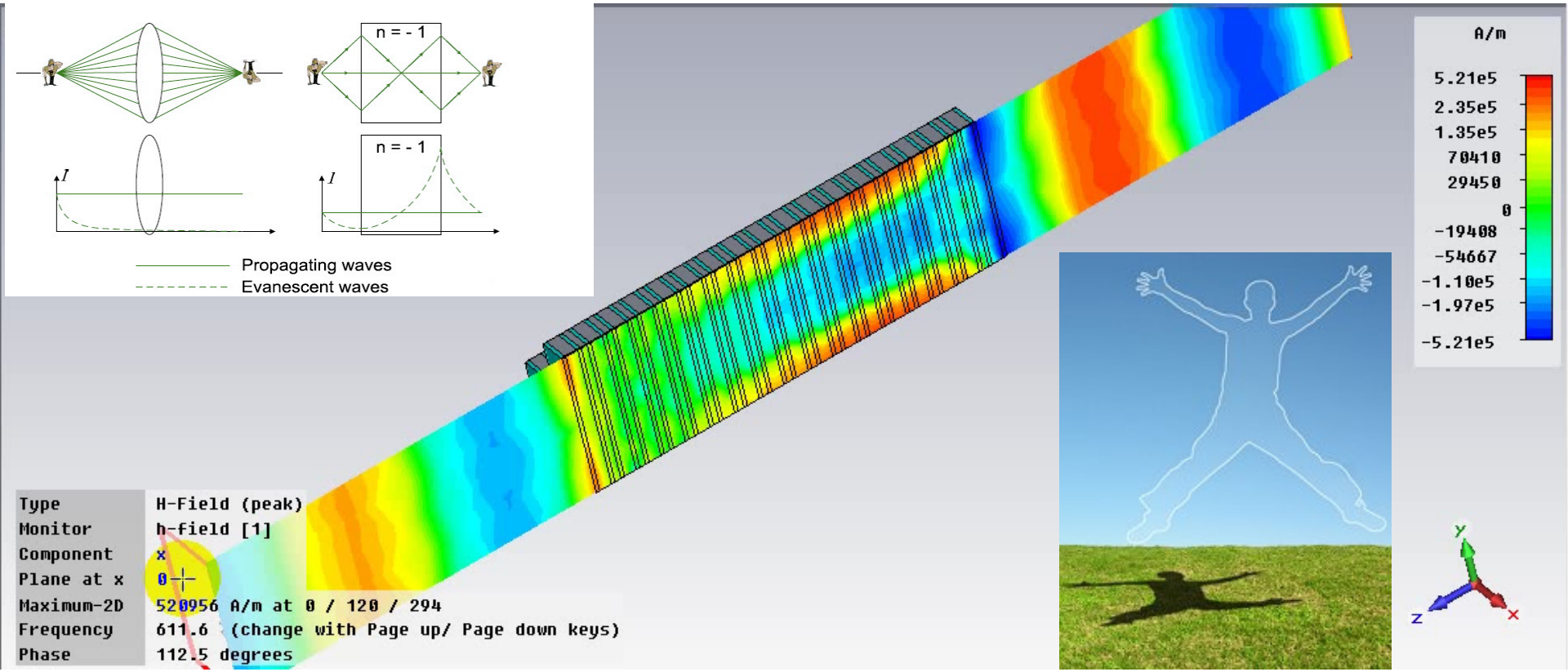
Pakistan Academy of Engineering

The 17th Symposium titled
"Emerging Technologies"

Saturday, June 27, 2020

Metamaterials- Manipulating light

Achieving super natural properties using composite materials



Dr. Muhammad Imran Aslam

NED University of Engineering and Technology, Karachi

INTRODUCTION

- Nature of Light
  - Light is Electromagnetic Wave (visible light: 400-780THz)
  - Not much difference between 1kHz (λ=300km) and 1THz (λ=0.3mm)
- Why can't optical light go through walls like mobile signals?
  - Material response varies at different frequencies
  - Determined by atomic structure and arrangement ($\sim 10^{-10} m$)
  - Electromagnetic properties of a material depends on its permittivity(ε) and permeability (μ)
    [commonly represented by it's refractive index $n = \sqrt{\varepsilon\mu}$]
- CAN WE GET NEW PROPERTIES?

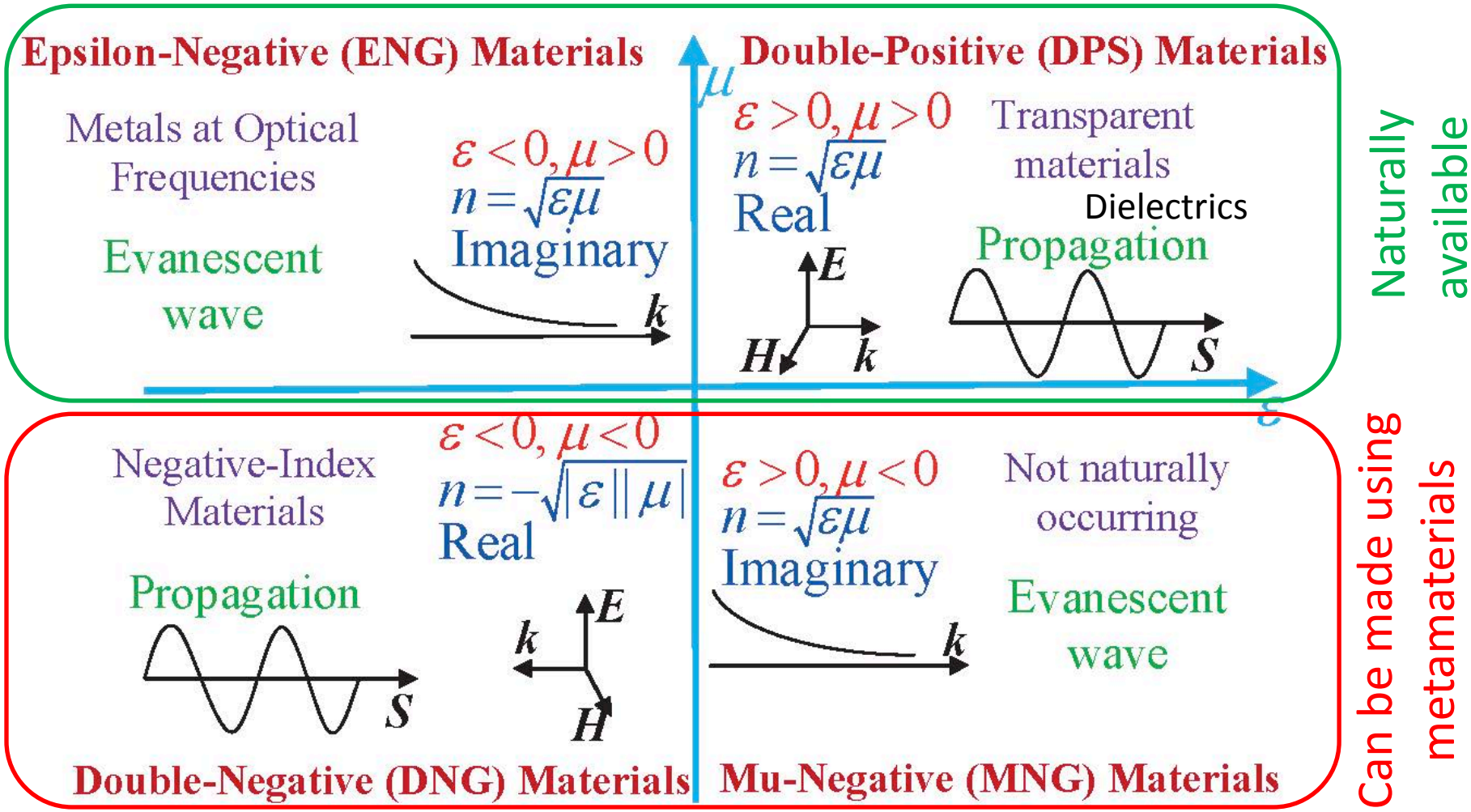
Natural Materials

- Composed of discrete entities ➔ Atoms
- Properties determined by atomic structure
- Natural material only exhibit a small subset of electromagnetic properties theoretically available
  - Dielectrics $\varepsilon \geq 1, \mu = 1$; Metals $\varepsilon < 0, \mu = 1$
- **Can we get new electromagnetic properties?**
  - **e.g, can we get simultaneously negative ε and μ**
  - Answers is YES (But how?)
  - We need to make a new type of atom
  - Make artificial atoms (Meta-atoms)
  - Meta-atoms: extermely small periodic structures
- Metamaterial: Material composed of meta-atoms

Metamaterials

- Meta: Beyond or after
- Meta-materials: Materials beyond nature
- Engineered materials: Generally metal-dielectric composites
- Subwavelength: size much smaller than wavelength of light
- Periodic structure: to exhibit effective material properties
- Superior properties: Properties not present in natural materials
- Properties depend on structure: Not on the constituent materials

Metamaterials



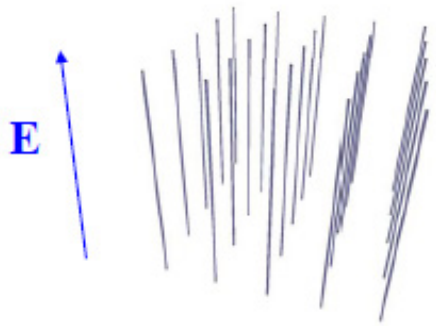
Metamaterial (Definition)

[1]	2000	Composite medium, based on a periodic array of interspaced conducting nonmagnetic split ring resonators and continuous wires
[2]	2005	An arrangement of artificial structural elements, designed to achieve advantageous and unusual electromagnetic properties
[3]	2010	Artificial media structured on a size scale smaller than the wavelength of external stimuli
[4]	2015	Manmade media providing electromagnetic properties on-demand
[5]	2017	Engineered material platforms for novel wave phenomena

[1] Smith et al, "Composite medium with simultaneously negative permeability and permittivity" *Phys. Rev. Lett.,* Vol. 84 pp. 4184–7 (2000)
[2] The Virtual Institute for Artificial Electromagnetic Materials and Metamaterials http://metamorphose-vi.org/index.php/metamaterials
[3] Zheludev N I, "The road ahead for metamaterials", *Science* Vol. 328 pp. 582–3 (2010)
[4] Zheludev N I, "Obtaining optical properties on demand", *Science,* Vol. 348 pp. 973–4 (2015)
[5] The Eleventh International Congress on Engineered Material Platforms for Novel Wave Phenomena – Metamaterials' 2017 http://congress2017.metamorphose-vi.org/

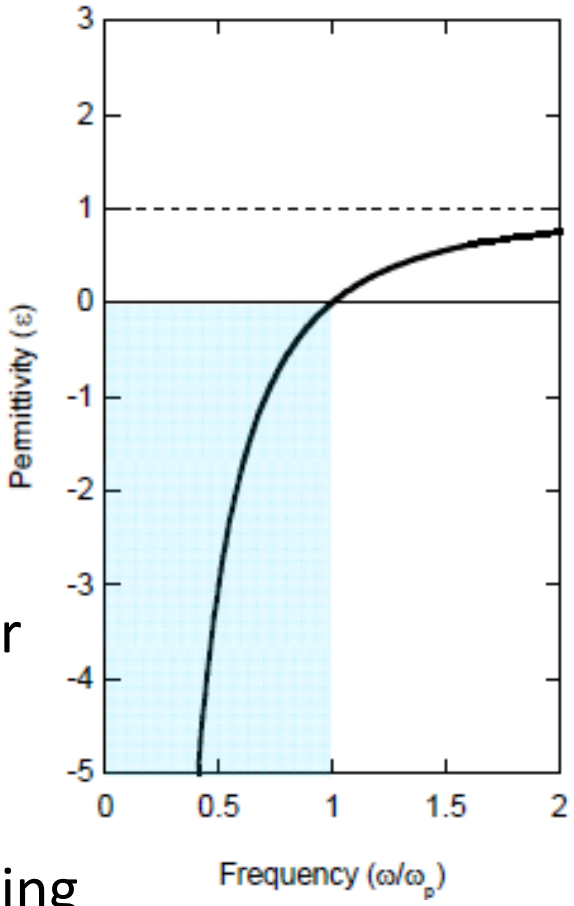
Negative Permittivity

- Metals Exhibit $\varepsilon < 0$ under their plasma frequency
- Periodic Metal wire structure (diluted metal) can be used to control the permittivity



$$\varepsilon(\omega) = 1 - \left(\frac{\omega_p}{\omega}\right)^2$$

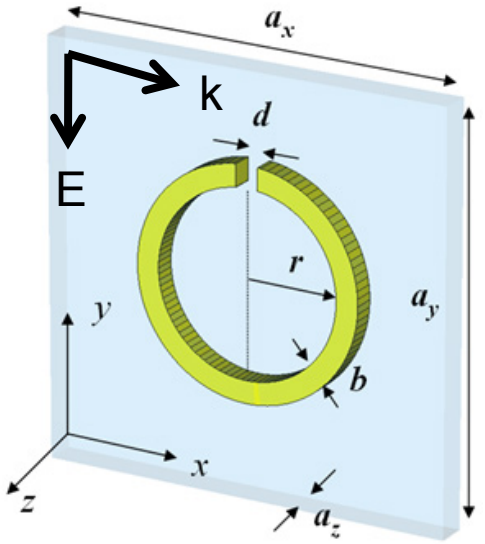
Permittivity is negative for $\omega < \omega_p$

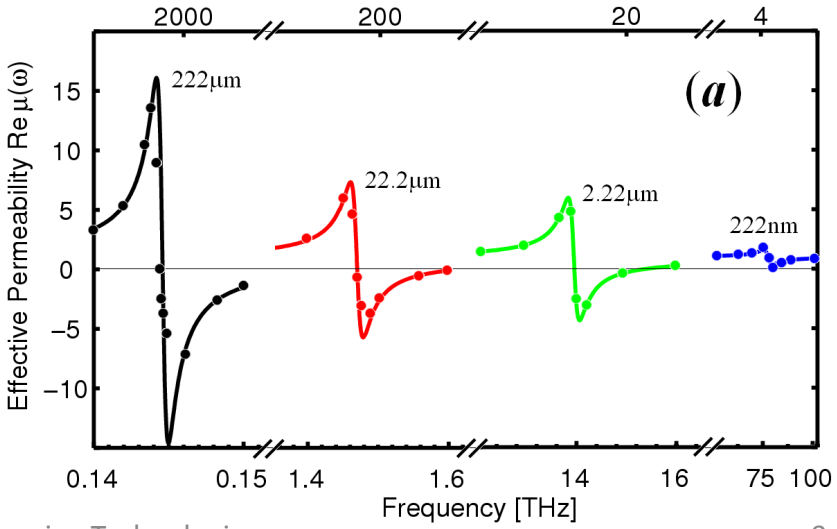


ω_p can be controlled by changing thickness or period of wires

Negative Permeability

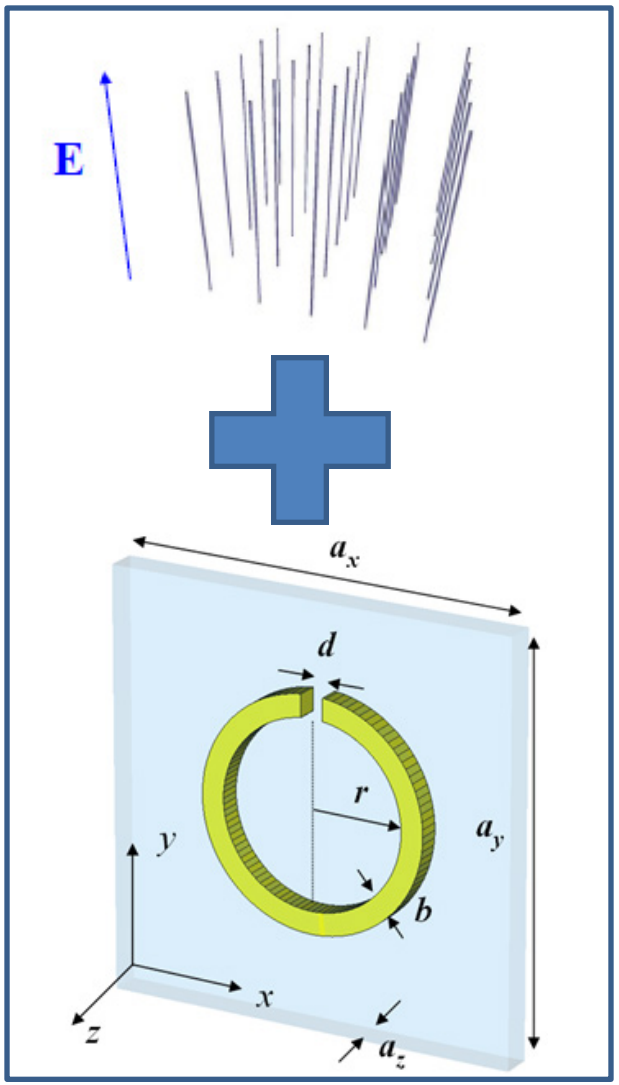
- Magnetic resonance require a current loop
- Simplest structure Split Ring Resonator (SRR)
- Gives negative permeability at resonance frequency
- Resonance frequency can be controlled by changing dimensions

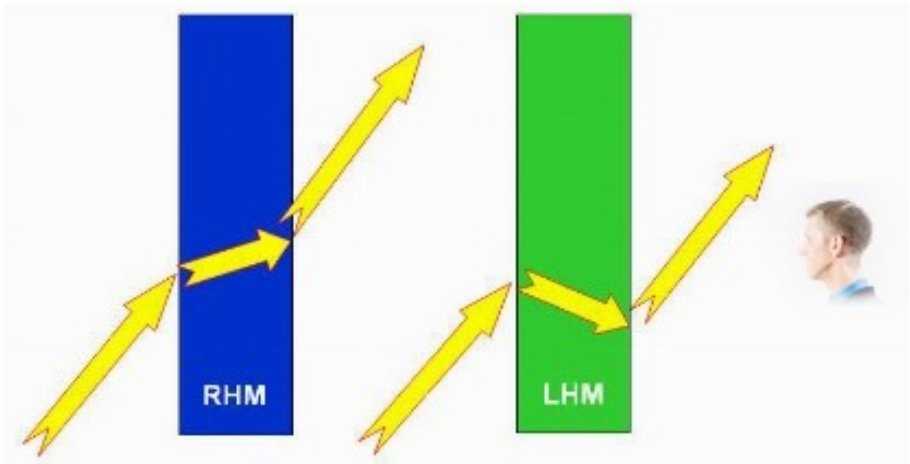




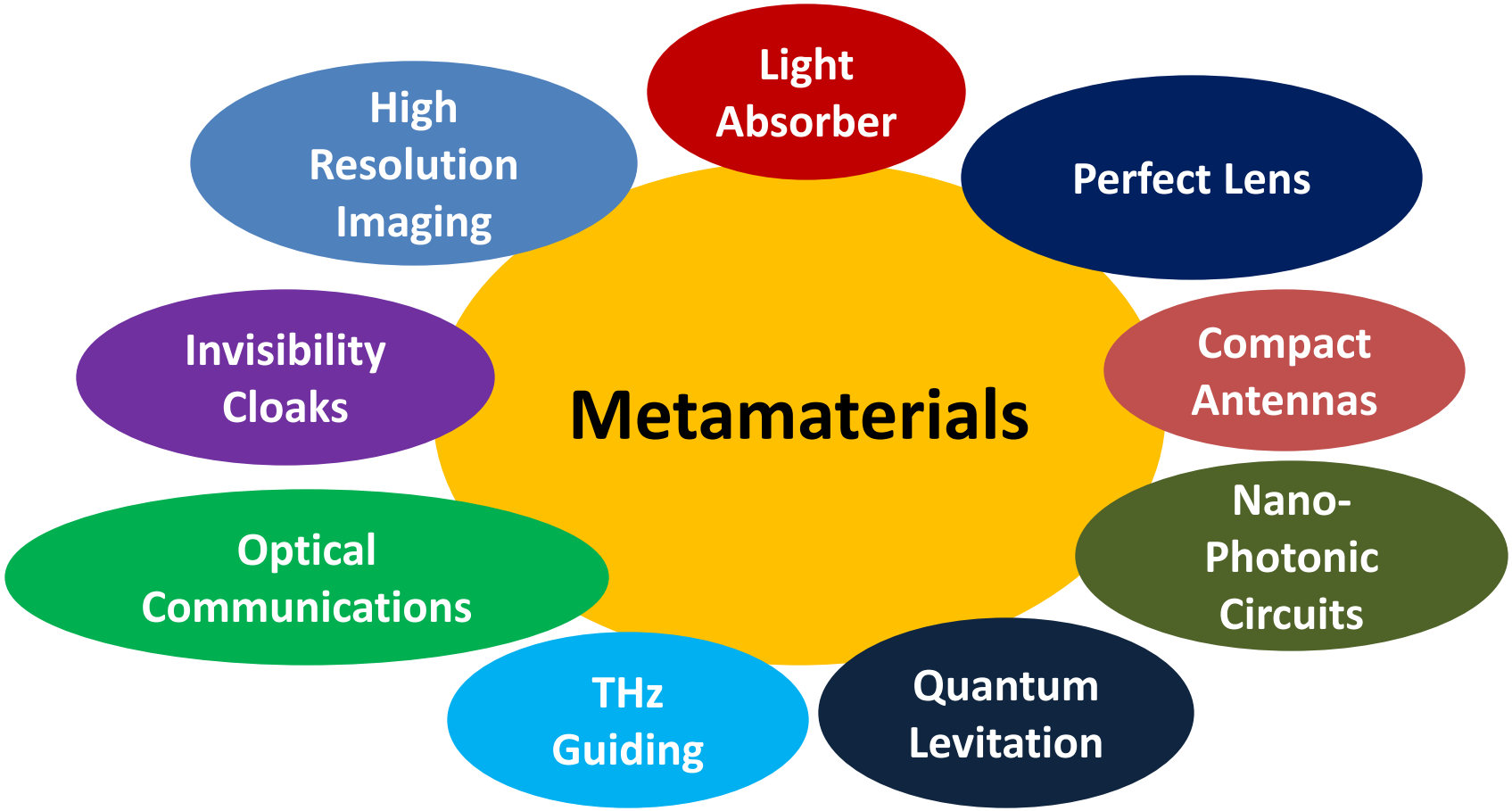
Guney et al, Phy. Rev. B, 80, 125129 (2009)

Negative Index Metamaterials (NIM)

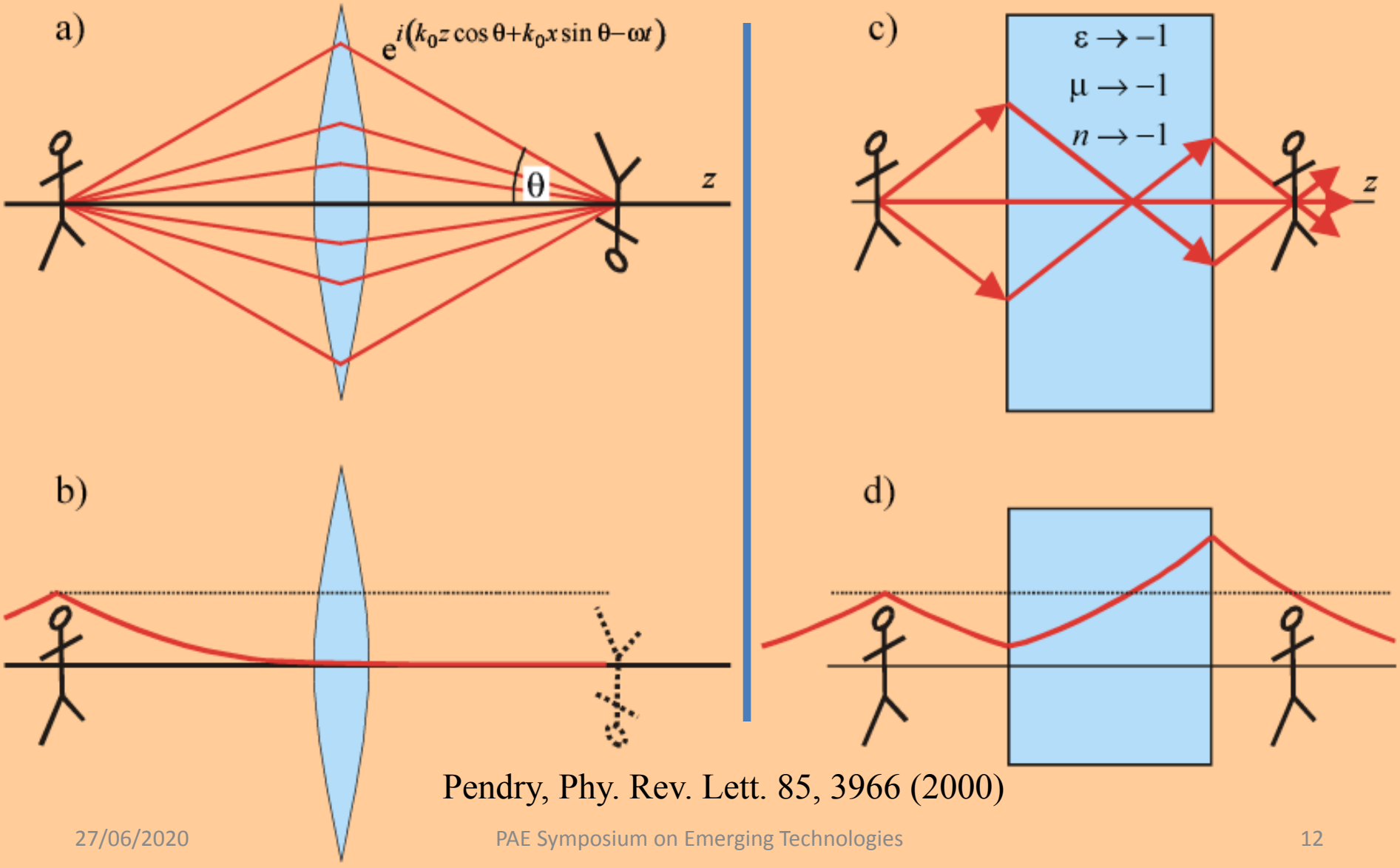




Metamaterial Applications



Perfect Lens (Super lens)



Pendry, Phy. Rev. Lett. 85, 3966 (2000)

Perfect Lens (Super lens)

By completely recovering both propagating and evanescent waves in phase and amplitude, a perfect image is created which is not limited by diffraction.

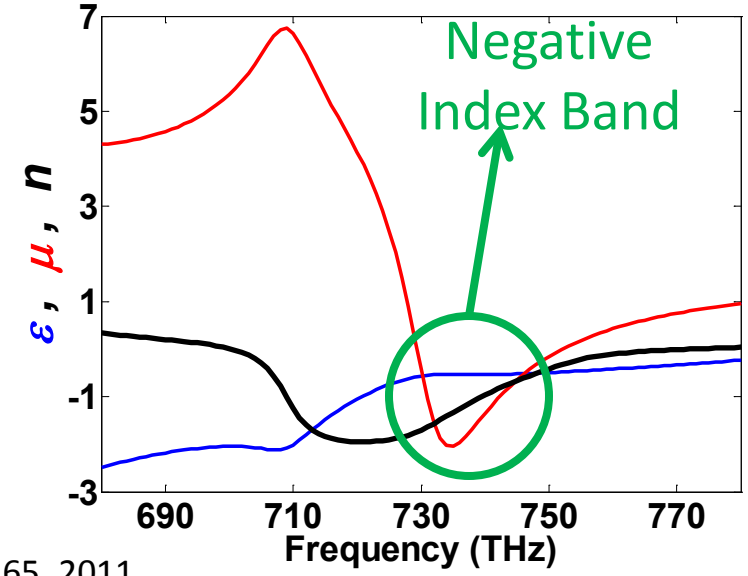
Applications in

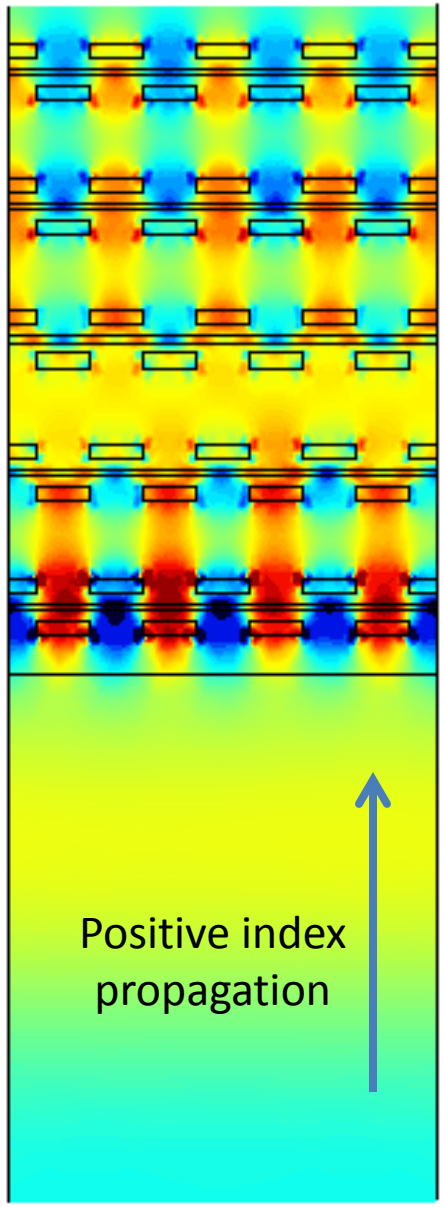
- High resolution imaging
- High precision lithography

Basic Requirement: $n = -1$

Our work on NIM

- New Physical phenomena to achieve negative index
- Surface Plasmon driven NIM
- High Operating Frequency
- Polarization Independence achievable
- High transmission
- Low-loss
- Scalable
- Bulk





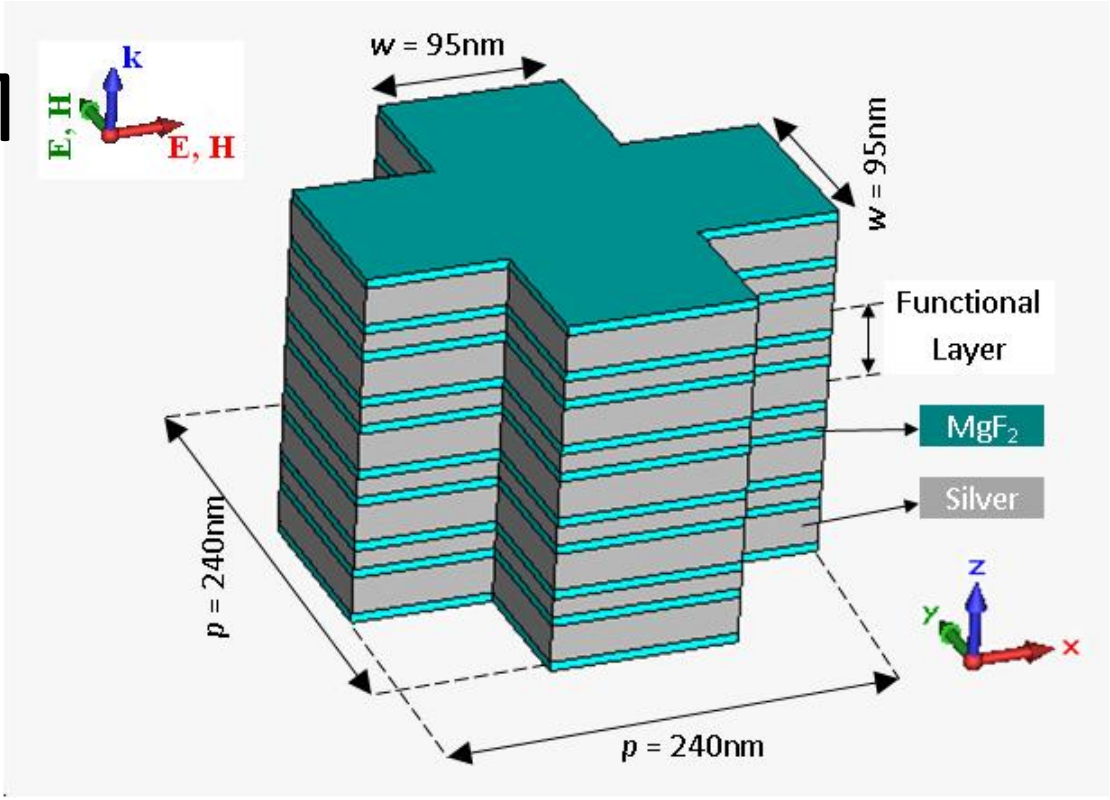
M. I. Aslam et al, *Phy. Rev. B*, 84, 195465, 2011

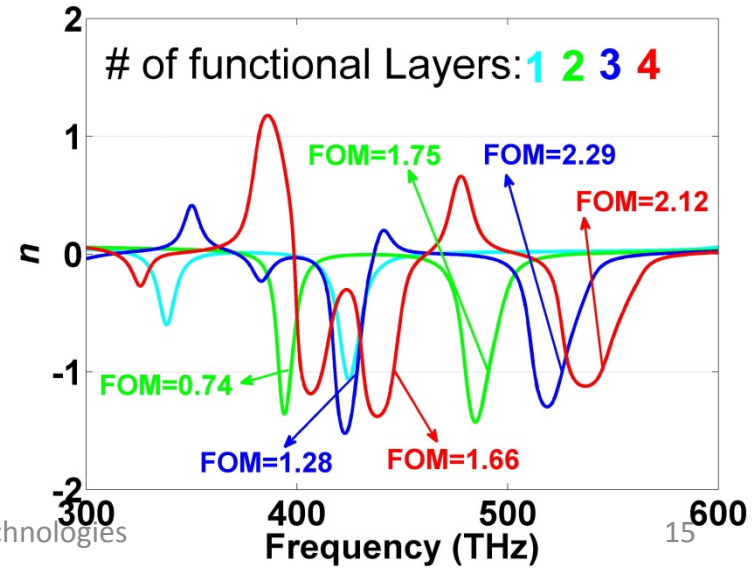
M. A. Farooqui et al, Opt. Exp., 23, 17941-54, 2015.

M. M. Rahman et al, 7th Int. Cong. Adv. Electromag. Mat. Microwav. & Opt. 262-4, 2013.

Our work on NIM

- Modified Fishnet NIM
- Utilize Surface Plasmons of perforated metal film
- Dual band in visible
- Both DNG
- Low-loss
- High frequency Operation
- Easy fabrication
- Polarization Independent





M. I. Aslam et al, J. Opt. Soc. Amer. B, 29, 2839-47 2012
M. I. Aslam et al, Opt. Exp., 22, 3773-4, 2014

Our Work on Metamaterial Absorbers

Efficient Light Absorbers

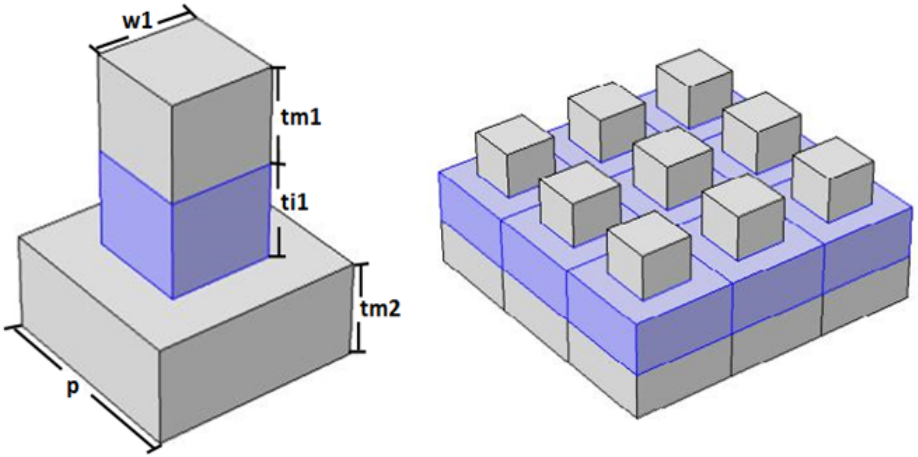
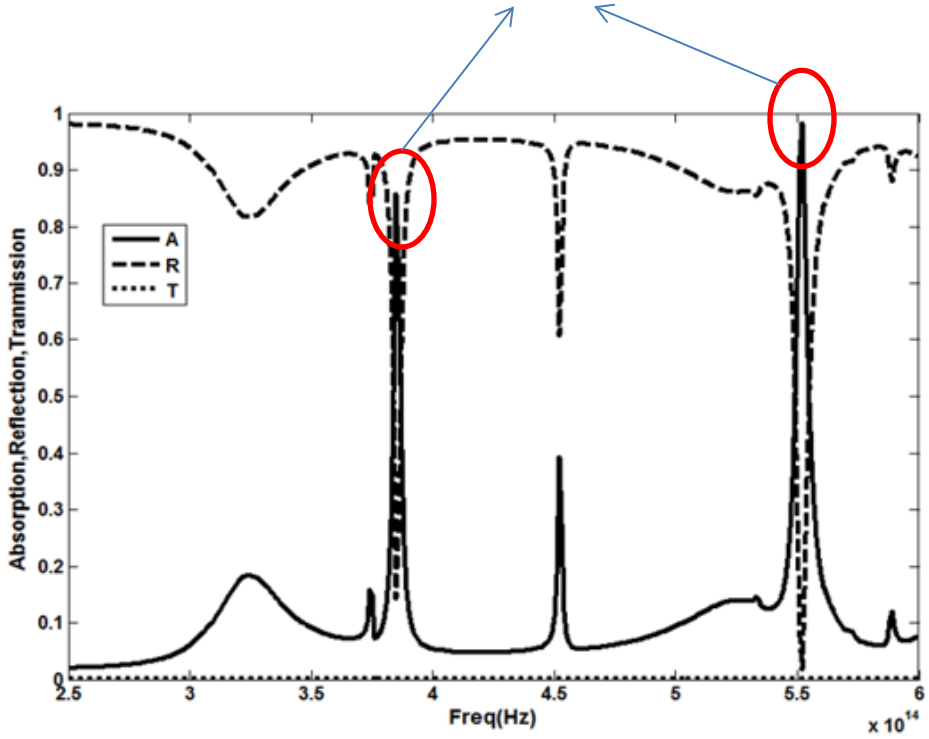


Fig (1) Unit cell and 3×3 array of proposed absorber. The grey layers represents the silver metal layer and blue represents MgF_2 of electric permittivity ε=1.9 dielectric layer.

High absorption peaks



M. I. Aslam et al, Proc. Int. conf. Energy and sustainability, 113-6, 2013
S. A. Shah et al, Int. Conf. Adv. Mat. & Proc. Eng., 2015.

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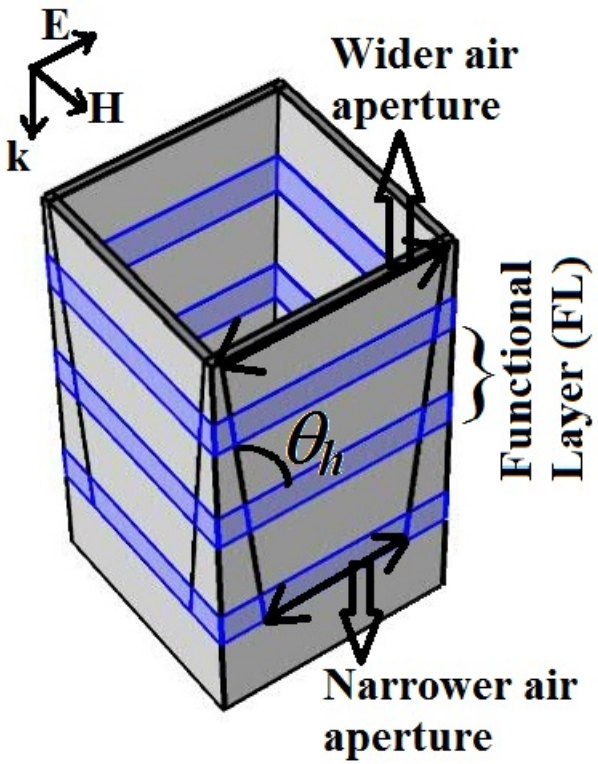
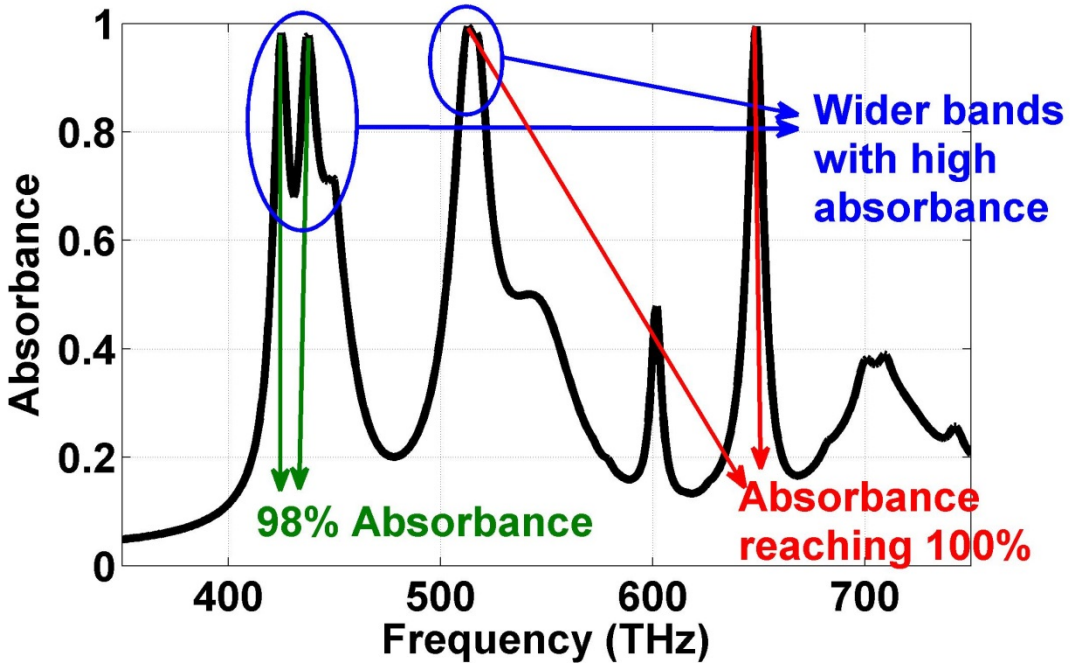


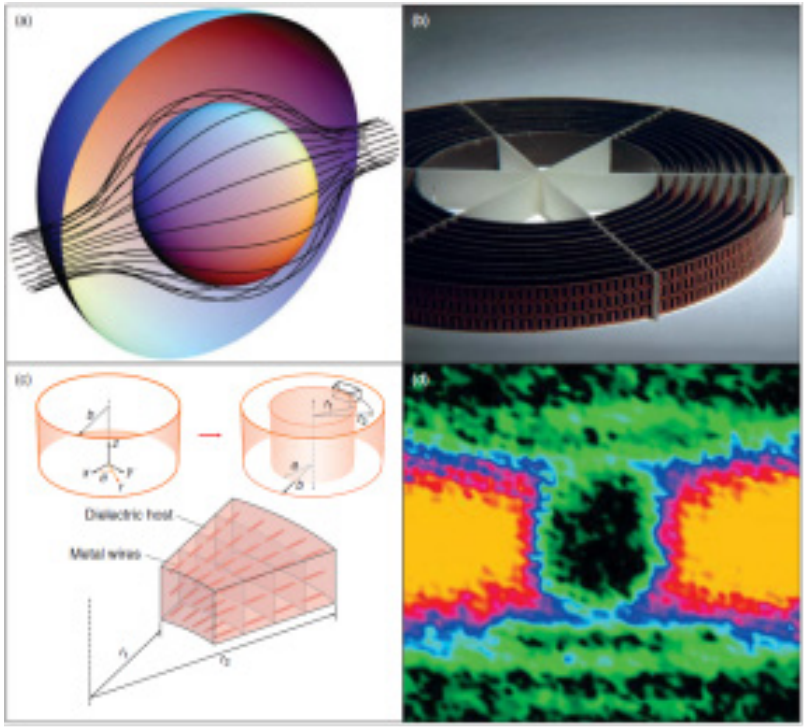


M. I. Aslam et al, Proc. Int. conf. Energy and sustainability, 113-6, 2013

S. A. Shah et al, Int. Conf. Adv. Mat. & Proc. Eng., 2015.

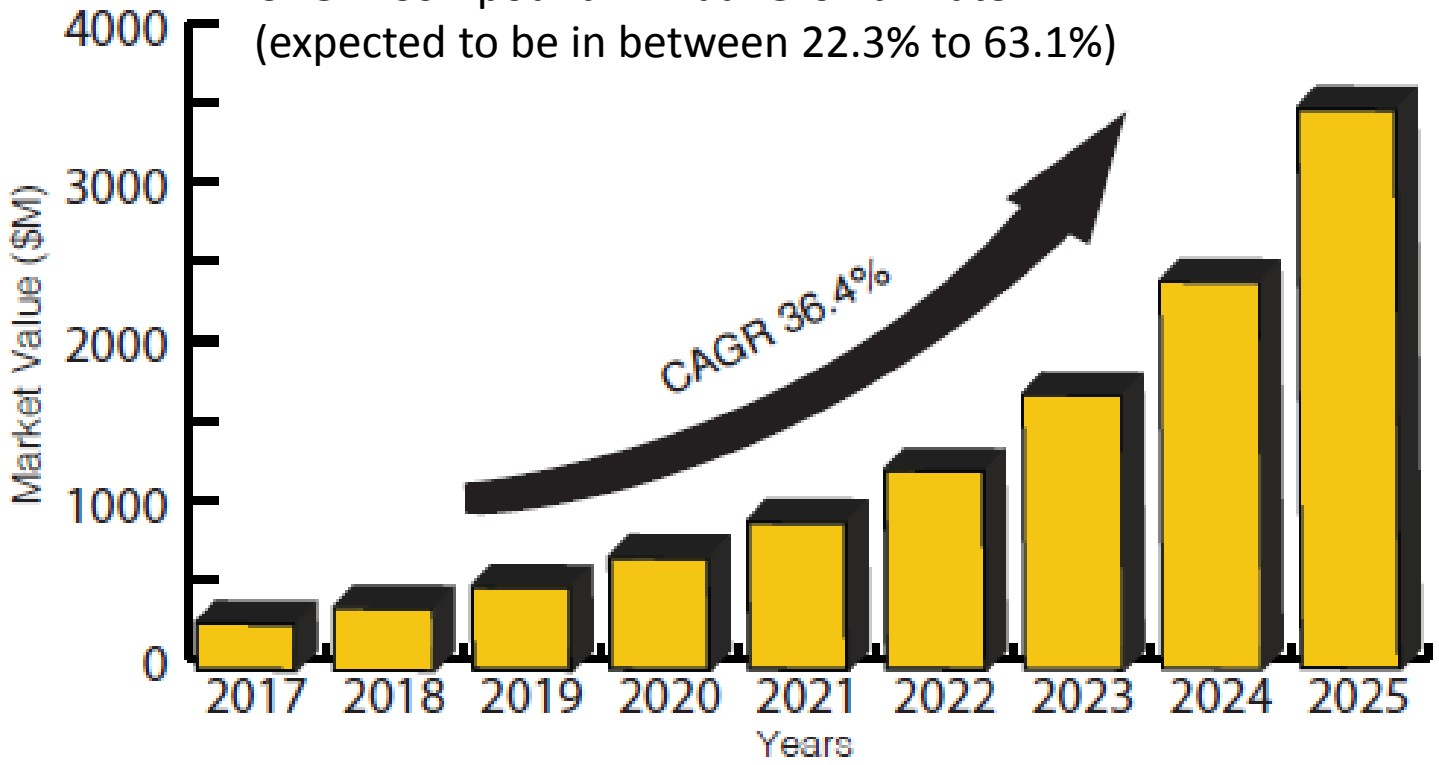
Cloaking Device

- Metamaterials direct and control the propagation and transmission of specified parts of the light spectrum and demonstrate the potential to render an object seemingly invisible.
- Incident waves are guided around them without being affected by the object itself.



Metamaterial-Market Growth

CAGR: Compound Annual Growth Rate
(expected to be in between 22.3% to 63.1%)



Source: Metamaterials Manufacturing: Pathway to Industrial Competitiveness
Report by: Bishop-Moser, Josh; Spadaccini, Chris; Andres, Christine
https://deepblue.lib.umich.edu/handle/2027.42/145155

Concluding Remarks

- Metamaterial is an emerging field (started in year 2000)
- ~20 years of active research in the filed
- Significant research thrust
- Diversified potential applications
- Growing market trends
- Currently there are around 25 market competitors
  (including: Applied EM, Inc.; Jem Engineering, LLC.; Kymeta Corporation; Metamagnetics, Inc.; Metamaterial Technologies, Inc.; Metashield LLC.; Multiwave Technologies AG; Nanohmics, Inc.; Phoebus Optoelectronics LLC.; Plasmonics, Inc.; Teraview Ltd)

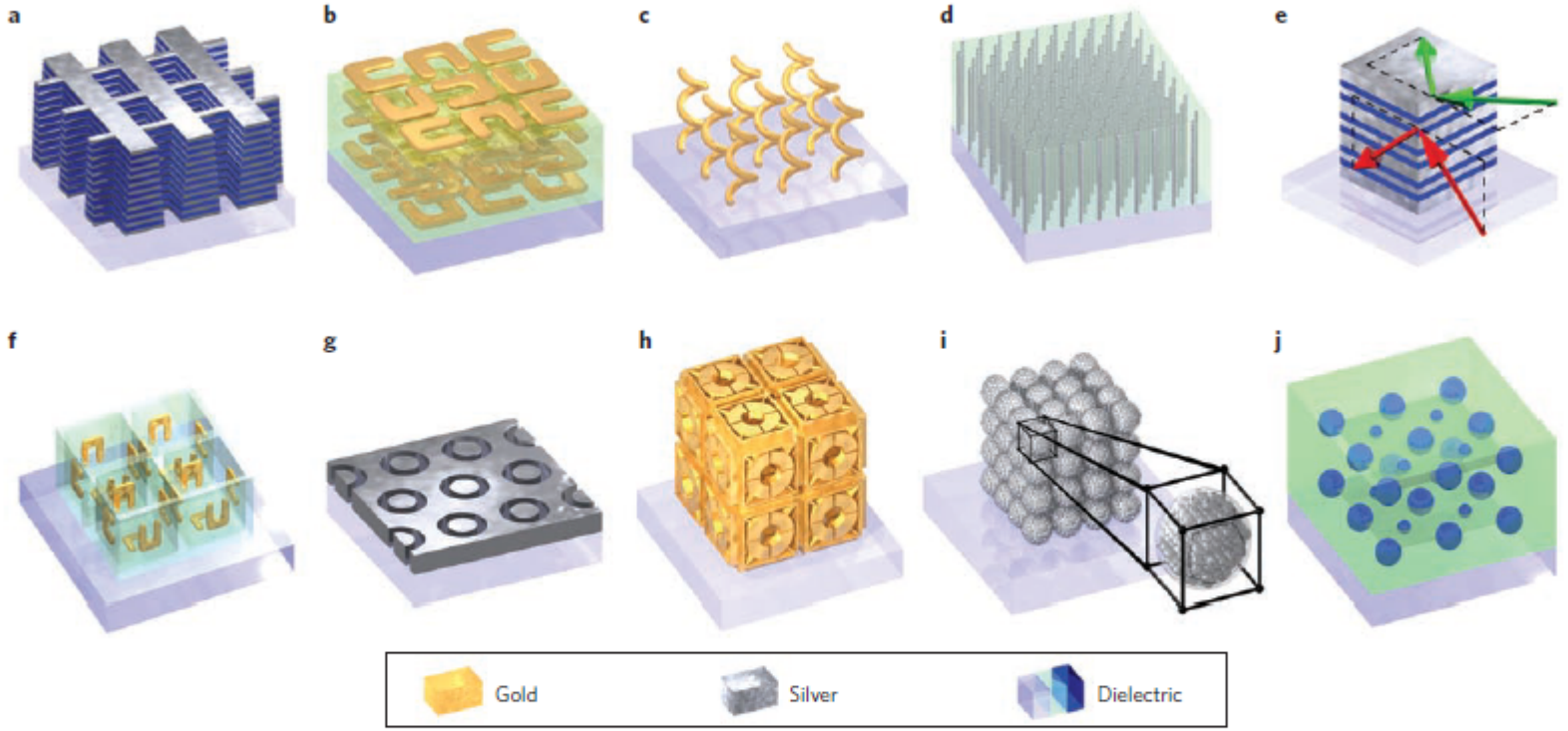


Figure 2 | 3D photonic-metamaterial structures. a, Double-fishnet negative-index metamaterial with several layers[13,15,19,22,27,71]. **b**, 'Stereo' or chiral metamaterial (see a… made using direct-laser writing and electroplating[38]. **d**, l… plates[49]. **e**, Metal–dielectric layered metamaterial comp… quencies[44,45]. **f**, SRRs oriented in all three dimensions, f… terial based on a coaxial design[89]. **h**, Connected cubic… ster-of-clusters visible-frequency magnetic metamat… ed of two sets of high-refractive-index dielectric spheres a…

Thank you

Soukoulis et al, Nature Photonics 5, 523 (2011)