Metamaterial Science and Technology
Grand Challenge LDRD

Sandia National Laboratories

M.B. Sinclair, F. B. (Rick) McCormick , L. Basilio, I. Brenner, P. Clem, M. Lee, L. Warne, D. Bender, D.B. Burckel, J. Carroll, S. Dirk, I. El-Kady, A.R. Ellis, J. Ihlefeld, J. Hu, W. Johnson, W. Langston, Y.J. Lee, H. Loui, B. Passmore, D. Peters, E. Shaner, G. Ten Eyck, J. Wendt

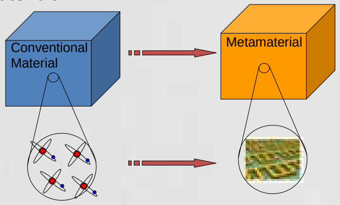
Problem

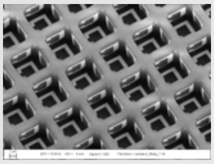
Background

μετα = meta = "beyond"

What is a metamaterial?

A **metamaterial** is an artificially structured material exhibiting electromagnetic properties not readily achievable with natural materials.



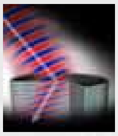


permittivity ε, & permeability μ derived from the constituent atoms

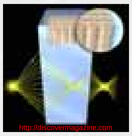
ε_{eff}, μ_{eff} are derived from "meta-units" (bigger than atoms, << λ)

Absolute local control of the permittivity (ε) and permeability (μ) has lead to new paradigms for optical design.

electromagnetic cloaking



negative refraction



Subdiffraction-limited lensing

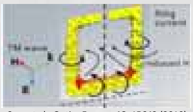
- Metamaterial devices have been demonstrated at RF frequencies.
- **Two problems** must be overcome to enable metamaterial applications in the infrared or shorter wavelengths:
  - optical loss: ohmic losses of metallic resonators lead to significant energy dissipation
  - lack of fabrication processes for the production of isotropic 3D metamaterials.

Approach

Low loss IR metamaterials

Replace lossy metallic resonators with high-Q dielectric resonators.

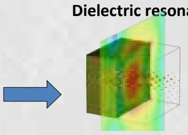
Metallic resonator



Sun, et al., Optics Express **18**, 15643 (2010)

Lossy conduction currents

Dielectric resonator



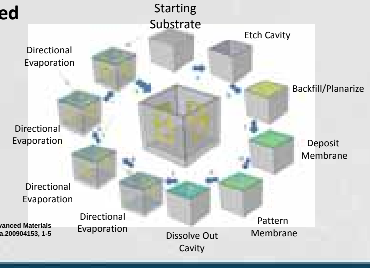
Low loss displacement currents

- Magnetic and electric dipole resonances can be utilized to tailor ε and μ.

3D Metamaterial fabrication

Membrane projection lithography (MPL) developed to enable isotropic 3D metamaterials in the infrared

- Out-of-plane resonators
- Planar lithography
- Many possible patterns
- Cavity geometry independent of resonator pattern
- Scalable
- Layer-by-layer → 3-D



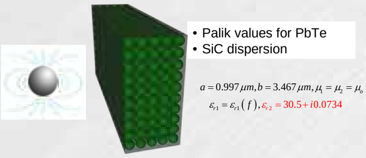
Burckel *et al*, Advanced Materials DOI 10.1002/adma.200904153, 1-5 (2010).

Results

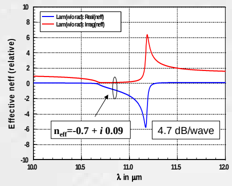
All-Dielectric Negative Index Metamaterial

High permittivity PbTe spheres in polaritonic SiC matrix.

- PbTe spheres provide negative magnetic permeability; SiC matrix provides negative permittivity → n_{eff}=-0.7+i0.09 at 10.8 μm.

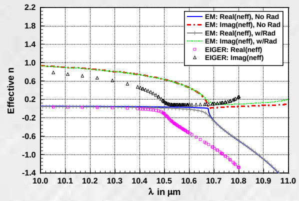


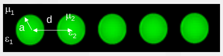
$a = 0.997\,\mu m, b = 3.467\,\mu m, \mu_1 = \mu_2 = \mu_o$
$\varepsilon_1 = \varepsilon_{r1}(f), \varepsilon_2 = 30.5 + i0.0734$



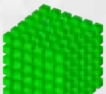
Full Wave Simulation

EIGER™ simulation of 5-layer metamaterial





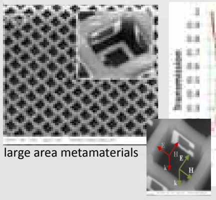
EIGER:
$n_{eff} = -0.729 + i0.094$
at 10.66 μm



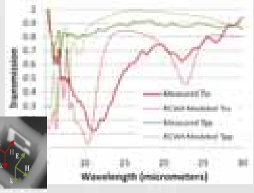
- Negative index optical lens
- Significantly lower loss than published metallic designs.
  - even lower loss designs have been developed
- Currently fabricating using **cube resonators** and low-loss polymer matrix

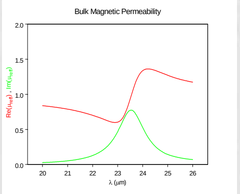
3D Cubic Infrared Metamaterial

Metallic Split Ring resonators arrayed in 3D → magnetic metamaterial



large area metamaterials





retrieved magnetic permeability

- Impedance matched zero-index metamaterials
  - optical couplers
  - coherent thermal emitters
- Multilayer bulk 3D materials under development

Significance

- **Reducing metamaterial loss is a key step toward realization of practical IR metamaterial devices**
  - lenses & other optics
  - high-Q filters
  - concentrators, couplers, and cloaks
- **Dielectric resonator metamaterials show best promise for low-loss operation**
  - Prototype metamaterials are currently being fabricated
- **Membrane Projection Lithography enables bulk IR metamaterials**
  - currently metal-based metamaterial resonators
  - wide angle filters, absorbers, and emitters

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

SAND 2010-5579P

Sandia National Laboratories