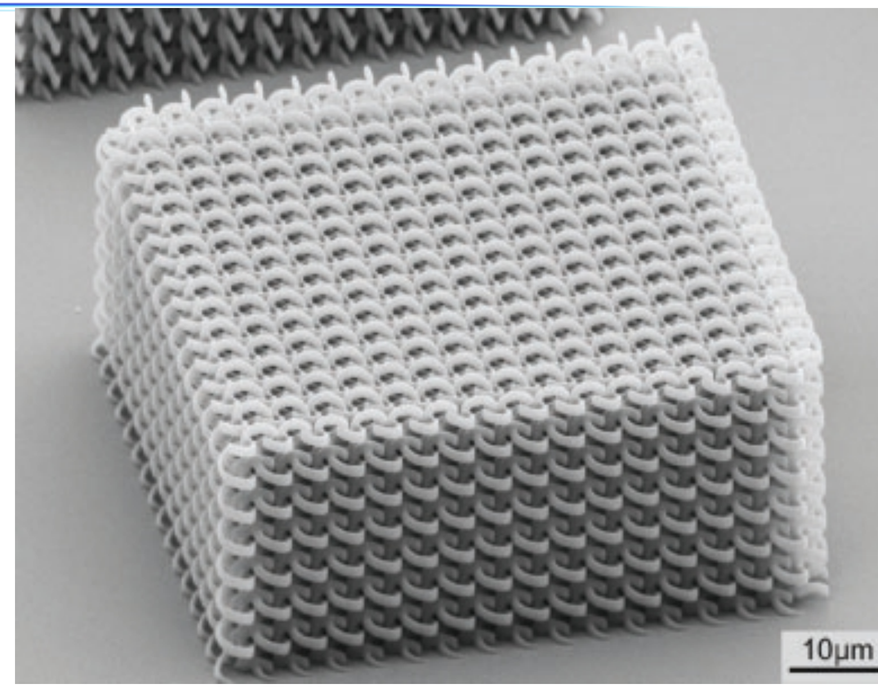
Time scan:

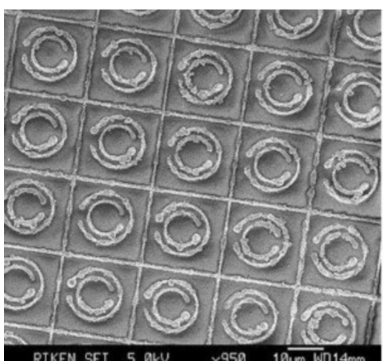


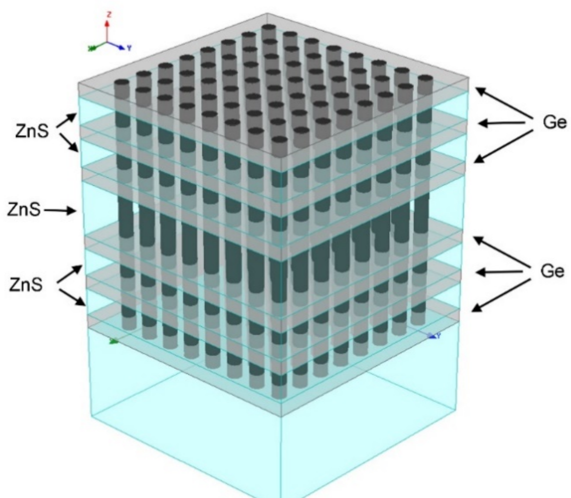
Smith, D. R.; Padilla, WJ; Vier, DC; Nemat-Nasser, SC; Schultz, S (2000). "Composite Medium with Simultaneously Negative Permeability and Permittivity" . *Physical Review Letters* **84** (18): 4184–7.

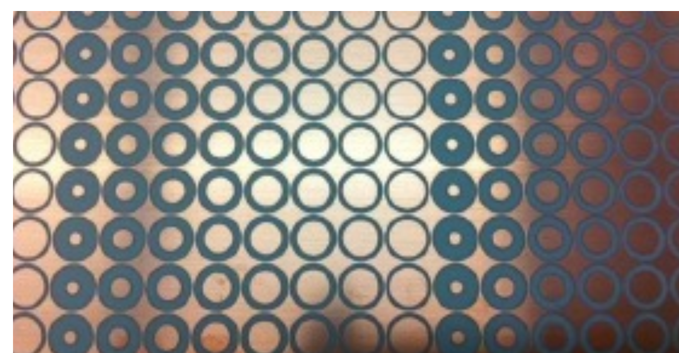
Meta “Atoms”











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Are we there yet?

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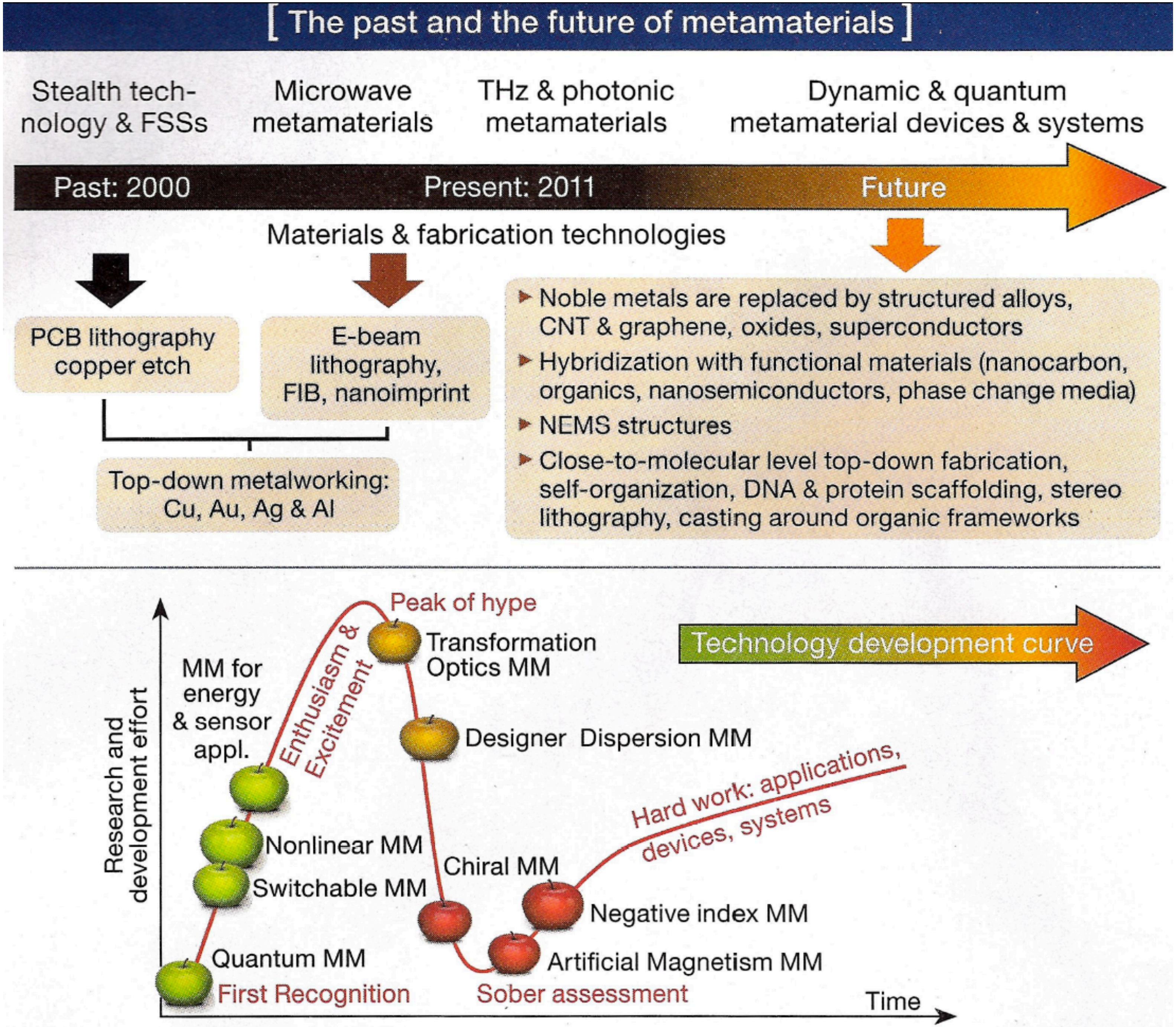
[The past and the future of metamaterials]
Stealth technology & FSSs
Microwave metamaterials
THz & photonic metamaterials
Dynamic & quantum metamaterial devices & systems
Past: 2000
Present: 2011
Future
Materials & fabrication technologies
PCB lithography copper etch
E-beam lithography, FIB, nanoimprint
Top-down metalworking: Cu, Au, Ag & Al
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
Peak of hype
Transformation Optics MM
Technology development curve
MM for energy & sensor appl.
Enthusiasm & Excitement
Designer Dispersion MM
Research and development effort
Hard work: applications, devices, systems
Nonlinear MM
Chiral MM
Switchable MM
Negative index MM
Quantum MM
Artificial Magnetism MM
First Recognition
Sober assessment
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.

CfM Research Focus

- **Sustainable Energy Technologies**
  - Solar cells, patterned electrodes, and light concentrators
- **Sensors**
  - Multiwavelength detectors, focal plane arrays, biological and chemical sensors
- **Antennas**
  - Lightweight, conformal, actively tunable, and directional
- **Optical Components**
  - Perfect lenses, micro-polarizers, and frequency selective surfaces

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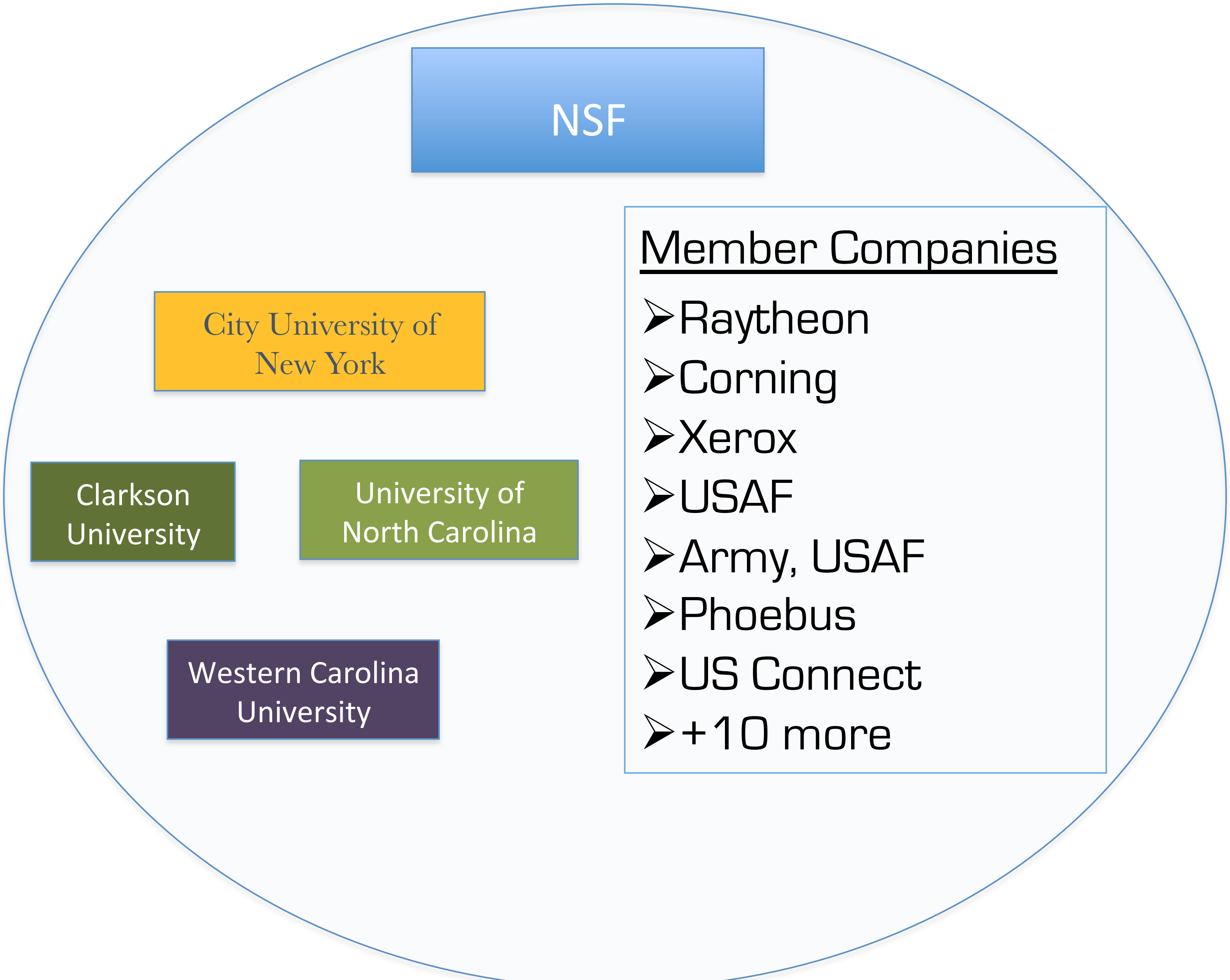
Structure of the Center for Metamaterials



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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

CfM
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Members – Collaborations and Directed Research

ARL

Air Force Research Laboratory

ARL Designs

CORNING

COBHAM

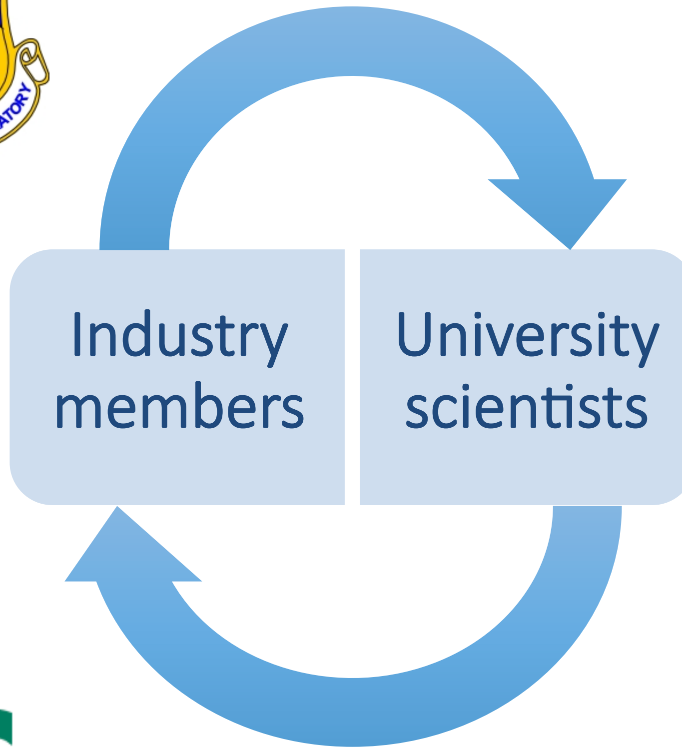
xerox

Raytheon

USCONEC

Ball Aerospace & Technologies Corp.

PHOEBUS
OPTOELECTRONICS LLC



CUNY The City University of New York

Clarkson UNIVERSITY defy convention

Western Carolina UNIVERSITY

UNC CHARLOTTE

MIT Lincoln Laboratory

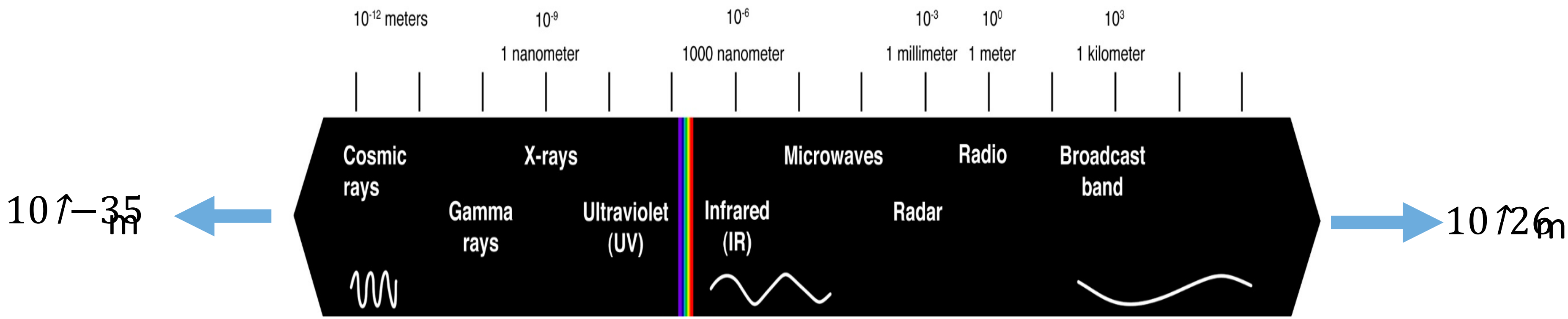
UTC Aerospace Systems

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

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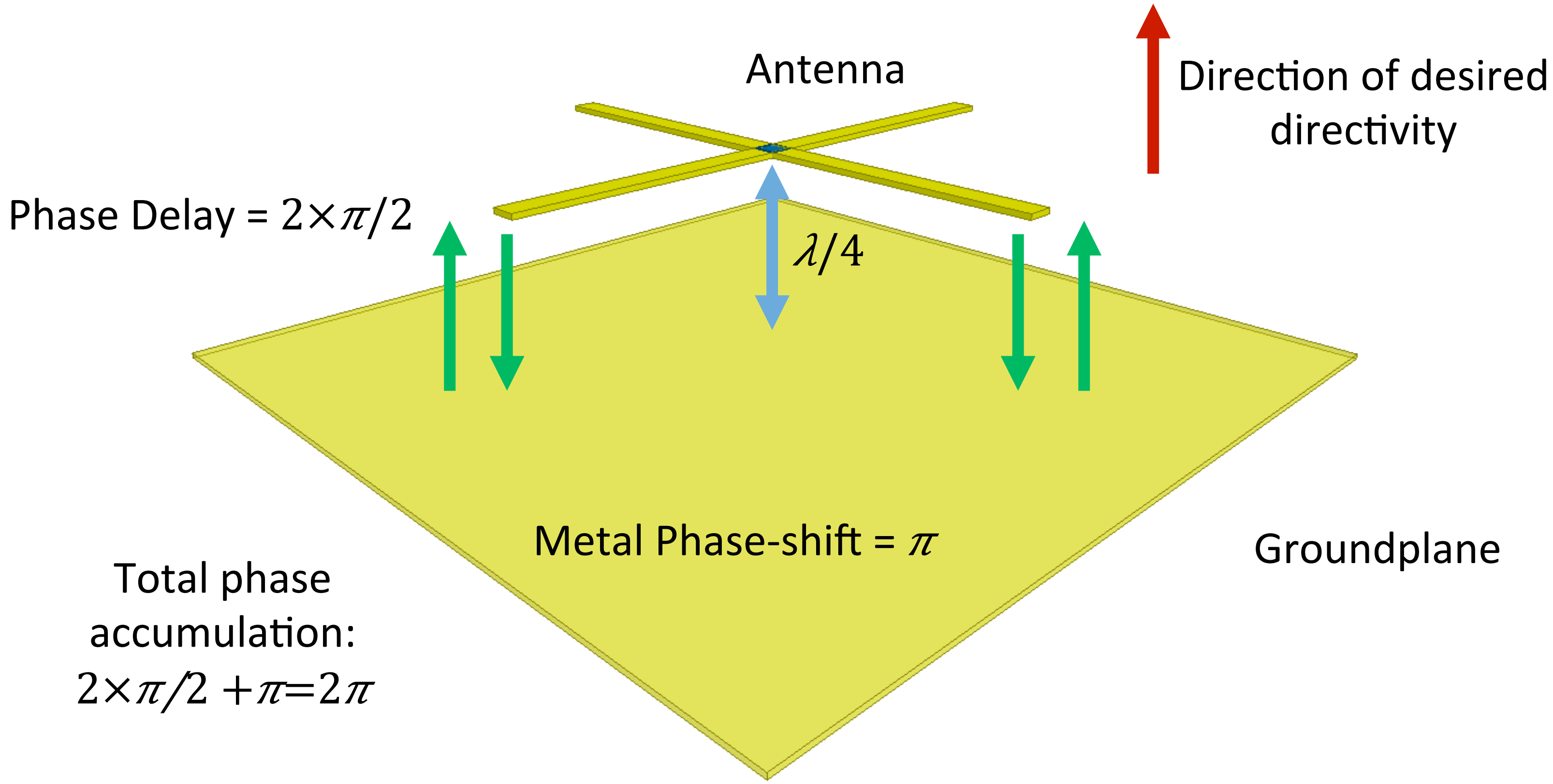
Split-Ring Resonator Metamaterials - Projects

- 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



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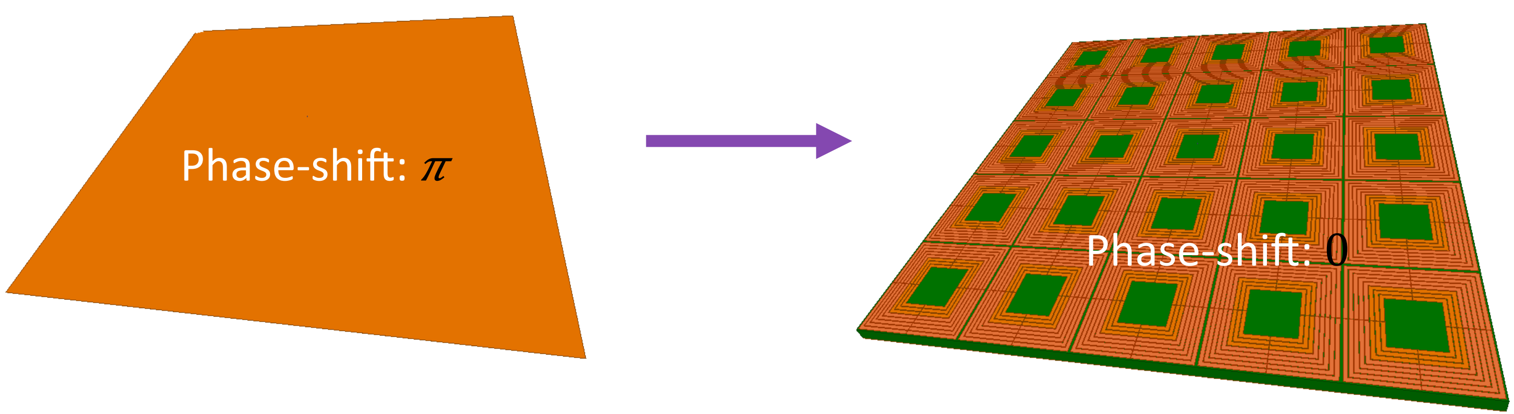
Objective

- 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)

Replace metal ground plane

With AMC array



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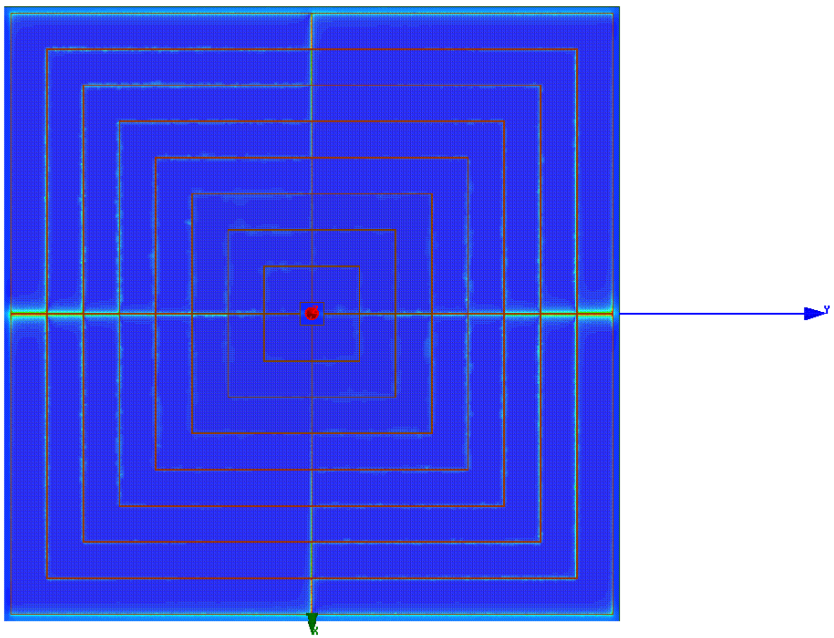
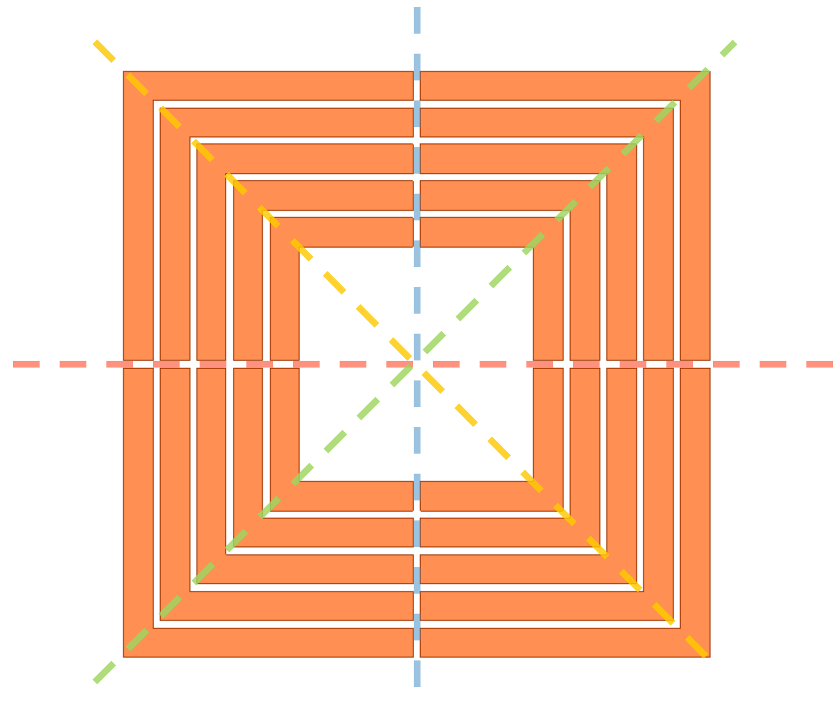
Polarization Independence

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





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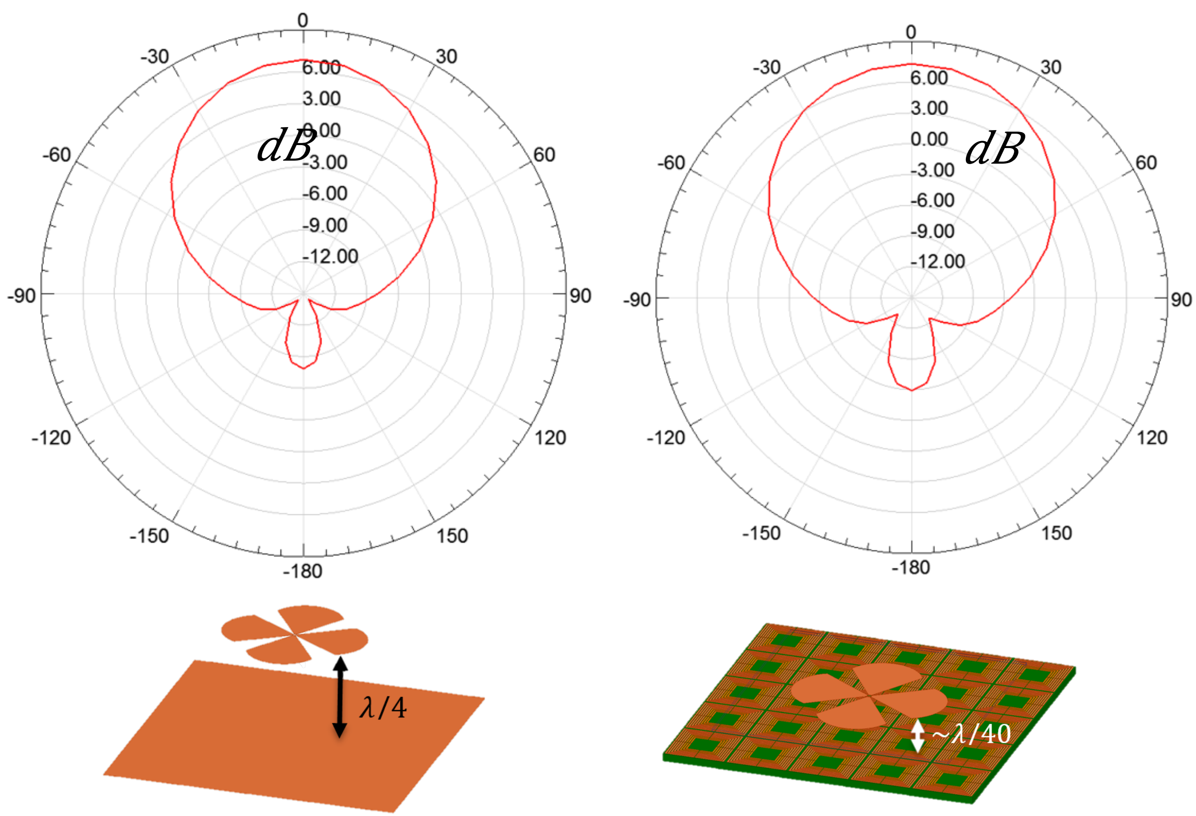
Antenna

- The Antenna maintained performance characteristics when it was placed closed to the AMC
- The AMC was simulated with an impendence boundary



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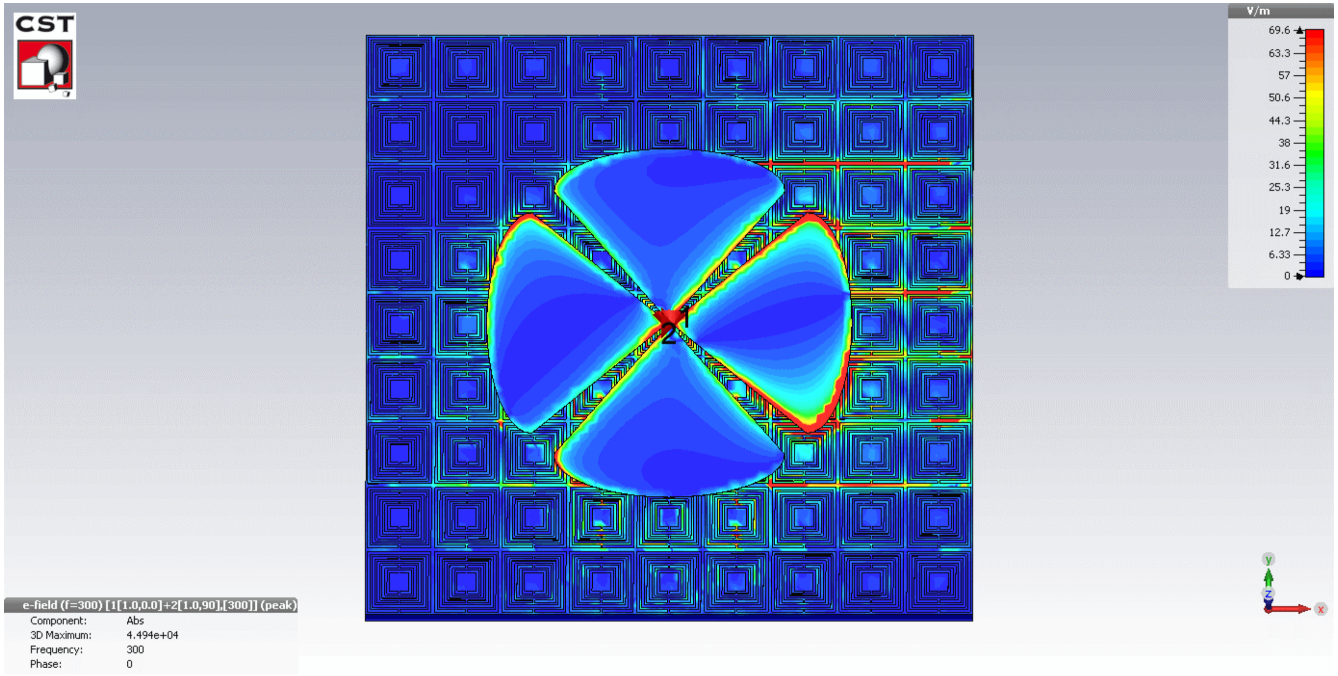
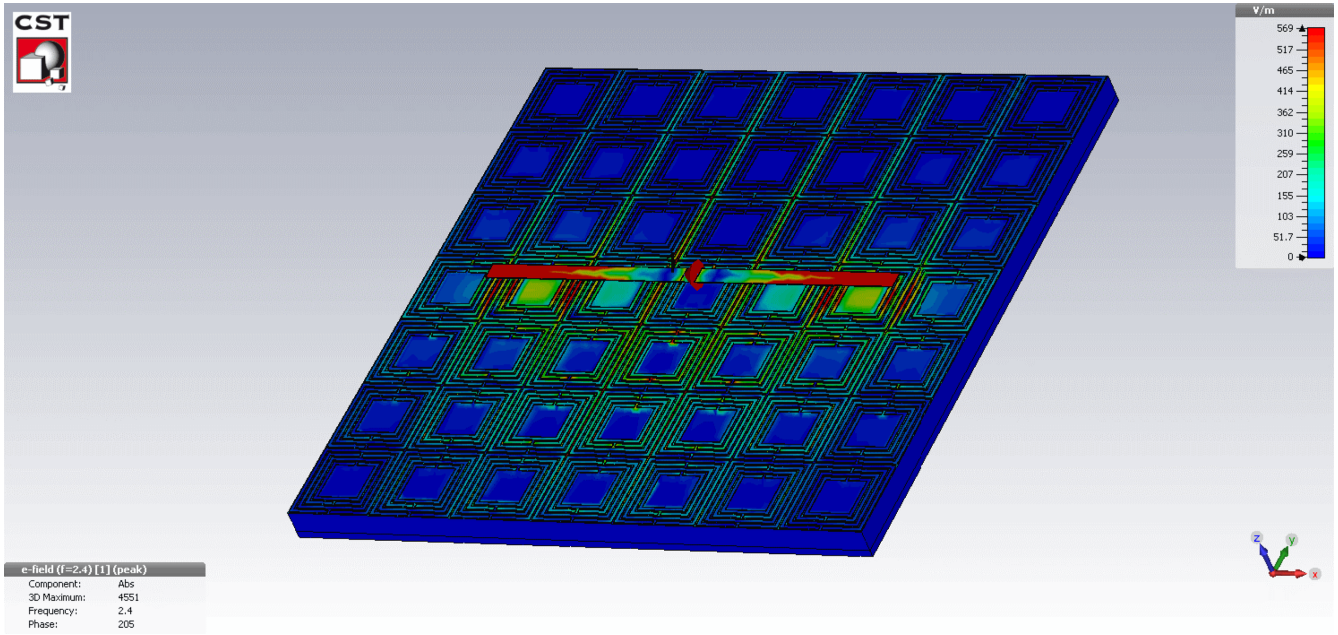
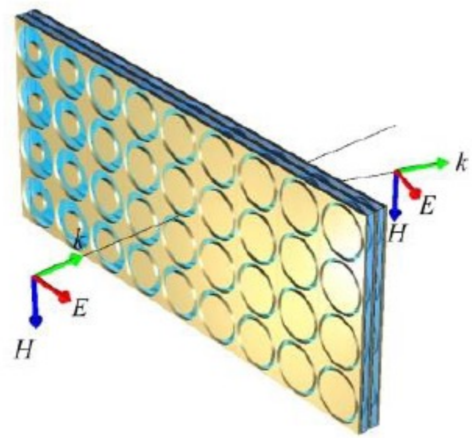
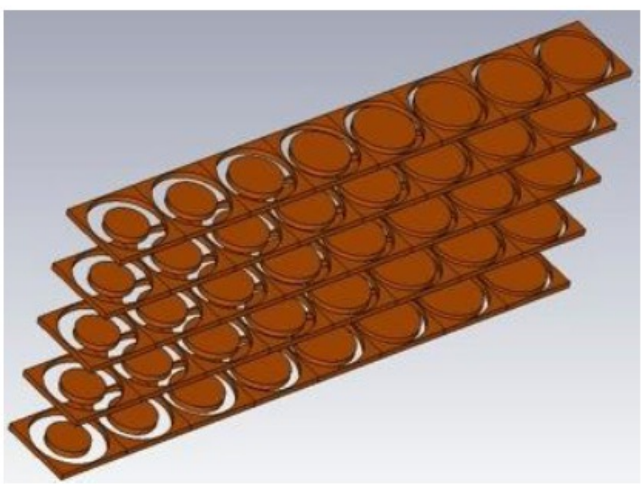

CST
V/m
69.6
63.3
57
50.6
44.3
38
31.6
25.3
19
12.7
6.33
0
e-field (f=300) [1[1.0,0.0]+2[1.0,90],[300]] (peak)
Component: Abs
3D Maximum: 4.494e+04
Frequency: 300
Phase: 0

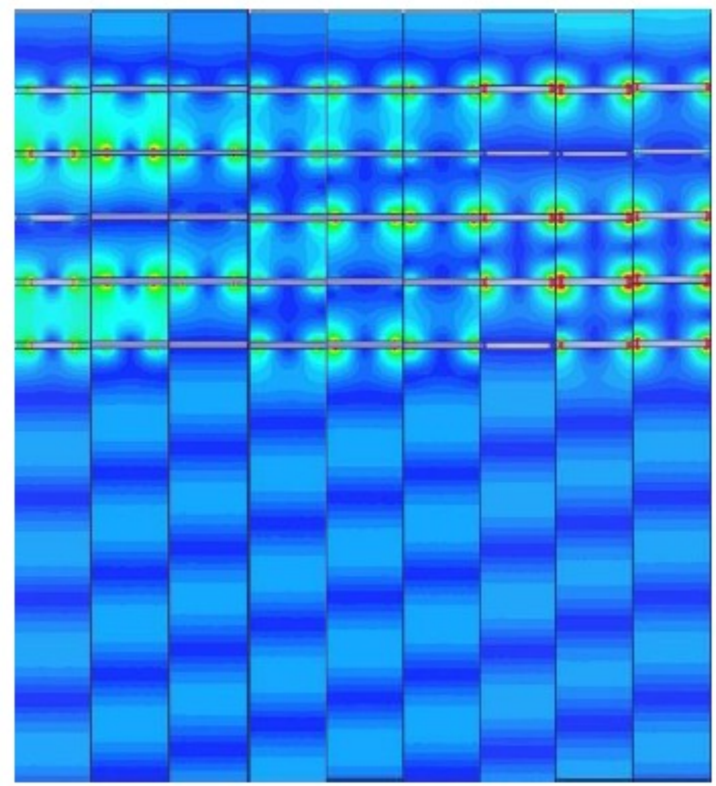

CST
V/m
569
517
465
414
362
310
259
207
155
103
51.7
0
e-field (f=2.4) [1] (peak)
Component: Abs
3D Maximum: 4551
Frequency: 2.4
Phase: 205

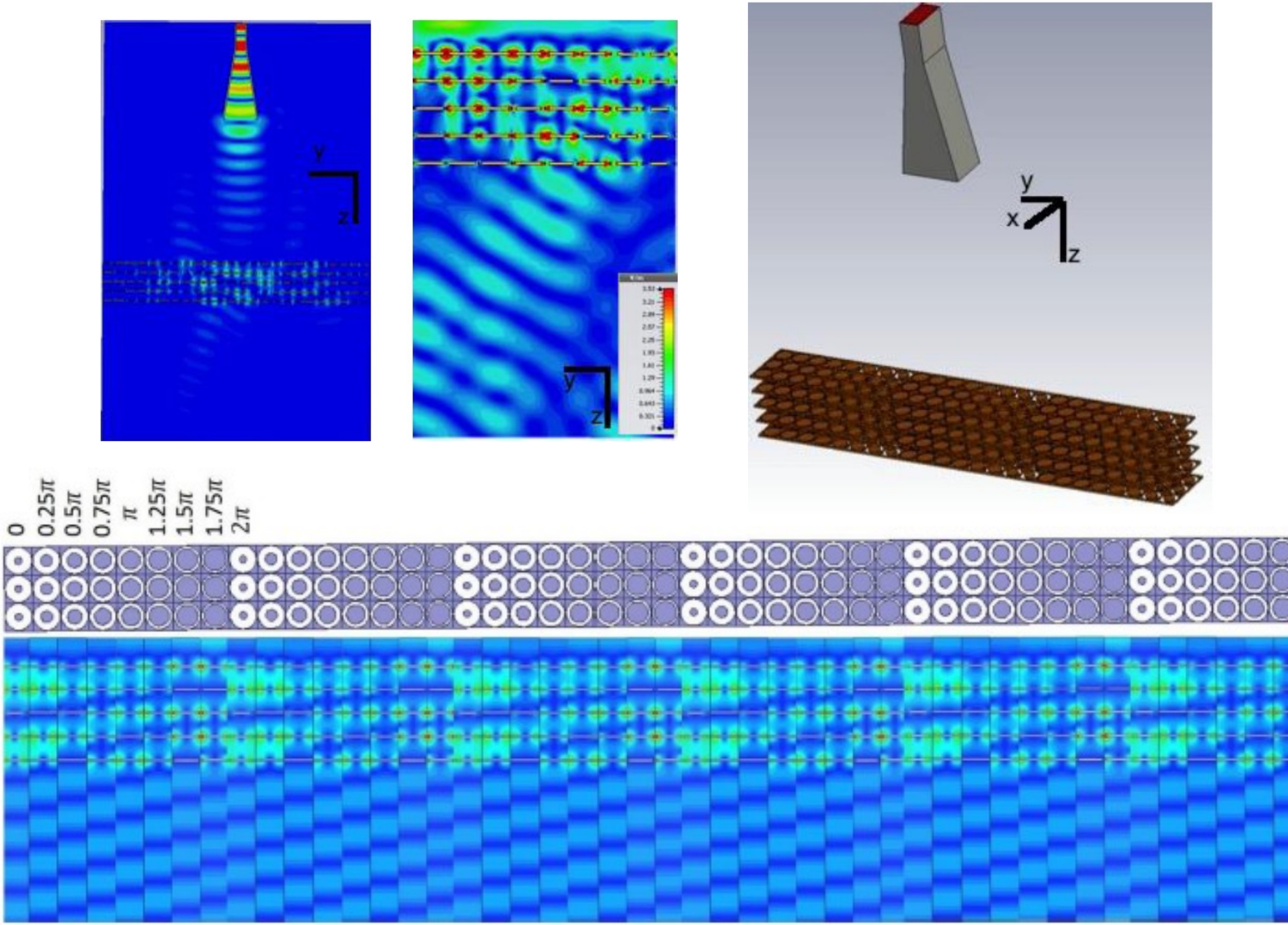
Actively Tunable Beam Steering

New concepts in metasurfaces, Generalized Snells Law structures, are being used in phased array structures for beam steering



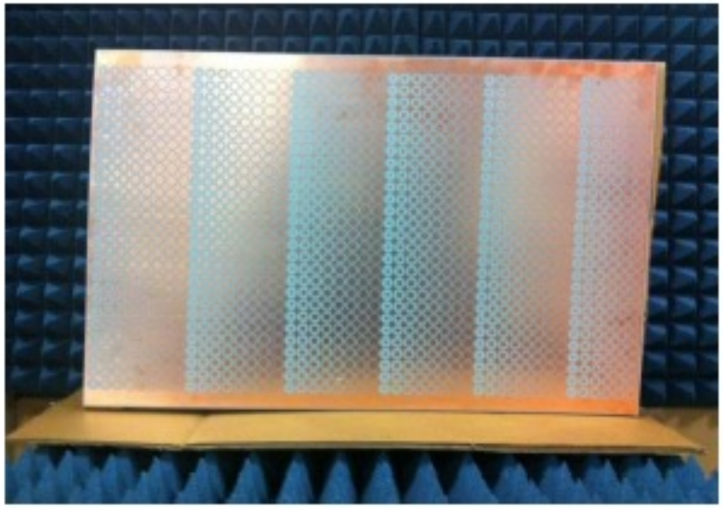


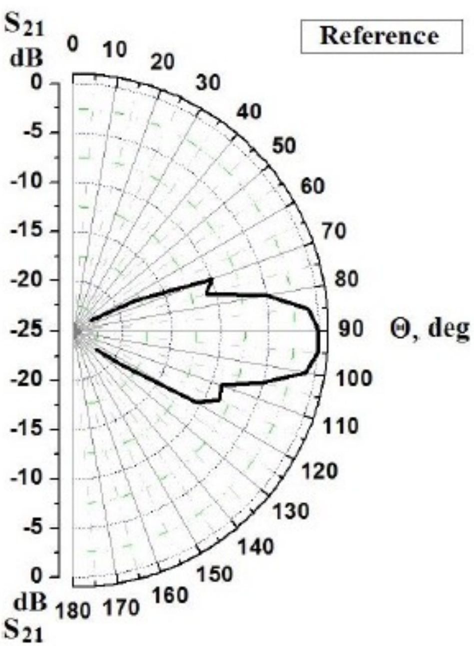


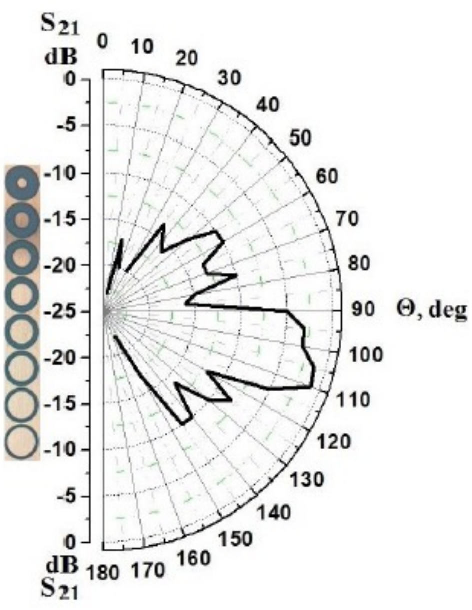


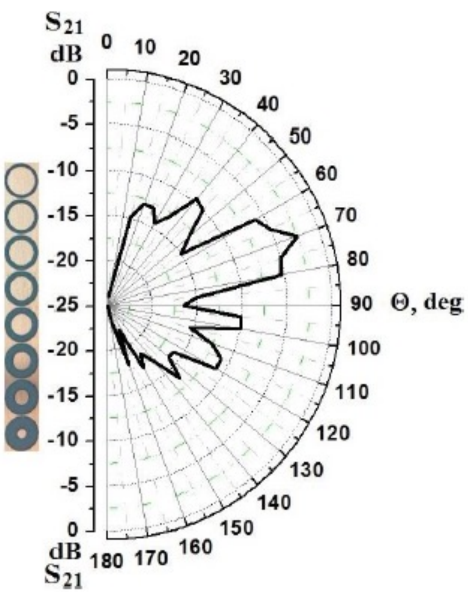
y
z
y
z
y
x
z
0
0.25π
0.5π
0.75π
π
1.25π
1.5π
1.75π
2π

Physical Structure and Performance







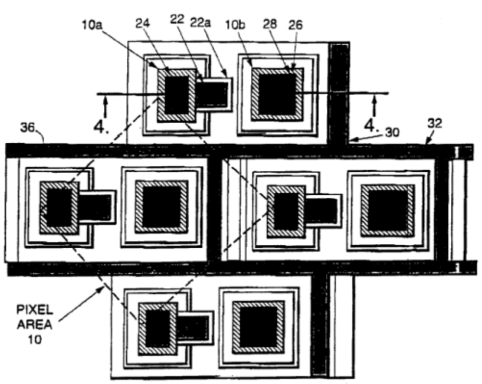


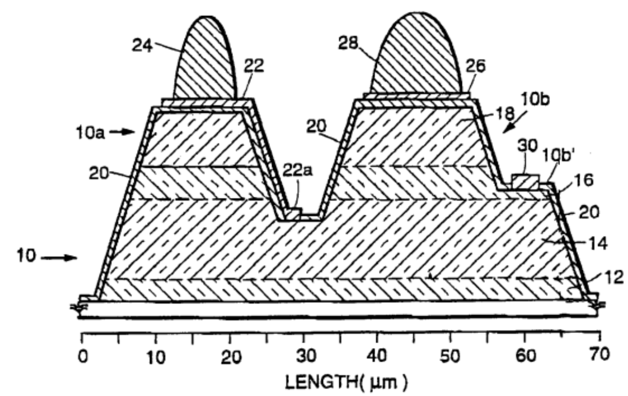
Multi-wavelength IR Photodetectors based on Metasurfaces

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

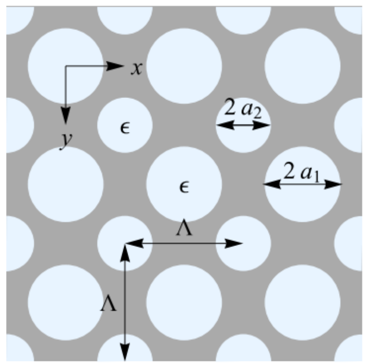
Yet, most multi-color IR detection systems involve costly and complicated vertically stacked semiconductor structures.

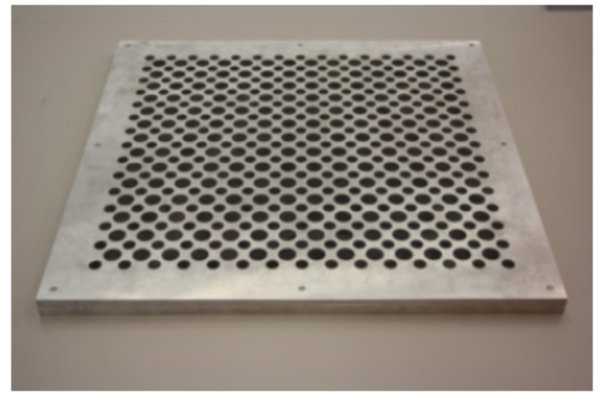


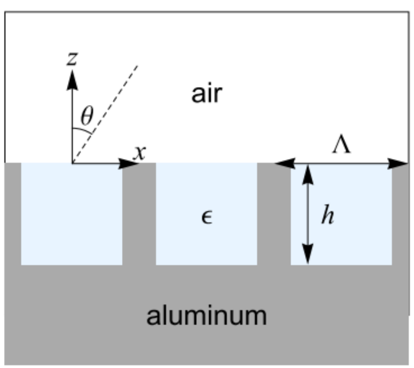


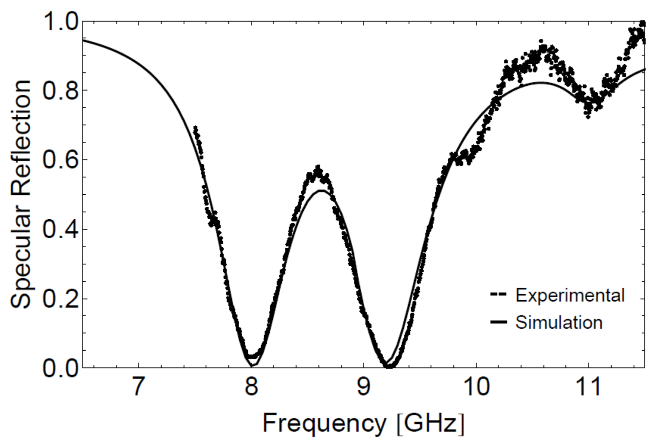
Photon Sorting in the Microwave

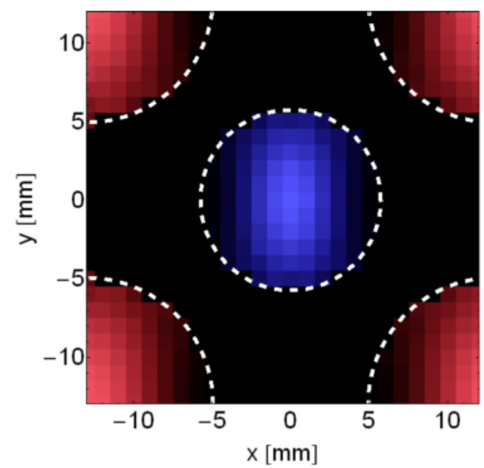
Waveguide-Cavity-Mode Photon Sorters









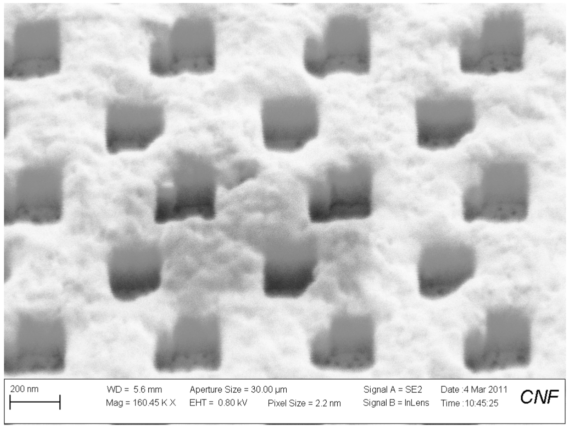


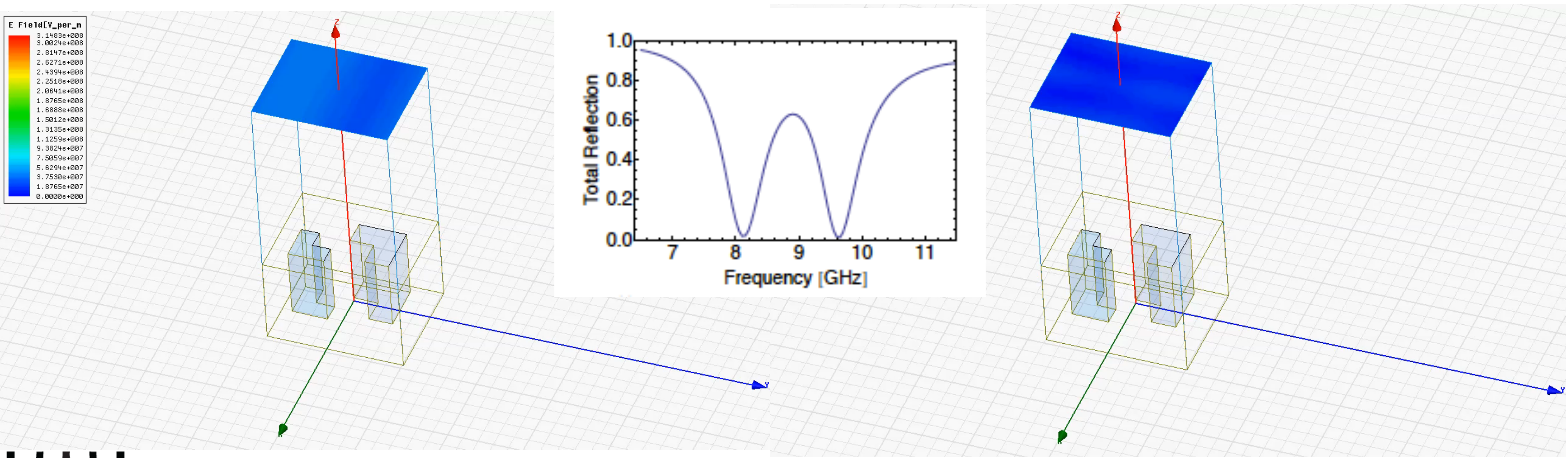
"Light localization, photon sorting, and enhanced absorption in subwavelength cavity arrays." by Lansey, E., Hooper, I. R., Gollub, J. N., Hibbins, A. P. & Crouse, D. T Optics express **20**, 24226–36 (2012).

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





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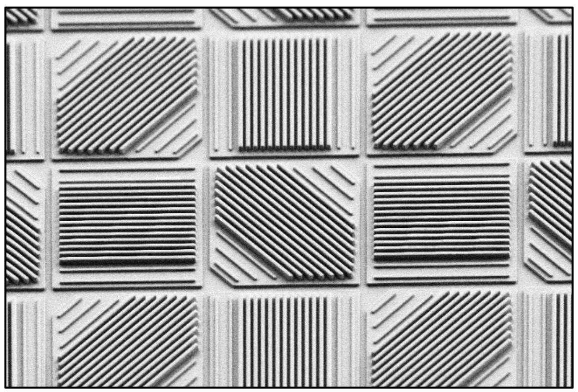
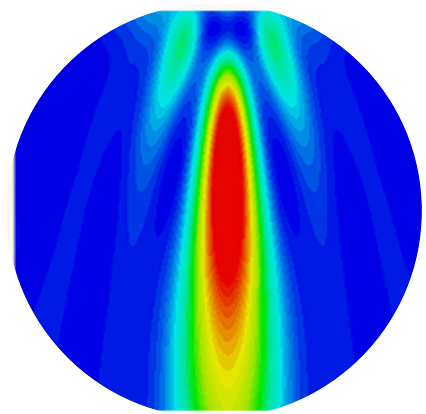
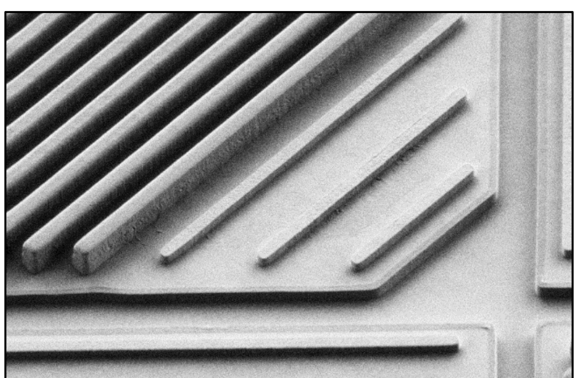
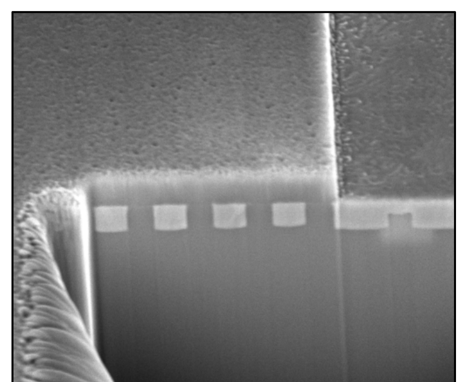
Pixelated Filters: Polarimetric, Multiwavelength, Hyperspectral and Superbeaming

- 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









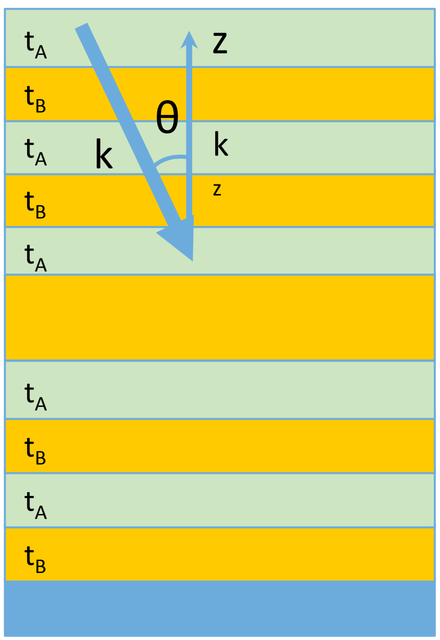
Metamaterial based narrow bandwidth angle-of-incidence independent transmission filters for hyperspectral imaging

- 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

Center for Metamaterials

Bragg Stack Filters have Dispersion

- 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



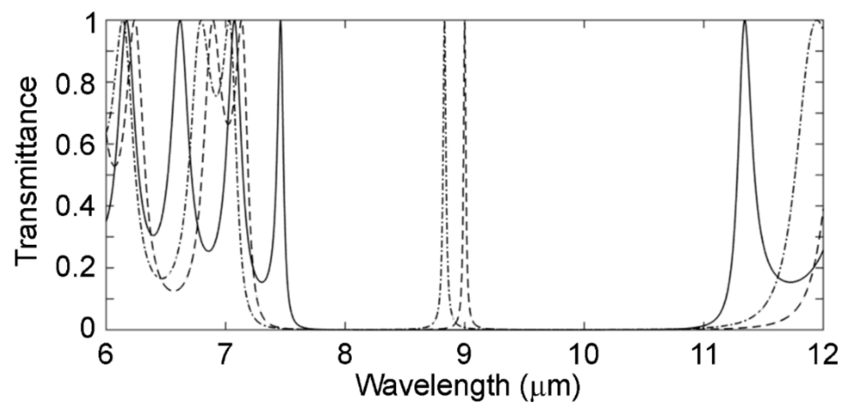
Thickness Calculation

$$2 t k_z \sqrt{\varepsilon} = \pi$$

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

$$t_o = \lambda_o / 4\sqrt{\varepsilon}$$

$$\lambda(\theta) = \lambda_o \cos\theta$$

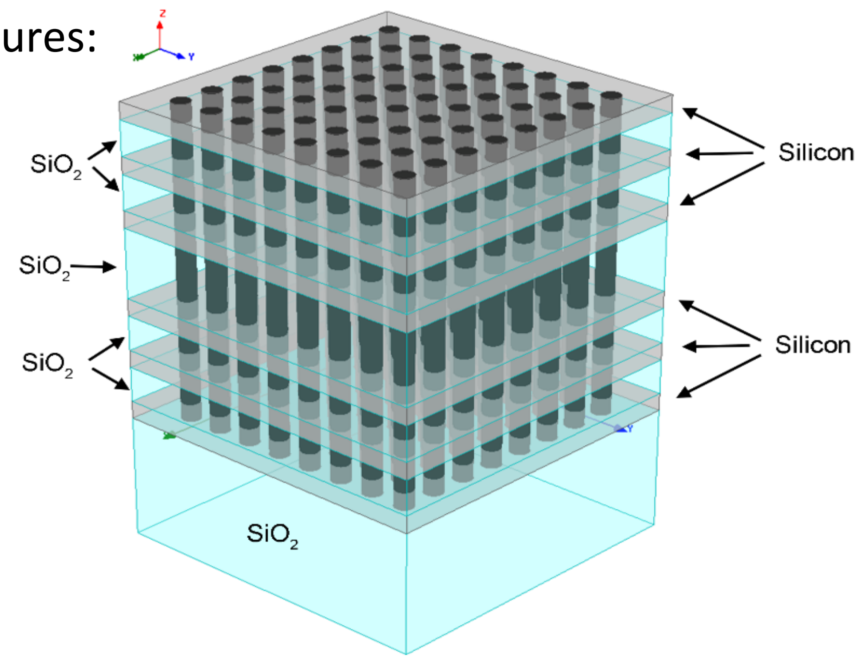


Solid line: The transmittance of a 19 layer Ge/ZnS Bragg stack (with the 5th Ge layer removed) for normal incident radiation. **Dashed line:** The transmittance for the modified Bragg stack for an incident angle of 30°.

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.

Hyperbolic Metamaterials - Fakir's Bed

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:

$$\frac{k_x^2}{\varepsilon_{zz}} + \frac{k_z^2}{\varepsilon_{xy}} = \varepsilon_{xy} k_o^2$$

$$\varepsilon = \begin{pmatrix} \varepsilon_{xy} & 0 & 0 \\ 0 & \varepsilon_{xy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}$$

$$\varepsilon_{xy} = (1+N)\varepsilon_{out}\varepsilon_{in} + (1-N)\varepsilon_{out}^2 / (1+$$

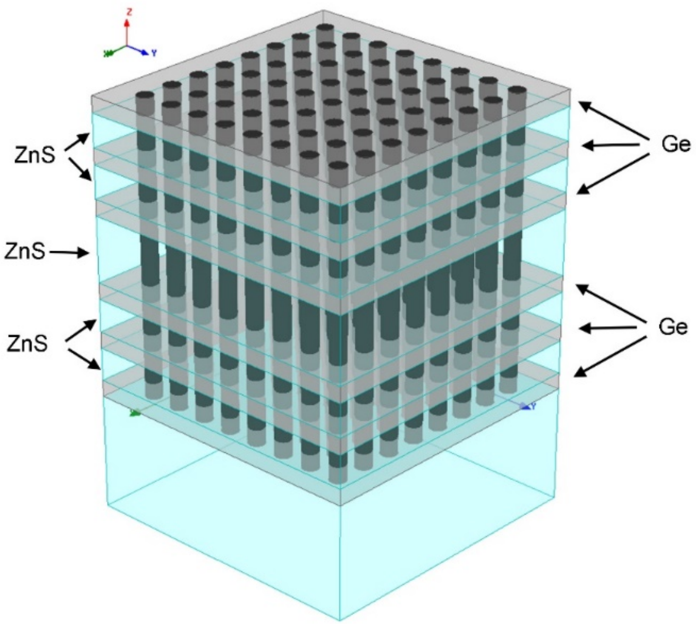
$$\varepsilon_{zz} = N\varepsilon_{in} + (1-N)\varepsilon_{out}$$

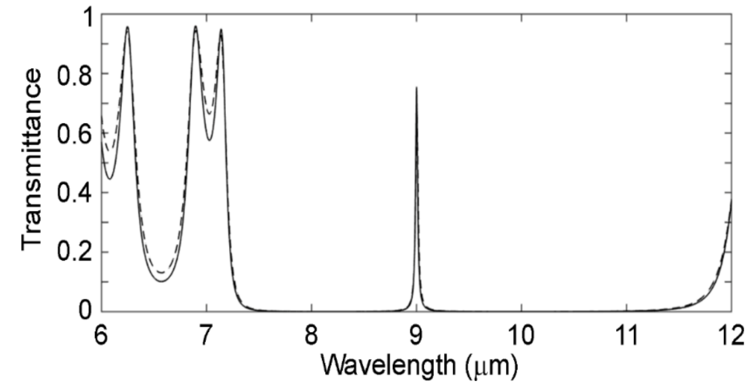
$$k_z(\theta) = \sqrt{\varepsilon_{xy} k_o^2 - \frac{\varepsilon_{xy}}{\varepsilon_{zz}} k_x^2(\theta)}$$

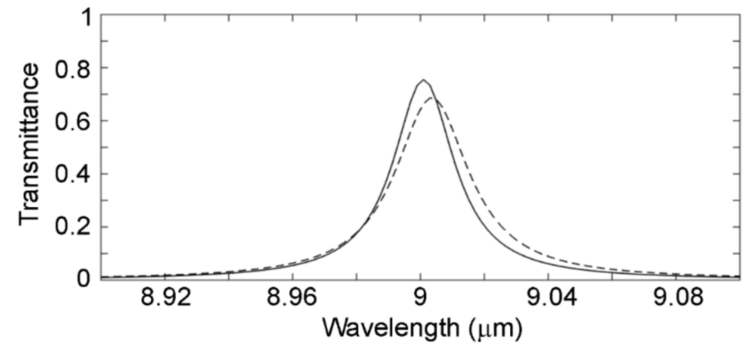
$$\rightarrow |\varepsilon_{zz}| \gg |\varepsilon_{xy}| \perp \sqrt{\varepsilon_{xy}}\, k_o = k_z(\theta = 0)$$

Mitigates the dependence of k_z on θ, therefore largely eliminates the dependence of transmission on θ

Ge/ZnS Bragg stack for 9mm center wavelength



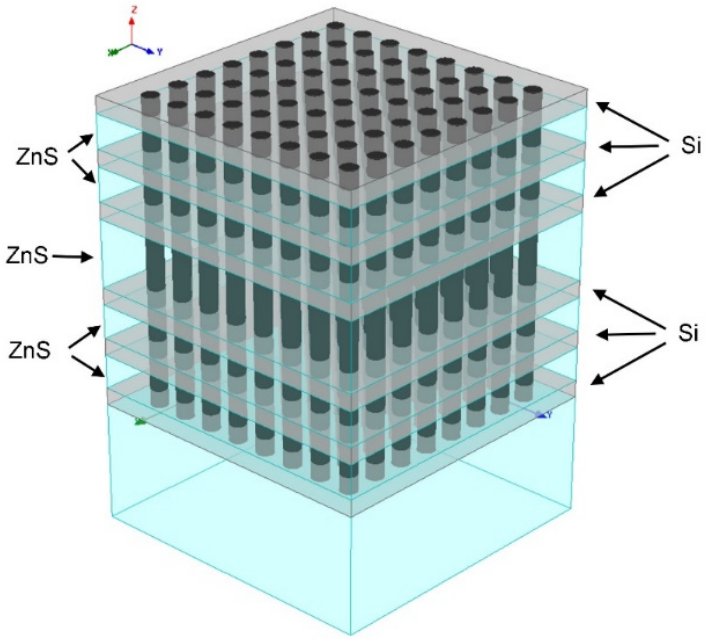




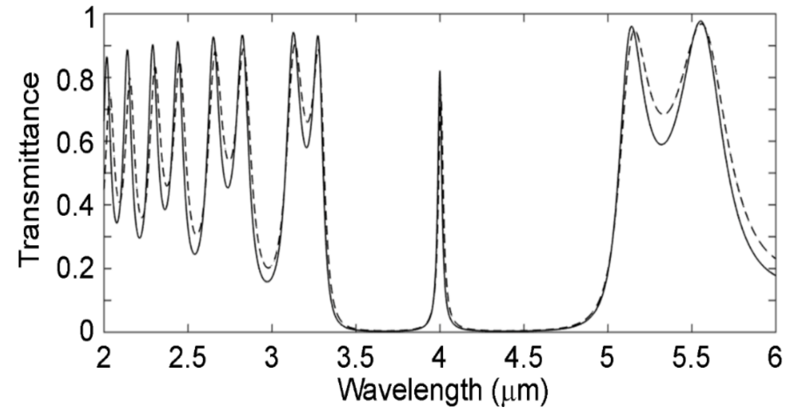
	ε_{xy}	ε_{zz}	Thickness	Details
Ge (n=4@λ=9μm)	$20+i1.2\times10^{-2}$	$-381+i130$	503 nm	Material: Gold Period= 800nm Diameter=300nm
ZnS (n=2.25@λ=9μm)	$6.3+i1.2\times10^{-3}$	$-391+i130$	895 nm	

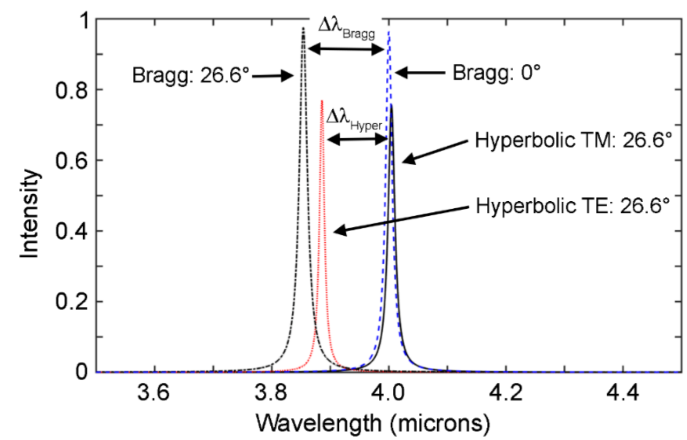
The transmittance of an 18 layer Ge/ZnS Bragg stack for normal incident radiation (**solid line**) and for 30° off-normal (**dashed line**). There is only a 4 nm change in the center wavelength.

Si/ZnS Bragg stack for 4mm center wavelength



	ε_{xy}	ε_{zz}	Thickness	Details
Si (n=3.4@λ=4μm)	$14.5+i1.5\times10^{-2}$	$-74.3+i12.4$	262 nm	Material: Gold Period= 300nm Diameter=113nm
ZnS (n=2.25@λ=4μm)	$6.3+i2.7\times10^{-3}$	$-80.2+i12.4$	397 nm	





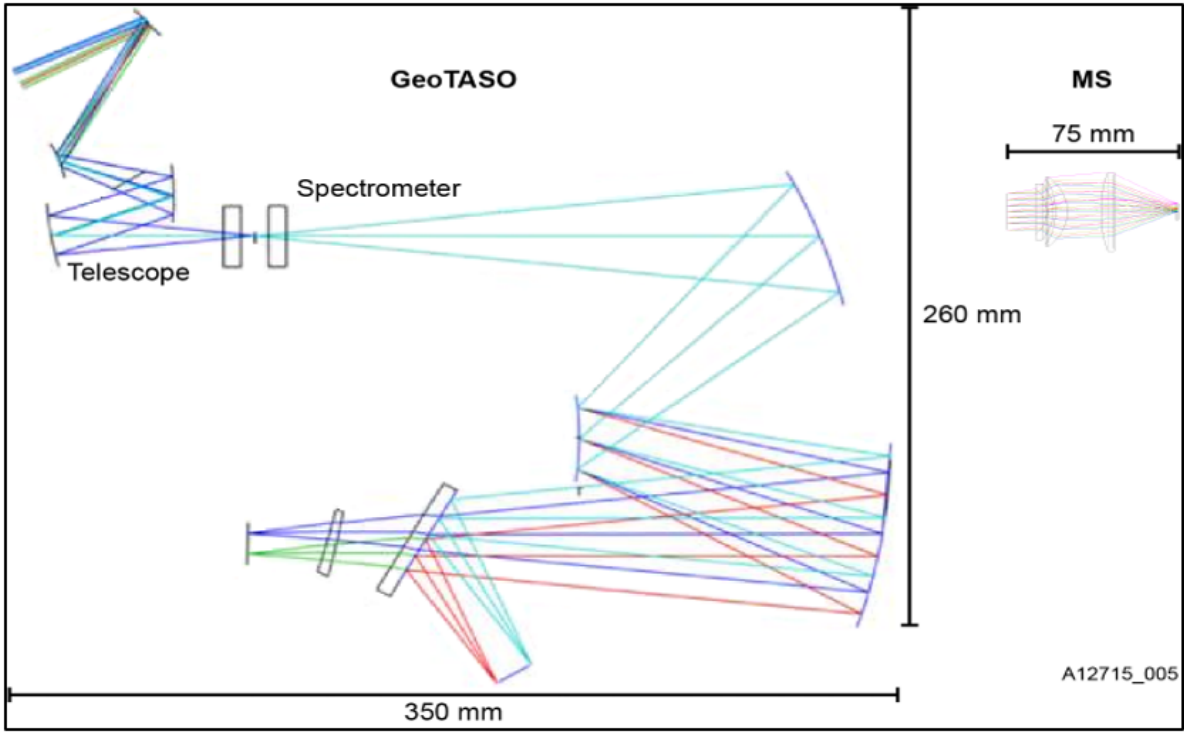
The transmittance of an 18 layer Si/ZnS Bragg stack for normal incident radiation (**solid line**) and for 30° off-normal (**dashed line**). There is only a 6 nm change in the center wavelength.

Clarkson University

NASA ACT Hyperspectral Filter: a spectrometer on a chip

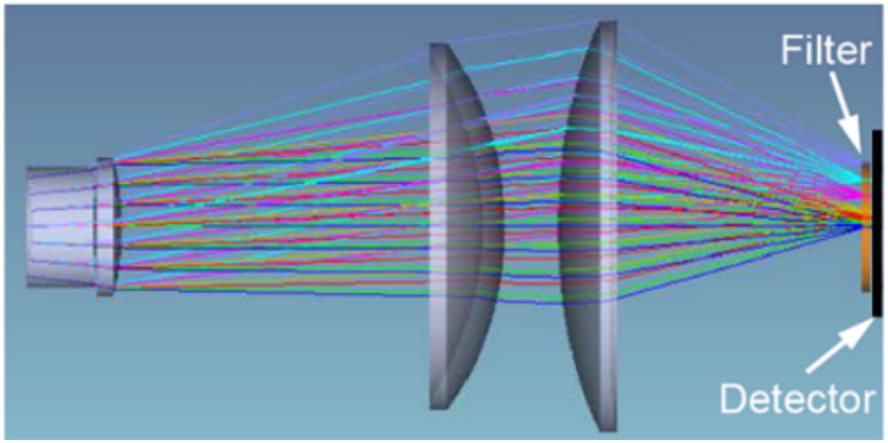
- While the MS technology reduces the demands on several subsystems through its selectable spectral channels, the most dramatic effect is the ***elimination of the spectrometer subsystem*** itself.

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

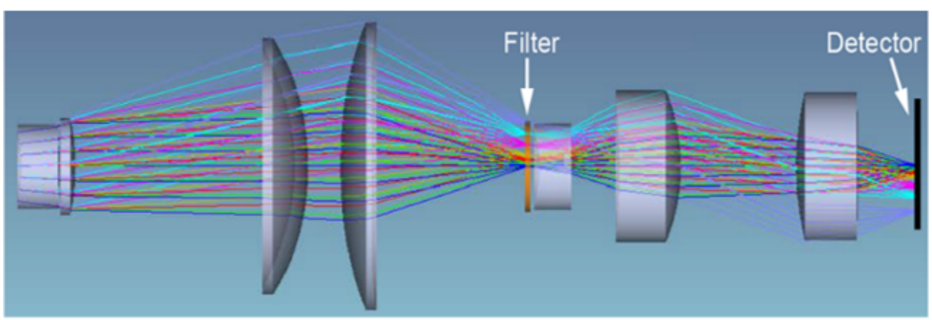


Configuration and Operational Concept

Monolithic Integration



Intermediate Image Filtering



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.

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 AoI 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.

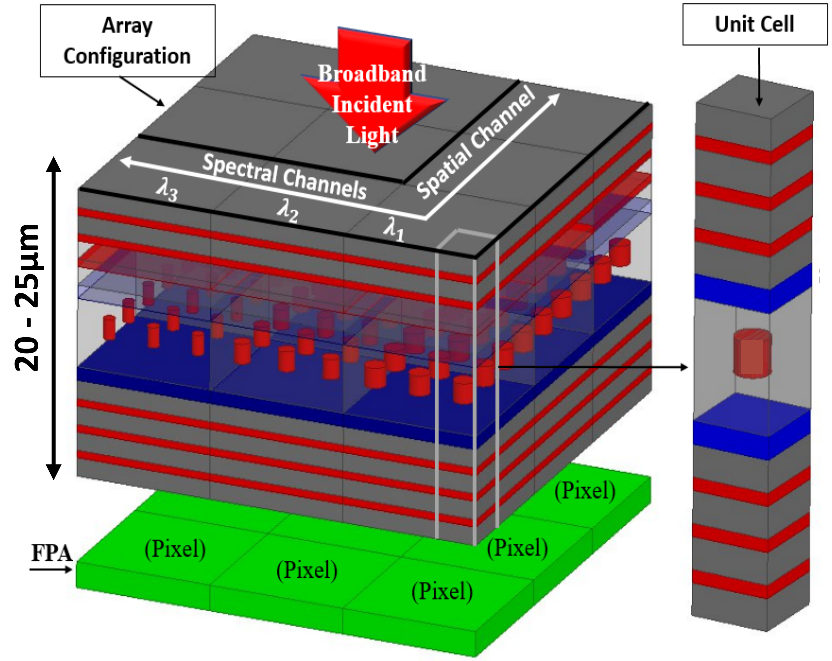
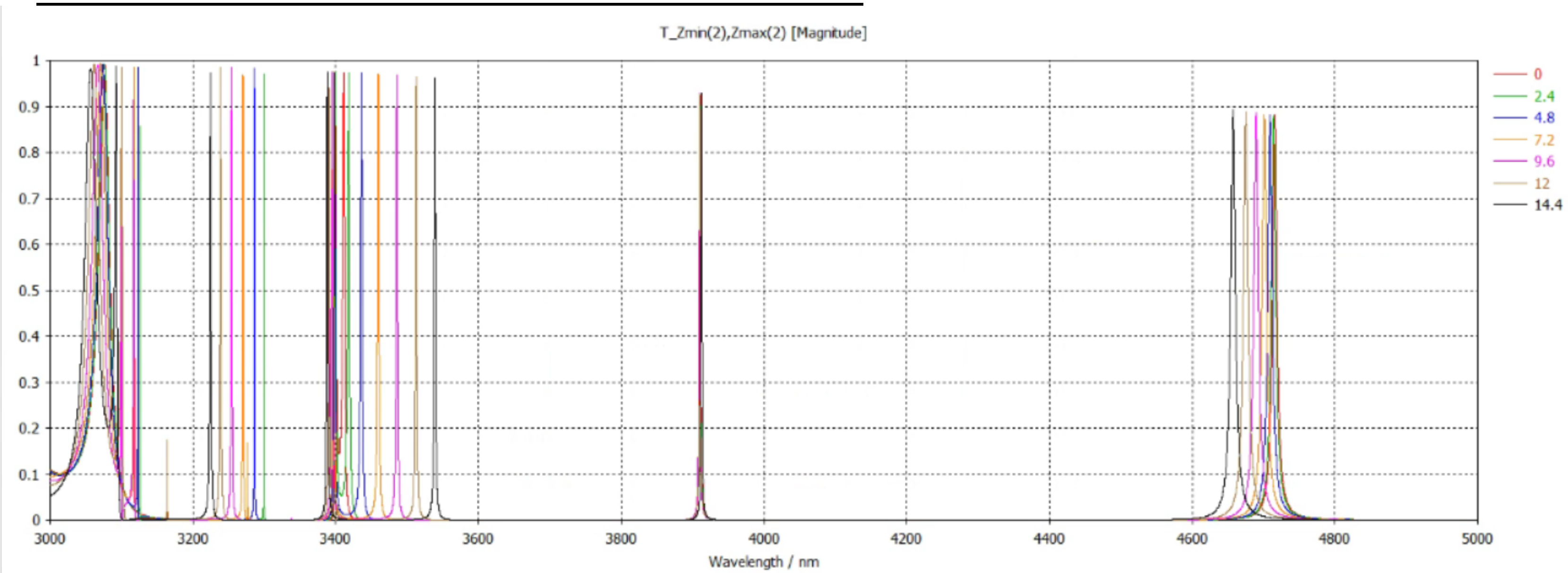
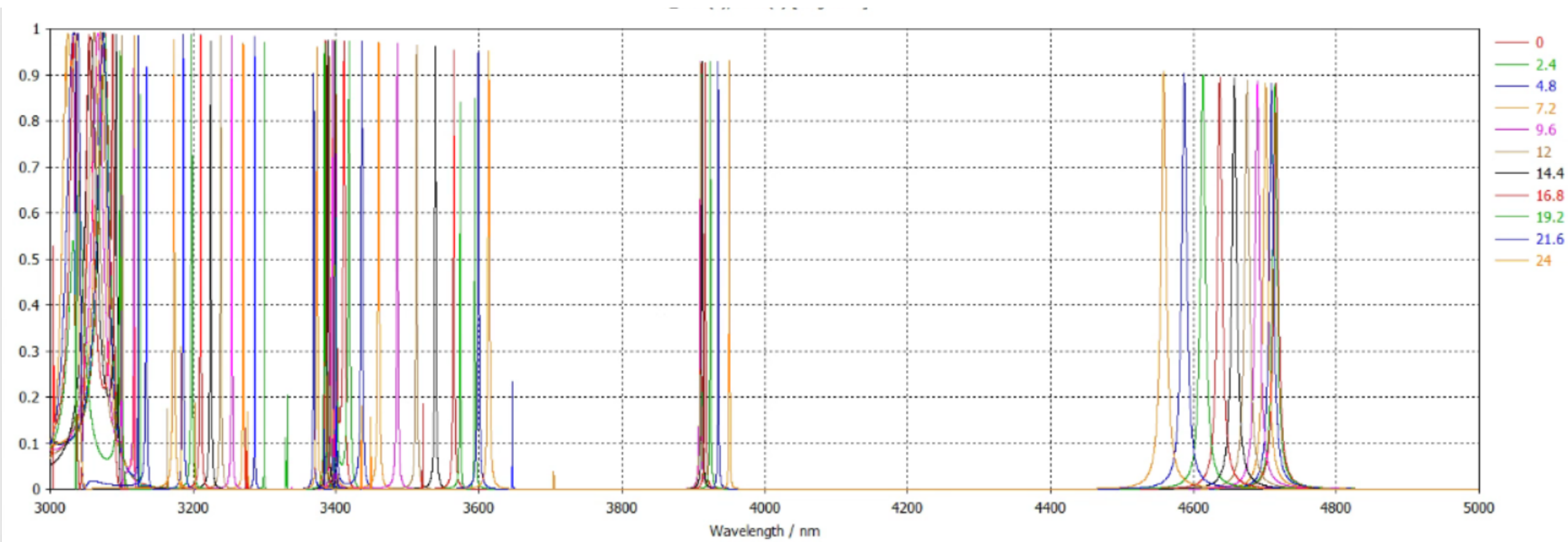


Figure 3. Spectral channels defined by pixel-scale unit cells in the metamaterial offer spectral sensing with minimal latency between spectral channels and spectral channels with passbands matched to the spectral signature of the target gas.

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