Metamaterials and Metasurfaces for Heat Transport Control

December 13 2016

Augustine Urbas
Materials and Manufacturing Directorate

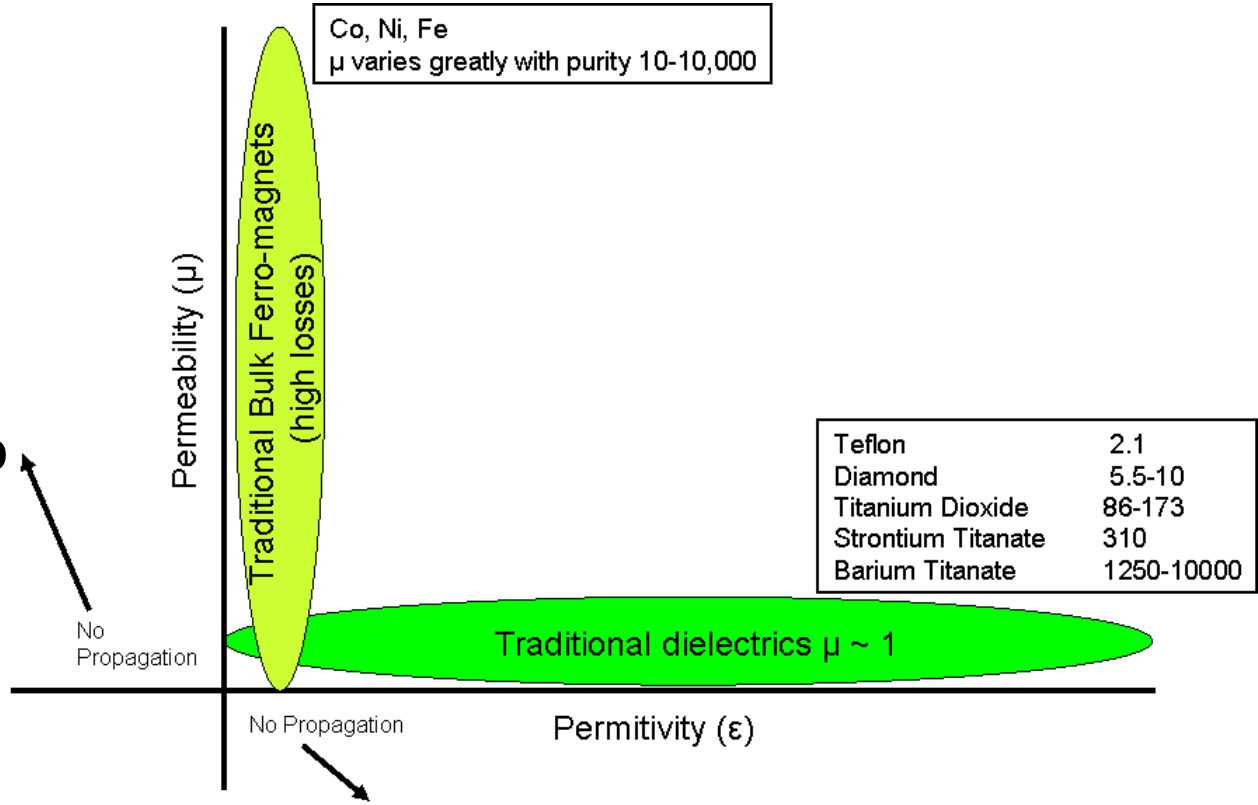
Integrity ★ Service ★ Excellence

Metamaterials

- Overview of structured materials
- Examples of controlling thermal emission
- Controlled heat transport with metamaterials

Electromagnetic properties of materials

- **Conventional dielectric materials have $\mu>1$ and $\varepsilon>1$ and we don't typically find materials with $\mu=\varepsilon$.**
- **The interaction with the magnetic field decreases as frequency increases and $\mu \rightarrow 1$**
- **Generally limited in choice of materials to available values/ranges**



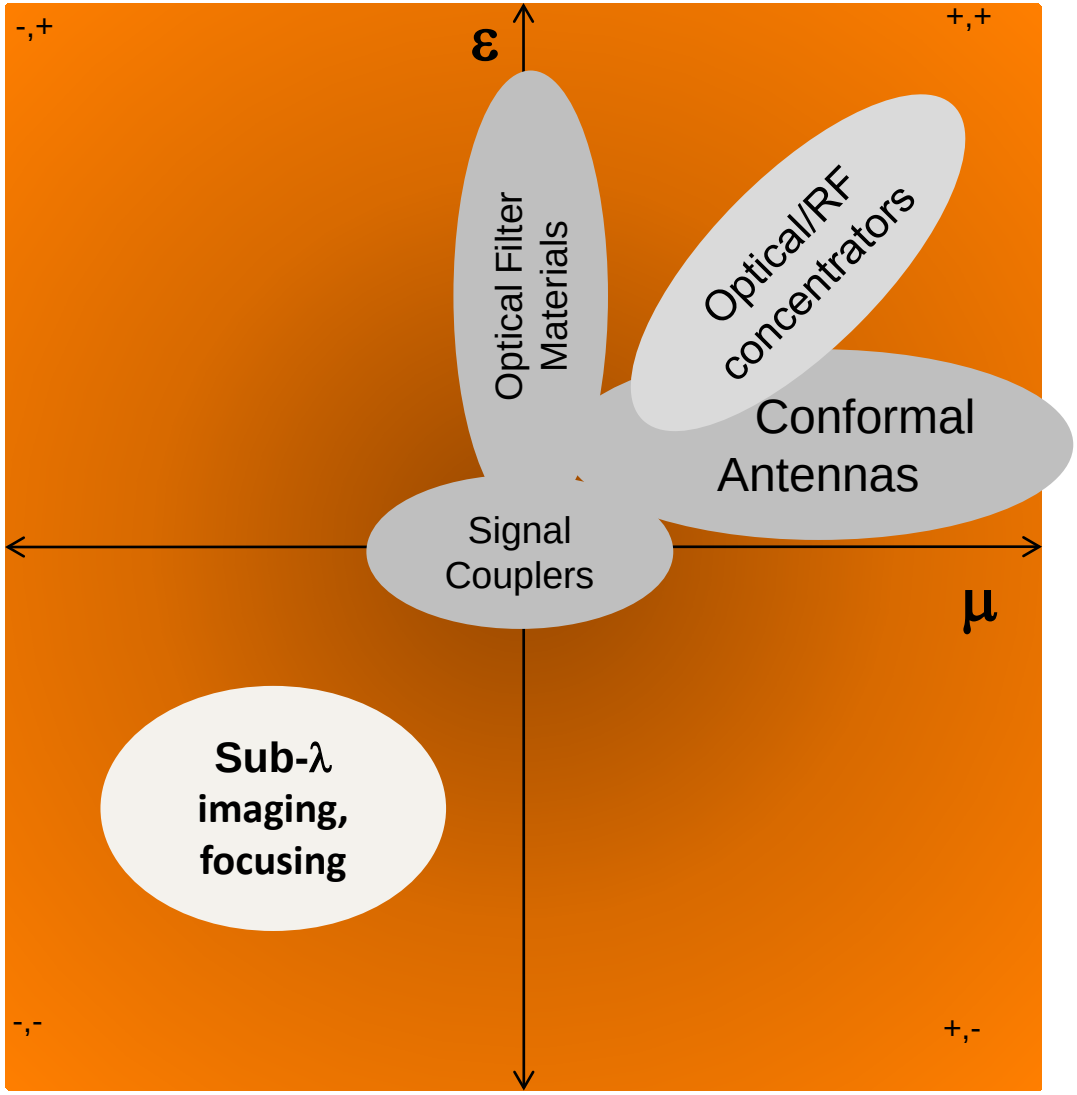
Metamaterials Design Space

Challenges to creating useful new properties

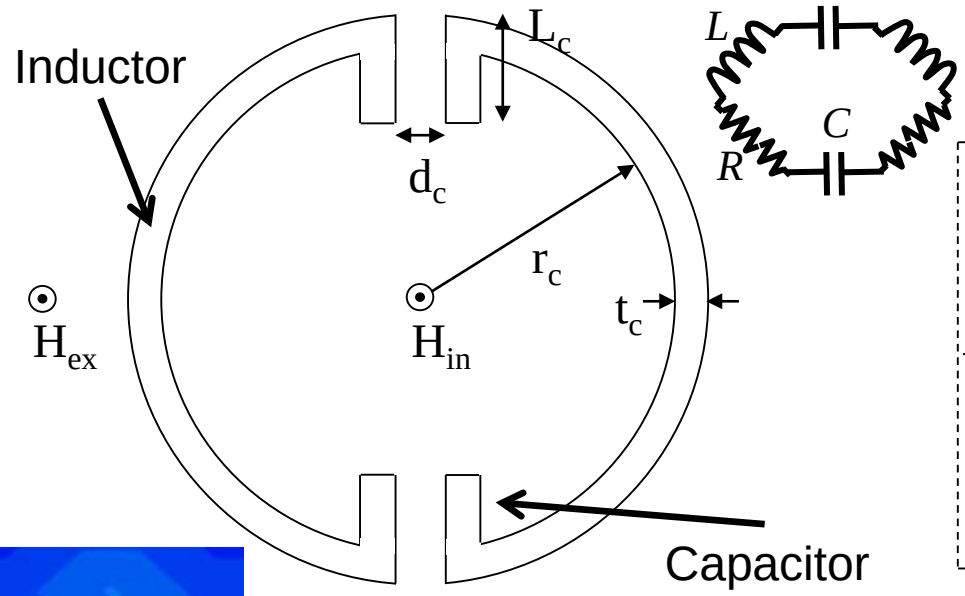
- Useful and well defined effective materials properties
- Mitigation/compensation of Losses

Other attributes to consider

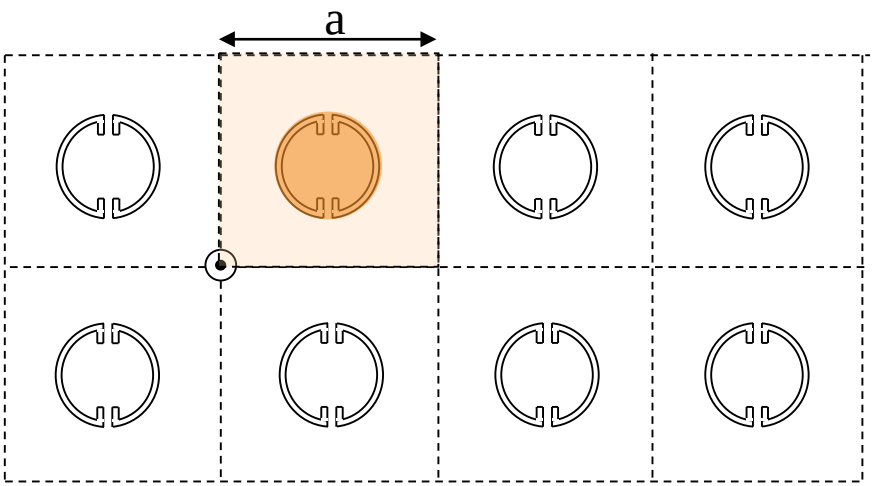
- Coupled properties
- Nonlinear effects
- Graded structures



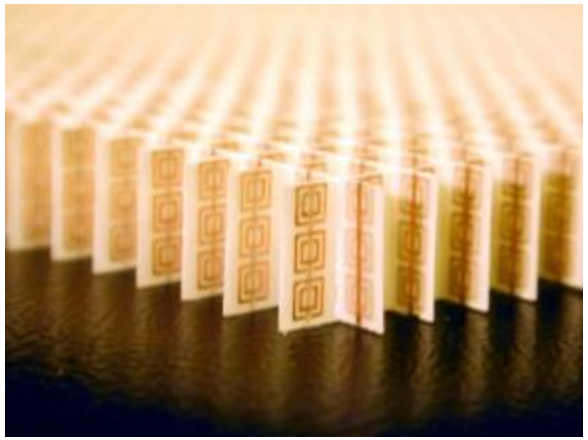
Artificial Material Response

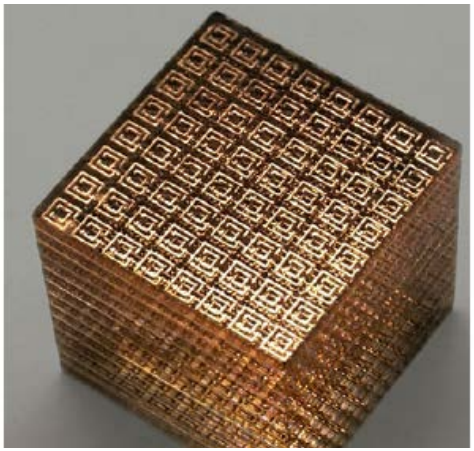


$$f = \pi r_c^2 / a^2$$



PRL 84, 2184, 2001

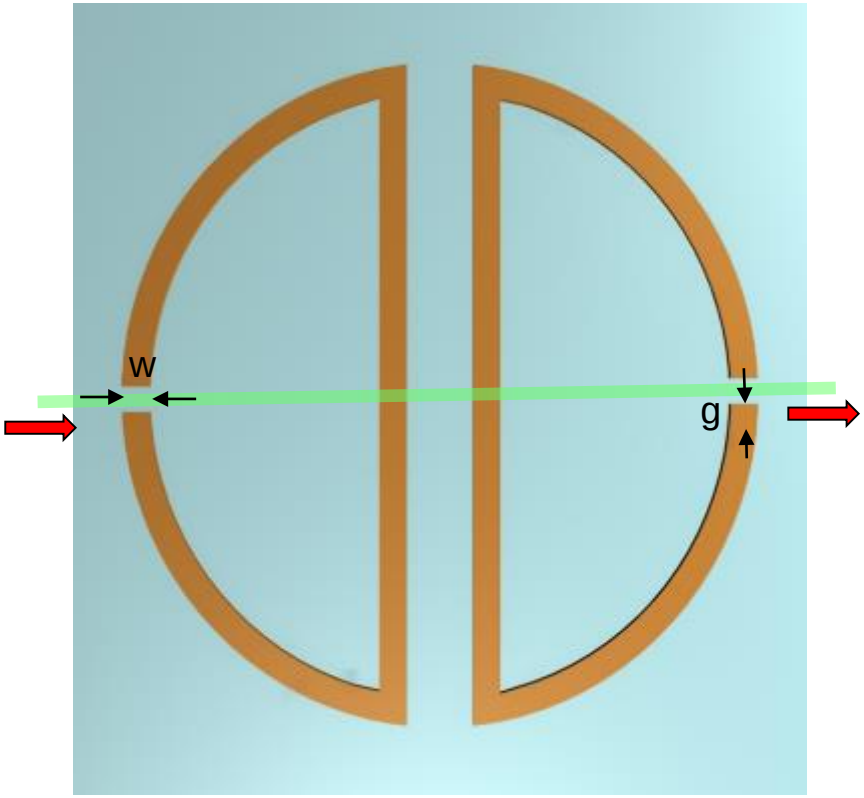




Physics today, June 2004

Meta inspired RF photonic Modulator

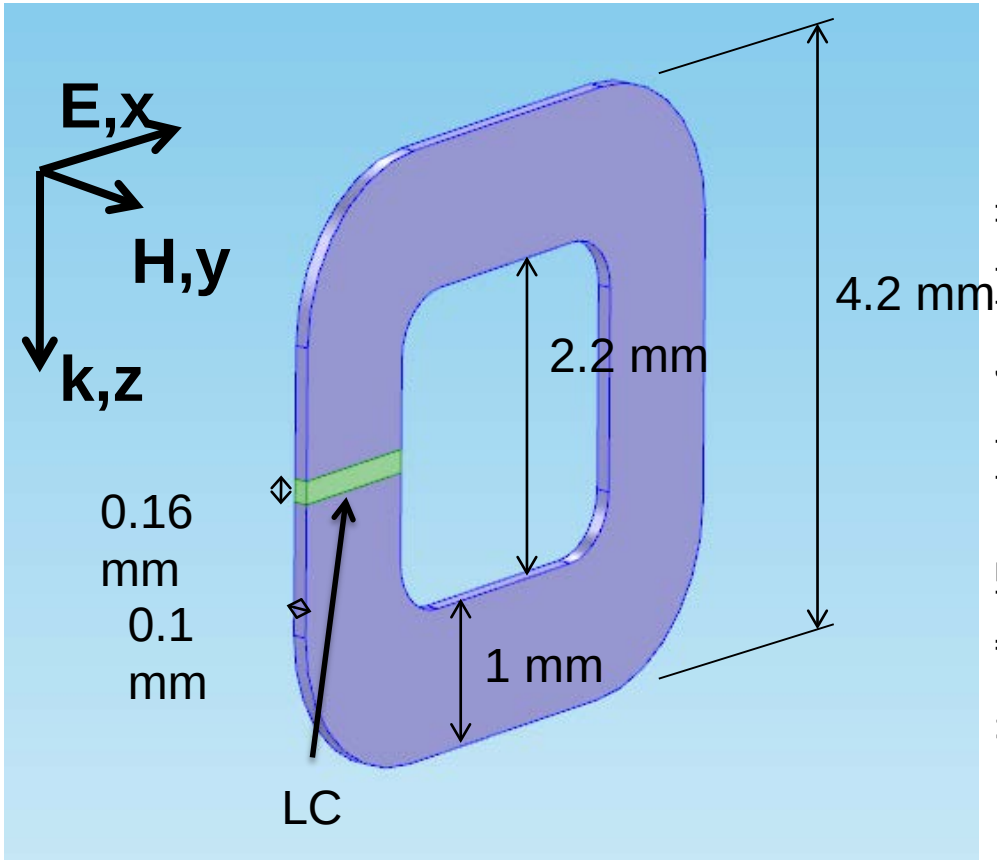
- **RF resonator to concentrate fields**
- **High efficiency EO materials to mix RF with optical carrier**
  - **Inorganics**
  - **Organics provide more flexibility**

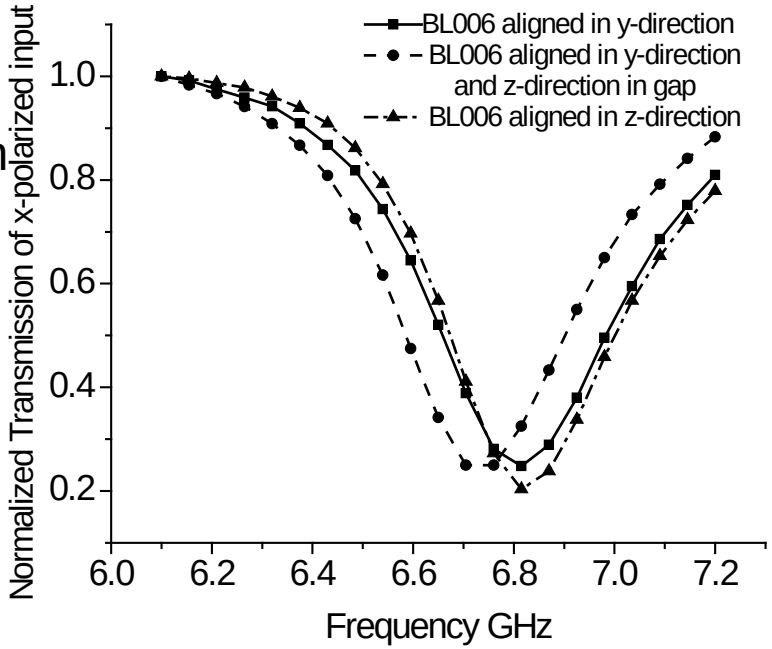


•Also potential for materials that modify resonant properties of Meta stuctures to tune properties

•Optical Magnetism and LC materials are potential candidates

Sensitivity of Metamaterials

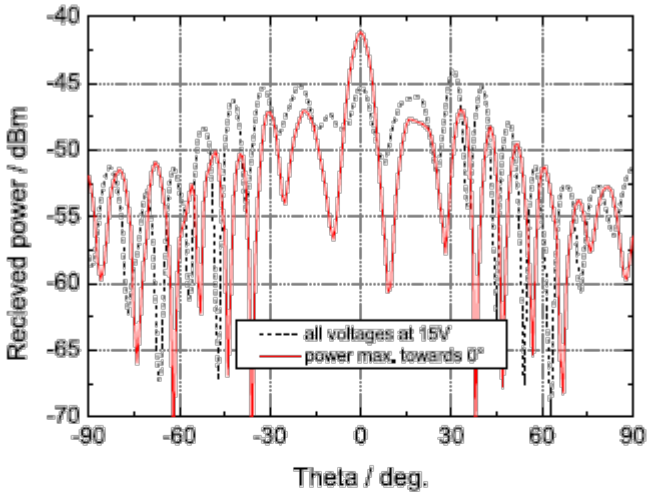




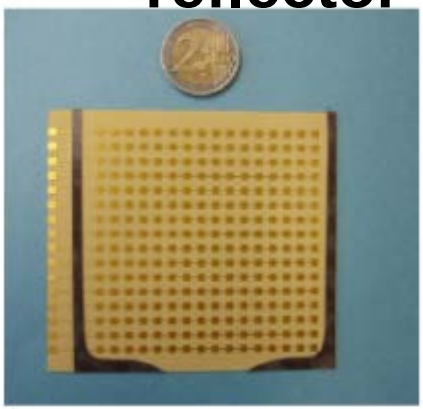
- SRR sensitivity to changes of gap materials properties.
  - 25 GHz/mm^3RIU sensitivity to gap material
  - 10^6 stronger than volumetric sensitivity to surrounding media

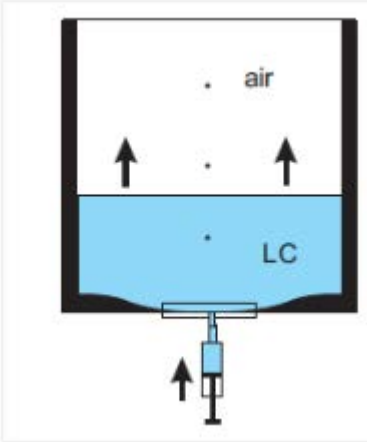
Liquid Crystal RF Beam Steering

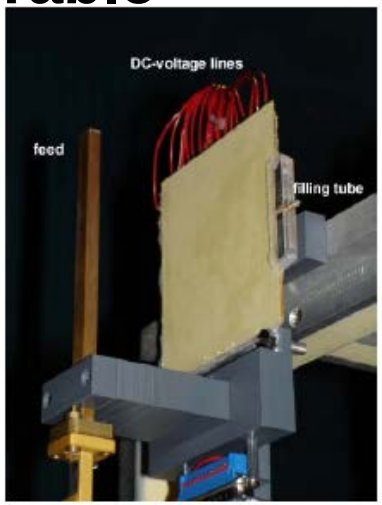
- **Liquid Crystal material used to tune interaction between ground plane and metal patch**
- **Changed phase of reflected RF signal**
- **Pixelated array → steerable reflector**

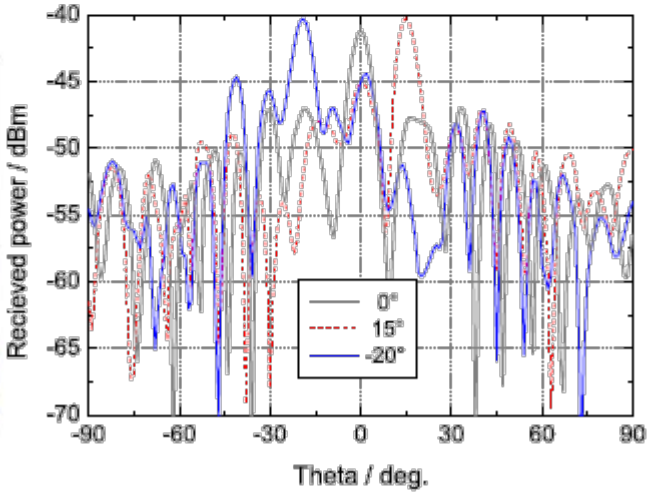


(a) Focussing of the beam.







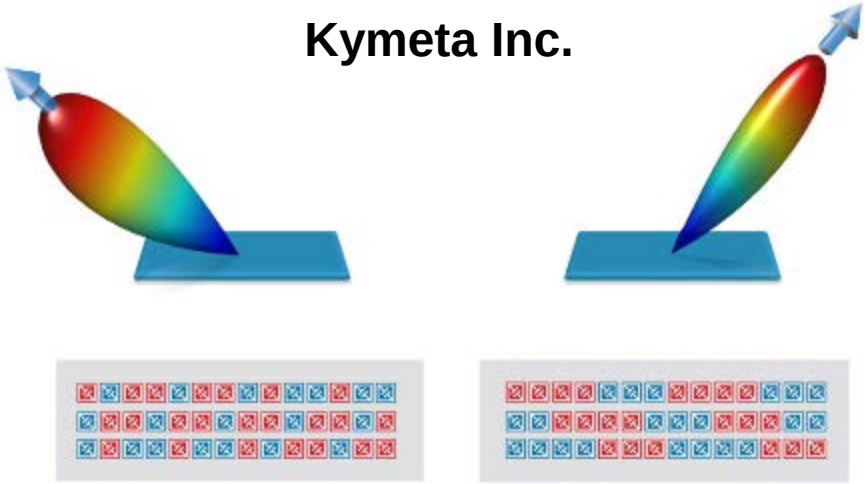


(b) Beam pointing to different steering angles.

Radu Marin "Investigations on liquid crystal reconfigurable …" 2008 Thesis, TU Darmstadt

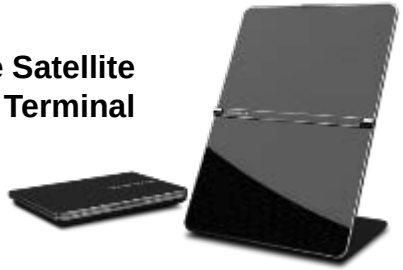
Metamaterial Steerable Antennas

Kymeta Inc.



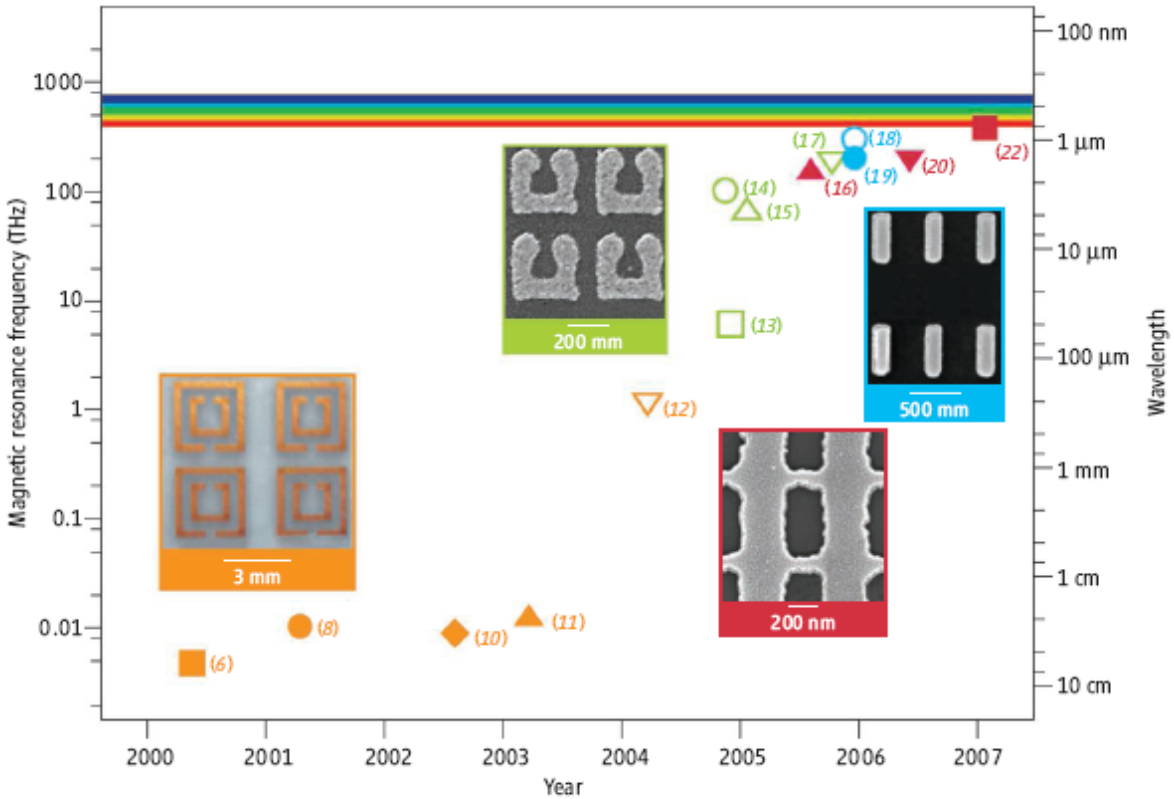
- Dynamic metamaterials can allow for tunable and steerable antennas

Portable Satellite Terminal

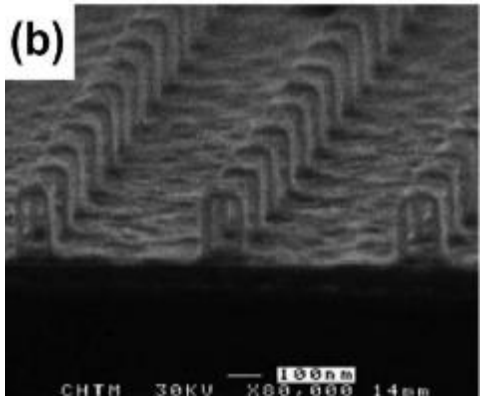


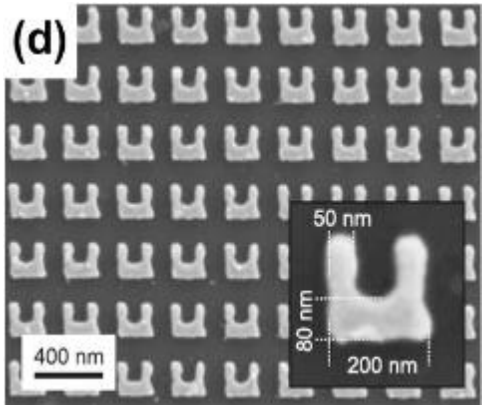
- This may make RF systems simpler and enable cheap wifi on commercial airlines

Metamaterials:
Size scales



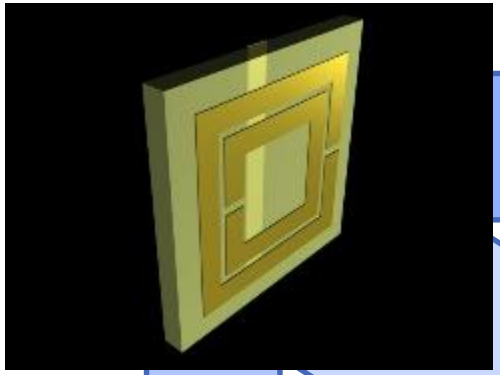
Advances in metamaterials. The solid symbols denote $n < 0$; the open symbols denote $\mu < 0$. Orange: data from structures based on the double split-ring resonator (SRR); green: data from U-shaped SRRs; blue: data from pairs of metallic nanorods; red: data from the "fishnet" structure. The four insets give pictures of fabricated structures in different frequency regions.

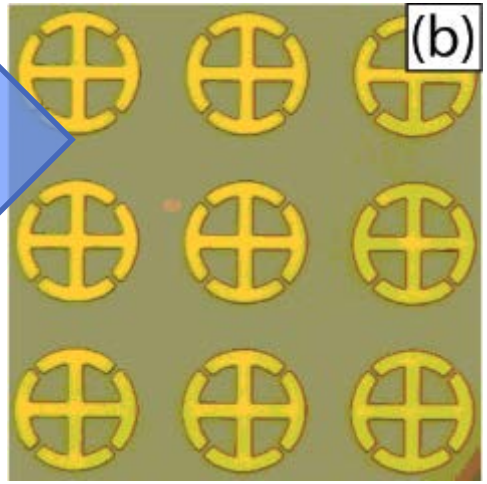


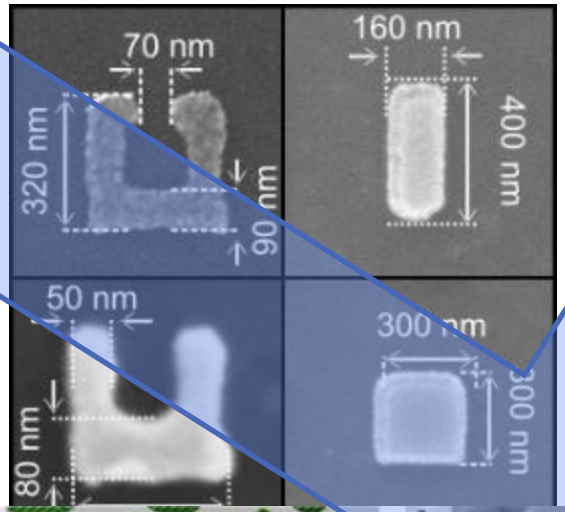


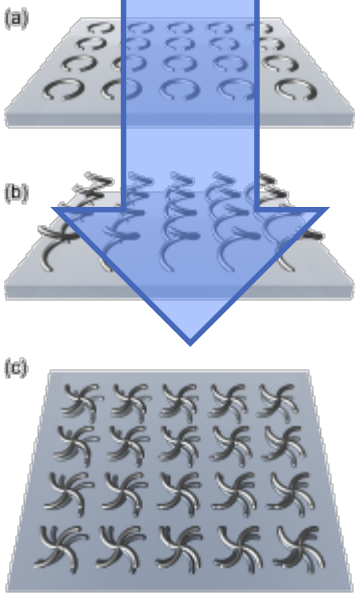
Negative Refractive Index at Optical Wavelengths Science 351 Jan2007
Soukoulis, Linden and Wegener

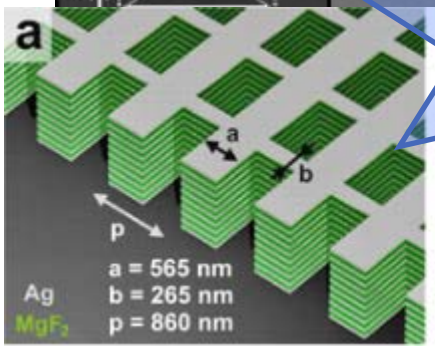
Unit Cell Design

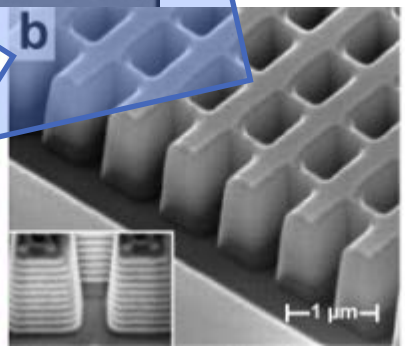


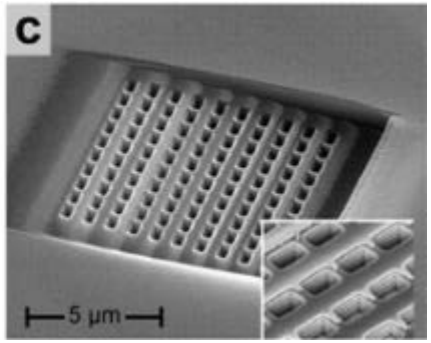




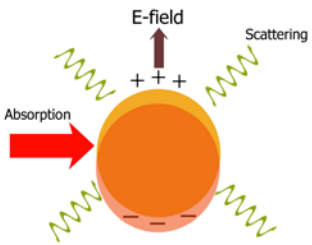


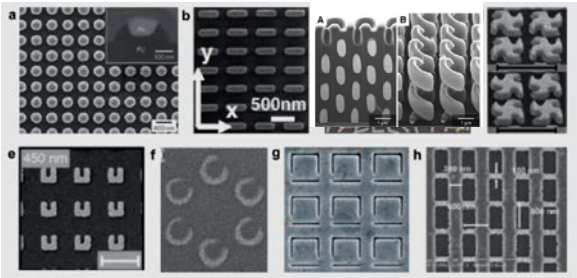


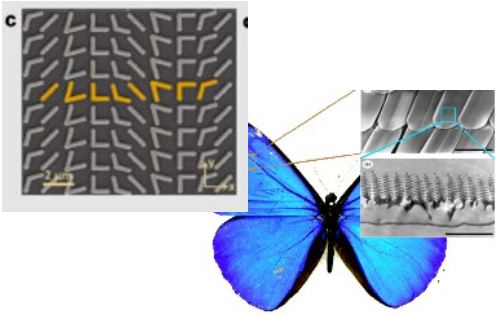


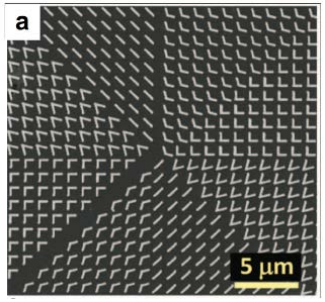


Metamaterial Structural Scales









Subunit

D<<λ

Metals: Au, Ag, Co, Pt, Al…

Nitrides: ZrN, TiN

Doped oxides: GZO, AZO, ITO…

High index dielectrics: Si, CdX, XTe…

Critical Features

- **Diameter**
- **Size distribution**
- **Shape**
- **Composition**
- **Microstructure**

Meta Atom

L~λ/10-λ/4

Multiple particles/materials

1D, 2D or 3D

Critical Features

- **Size**
- **Shape and distribution of component particles**
- **Separation between particles**
- **Symmetry**

Photonic Element

L~λ/4-λ

Multiple particles/materials

1D, 2D or 3D

Critical Features

- **Size**
- **Shape and distribution of component particles**
- **Separation between particles**
- **Symmetry**

Meta or Photonic Material

L>λ

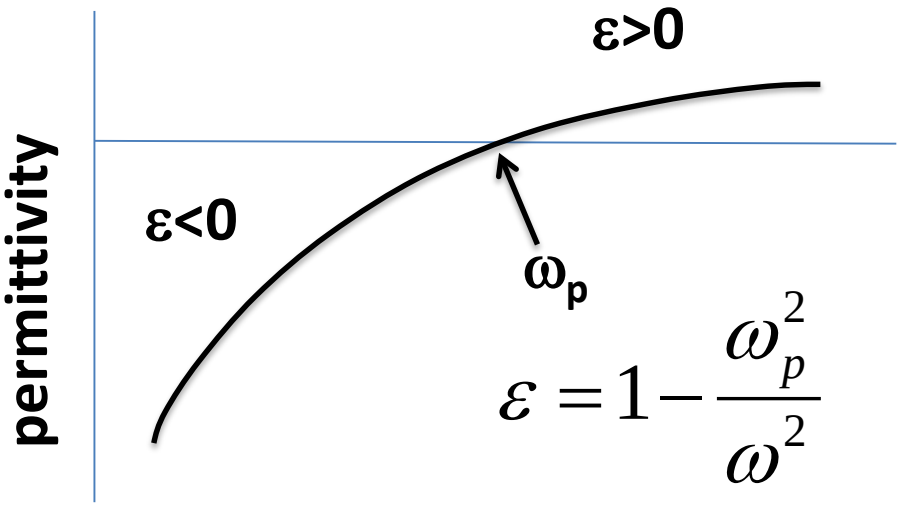
Multiple assembly types

Linear, Surface or Bulk

Critical Features

- **Positional Order**
- **Rotational Order**
- **Meta-atom types**
- **Separation between assemblies**
- **Gradations in composition at λ scale**

Plasmonics

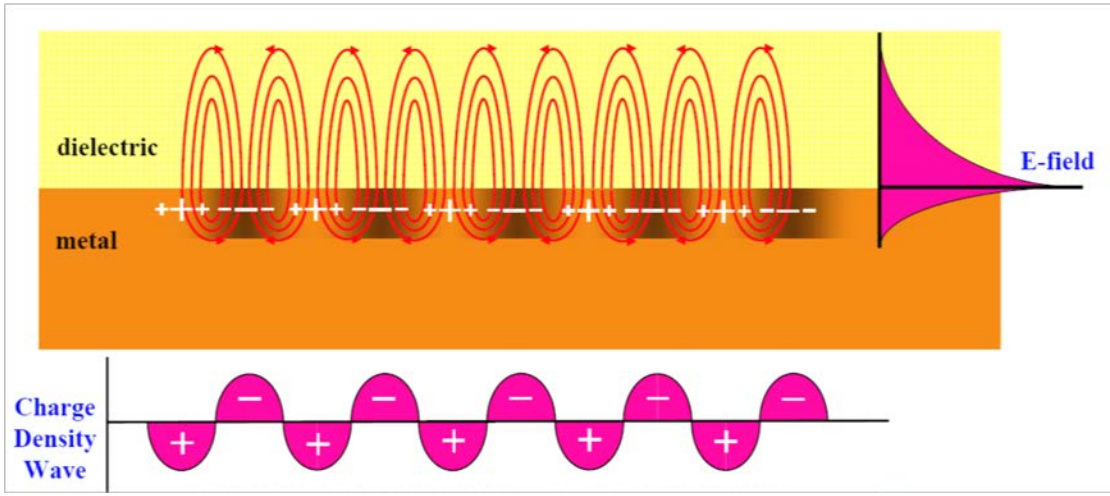


$$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2}$$

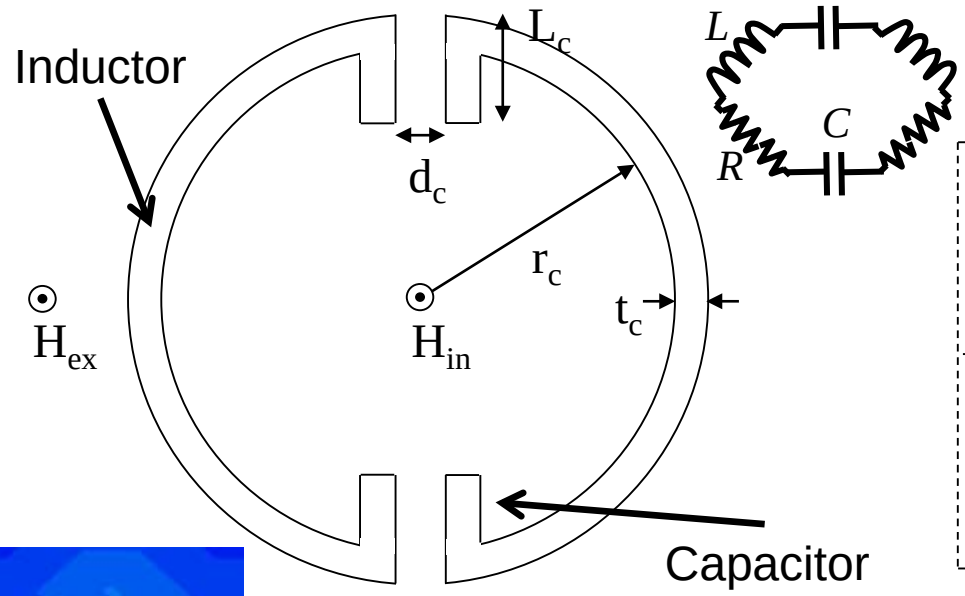
- Surface waves at the interface between materials with ε>0 and ε<0
- TM waves with nanometer scale surface confinement

- Relative energy partition and loss depend on frequency and material properties

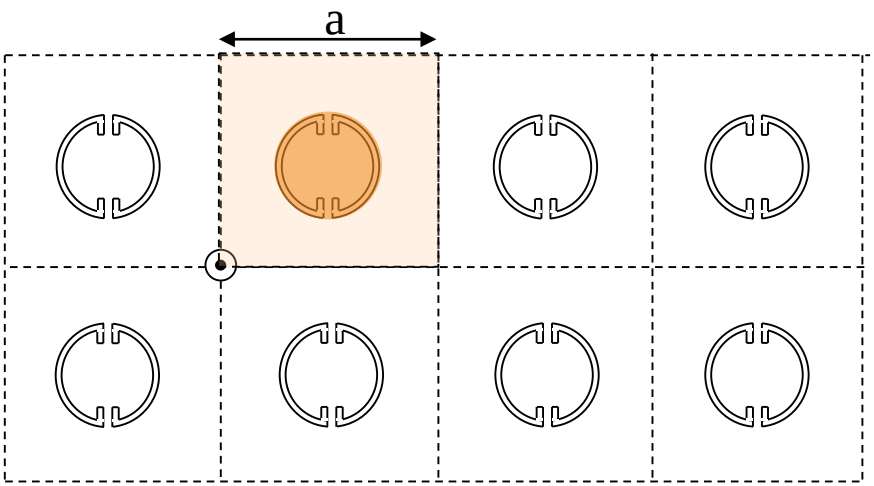
$$\frac{k_{dz}}{k_{mz}} = -\frac{\varepsilon_{dz}}{\varepsilon_{mz}}$$



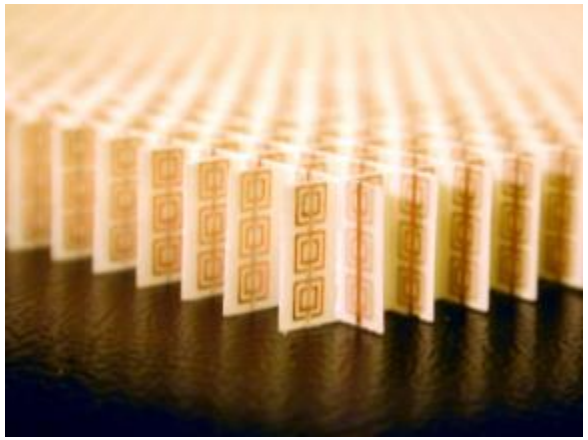
Artificial Material Response

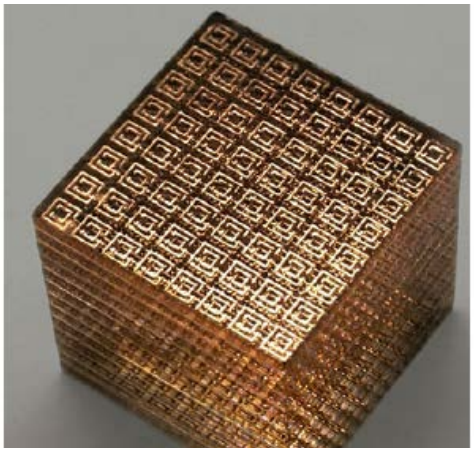


$$f = \pi r_c^2 / a^2$$



PRL 84, 2184, 2001





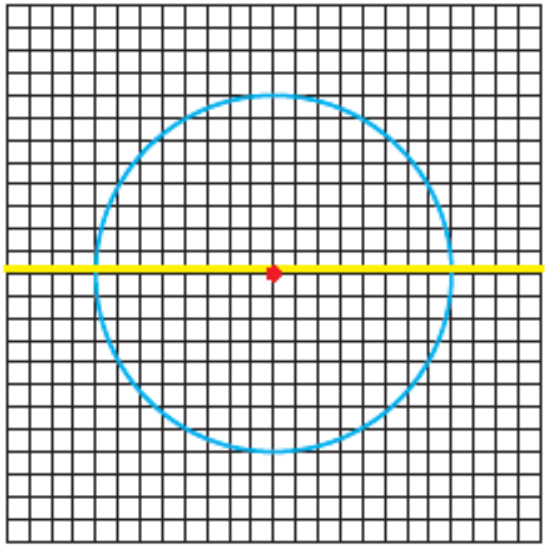
Physics today, June 2004

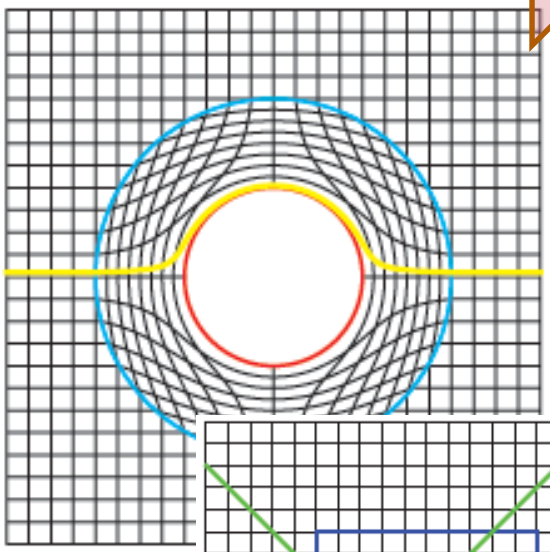
Transformation Optics

$$\nabla \times E + i\omega\mu H = 0 \qquad \nabla \times E' + i\omega\mu' H' = 0$$

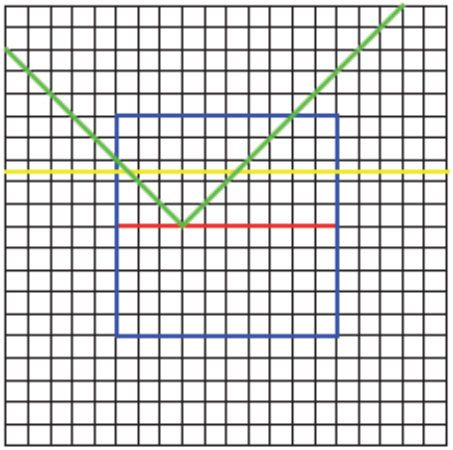
$$x' = x'(\mathbf{x})$$

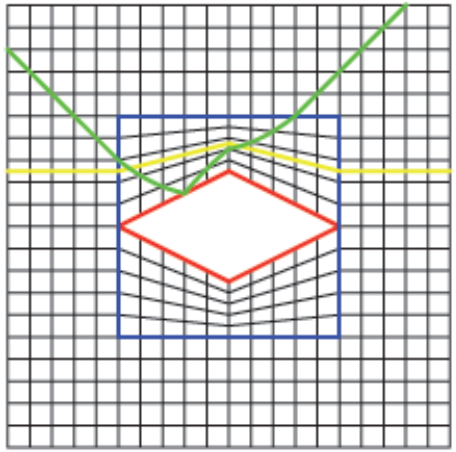
$$\nabla \times H - i\omega\varepsilon E = 0 \qquad \nabla \times H' - i\omega\varepsilon' E' = 0$$





Texturing of ε and μ can mimic spatial coordinate tranform





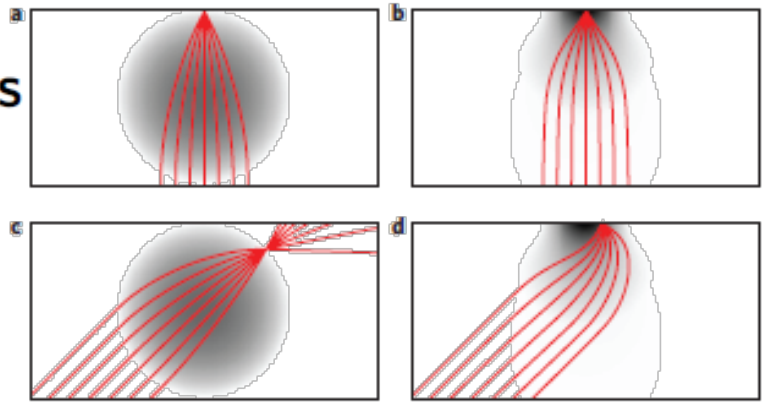
Transformation optics and metamaterials,
Chen, Chan, Sheng,
Nature Materials | VOL 9 | MAY 2010 | p387

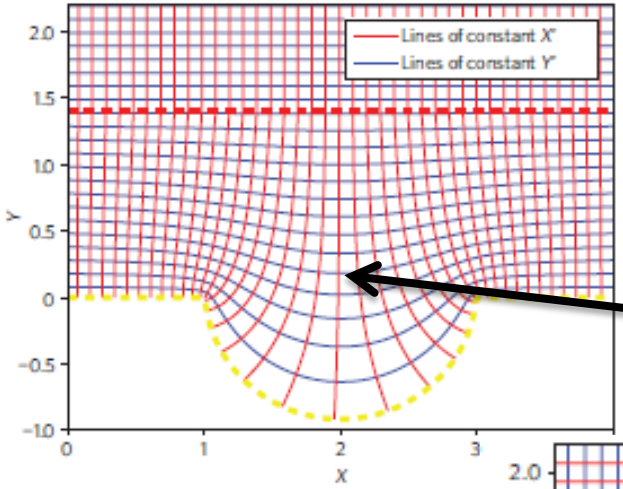
Transformation Optics: Luneburg Lens

nature materials
LETTERS
PUBLISHED ONLINE: 20 DECEMBER 2009 | DOI: 10.1038/NMAT2610

Extreme-angle broadband metamaterial lens

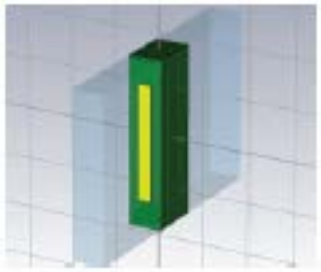
Nathan Kundtz* and David R. Smith

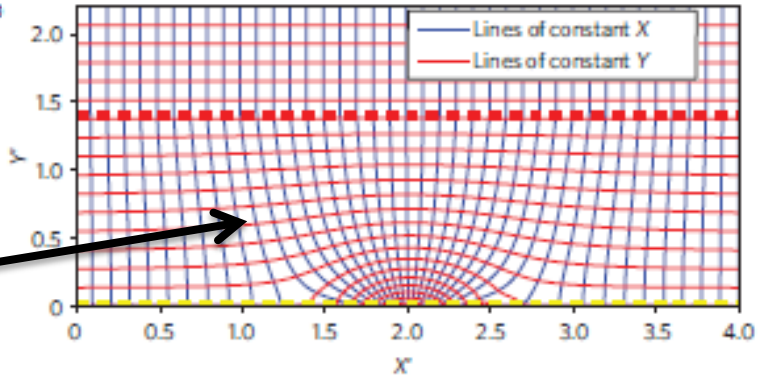




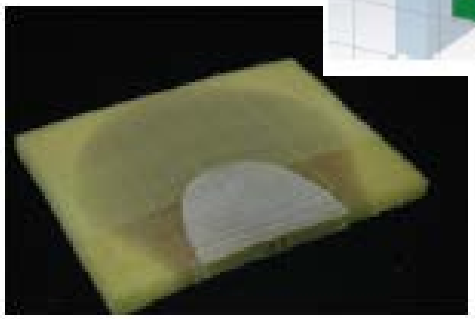
Original profile with curved focal plane

Unit cell



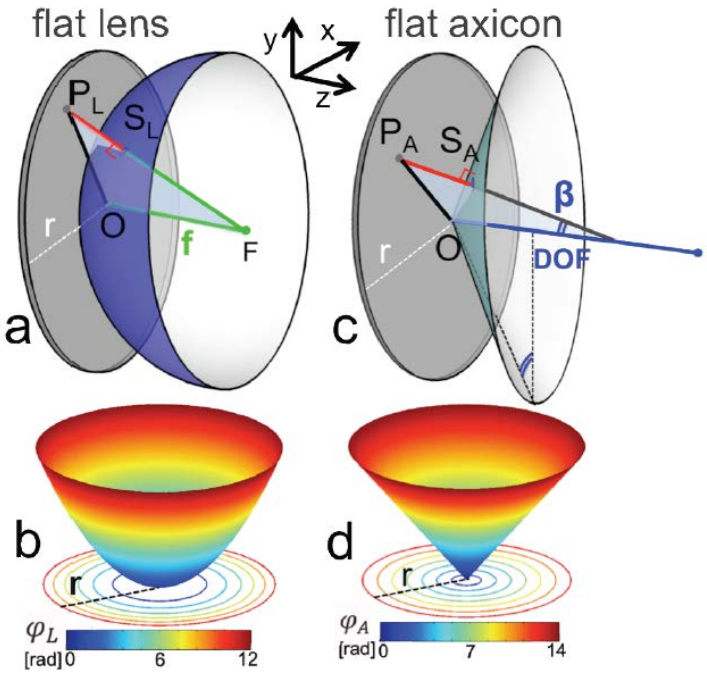


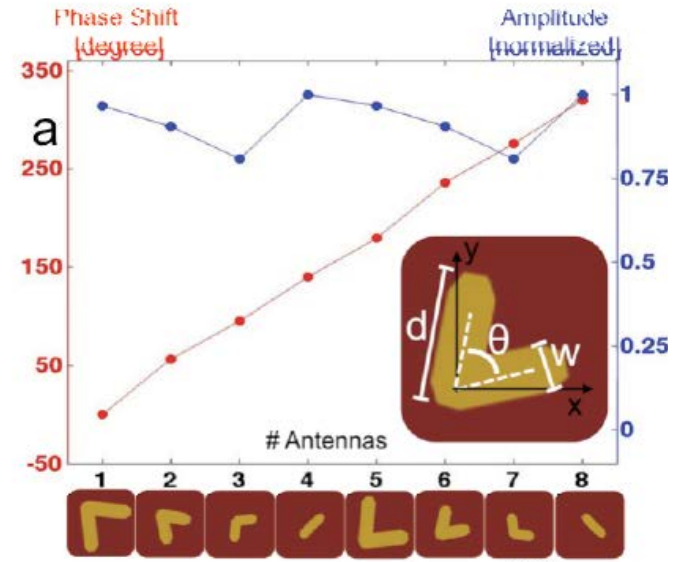
Transform with flat focal plane



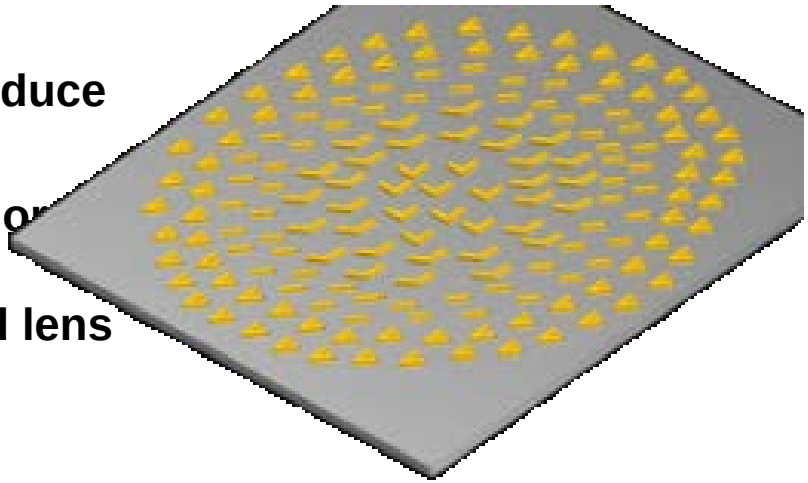
Constructed Lens

Metamaterial Flat Lenses





- **In the optical domain, small crescents produce geometry dependent scattering phase**
- **Flat lenses created with single layer of tailor scatterers, spatially mapped to create the appropriate phase funtion to mimic a solid lens**



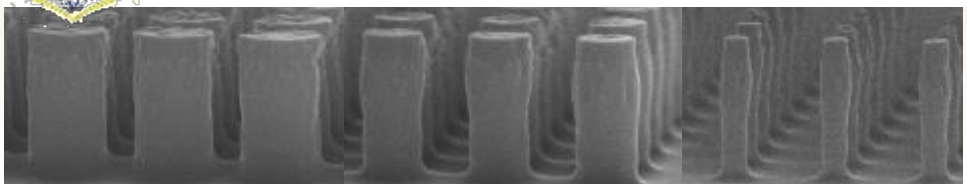
•Capasso et al. 2012

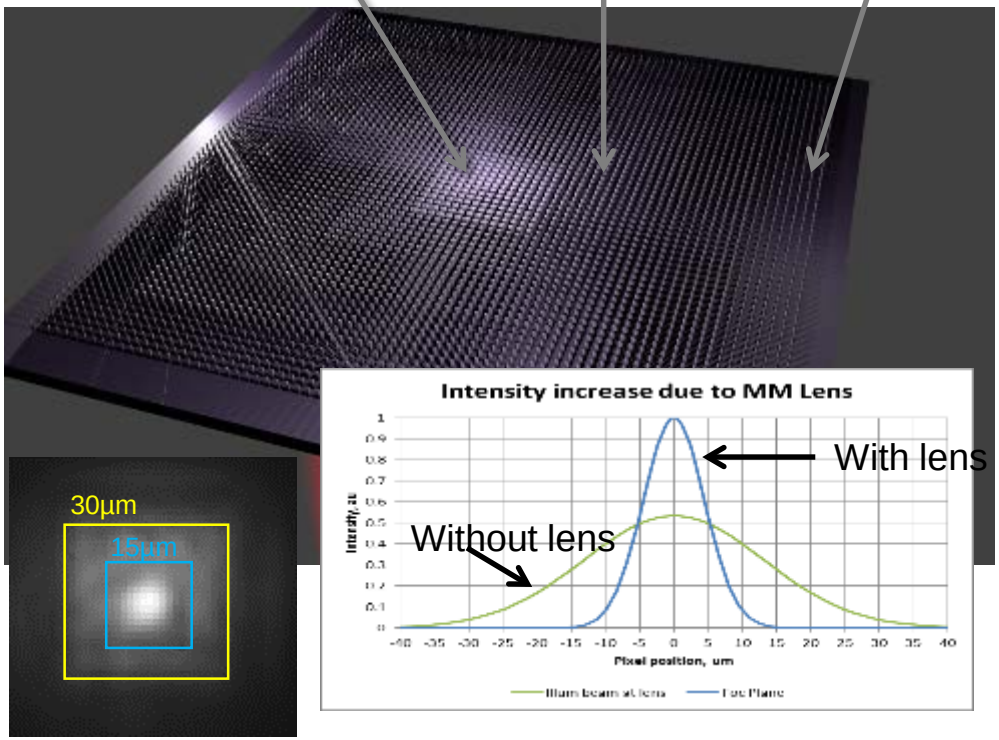
Planar Focusing Lens

Raytheon
Space and Airborne Systems

PURDUE UNIVERSITY

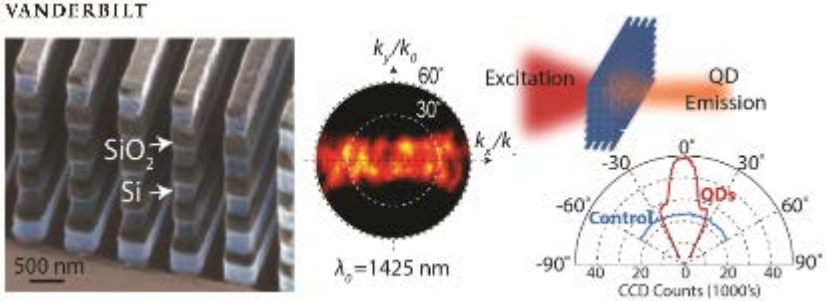
ARL





- **Semiconductor based, low-loss zero-index optical metamaterials**
- **Demonstration of enhanced directional emission from quantum dots (QDs) within the ZIM.**
  - **Jason Valentine (Vanderbilt University)**

VANDERBILT



SEM of Si based ZIM (left), angular confinement of transmission (center) and confinement of QD emission within the ZIM (right).

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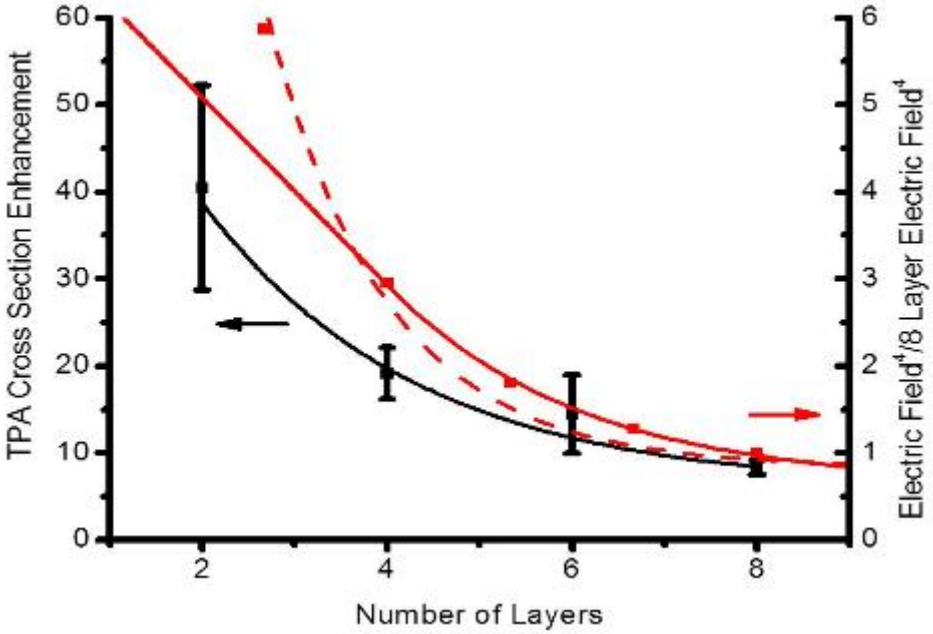
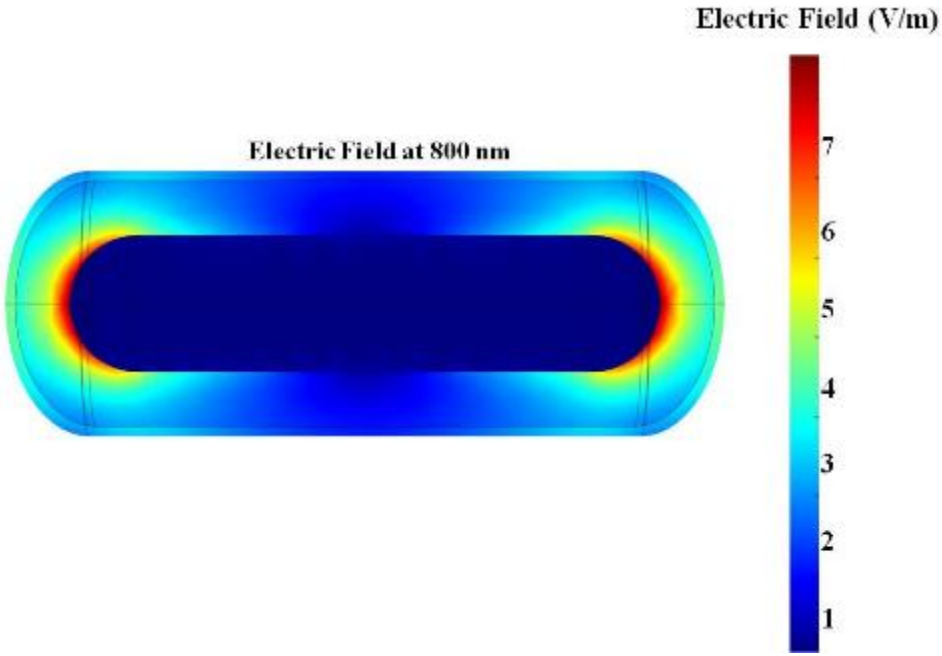
Cross-section Enhancement

TPA Enhancement and Predicted Relationship





Number of Layers	Calculated Ratio*	Measured Ratio
2	9.57	4.84 ± 14.7
4	2.94	2.28 ±3 .7
6	1.49	1.72 ± 5.61
8	1	1

*for n = 1.5, but changes little from n = 1.3 – 1.7

Electric field calculated in COMSOL

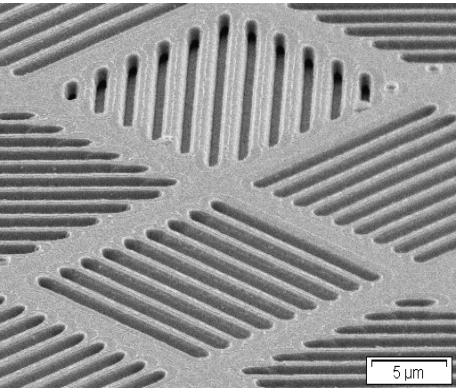
Predicted slope (COMSOL) = -0.477 ± 0.020 layer^{-1}

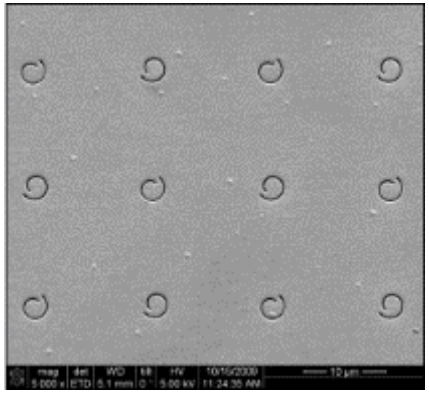
Measured slope = -0.434 ± 0.18 layer^{-1}

Fit using $y = b + Ae^{mx}$

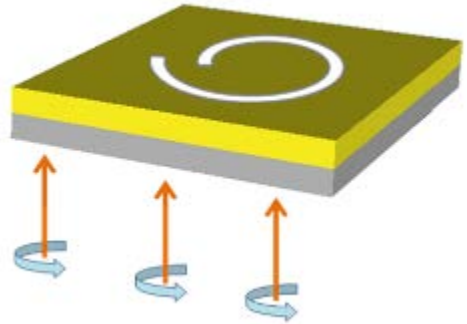
Murphy *et al*, Langmuir, 2012, submitted

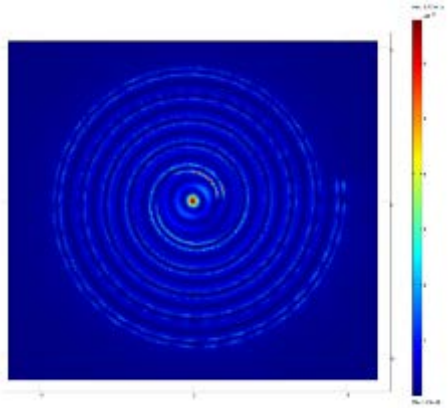
Micro Spiral Plasmonic Lens/Circular Polarizer for Polarimetry





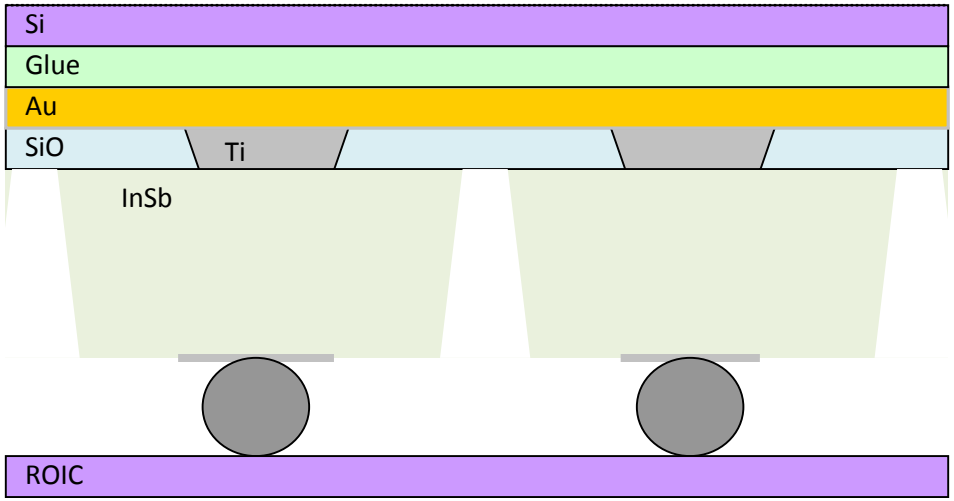
200 nm thick Gold film
Slot width 200 nm



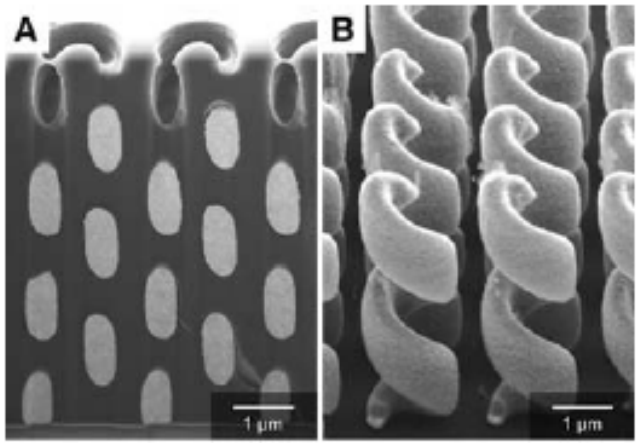


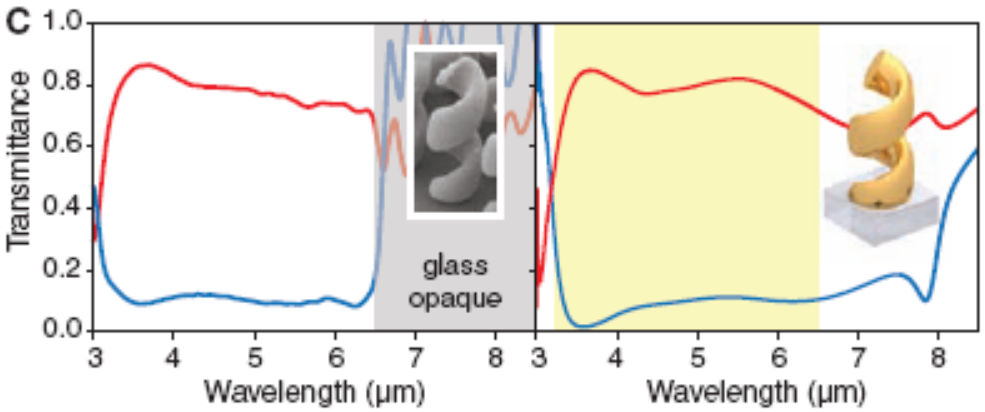
Left: Traditional linear micro-polarizers on a focal plane array
Right 3: planned spiral circular polarizers/lenses to be deposited on a FPA, and simulation showing selective focusing of a particular circular polarization. Extinction ratios of >40 are possible with energy efficiencies around 30%.

FPA pixel morphology, spirals will be milled into gold layer and centered on InSb island. Light from top will then be selectively focused into InSb pixel.



IR polarizer





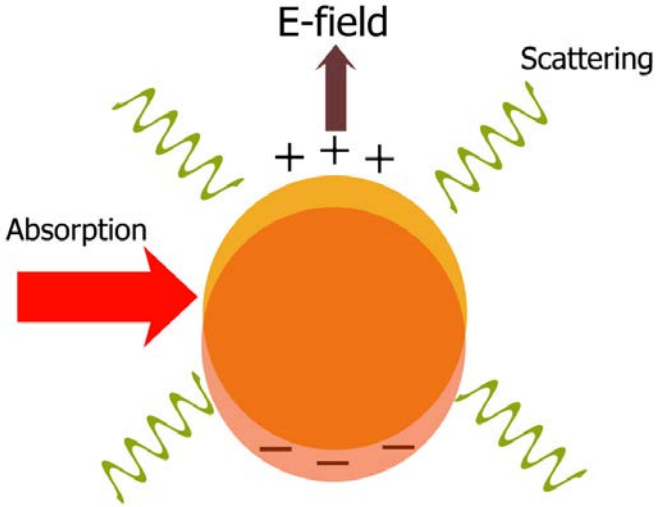
- **Recent experimental study in spiral MMs**
- **High efficiency CP in broad band IR**
- **Reflective, novel detection schemes?**

- **Few percent integrated loss**
- **3.5um – 8um by design**
- **No competing technology (?)**

Science ***325, 1513 (2009);***
Gansel, Wegener, *et al.*
Circular Polarizer
Gold Helix Photonic Metamaterial as Broadband

Plasmonic Enhancement of Solar Energy Generation

Objective: Increase power output from lightweight, flexible solar cells for AF needs.

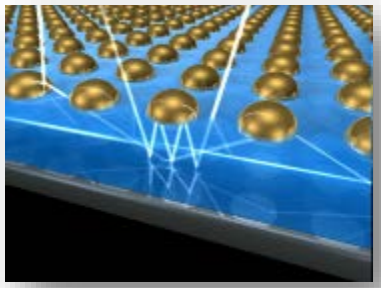


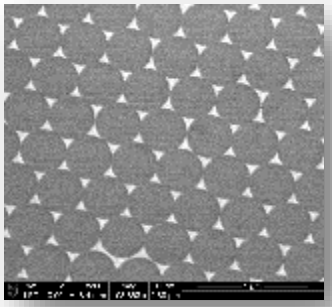
Four-Fold Approach:

1. Utilize the high <u>scattering</u> cross-sections of metallic nanoparticles to increase the path length in a photovoltaic cells.
2. Focus the high <u>electric near-fields</u> of resonant nanoparticles to enhance the media's photophysical properties.
3. **Design a cell with the <u>absorbing</u> metal nanoparticles as the active hot electron injector.**
4. Couple incoming light into horizontal <u>block mode</u> resonances to trap light into guided modes in the cell.

Metamaterials for Improved Solar Power Generation

Scattering

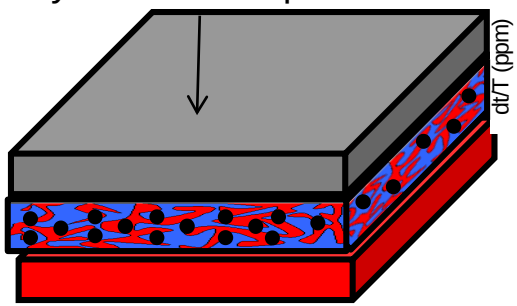


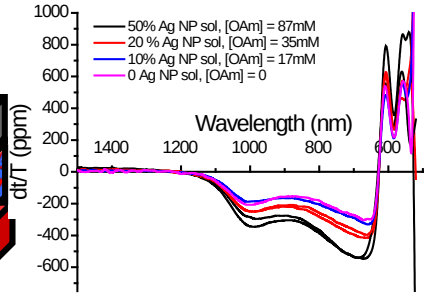


Plasmonic nanoparticles outperform current anti-reflection coatings on solar cells.

Electric Near-Field

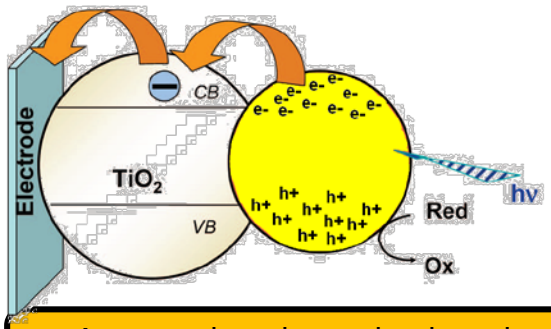
Nanoparticle / Organic Polymer PV Composite

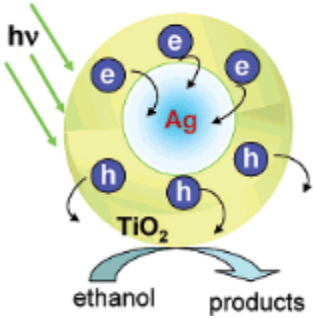




Localized near-field enhancements largely influence the photophysical properties of the local media.

Absorption

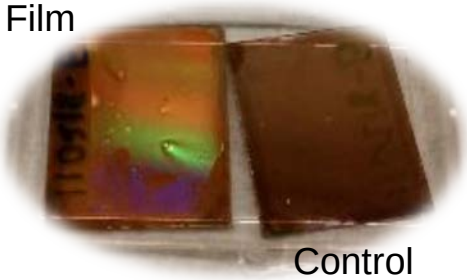




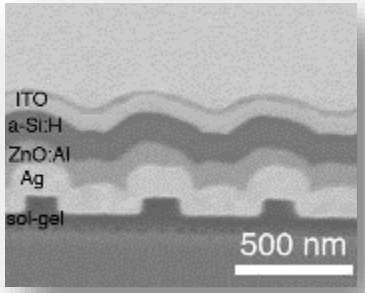
A game-changing technology that harnesses tunable plasmonic nanoparticles as the active PV species.

Block Mode Propagation

Stamped Film

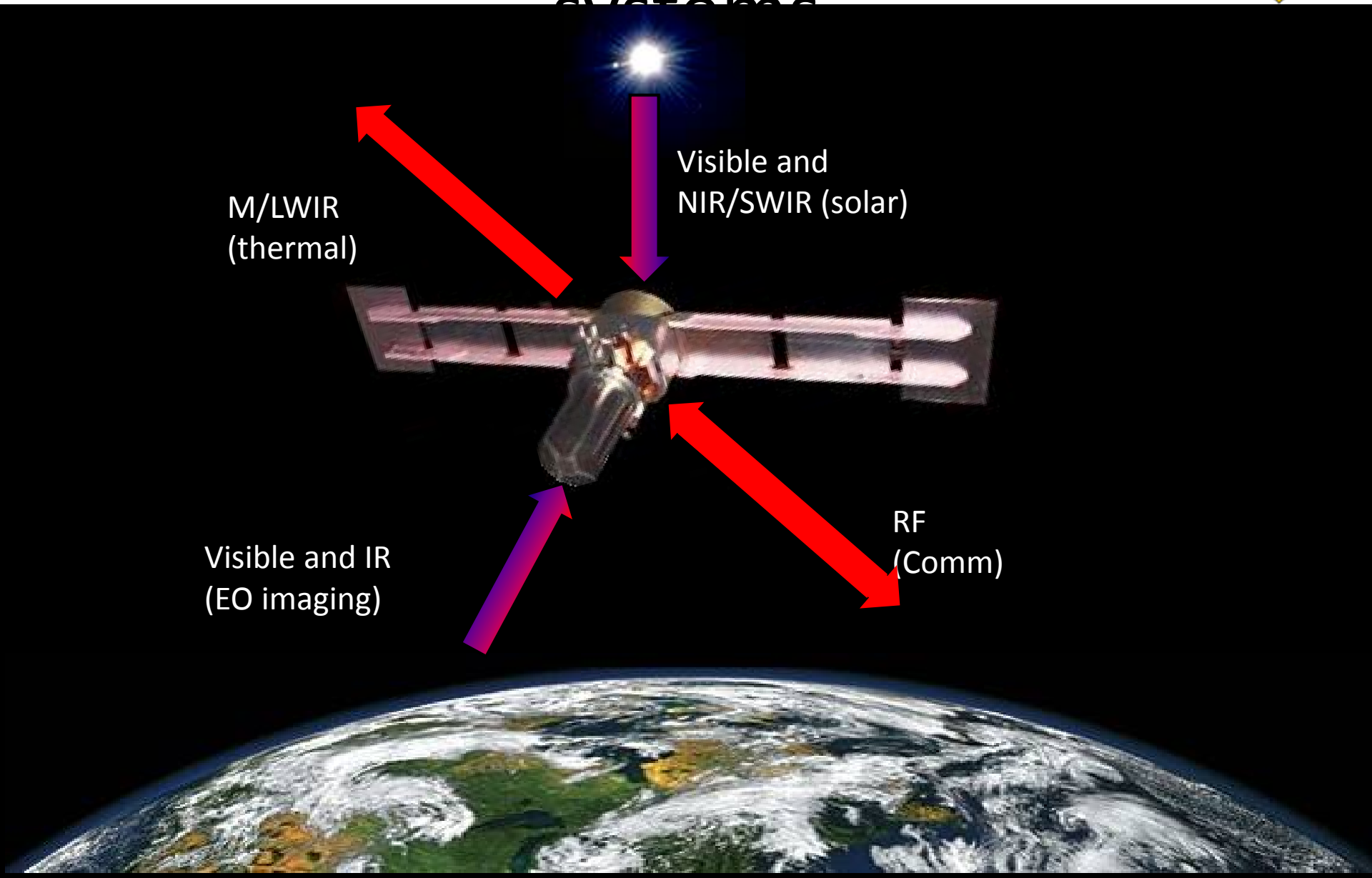


Control

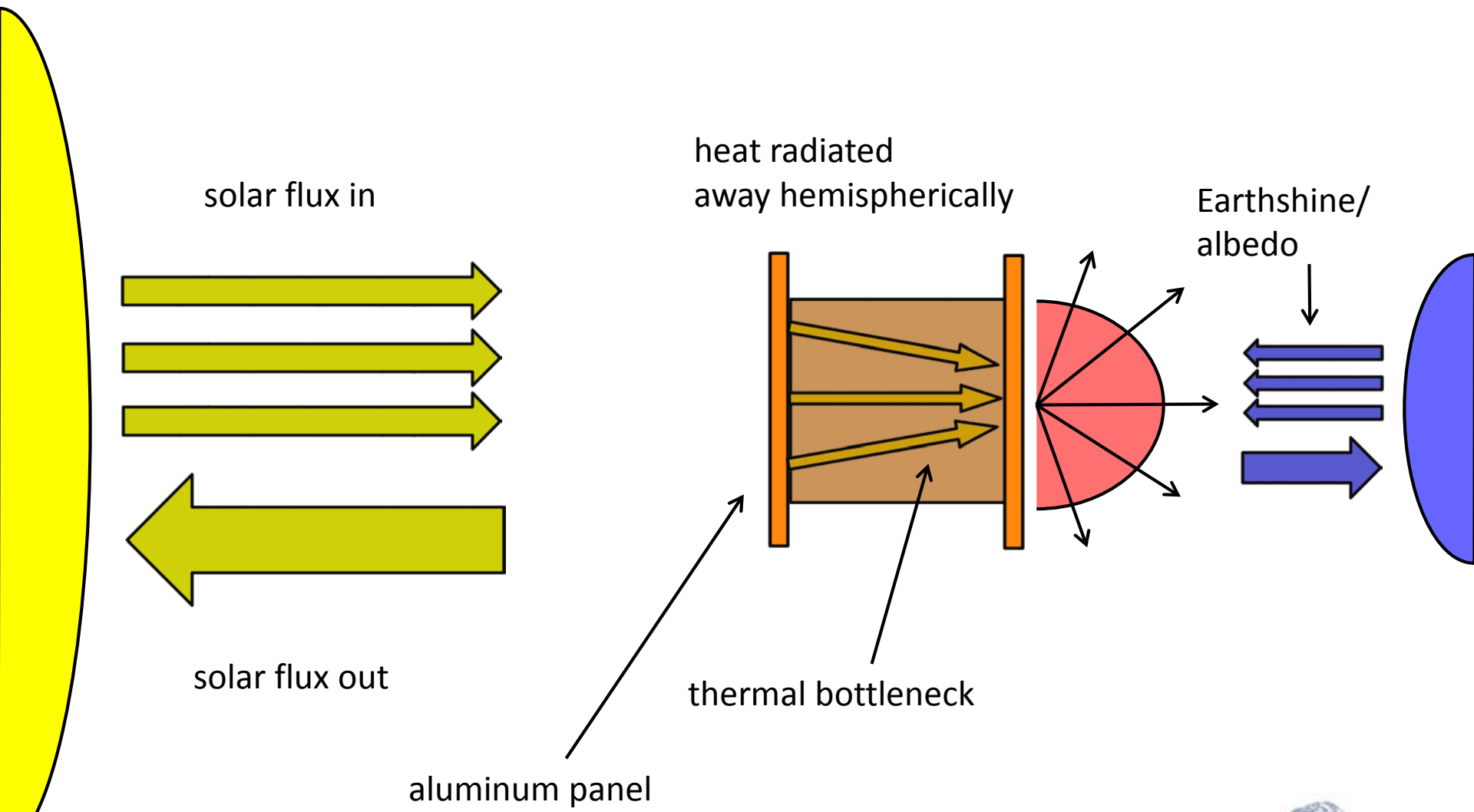


ICMSE will be used to design sub-wavelength structures to trap light with the polymer solar cell.

Thermal control for space systems

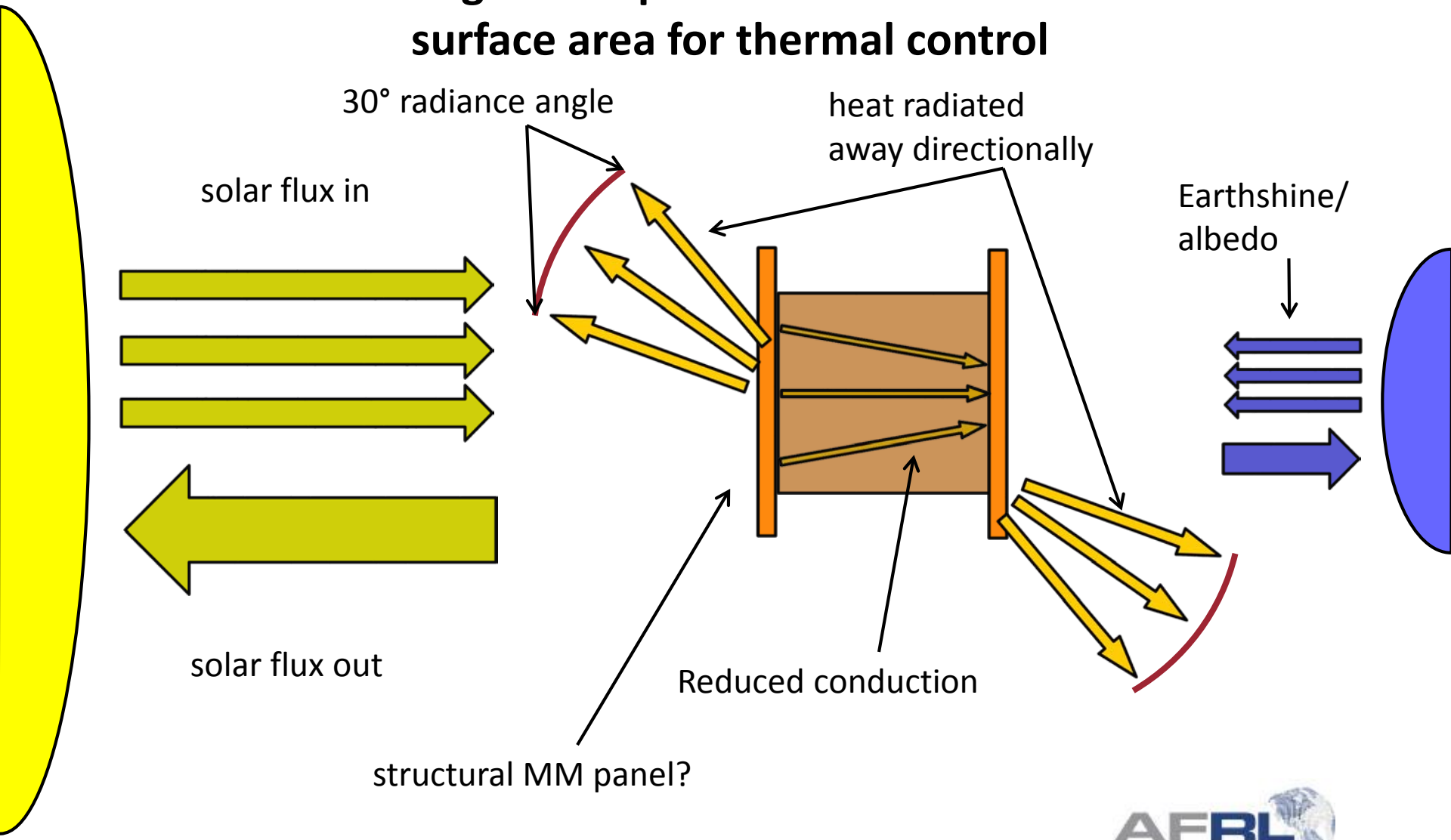


Non-Directional IR Emittance



Directionally-Tailored IR Emittance

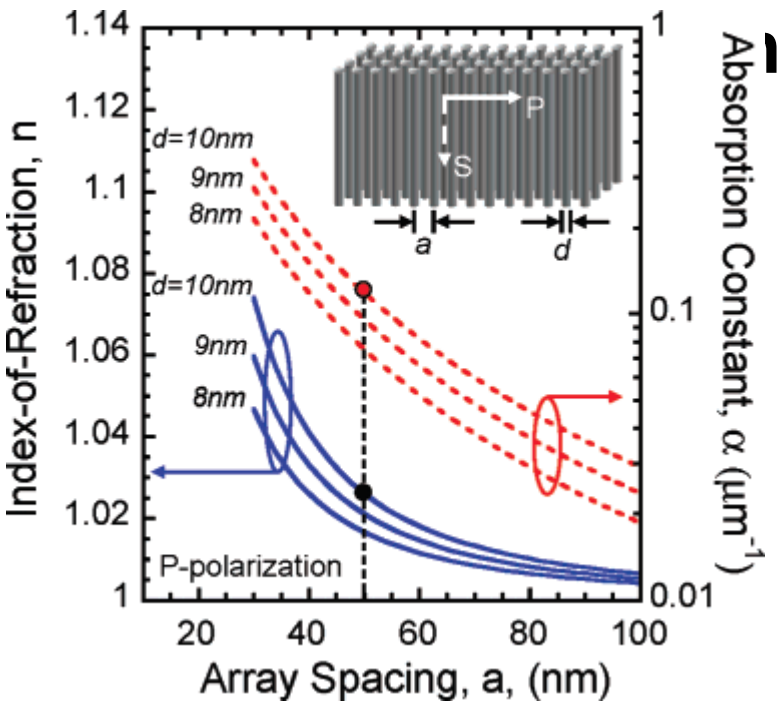
Goal is to tune angle and spectrum of emission to utilize more surface area for thermal control



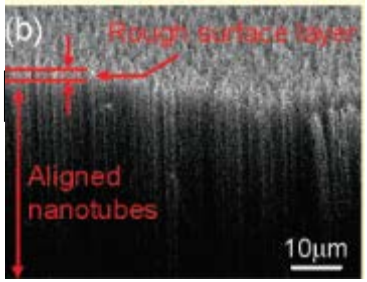
Metamaterials: Extreme Absorbers

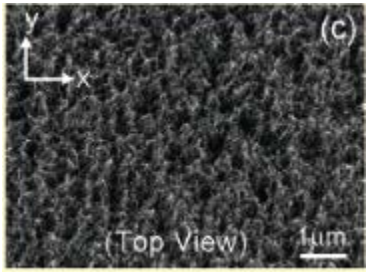
Experimental Observation of an Extremely Dark Material Made By a Low-Density Nanotube Array., Nanoletters 2008Yang, Ci, Bur, Lin, Ajayan

- **A non-dense carpet of nanotubes was analyzed by its effective index to determine the nature of its record setting absorption**



n in T

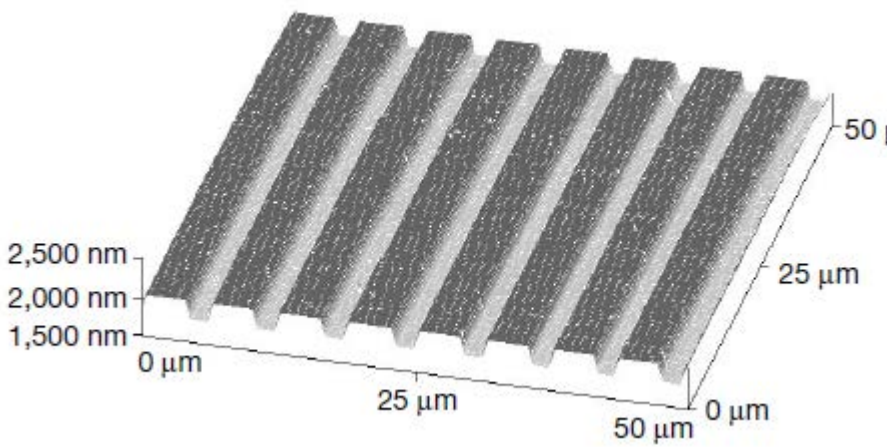


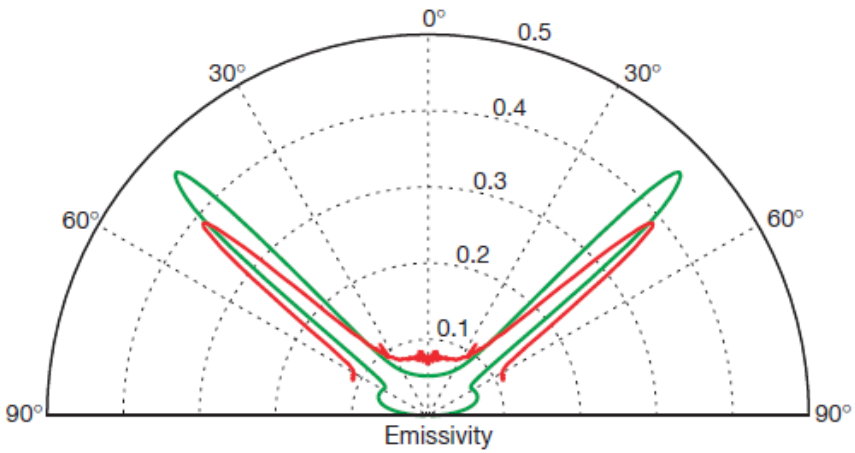


- **Modeling with MG to get effective medium properties shows an index close to 1 providing for a total reflectance of <0.1**

Photonic Structures for Emissivity Control

Coherent Direction of Thermal Radiation from Surfaces



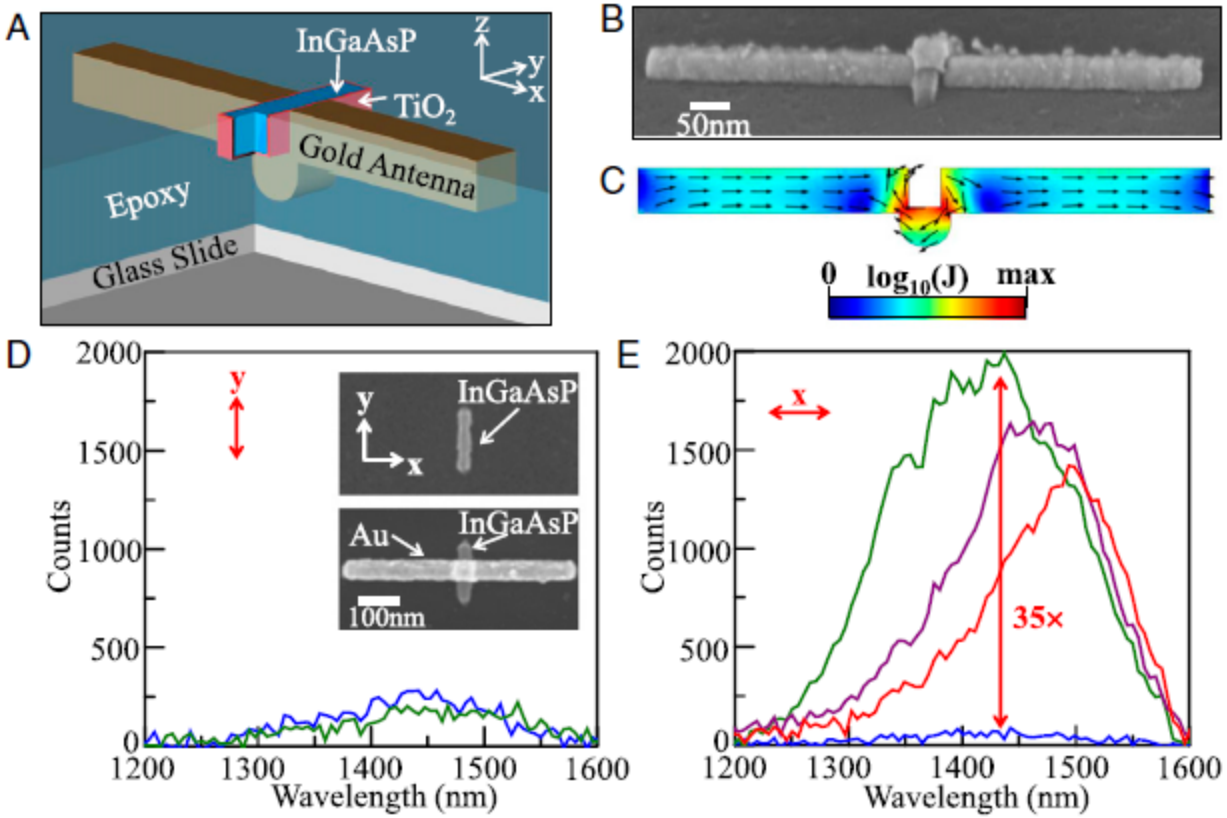


NATURE |VOL 416 | 7 MARCH 2002

AFM image of SiC grating designed for peak emissivity at λ = 11.36 um

Emission from surface heated to 500 ^{o}C as a function of detector position for λ =11.36 um. Red line is experimental data, green is predicted.

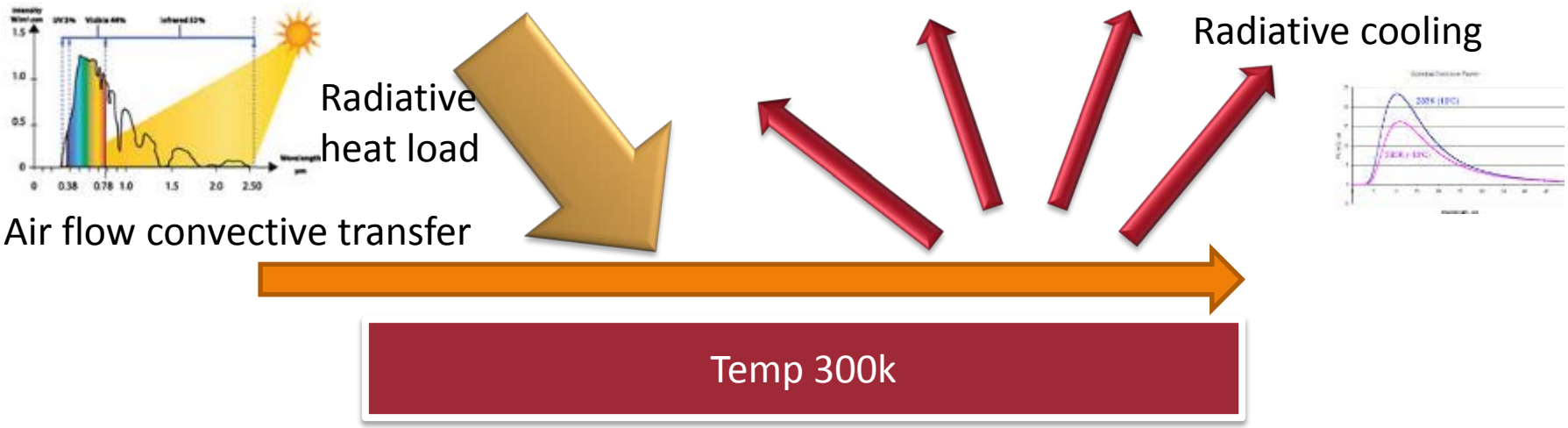
Enhanced Emission



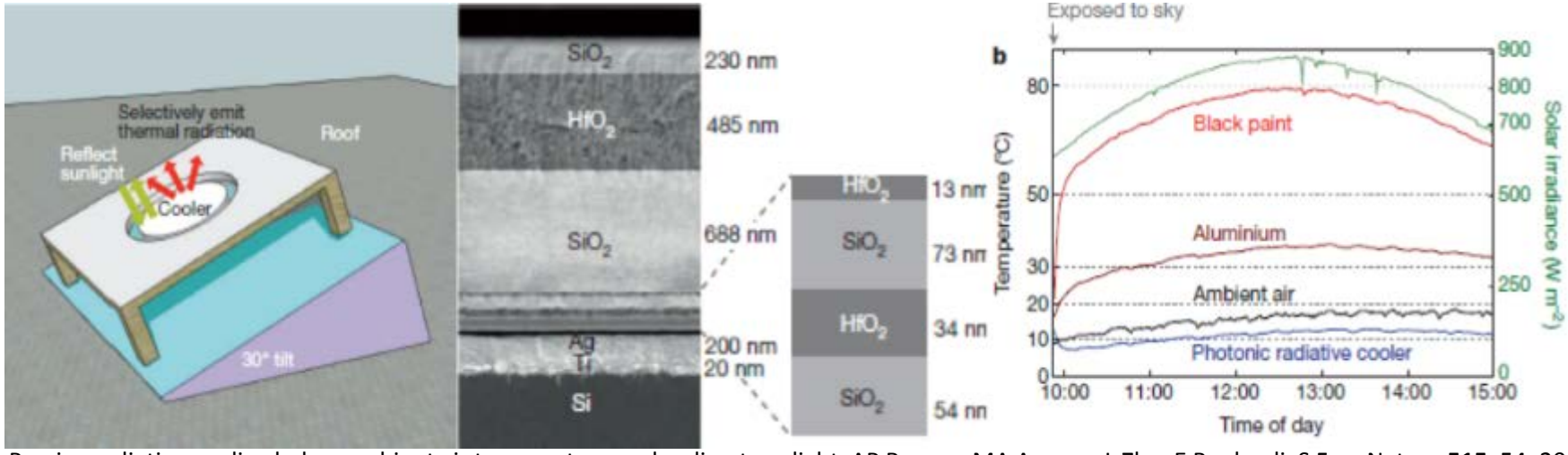
Eggelston et al. PNAS 2014

Radiative Cooling for Thermal Control

Temp 5000k

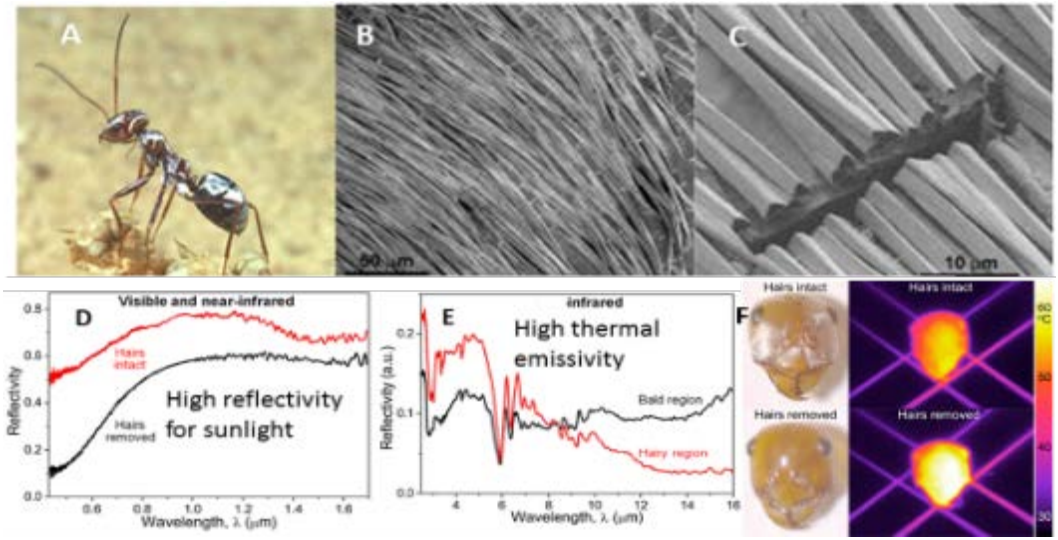


- **Control of thermal surfaces in radiative heating dominated environments can be important**



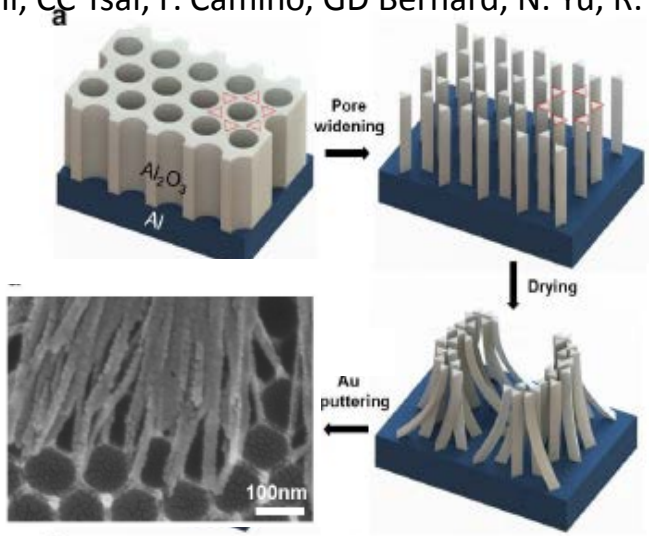
Passive radiative cooling below ambient air temperature under direct sunlight, AP Raman, MA Anoma, L Zhu, E Rephaeli, S Fan. Nature **515**, 54, 2014

Bio-Inspired Photonic Heat Shields



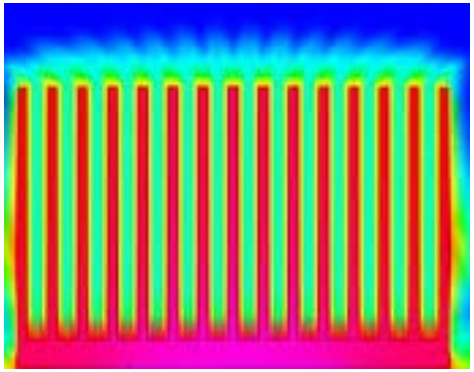
Keeping Cool: Enhanced optical reflection and heat dissipation in silver ants, NN Shi, CC Tsai, F. Camino, GD Bernard, N. Yu, R. Wehner. Science **349**, 298, 2015

- **Examples of biological control of temperature by controlled daytime radiative cooling.**
- **Balance of reflection and absorption and thermal properties to reject load, radiatively cool and insulate.**



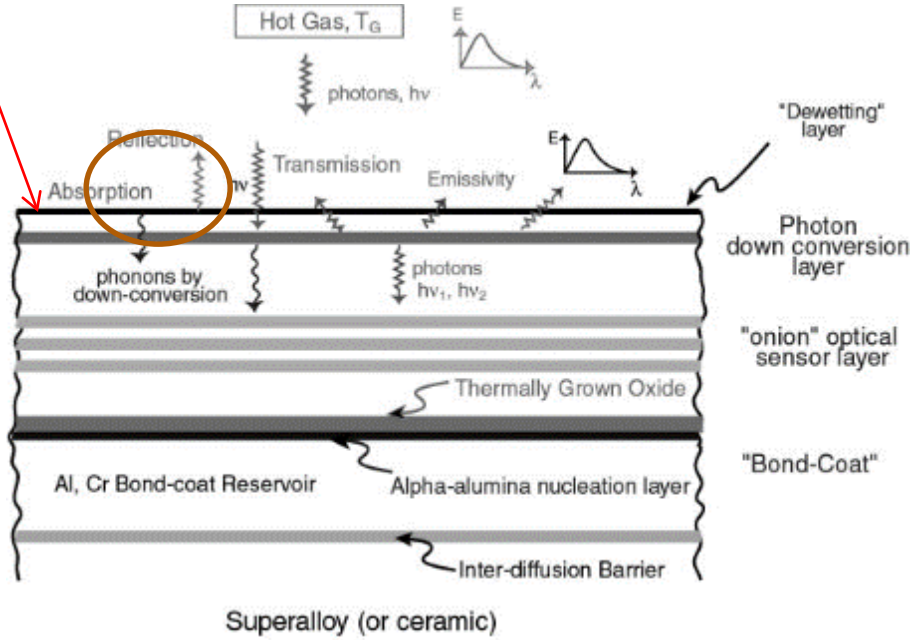
Kyoungsik Kim, Yonsei U.

- Synthetic example made of alumina mimics bio-system
- Performing combined modeling and experimental studies to control heating



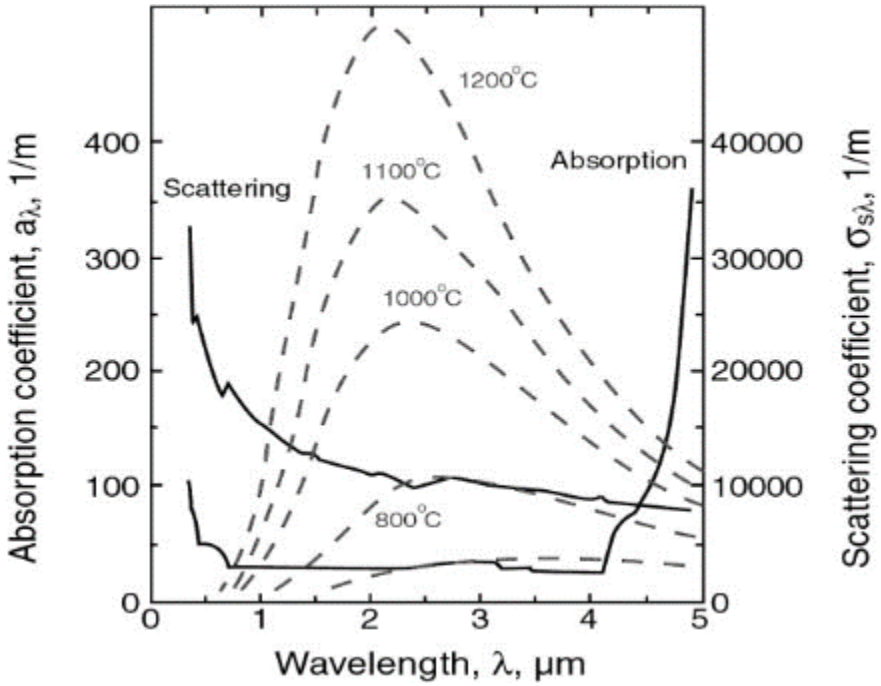
Thermal Barrier Coaings to Reduce Heat Transfer

Next generation thermal barrier coating



(Clarke, Levi Ann. Rev. Mat. Sci. 2003)

SOTA thermal barrier coatings for jet turbines are IR transparent



Siegel R, Spuckler CM. 1998. *Mater. Sci. Eng. A 245:150–59*

$$P = e\sigma A(T^4 - T_C^4)$$

P = net radiated power	e = emissivity (=1 for ideal radiator)
A = radiating area	T = temperature of radiator
σ = Stefan's constant	T_C = temperature of surroundings

$$\sigma = 5.6703x10^{-8} watt / m^2 K^4$$

Higher gas temperatures in future jet engines will need to accommodate increased radiated power to TBC substrate

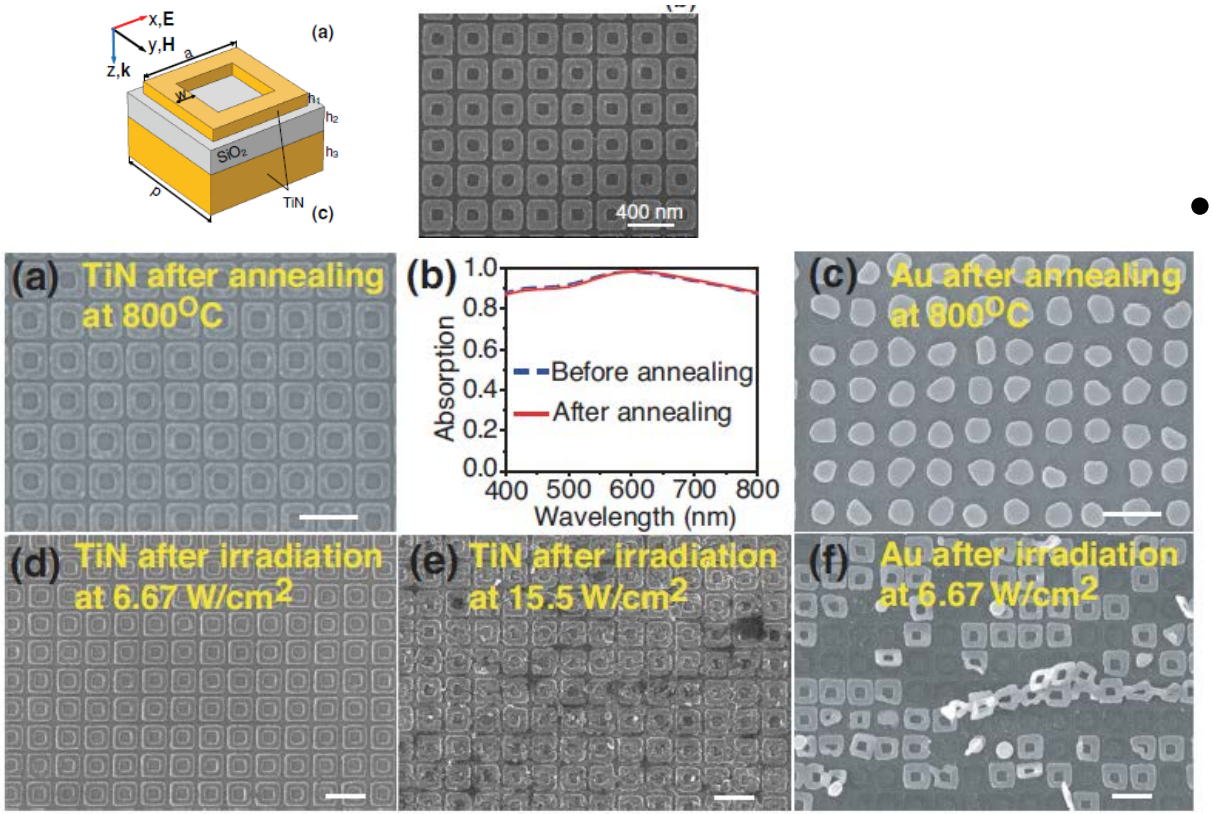
Two approaches:

- -absorb IR
  - -convert to lower E phonons
  - -re-emit at longer λ
- -reflect IR

Nonlinear plasmonics: Nitrides

Refractory Plasmonics with Titanium Nitride: Broadband Metamaterial Absorber

Wei Li, Urcan Guler, Nathaniel Kinsey, Gururaj V. Naik, Alexandra Boltasseva, Jianguo Guan, Vladimir M. Shalaev, and Alexander V. Kildishev**

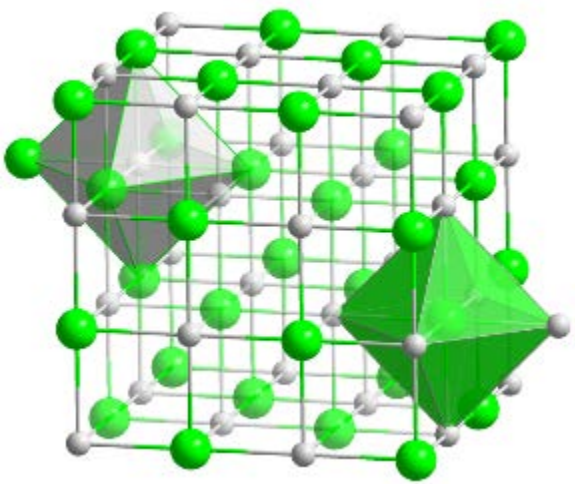


Adv. Mater. **2014**, *26*, 7959–7965

- **Nitride materials are useful plasmonic materials**
- **More resilient for nonlinear optical systems**

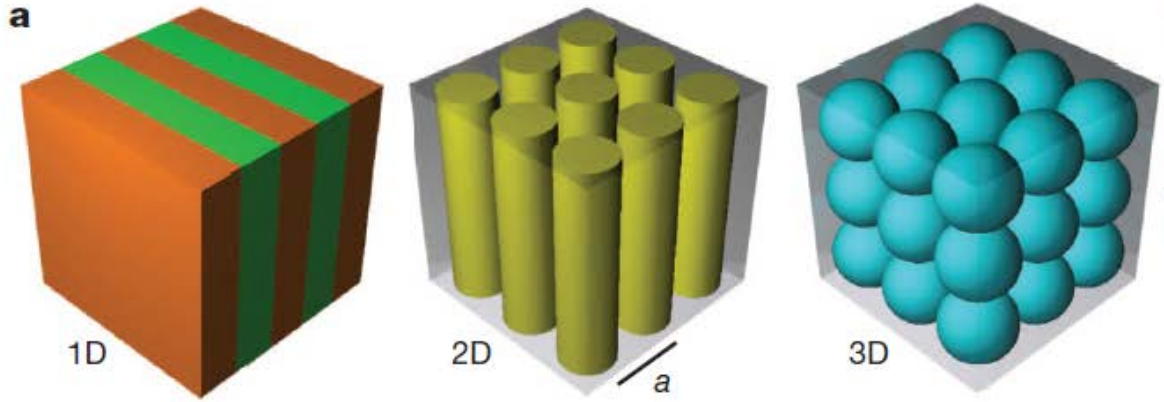
Thin Film Titanium Nitride

- **Transition metal nitride**
  - **Nonstoichiometric semiconductor**
  - **Cubic crystal structure**
  - **Compatible with CMOS technology**
- **Plasmonic material**
  - **More robust than gold and silver**
    - High hardness
    - Chemically stable
    - High T_{melt} >2900º C
  - **Large free carrier concentration** $10^{22} cm^{-3}$
    - 10x concentration of TCOs
    - Same order of magnitude as Au
    - Very large optical nonlinearity
- **Tunable optical properties**
  - **Stoichiometry**
  - **Temperature of deposition**
  - **Substrate**

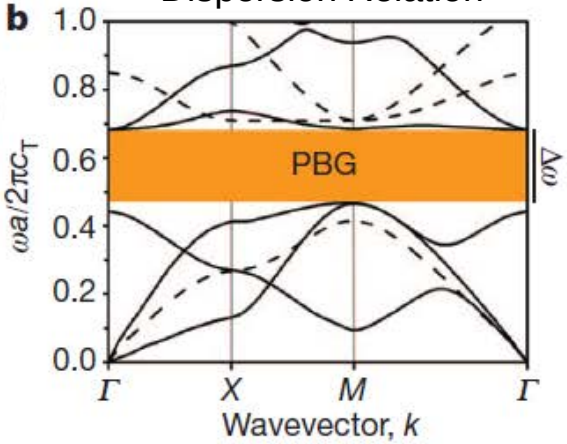


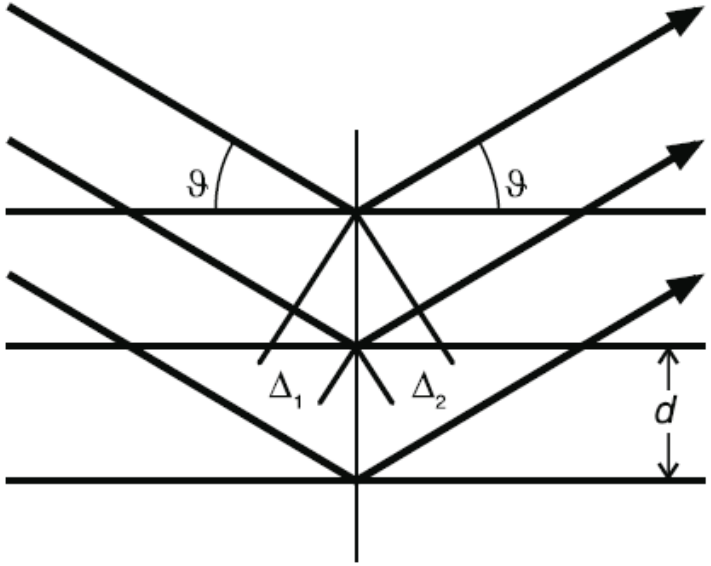
Artificially Structured Acoustic Materials

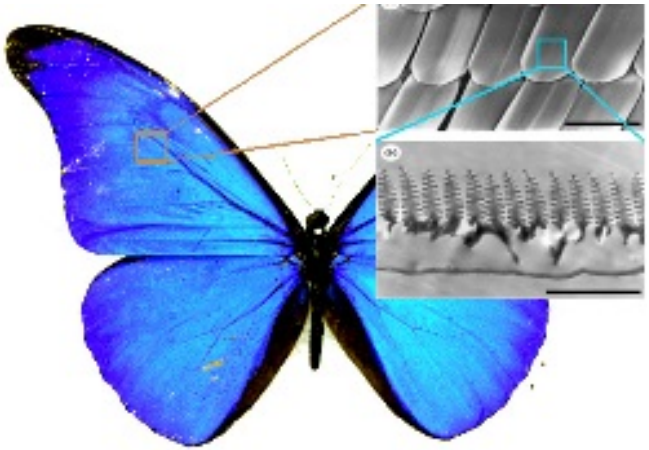
1. Phononic Crystals



Dispersion Relation



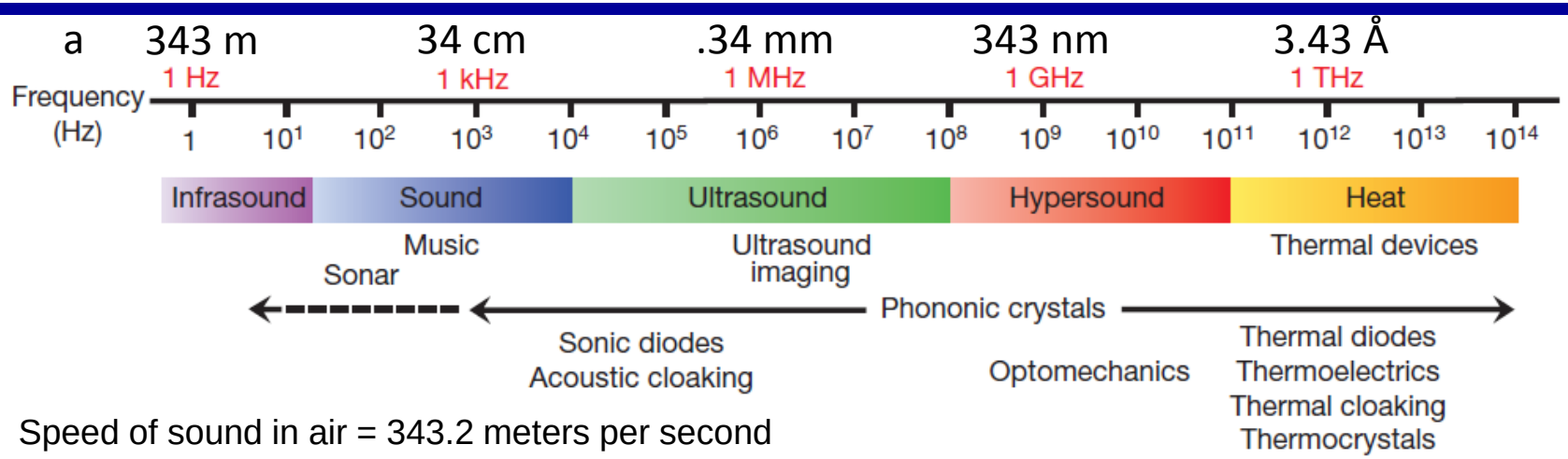




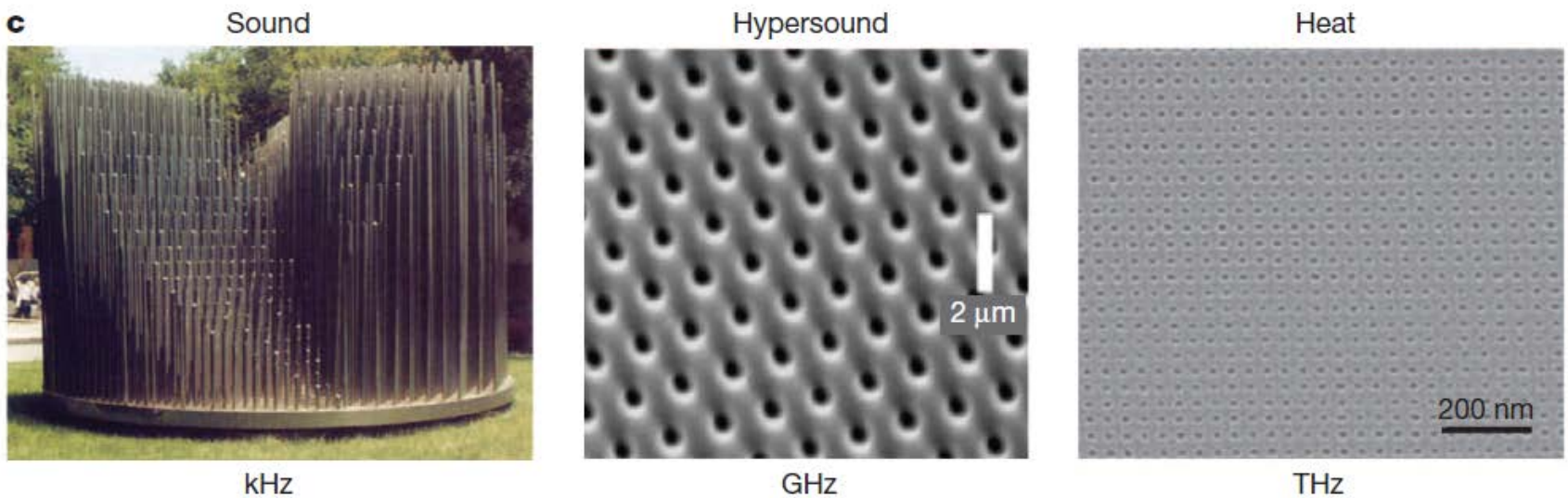
Maldovan, M. *Nature* **2013,** 503, (7475), 209- 217

http://emps.exeter.ac.uk/physics-astronomy/

Phononic Crystals



Speed of sound in air = 343.2 meters per second

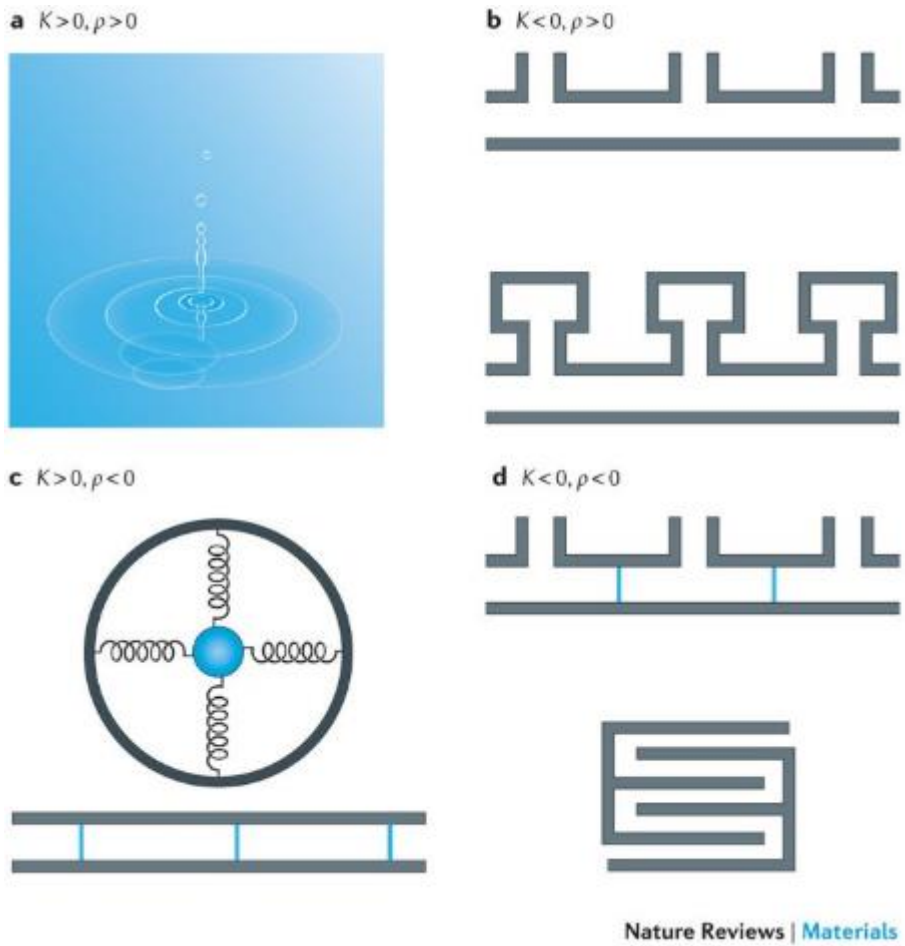


Maldovan, M. *Nature* **2013,** 503, (7475), 209- 217

Artificially Structured Acoustic Materials

2. Acoustic Metamaterials (local response)

Bulk modulus (K): compressional stiffness of the material
mass density (ρ): controls wave propagation



- Metamaterials are artificial structures, with unconventional effective properties.
- A metamaterial structure is typically 10 or more times smaller than the smallest acoustic wavelength being manipulated.
- Do not need to be periodic
- Negative ρ or β means that at certain frequencies the medium expands when experiencing compression (negative modulus), and accelerates to the left when being pushed to the right (negative density)

Applications in acoustic absorption, bend sound the wrong way, acoustically conceal an object

Nature Reviews Materials 1, 16001 (2016)

AIR FORCE RESEARCH LABORATORY