Periodic Structure

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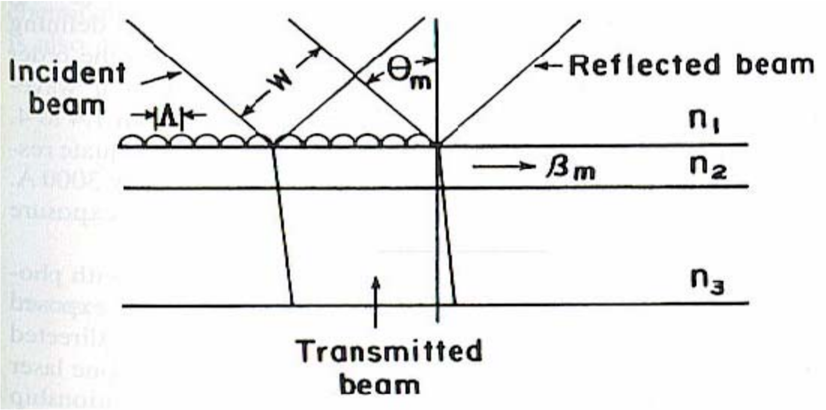
Suggested Reading Materials

- An excellent (and free!) book on nonlinear optical fibers by J.D. Joannopoulos, S.G. Johnson, J.N. Winn, and R.D. Meade, Photonic Crystals: Molding the Flow of Light. Chapter 9 discusses photonic-crystal fibers.

Materials Covered

- Bragg grating
- Grating Coupler
- Long period grating
- Photonic crystal
- Metamaterial

Grating Coupler



The light coupled into the thin film is achieved by the fact that the diffracted incident light is phase-matched to a mode of the film. Grating couplers viewed as surface-wave to leaky-wave converter (output coupler)

Because of its periodic nature, the **grating perturbs the waveguide modes in the region underneath the grating**, thus causing each one of them to have a set of **spatial harmonics with z-direction propagation constants given by**

$$\beta_\nu = \beta_0 + \frac{\nu 2\pi}{\Lambda}, \quad \nu = 0, \pm 1, \pm 2, \ldots$$

The fundamental factor is approximately equal to the of the particular mode in the waveguide region not covered by the grating. Because of the negative values of *v*, the phase matching condition $\beta_m = kn_1 \sin\theta_m$ (continuity of tangential field component) can now be satisfied so that

$$\beta_\nu = kn_1 \sin\theta_m$$

Why grating coupler?

1. A simple reproducible and permanent coupler compatible with planar device technology.

2. The grating coupler can also be used on high-index semiconductor waveguide where it is difficult to obtain suitable prism material.

Example

Grating: $\Lambda = 0.4\mu m$ on a GaAs planar waveguide

$\lambda_o = 1.15\mu m$

Propagation constant for the lowest-order mode in the waveguide: β_o=3.6k

Assume 1st _order coupling, $|\nu| = 1$, what incident angle should the Light make in order to coupe to the lowest-order mode?

Assignment

Grating: $\Lambda = 0.4\mu m$ on a SiO planar waveguide

$\lambda_o = 1.310\mu m$

Propagation constant for the lowest-order mode in the waveguide:
β_o=3.6k

Assume 1st _order coupling, $|\nu| = 1$, what incident angle should the Light make in order to coupe to the lowest-order mode?
At what λ_0 do we start to need higher-order coupling?

Photonic Crystal

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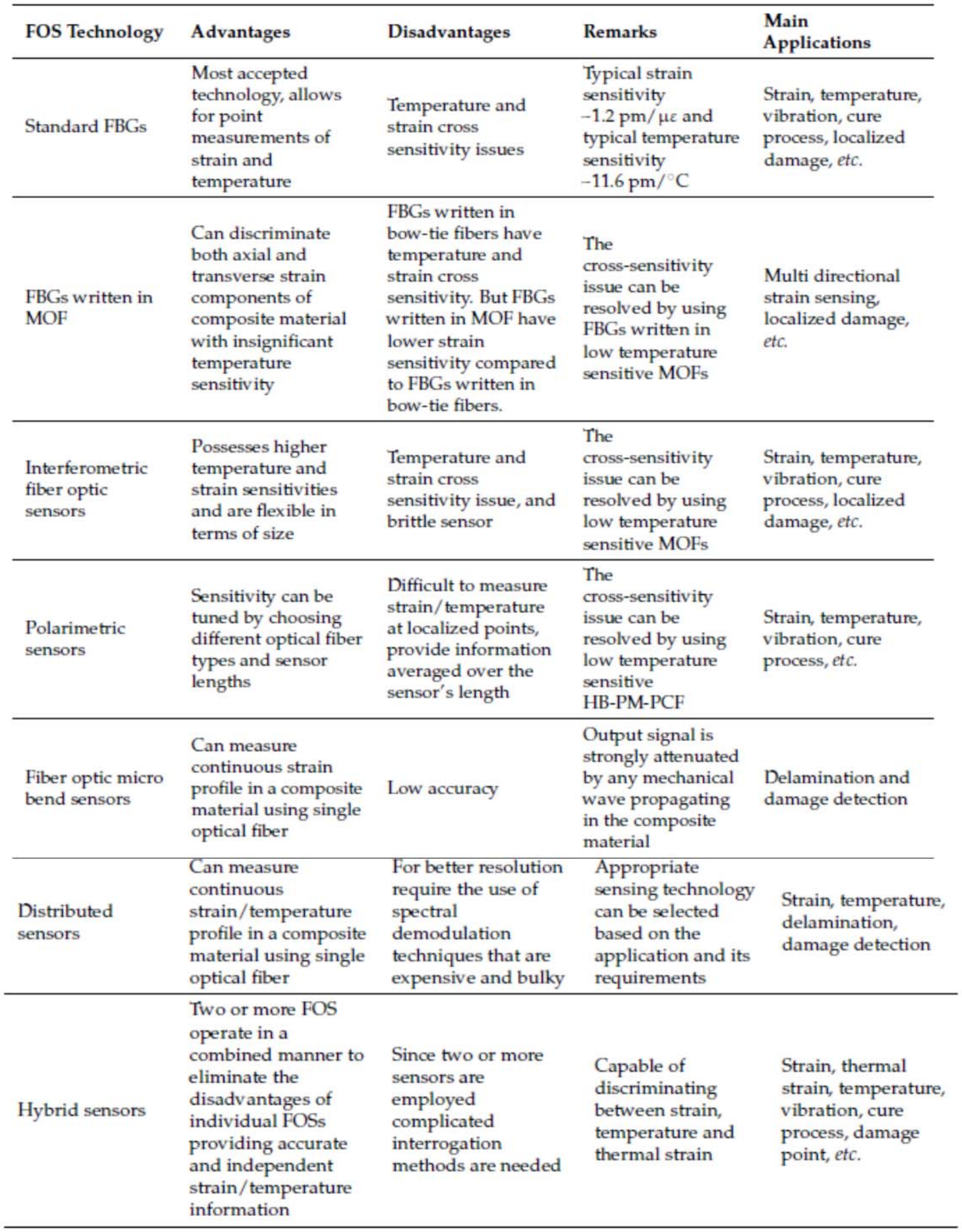
Table 1. Comparison of FOSs.



FOS Technology	Advantages	Disadvantages	Remarks	Main Applications
Standard FBGs	Most accepted technology, allows for point measurements of strain and temperature	Temperature and strain cross sensitivity issues	Typical strain sensitivity ~1.2 pm/$\mu\varepsilon$ and typical temperature sensitivity ~11.6 pm/°C	Strain, temperature, vibration, cure process, localized damage, *etc.*
FBGs written in MOF	Can discriminate both axial and transverse strain components of composite material with insignificant temperature sensitivity	FBGs written in bow-tie fibers have temperature and strain cross sensitivity. But FBGs written in MOF have lower strain sensitivity compared to FBGs written in bow-tie fibers.	The cross-sensitivity issue can be resolved by using FBGs written in low temperature sensitive MOFs	Multi directional strain sensing, localized damage, *etc.*
Interferometric fiber optic sensors	Possesses higher temperature and strain sensitivities and are flexible in terms of size	Temperature and strain cross sensitivity issue, and brittle sensor	The cross-sensitivity issue can be resolved by using low temperature sensitive MOFs	Strain, temperature, vibration, cure process, localized damage, *etc.*
Polarimetric sensors	Sensitivity can be tuned by choosing different optical fiber types and sensor lengths	Difficult to measure strain/temperature at localized points, provide information averaged over the sensor's length	The cross-sensitivity issue can be resolved by using low temperature sensitive HB-PM-PCF	Strain, temperature, vibration, cure process, *etc.*
Fiber optic micro bend sensors	Can measure continuous strain profile in a composite material using single optical fiber	Low accuracy	Output signal is strongly attenuated by any mechanical wave propagating in the composite material	Delamination and damage detection
Distributed sensors	Can measure continuous strain/temperature profile in a composite material using single optical fiber	For better resolution require the use of spectral demodulation techniques that are expensive and bulky	Appropriate sensing technology can be selected based on the application and its requirements	Strain, temperature, delamination, damage detection
Hybrid sensors	Two or more FOS operate in a combined manner to eliminate the disadvantages of individual FOSs providing accurate and independent strain/temperature information	Since two or more sensors are employed complicated interrogation methods are needed	Capable of discriminating between strain, temperature and thermal strain	Strain, thermal strain, temperature, vibration, cure process, damage point, *etc.*

M. Ramakrishnan,
Sensors, 2016

Photonic Crystal Fiber

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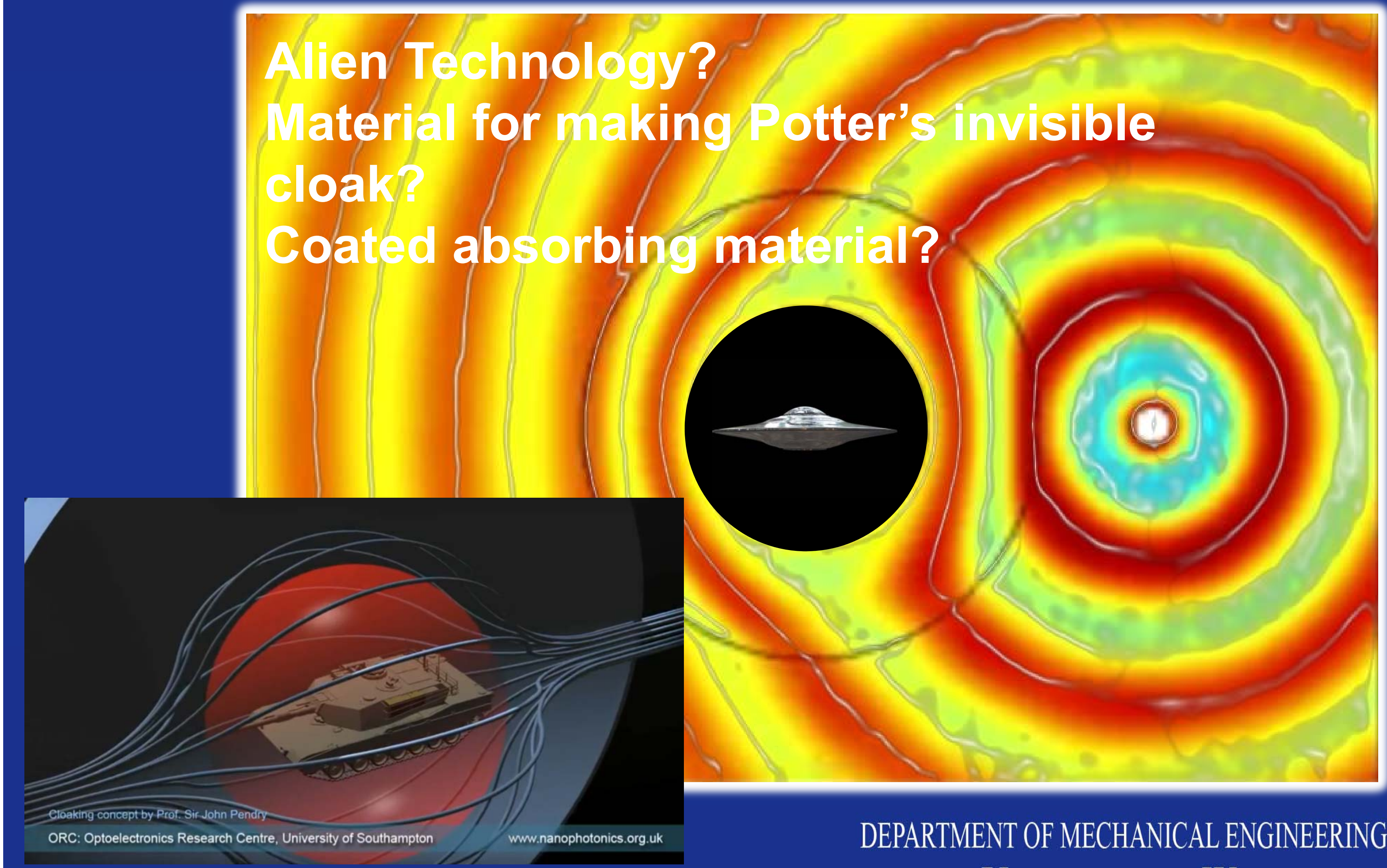
Metamaterial

Stealth?



Alien Technology?

Material for making Potter's invisible cloak?

Coated absorbing material?

Cloaking concept by Prof. Sir John Pendry

ORC: Optoelectronics Research Centre, University of Southampton

www.nanophotonics.org.uk

What’s a Metamaterial?

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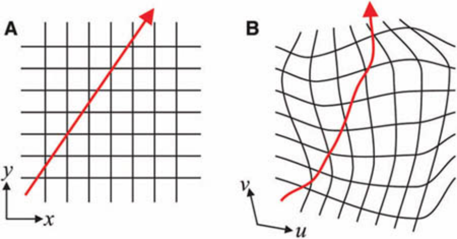
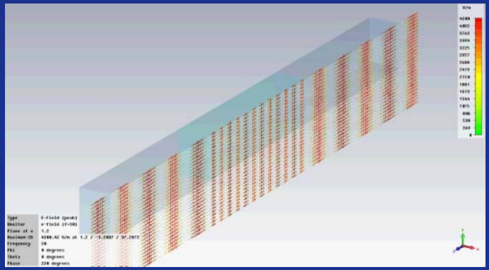
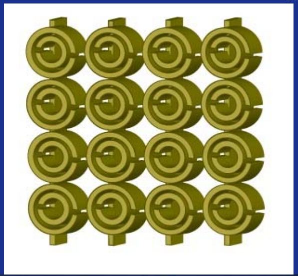
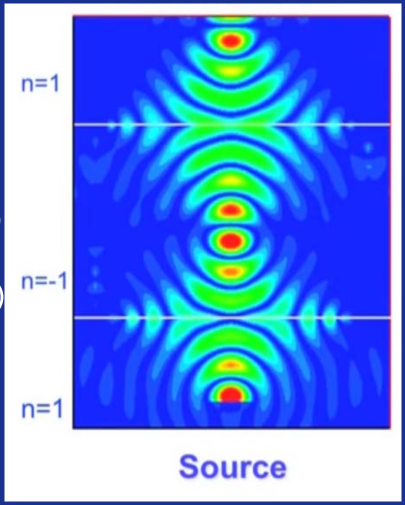
- Meta-?
  - Alloy?
  - Concrete?

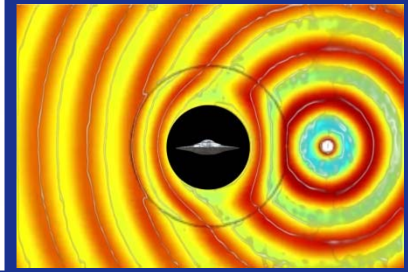






- Artificially engineered materials
  - V.G.Veselago (1968) Theory
  - J.B.Pendry (1996, 1998) –ε (thin wires)
  - J.B.Pendry (1999) –μ (split-ring resonator)
  - D.R.Smith (2000) LHM (combo)





Ortwin Hess. Optics: arewell to Flatland
Nature 455, 299 (2008).

- Applications
  - Wave manipulation: -n, cloaking, superlens, transformation optics
- How to categorize it?

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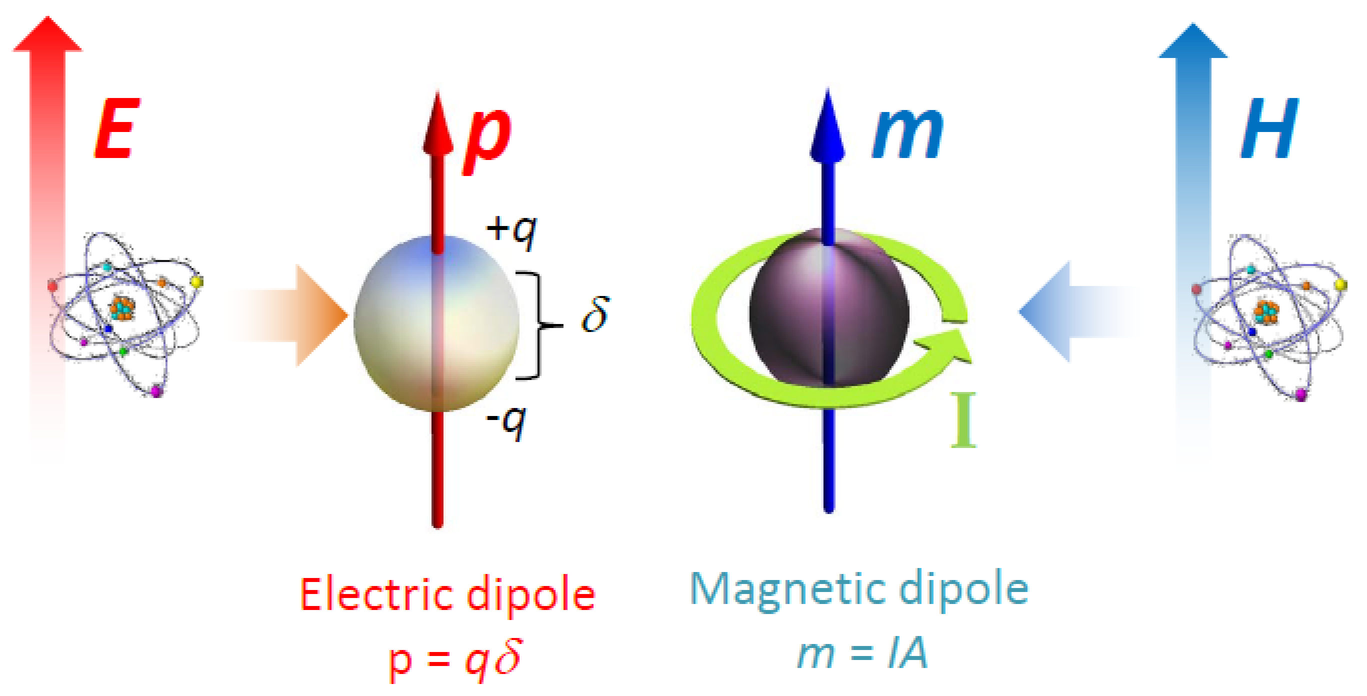
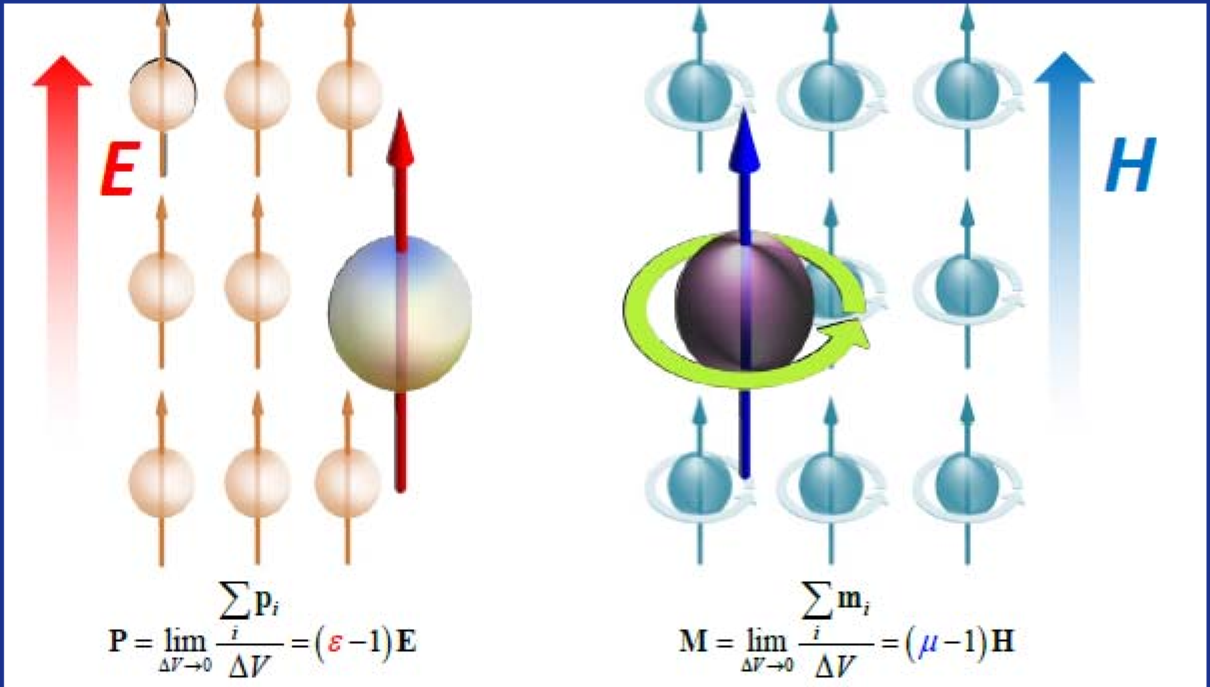
Electromagnetic response

From the electromagnetic point-of-view, an atom is just an electric or magnetic, *polarizable* dipole.



Electromagnetic response

A material is a collection of electric and magnetic dipoles.
Homogenization allows this collection to be *continuous*.

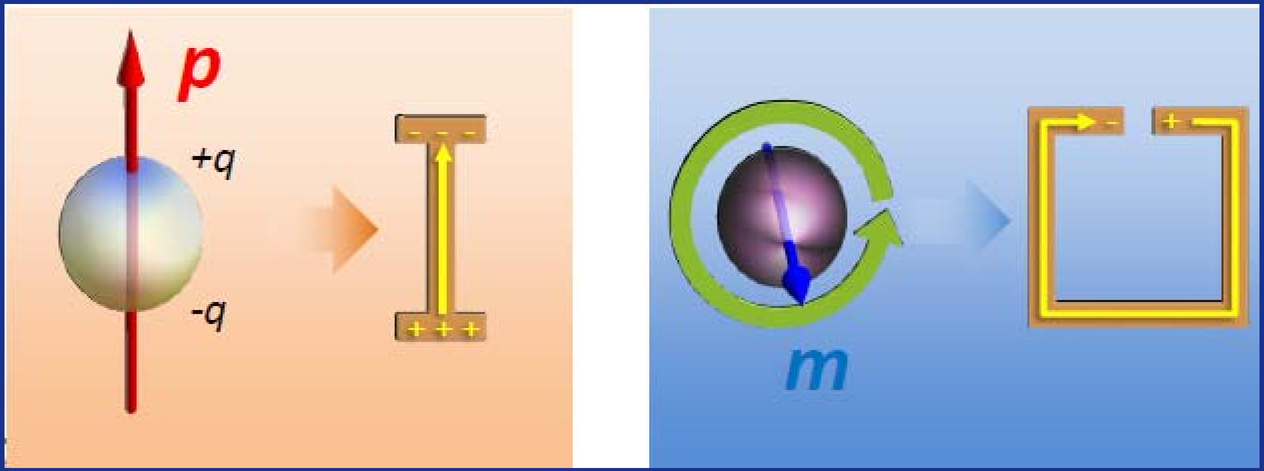


$$\mathbf{P} = \lim_{\Delta V \to 0} \frac{\sum_i \mathbf{p}_i}{\Delta V} = (\varepsilon - 1)\mathbf{E}$$

$$\mathbf{M} = \lim_{\Delta V \to 0} \frac{\sum_i \mathbf{m}_i}{\Delta V} = (\mu - 1)\mathbf{H}$$

What are metamaterials?

Maxwell’s equations do not *know* about atoms or molecules — all they *know* are magnetic and electric dipoles!
We can use any object to create a dipole response, and use that object to form an artificial material, or metamaterial.



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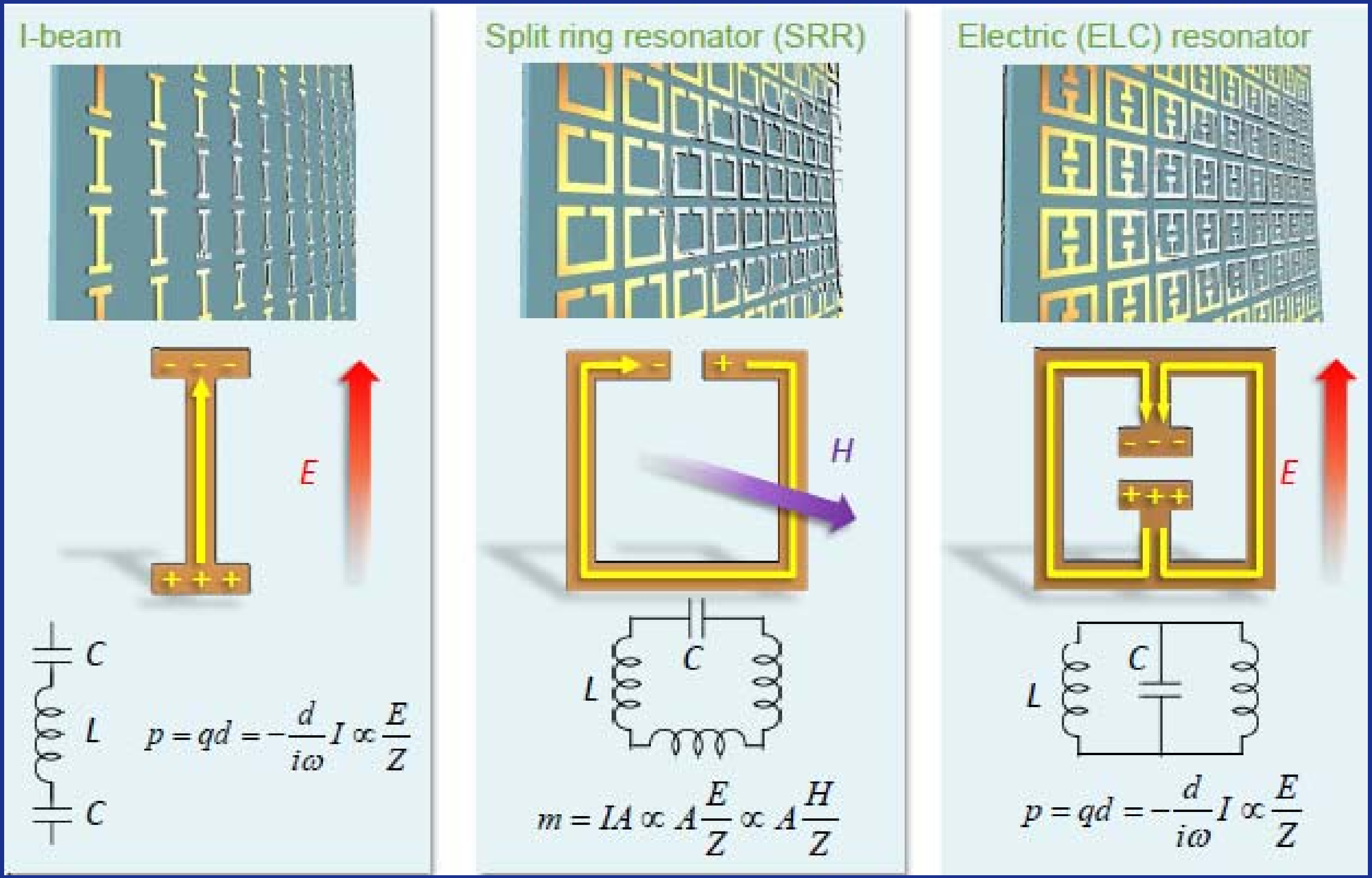
Circuit Metamaterials



$$p = qd = -\frac{d}{i\omega} I \propto \frac{E}{Z}$$

$$m = IA \propto A\frac{E}{Z} \propto A\frac{H}{Z}$$

$$p = qd = -\frac{d}{i\omega} I \propto \frac{E}{Z}$$

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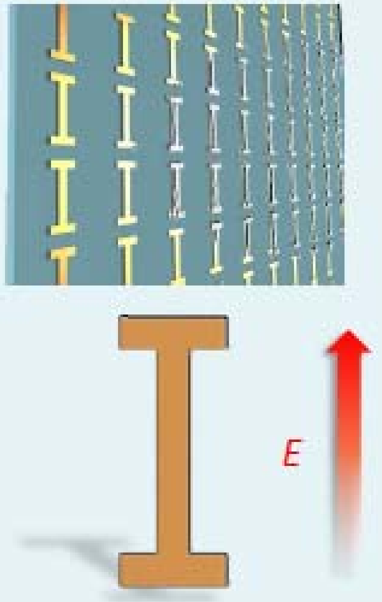
Circuit Metamaterials

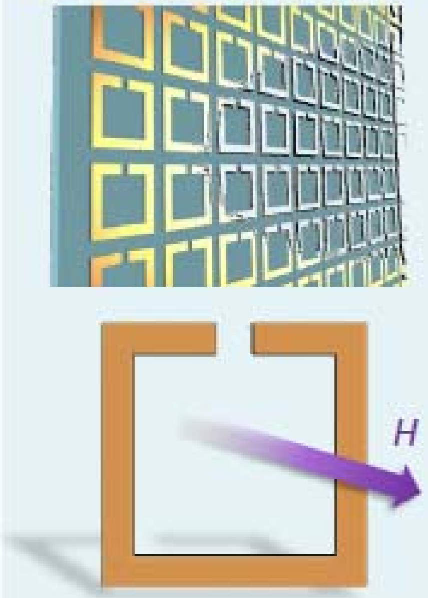
I-beam



non-resonant, positive dielectric response

$$\varepsilon(\omega)=1+\frac{\omega_p^2}{\omega_0^2}$$

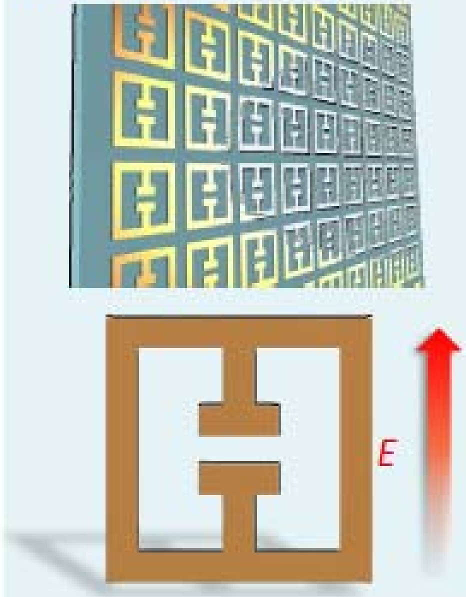
Split ring resonator (SRR)



resonant, magnetic response

$$\mu(\omega)=1-\frac{F\omega^2}{\omega^2-\omega_{0,m}^2}$$

Electric (ELC) resonator

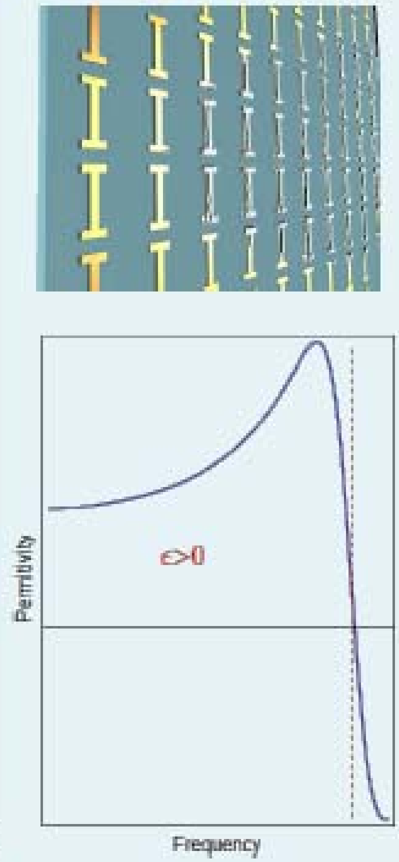


resonant, electric response

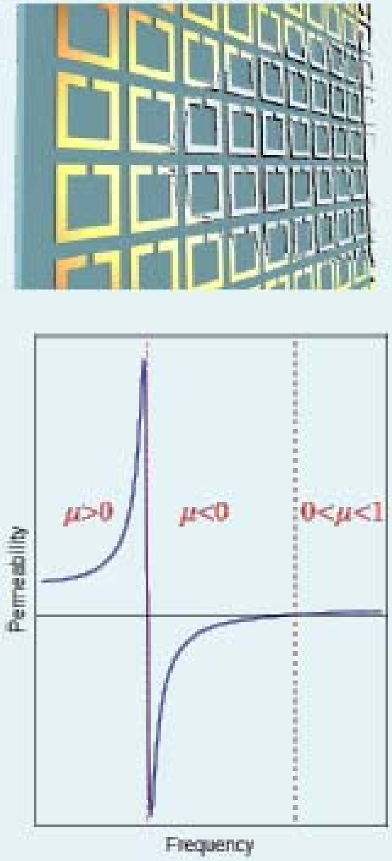
$$\varepsilon(\omega)=1-\frac{F\omega^2}{\omega^2-\omega_{0,e}^2}$$

Metamaterial Response

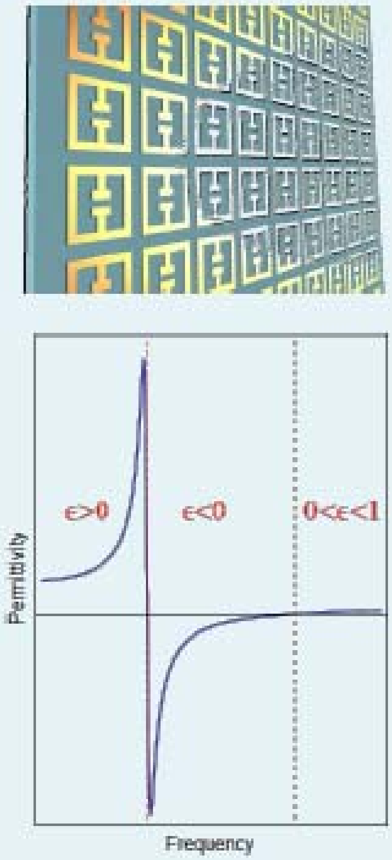
I-beam



Split ring resonator (SRR)



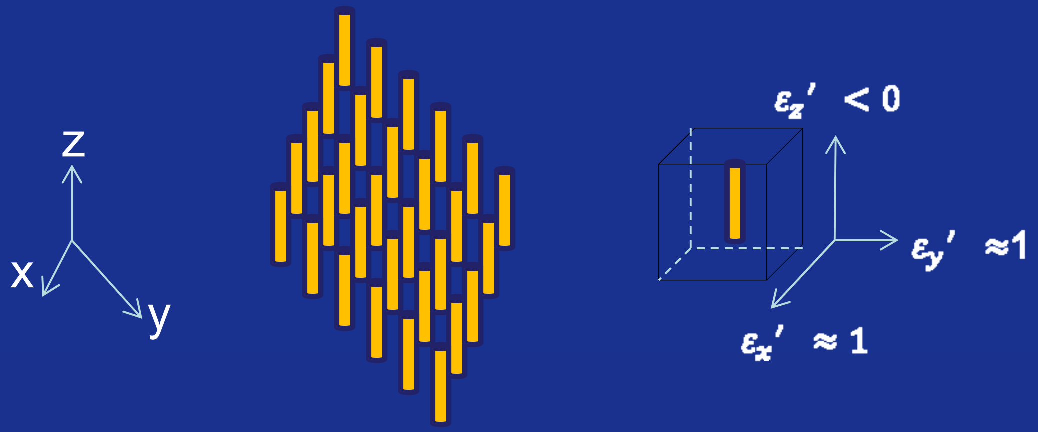
Electric (ELC) resonator



Epsilon-Negative (ENG) Metamaterials

- Frequency dispersive Drude Model

$$\varepsilon_{rz} = \varepsilon_{rz}' - j\varepsilon_{rz}'' = 1 - \frac{{f_{ep}}^2}{f^2 - j\,\gamma_e f/2\pi}$$

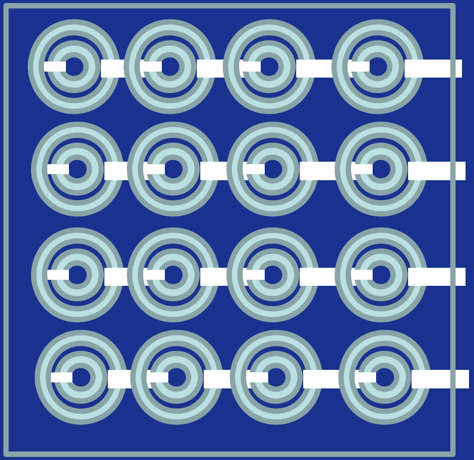


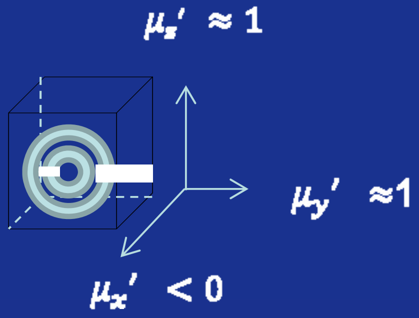
Au: $\omega_{p\_Au} = 1.37 \times 10^4\ THz$

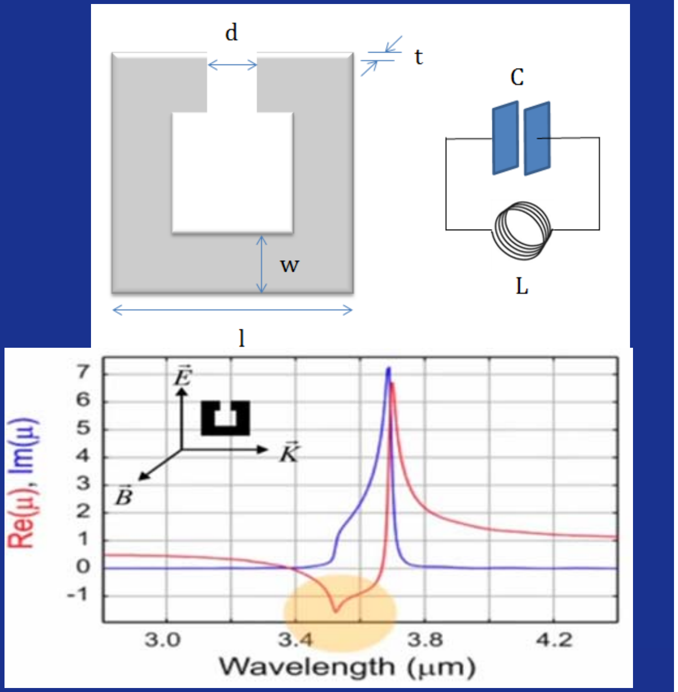
Mu-Negative (MNG) Metamaterials

- Frequency dispersive Lorentz Model

$$\mu_{rx} = \mu_{rx}' - j\mu_{rx}'' = 1 - \frac{{f_{mp}}^2 - {f_{mo}}^2}{f^2 - {f_{mo}}^2 - j\,\gamma_m f/2\pi}$$



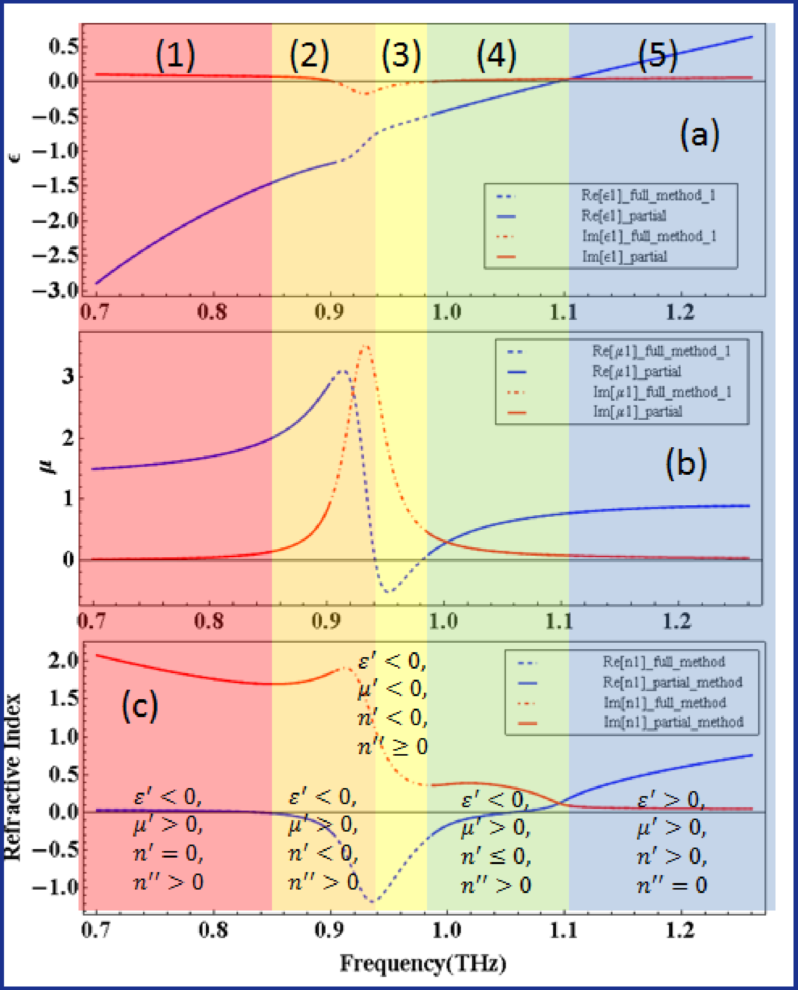


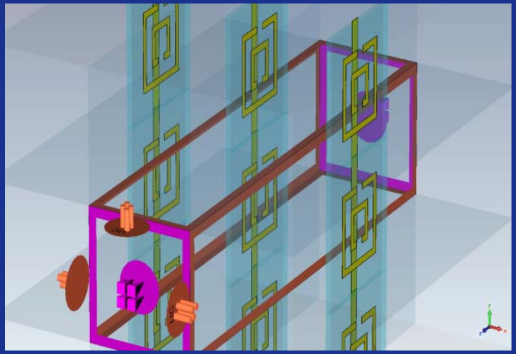


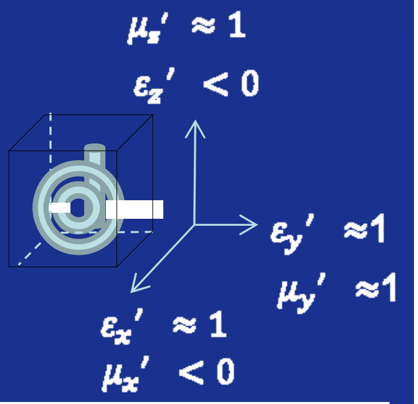
S Linden et al. Science 2004;306:1351-1353

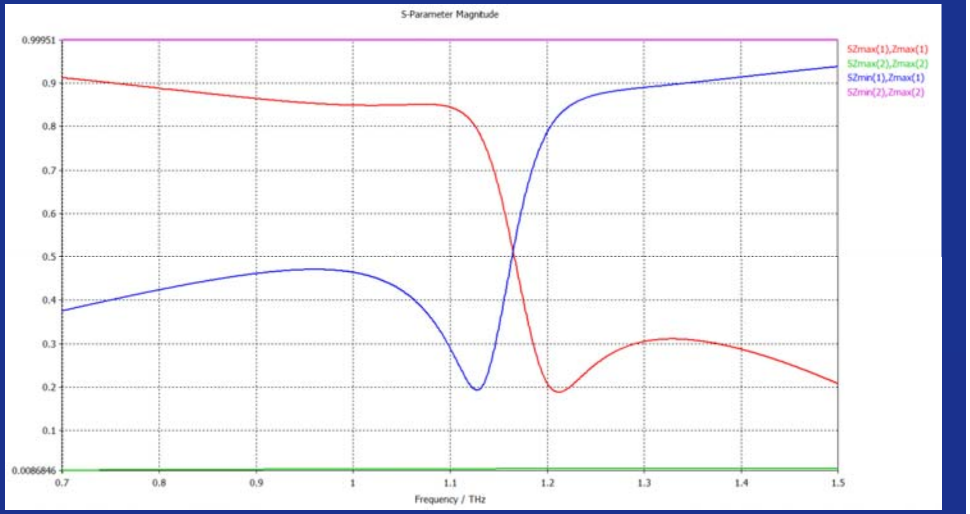
$$\omega_{mo} = \frac{1}{\sqrt{LC}} = \frac{1}{l}\frac{c}{\varepsilon_c}\sqrt{\frac{d}{w}}$$

Double negative (DNG) metamaterials



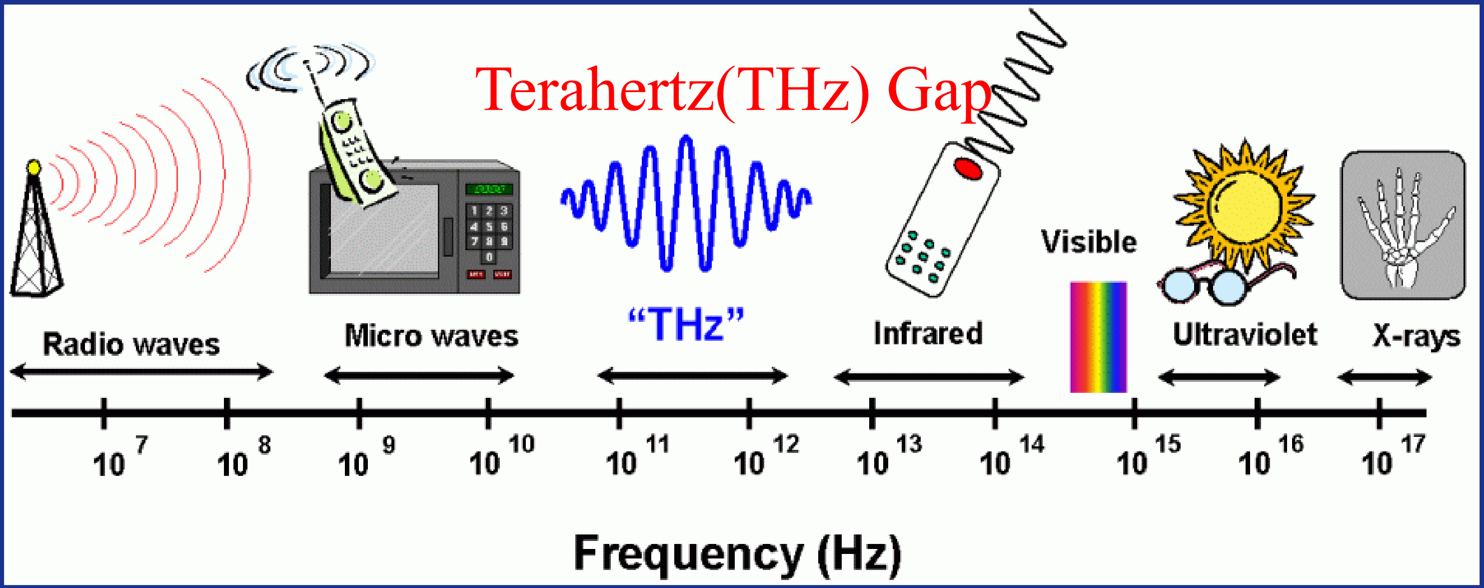






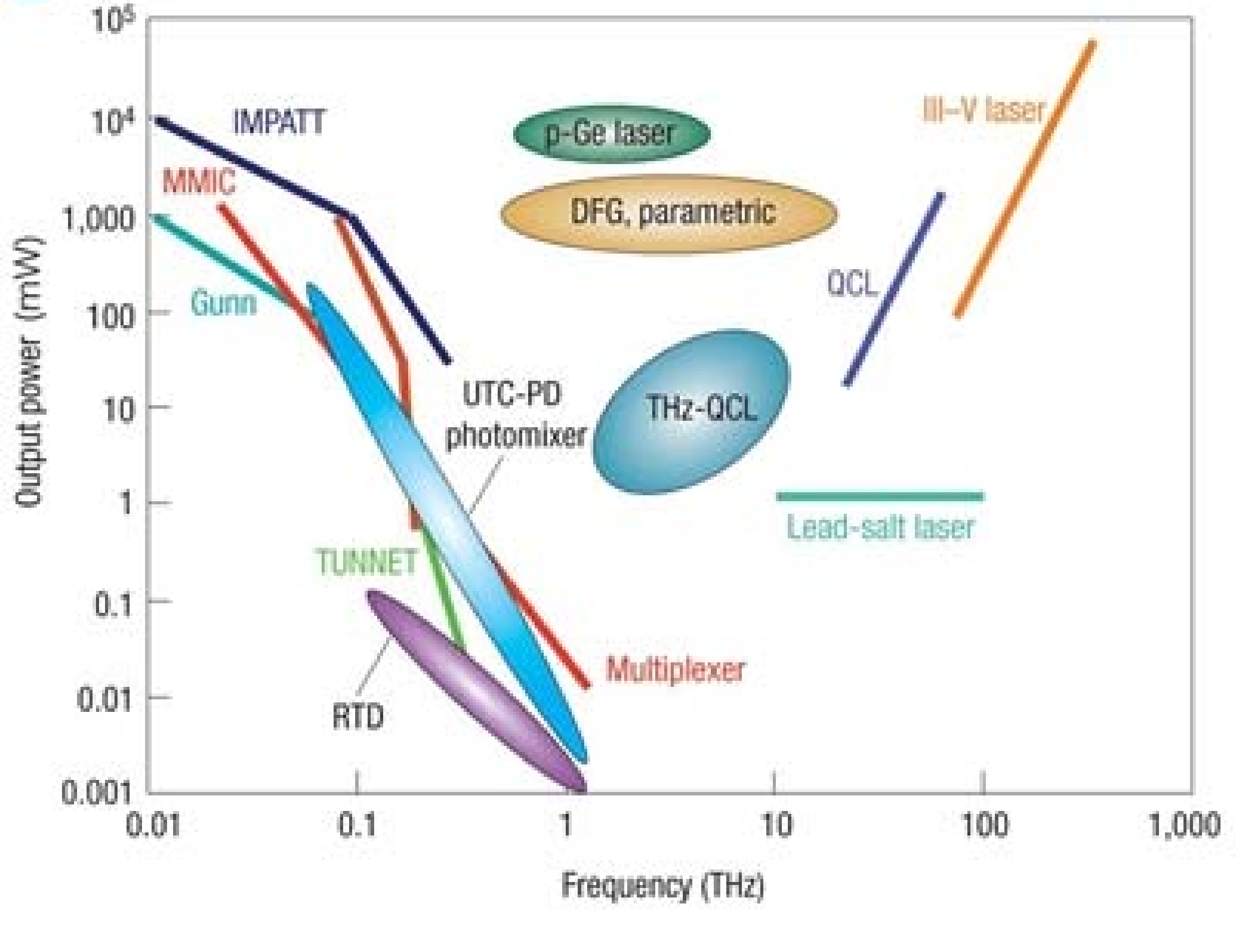
Terahertz

What is TeraHertz?



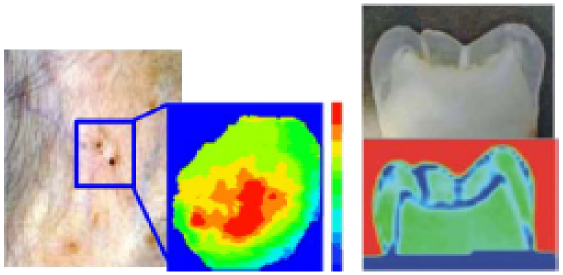
- **THz radiation (EM wave)**
  - THz wave (0.1 THz to 10THz, 30μm to 3mm)
  - Non-ionizing & non-destructive (frequency is low)
  - Penetrate most of dielectric material (fabric, plastic or tissue)
  - Several absorption lines for water
  - Rotational & vibrational frequencies of most molecules

Physical Limitations of Existing THz sources



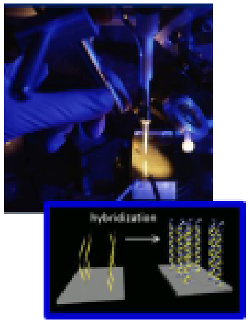
M. Tonouchi, Nature Photonics 1 (2007)

THz Applications



Medical Imaging

Wallace et. al, Faraday Discuss (2004)



Biological and Genomic studies

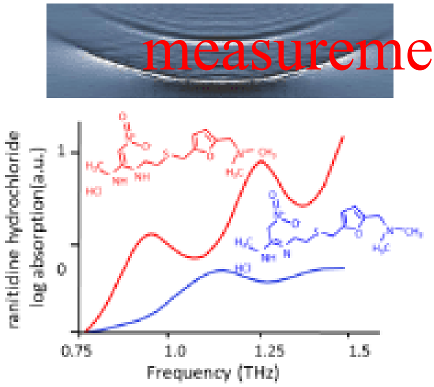
Nagel et. al, (RWTH Aachen)

L-3 Communications Security & Detection Systems, Inc.

Security Screening

http://www.teraview.com

Based on Imaging or Spectrum measurement !

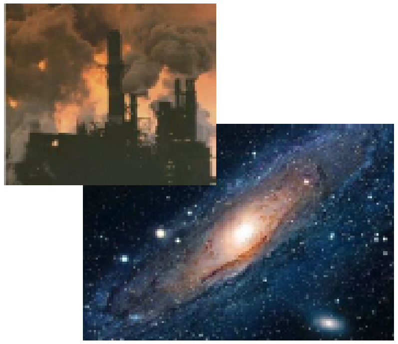


Pharmaceutical Industry

Taday, Pharma. Sci. 92 (2003)

Industrial Quality Control

Hu et. al, Optics Lett. 20 (1995)



Atmospheric /space studies

T. G. Phillips et. al., Proc. IEEE 80,(1992)