MetaMaterials

Atomic and Molecular Physics

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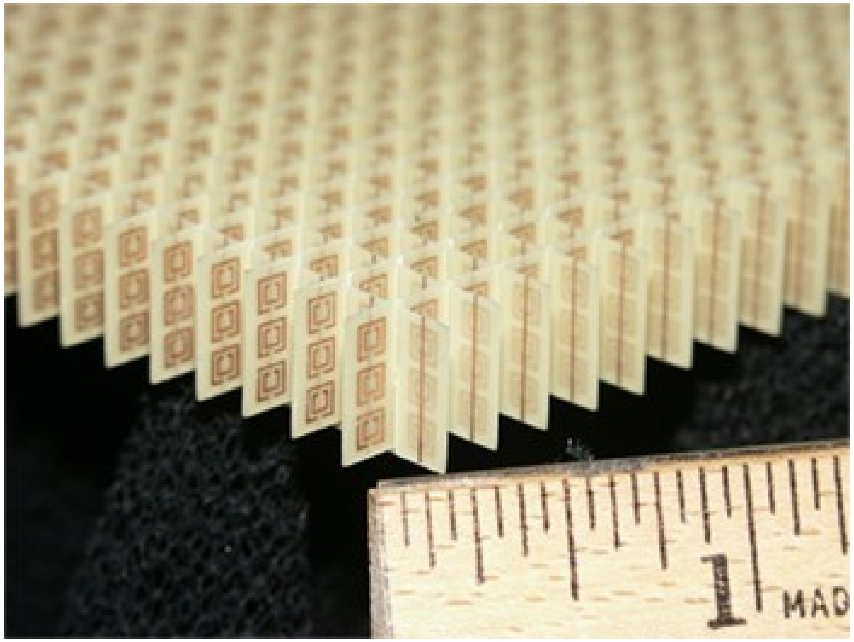
Contents

Introduction

- In 1968 Veselago discussed the likelihood of a negative index of refraction material.
- Metamaterials are engineered composites. Acting as an effective medium for the wavelengths larger than the size and periodicity of their unit cell.
- Derive their properties from their physical structure of their constituents and not from their chemistry.
- Exhibit properties not observed in their constituents. Such as effective negative index of refraction.
- The size and the periodicity of the unit cells are much smaller than the wavelength of the pheonemon they affect.



Types of physical materials

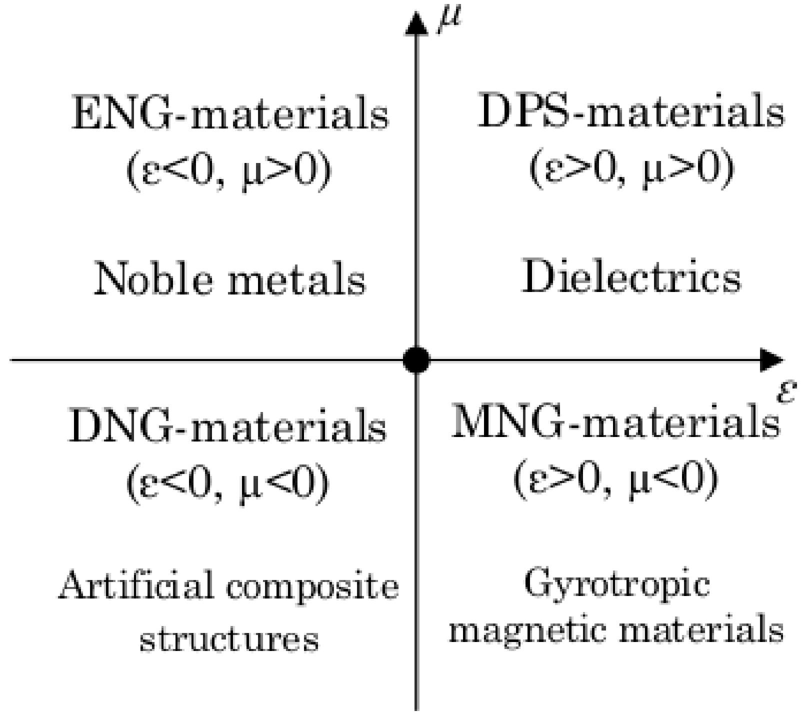
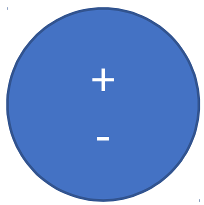
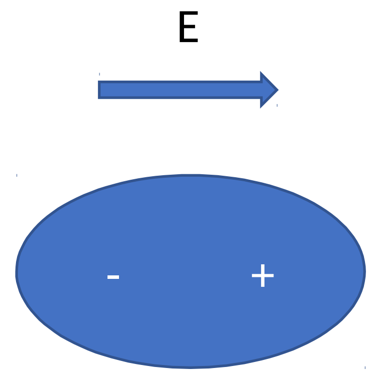


Fig. 1 – The general classification of physical materials depending on values of permittivity and permeability

Lorentz oscillator model for Dielectric Materials



In absence of electric field



Polarization in presence of electric field

The eq. of motion :-

$$m\ddot{\vec{x}} + m\omega_0^2\vec{x} + m\gamma\dot{\vec{x}} = q\vec{E}$$

Solving this equation in frequency domain we get the following solution.

$$x_0(\omega) = \frac{\left(\frac{qE_0}{m}\right)}{(\omega_0^2 - \omega^2) + j\omega\gamma}$$

$\vec{p}$ = nq$\vec{x}$= $\epsilon_0 \chi \vec{E}$

$permittivity \quad \epsilon_\gamma = 1 + \chi$

$\epsilon_\gamma = 1 + \frac{q^2}{m\epsilon_0} \sum_i \frac{N_i}{(\omega_i^2 - \omega^2) + j\omega\gamma_i}$ *it's a complex quantity* let's make separate the real and imaginary part

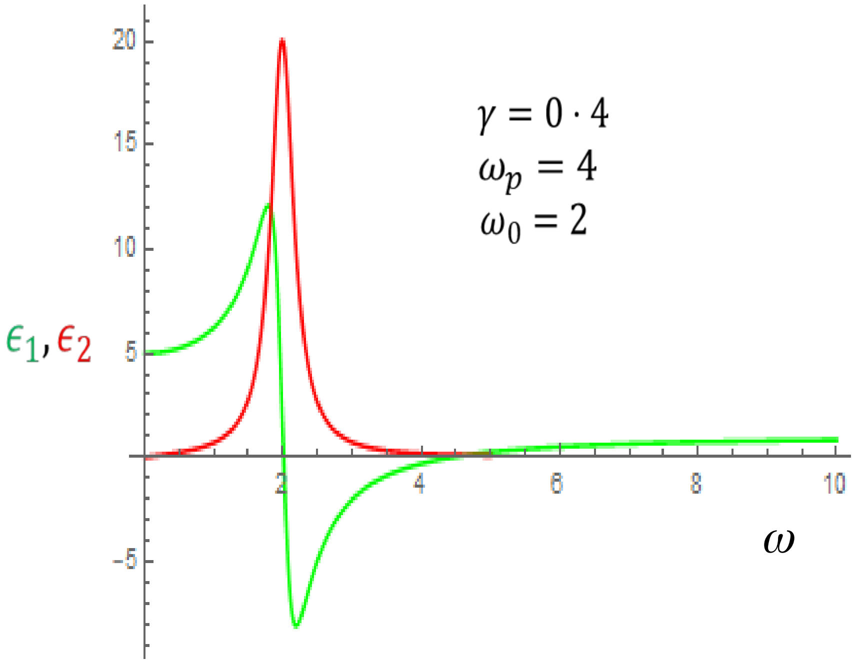
$$\epsilon_\gamma = \epsilon_1 + j\epsilon_2$$

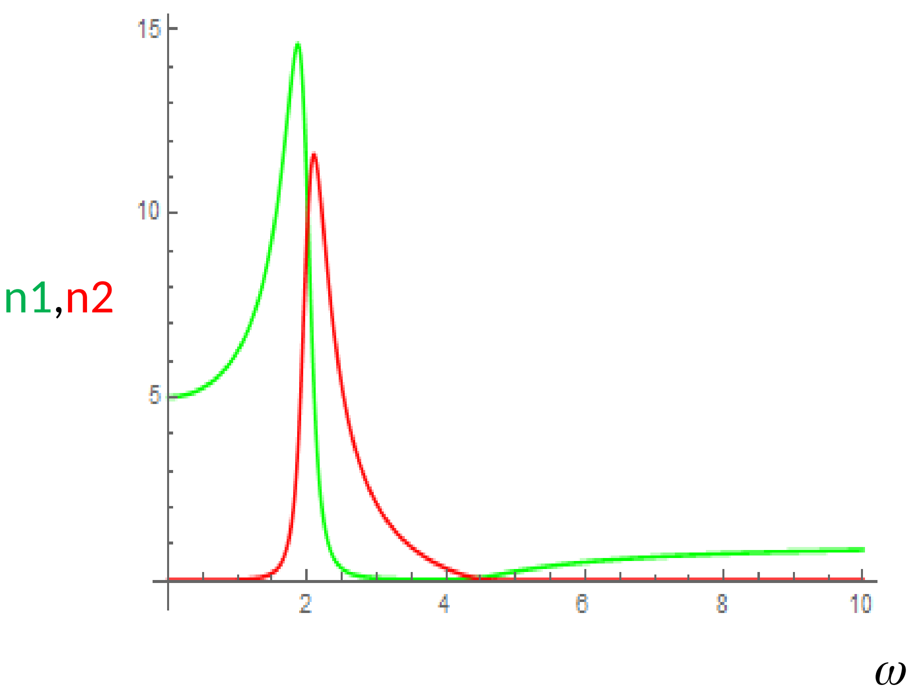
$$\epsilon_1 = 1 + \frac{q^2}{m\epsilon_0} \sum_i \frac{N_i(w_i^2 - \omega^2)}{(w_i^2 - \omega^2)^2 + \omega^2\gamma_i^2}$$

$$\epsilon_2 = \frac{q^2}{m\epsilon_0} \sum_i \frac{N_i\omega\gamma_i}{(\omega_i^2 - \omega^2)^2 + \gamma_i^2\omega^2}$$

Plasma frequency $\omega_p^2 = \frac{Nq^2}{m\epsilon_0}$

Dispersion for permittivity





$$n = \sqrt{\epsilon_r}$$

$$\epsilon_r = \epsilon_1 + j\epsilon_2$$

and n also complex

$$(n_1 + jn_2) = \sqrt{(\epsilon_1 + j\epsilon_2)}$$

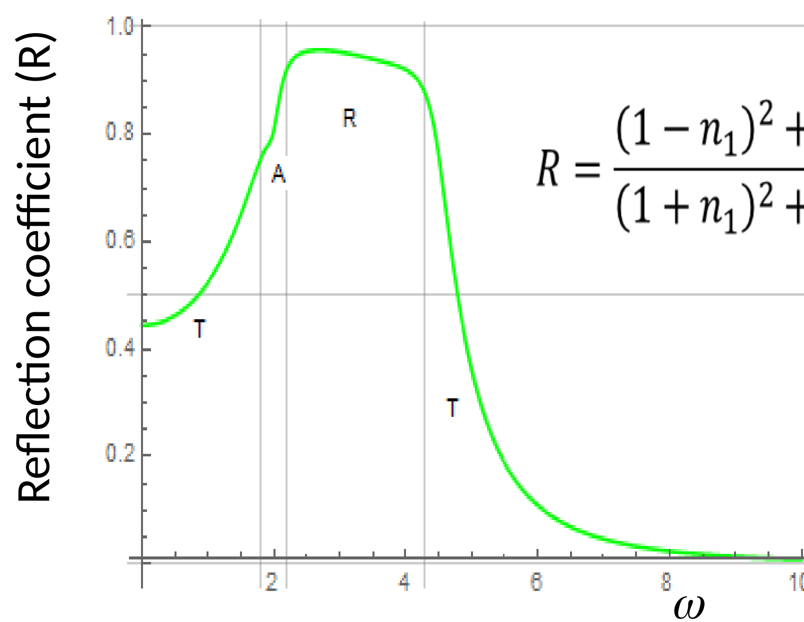
$$\epsilon_1 + j\epsilon_2 = (n_1 + jn_2)^2$$

$$\Rightarrow \epsilon_1 = n_1^2 - n_2^2 \;\; \& \;\; \epsilon_2 = 2n_1n_2$$

we can get by using these eqns

$$n_1 = \frac{1}{2}\left[\sqrt{\epsilon_1^2 + \epsilon_2^2} + \epsilon_1\right]$$

$$n_2 = \frac{1}{2}\left[\sqrt{\epsilon_1^2 + \epsilon_2^2} - \epsilon_1\right]$$

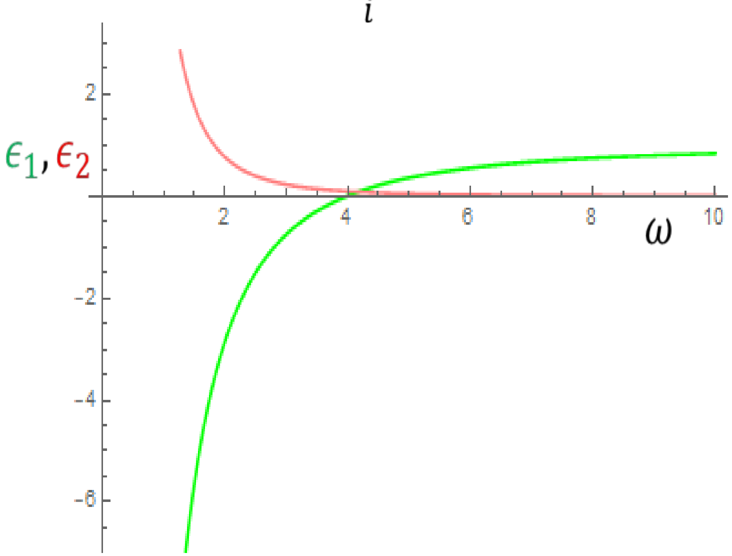


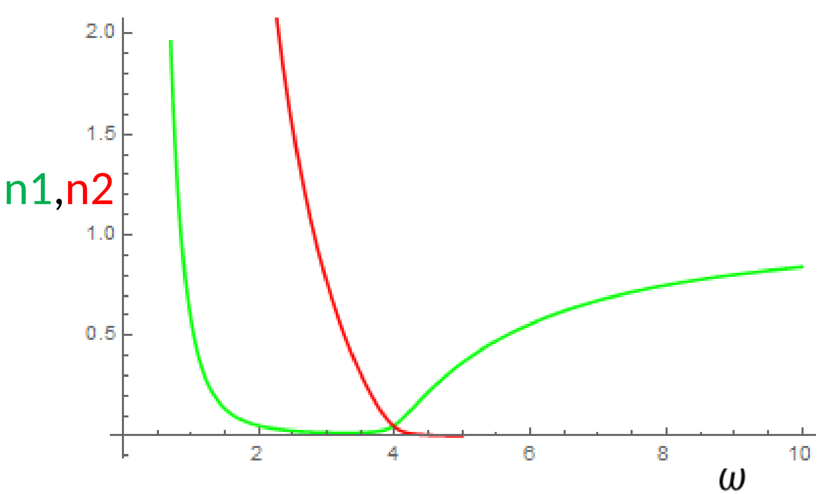
$$R = \frac{(1 - n_1)^2 + n_2^2}{(1 + n_1)^2 + n_2^2}$$

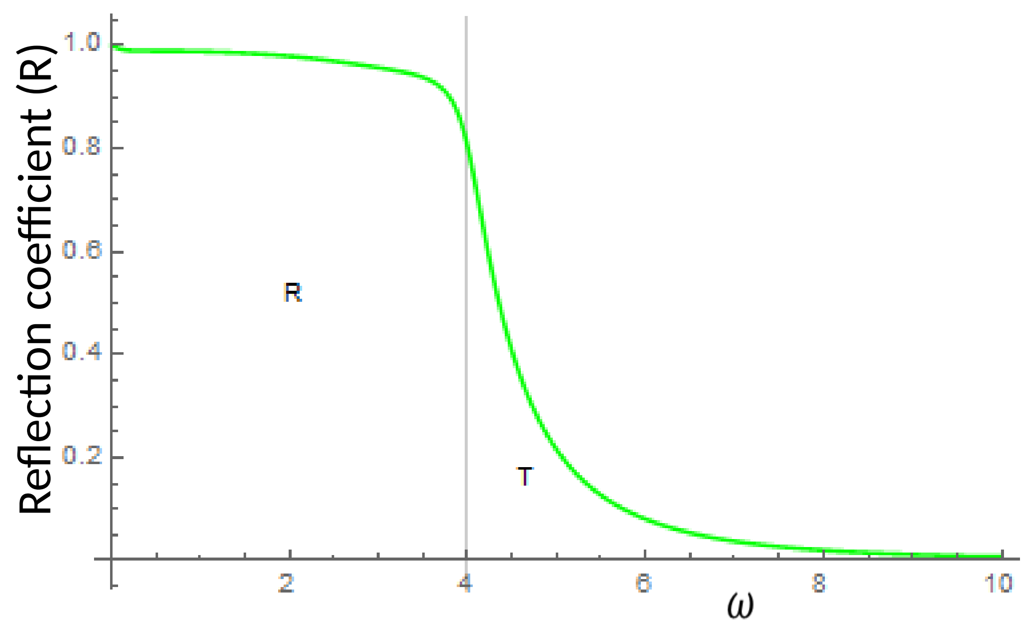
Drude Model for metals

$$\epsilon_1 = 1 + \frac{q^2}{m\epsilon_0}\sum_i \frac{N_i(-\omega^2)}{(-\omega^2)^2 + \omega^2\gamma_i^2}$$

$$\epsilon_2 = \frac{q^2}{m\epsilon_0}\sum_i \frac{N_i\omega\gamma_i}{(-\omega^2)^2 + \gamma_i^2\omega^2}$$

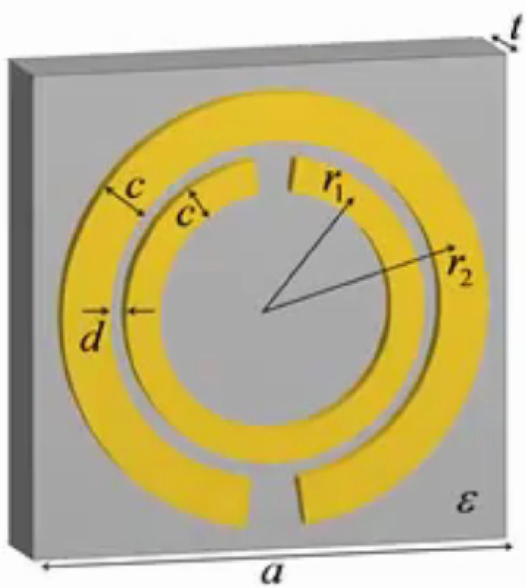


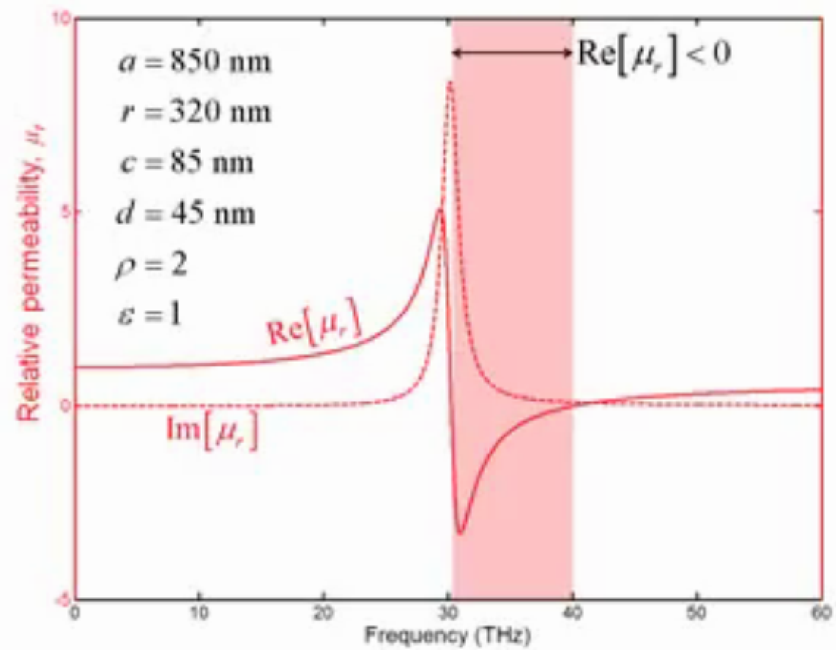




Artifical negative index of refraction

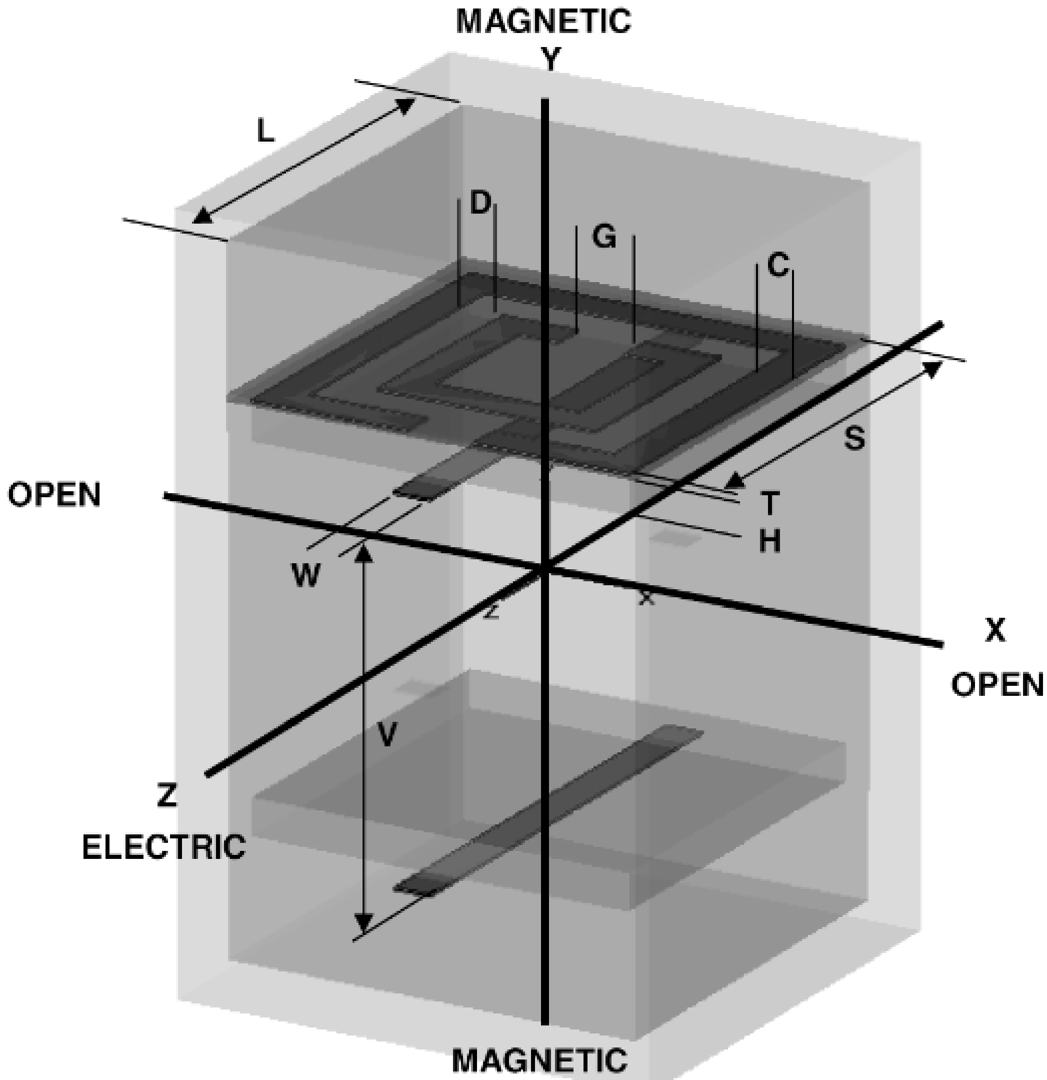
- Resonant type metamaterials are made from periodic array of resonant unit cells. Which have negative effective medium responce. For example array of split ring resonators gives negative permeability.





J. B. Pendry, A. J. Holden, D. J. Robbins, W. J. Stewart, "Magnetism from Conductors and Enhanced Nonlinear Phenomena," IEEE Trans. Microwave Theory and Techniques **47**(11), 2075–2084 (1999).

Artifical negative index of refraction

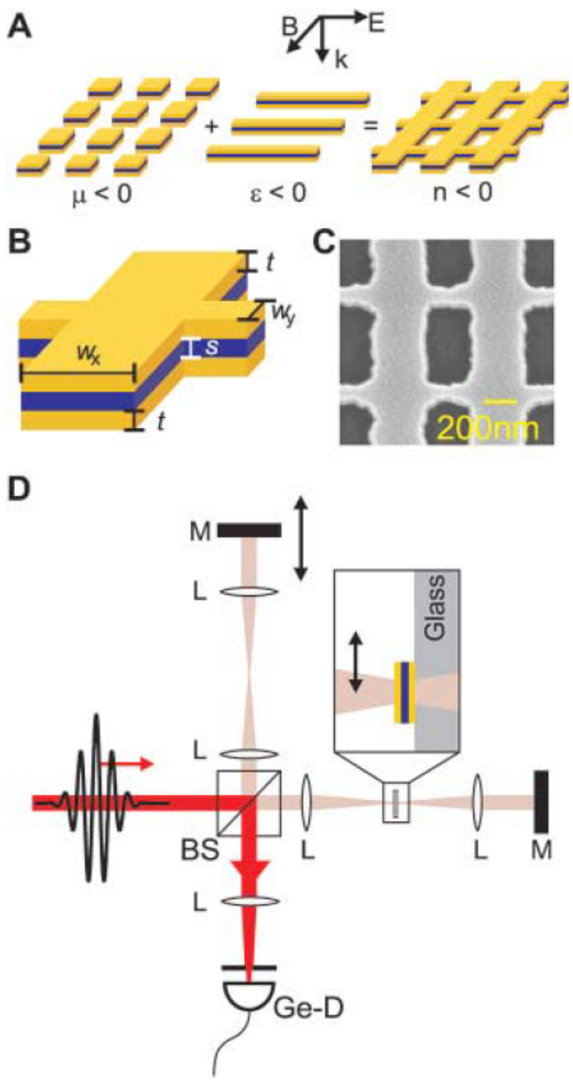


Simultaneous Negative Phase and Group Velocity Of Light In Metamaterials

Gunnar Dolling and Christain Enkrich

- In case of positive refrative index materials, the group velocity of a wave can become negative in the region of anamalous dispersion.
- For a material to have negative index of refraction both phase and group velocity must have negative numerical values.
- In the experiment the group and phase velocities are measured by propogating a femtosecond pulse through a negative index metamaterial and then time resolving the transmitted pulse using interferrometry.
- All four combiations of signs of group and phase velocities have been observed and for all combinations the poynting vector is along the forward direction.
- The metamaterial under test consists of double-wire pairs for negative permiability, and long metal wire which give negative permittivity below plasma frequency.
- Sample has a footprint of 100um*100um.

Simultaneous Negative Phase and Group Velocity Of Light In Metamaterials



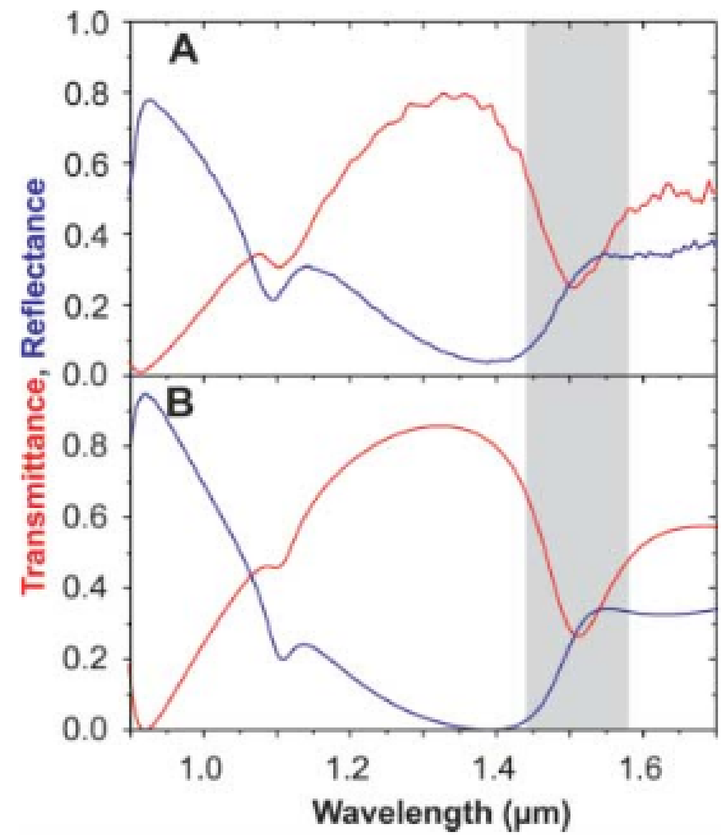
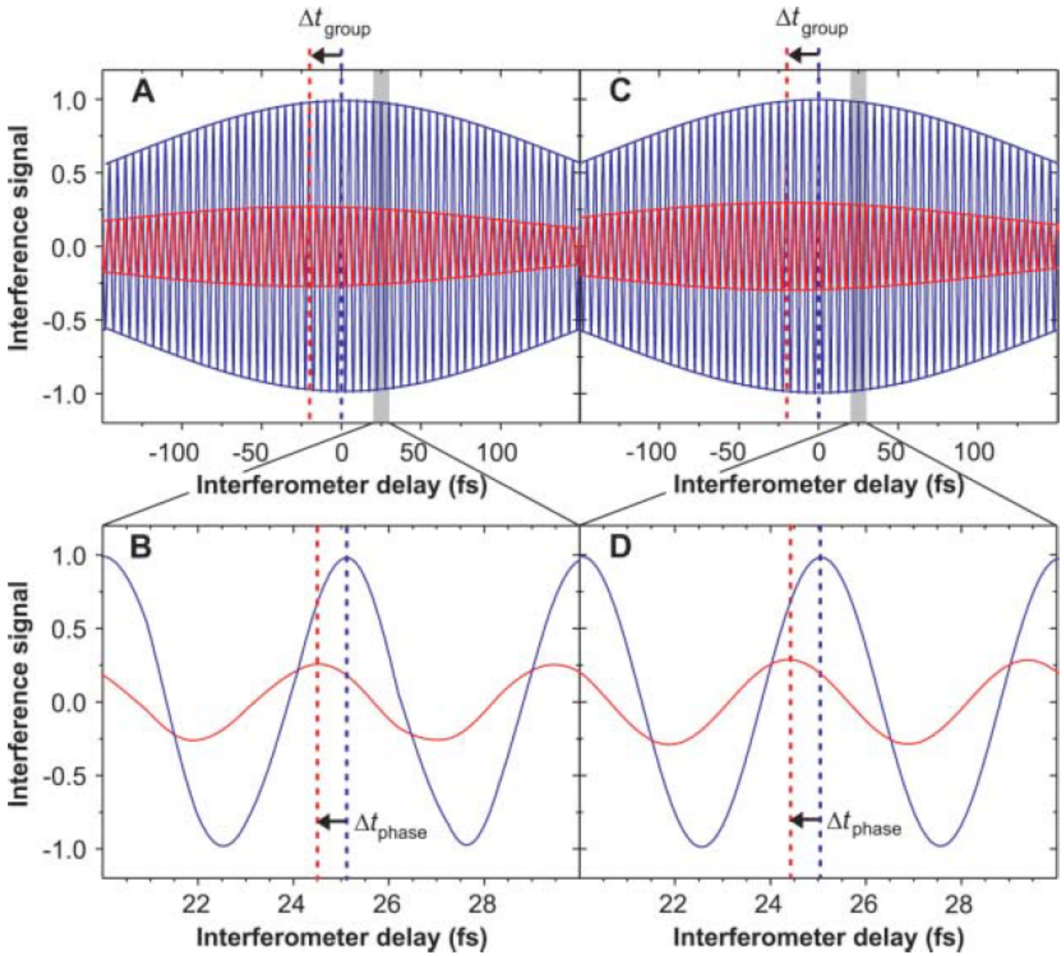


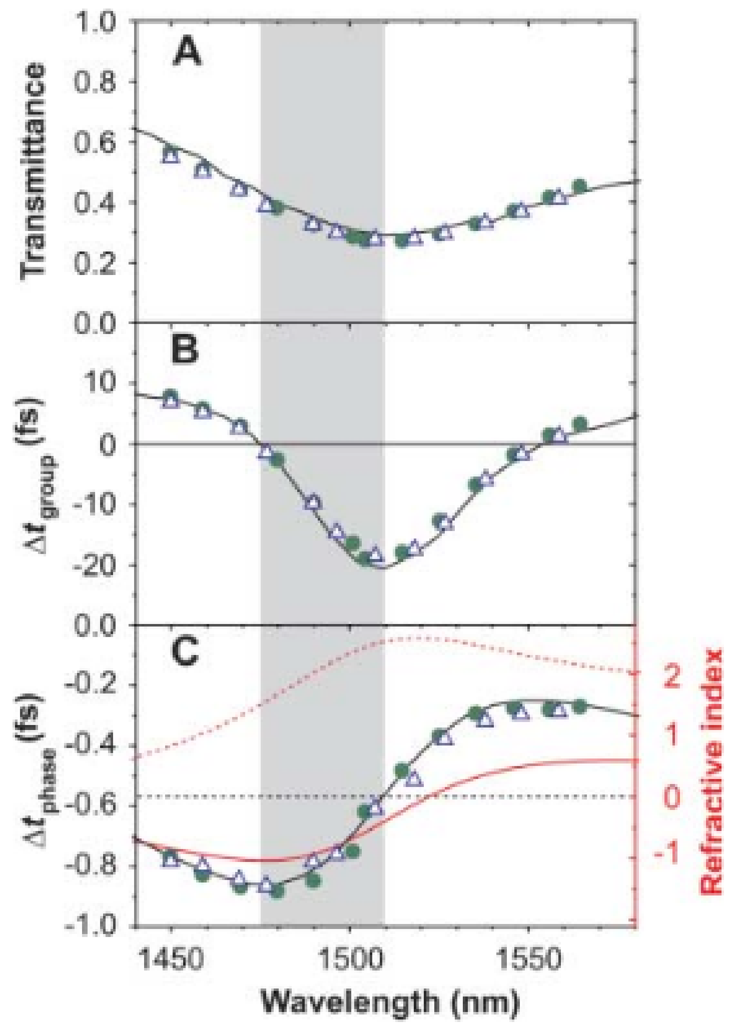
Fig. 2. Transmittance (red) and reflectance (blue) spectra for the polarization configuration and sample shown in Fig. 1. (**A**) Measurements with a white-light source. (**B**) Theory. To guide the eye, the total spectral region shown in Fig. 4 is highlighted by the gray area.

Simultaneous Negative Phase and Group Velocity Of Light In Metamaterials

- Standard michelson interferrometer is used into one arm of which sample is inserted.
- The output of the interferrogram is recorded as a function of length of the arm. Which can be translated to interferrometer time delay.
- When inserting the sample the interferrogram shifts on the time delay axis. The shift of the envelope is determined by group velocity. The shift of rapidly oscillating fringes contains information about phase velocity.
- To unambiguosly infer phase velocity from phase delay, the phase delay must be smaller than one period of light. This condition translates to thin samples.
- For a sample of length of about 85nm the phase delay is expected to be about 0.56fs , while period of light is about 5fs at wavelength of 1500nm.

Simultaneous Negative Phase and Group Velocity Of Light In Metamaterials



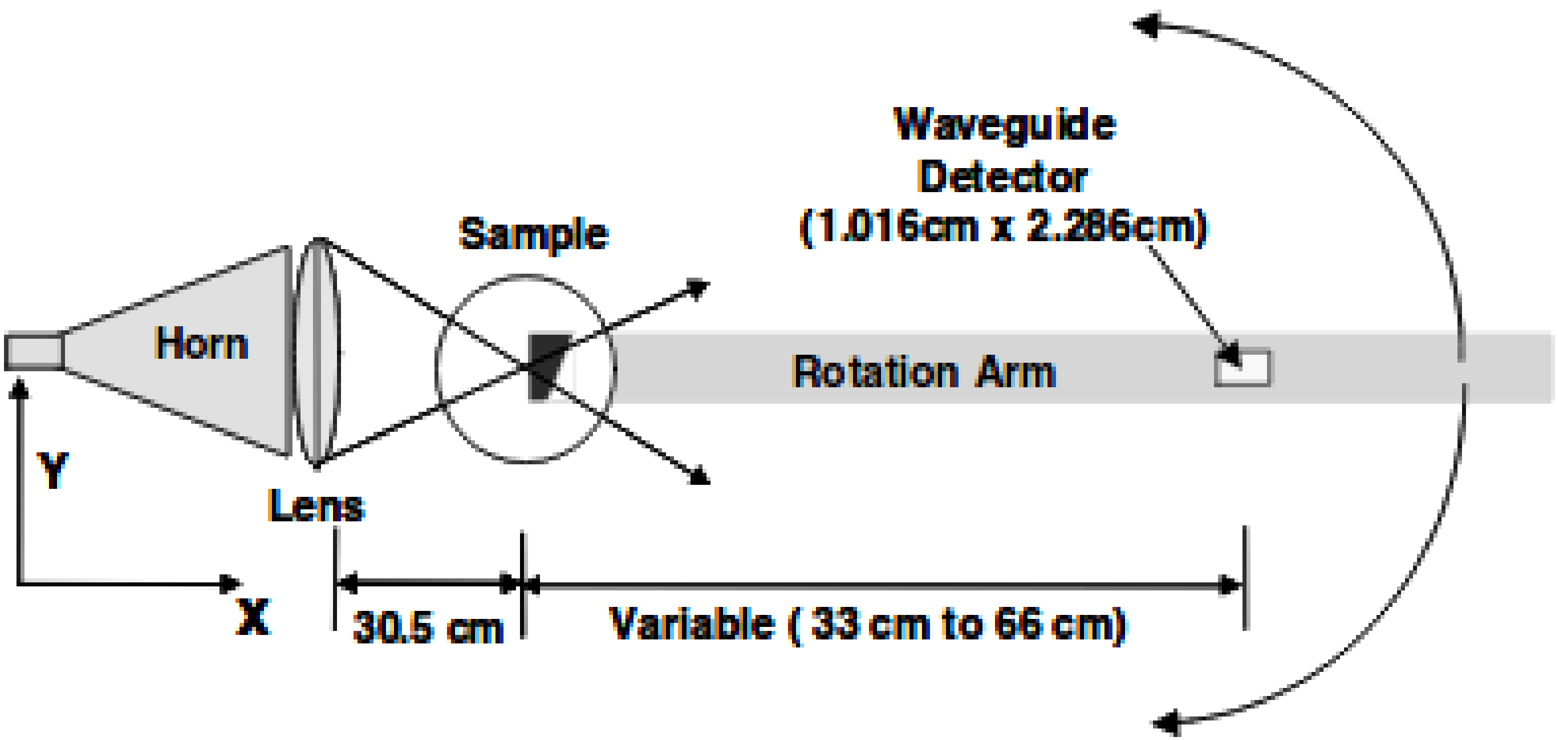


Simultaneous Negative Phase and Group Velocity Of Light In Metamaterials

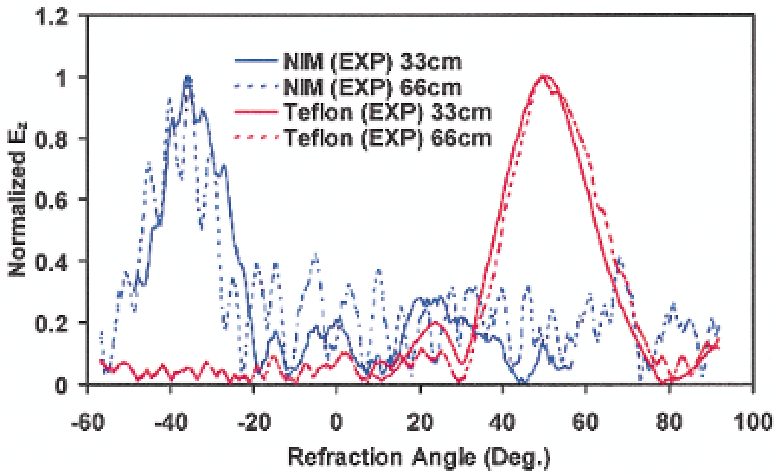
- For the material to have negative index of refraction phase delays are required to be more negative than -2*d/c = -0.57fs , where d is sample size.
- The values for phase and group delay obtained from averaging 20 scans are -0.62fs , -19.1fs respectively. Hence in the spectral region around 1500nm , both phase and group velocities are found to be negative.

Experimental verification and simulation of Negeative Index of refraction using Snell's Law

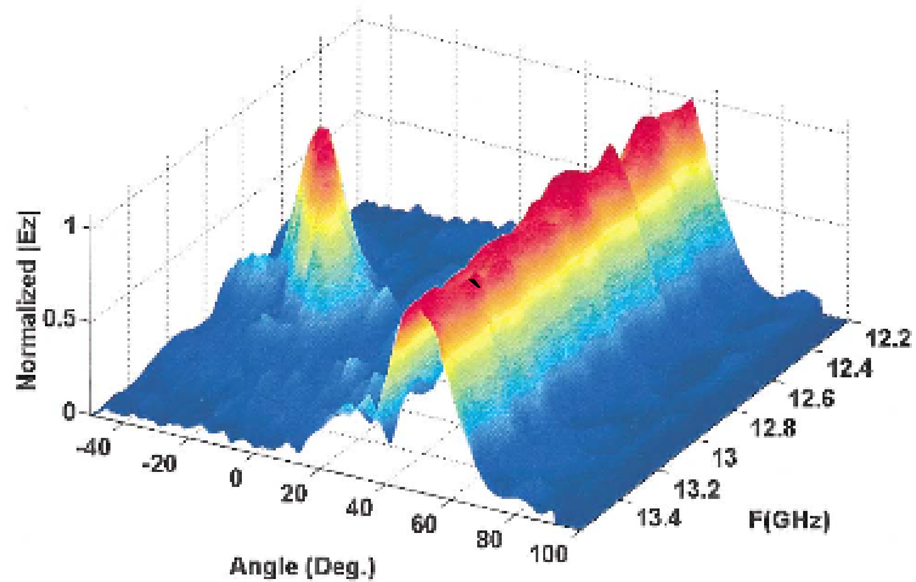
C.G. Parazzoli , R.B. Greegor

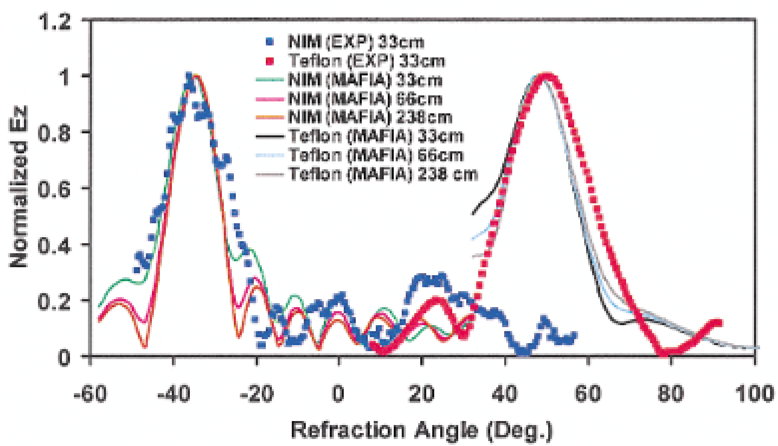


Experimental verification and simulation of Negeative Index of refraction using Snell's Law

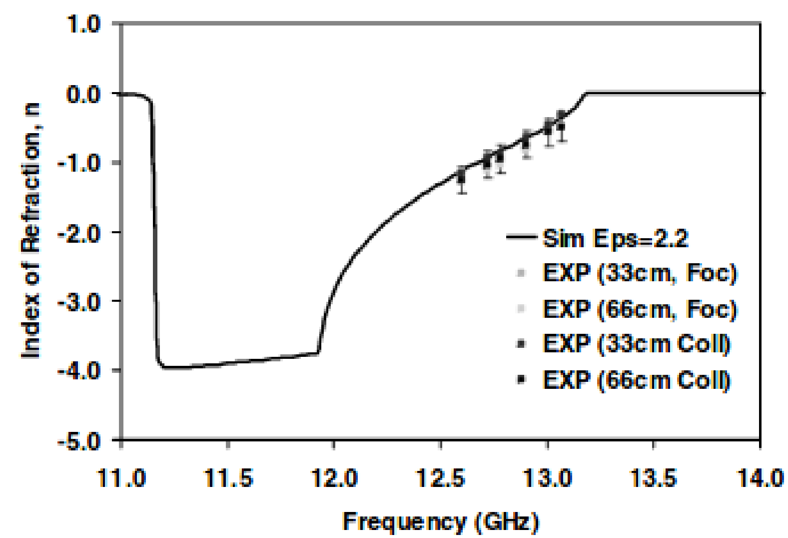


(a)



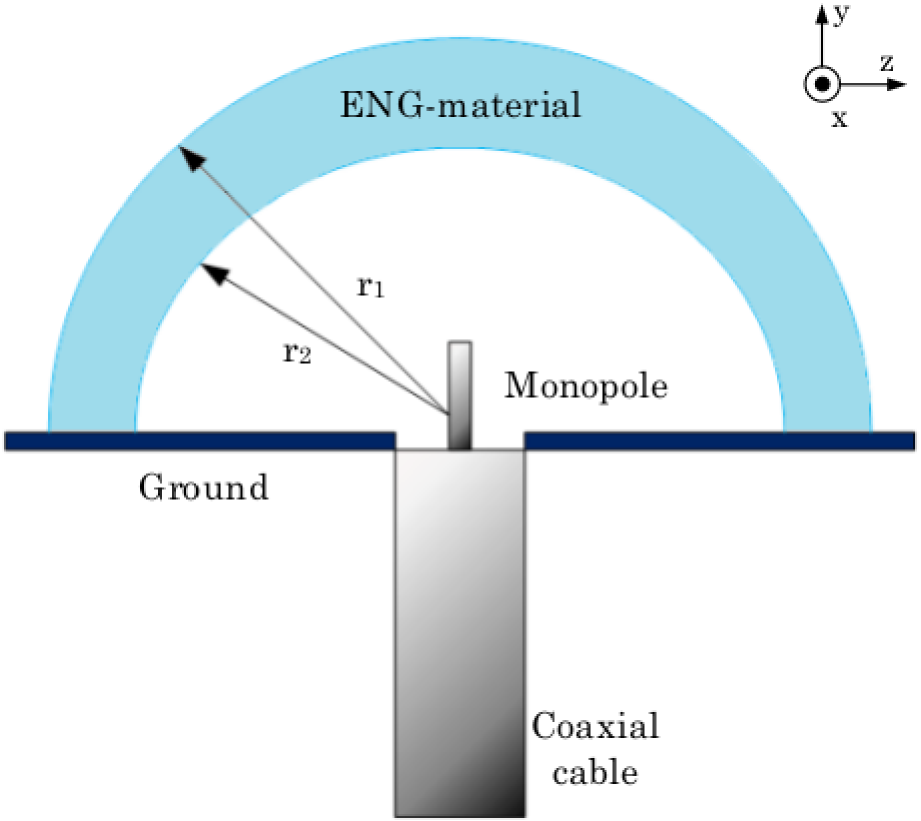


(b)



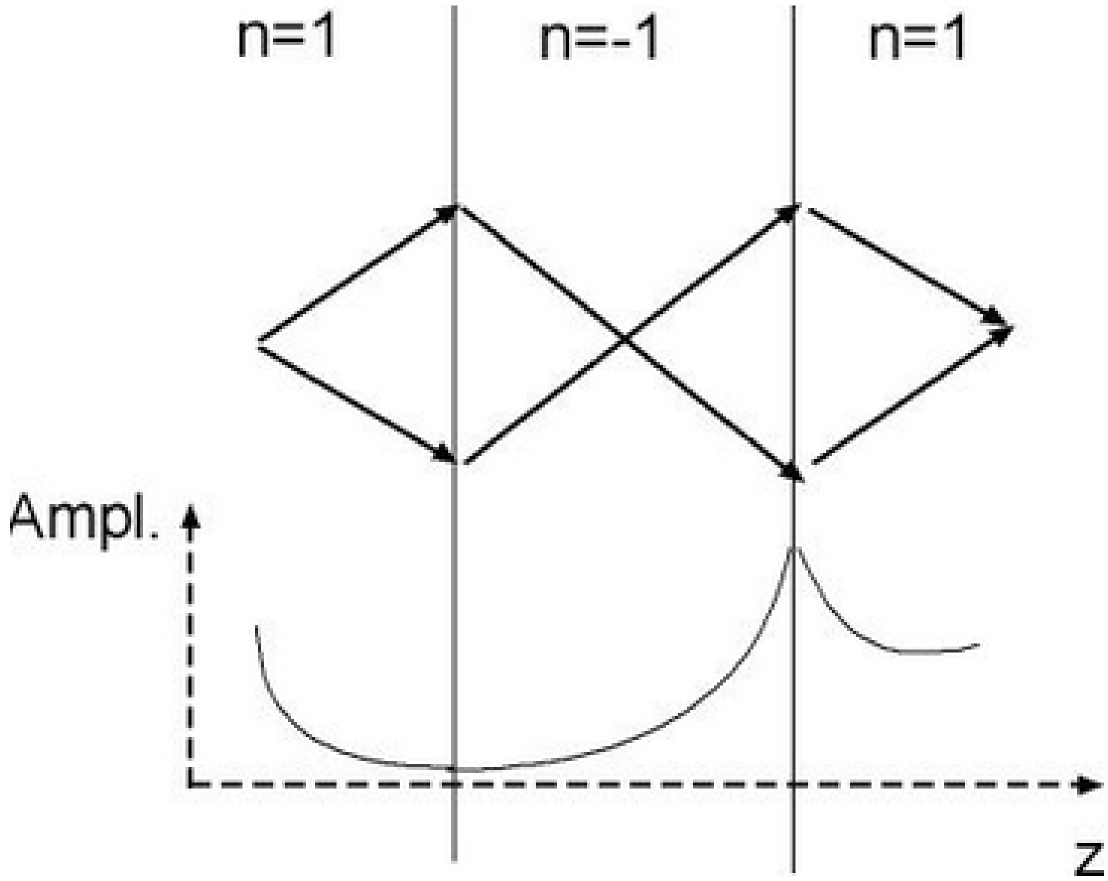
Applications

- Metamaterial coatings have been used to enhance the radiation and matching properties of electrically small electric and magnetic dipole antennas



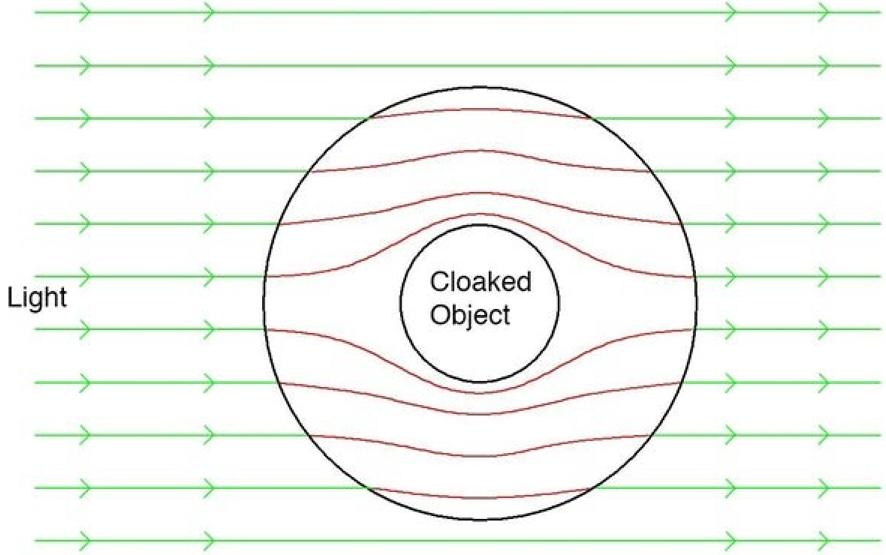
Applications

- Superlens uses metamaterials to go beyond the diffraction limit. Giving subwavelength resolution.



Applications

- Cloaking can be achieved by cancellation of the electric and magnetic field generated by an object or by guiding the electromagnet wave around the object. Guiding the wave means transforming the coordinate system in such a way that inside the hollow cloak electromagnetic field will be zero this makes the region inside the shell disappear.
- Metamaterials can be used as phase compensators.
- Can also be used for sensors, selective absorbers, resonators,repeater etc.



Thank You