Metamaterials
– from Microwave to Optical Range

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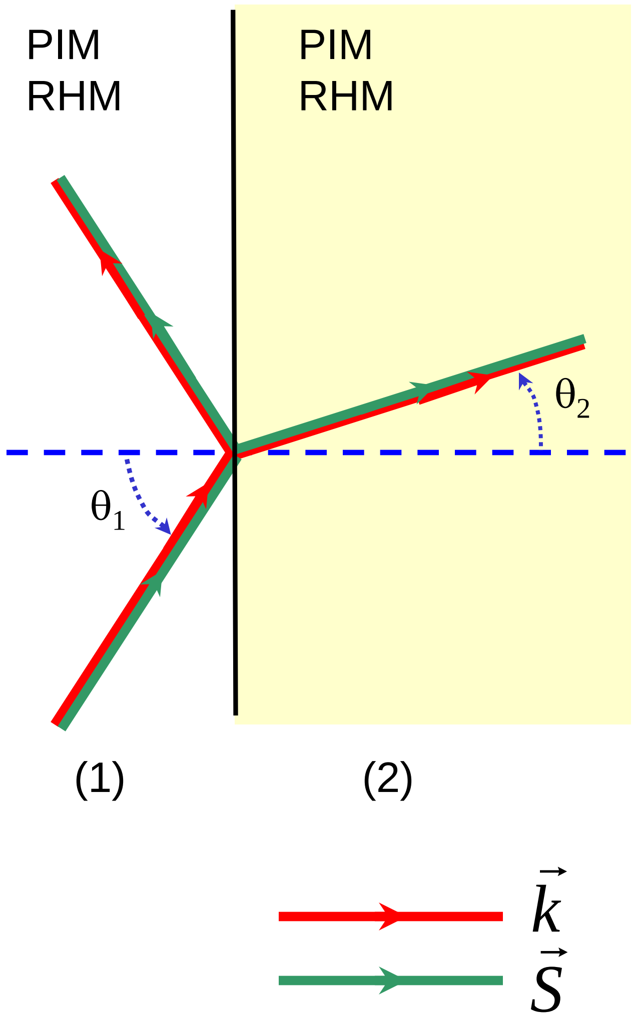
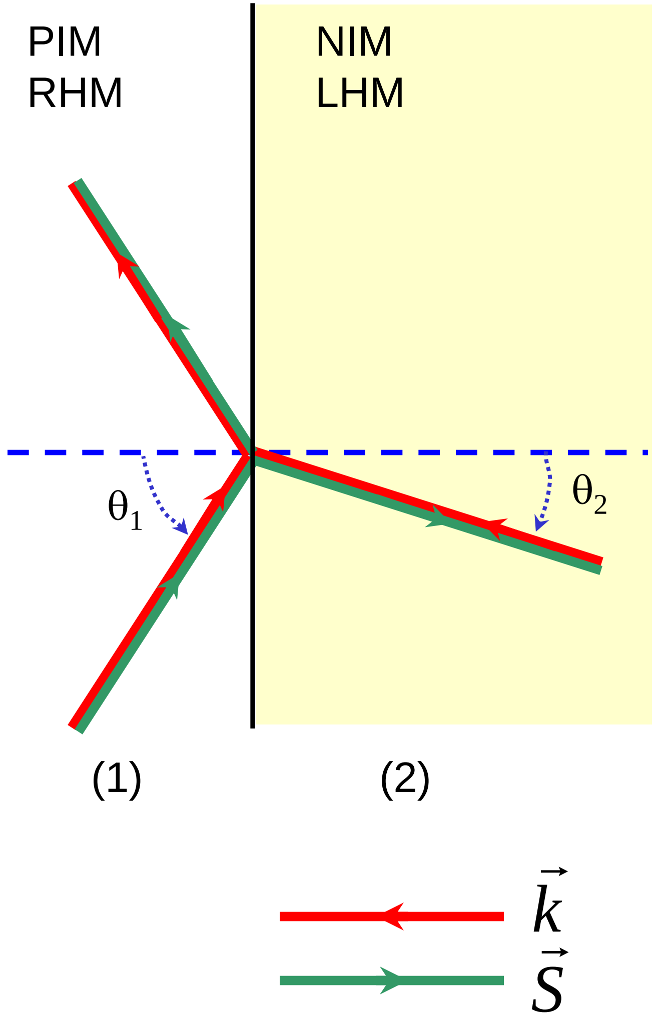
Outline

- What are metamaterials?
- Dielectrics and metals, plasma frequency, normal and anormal dispersion
- Determination of the effective and negative refractive index
- Short historical review of Left-Handed Materials
- Technology of metamaterials
- Tunable metamaterials
- Applications
- Summary

“Reversal” of Snell’s Law





“Left hand” materials:
(E in plane of incidence)

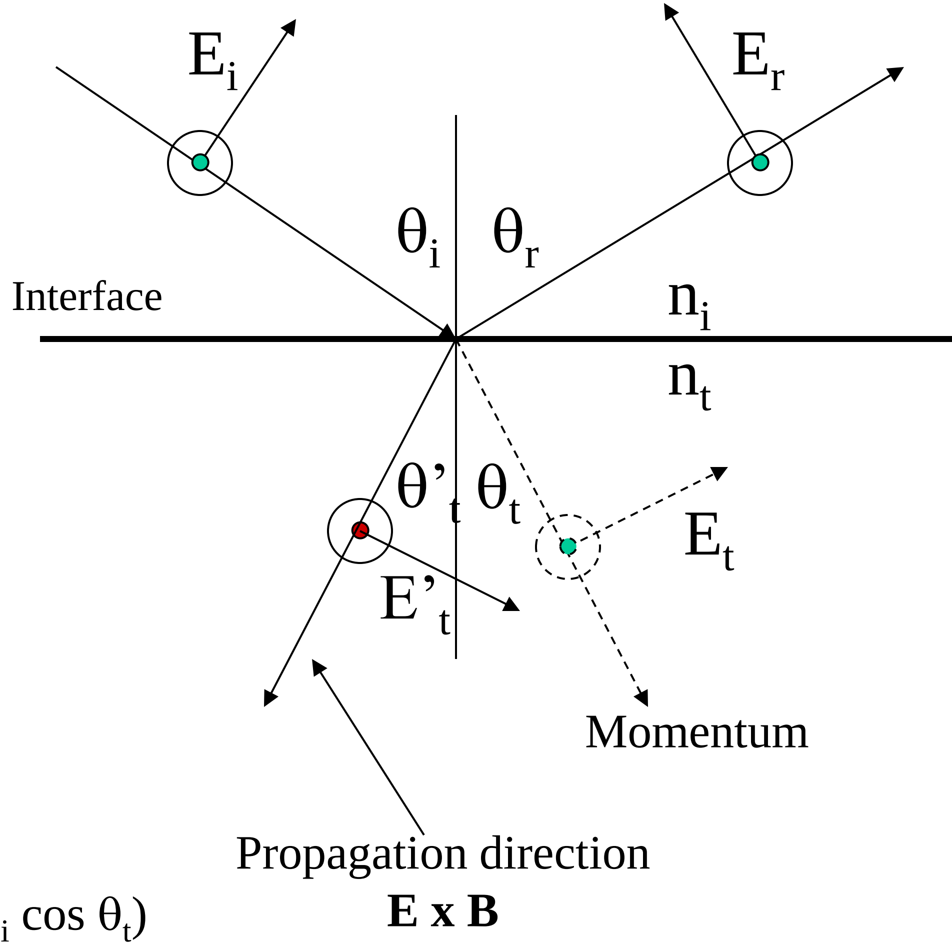
Sign of ε and μ both negative

- Strange properties
- Refraction backward

Example -- $E_{parallel}$, P-polarization

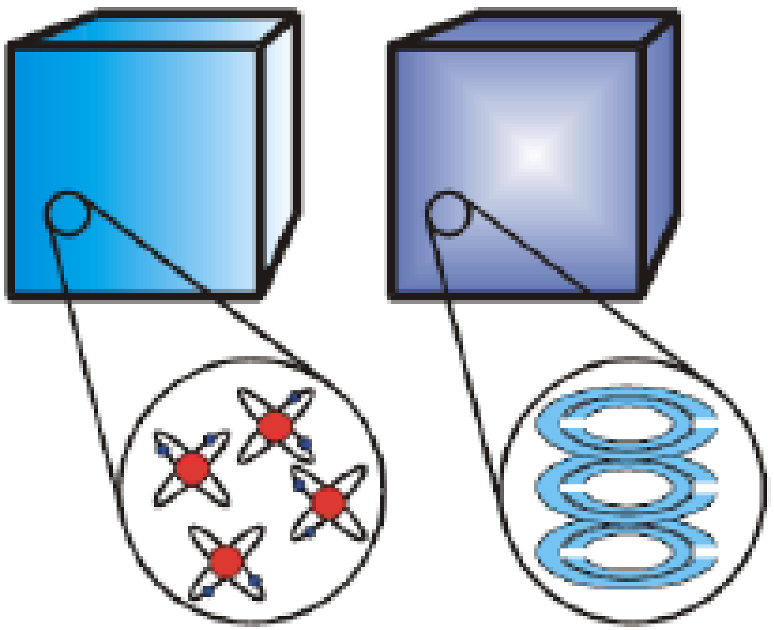
Two components of E

- Parallel to surface
  - $E_i \cos \theta_i + - E_r \cos \theta_r = E_t \cos \theta_t$
- Perpendicular to surface
  - 1. Space charge attenuates E_t
  - $\varepsilon_i E_i \sin \theta_i + \varepsilon_r E_r \sin \theta_r = \varepsilon_t E_t \sin \theta_t$
  - **Sign of ε_t is negative**
  - 2. Use Snell’s law
  - $n_i E_i + n_r E_r = n_t E_t$
- B is parallel to surface
  - same as perpendicular E
- $r_{parallel} = (n_t \cos \theta_i - n_i \cos \theta_t) / (n_t \cos \theta_i + n_i \cos \theta_t)$
- $t_{parallel} = (2n_i \cos \theta_i) / (n_t \cos \theta_i + n_i \cos \theta_t)$



Metamaterials vs. conventional materials

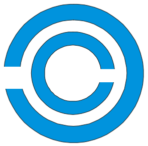
$\varepsilon, \mu > 0$
$\lambda >>$ structure



$\varepsilon, \mu < 0$
$\lambda >>$ structure

Atomy ordered in crystal structure
Lambda < 1 nm.
EM wave ~ 1 um do not see structure of network but material with ε i μ.

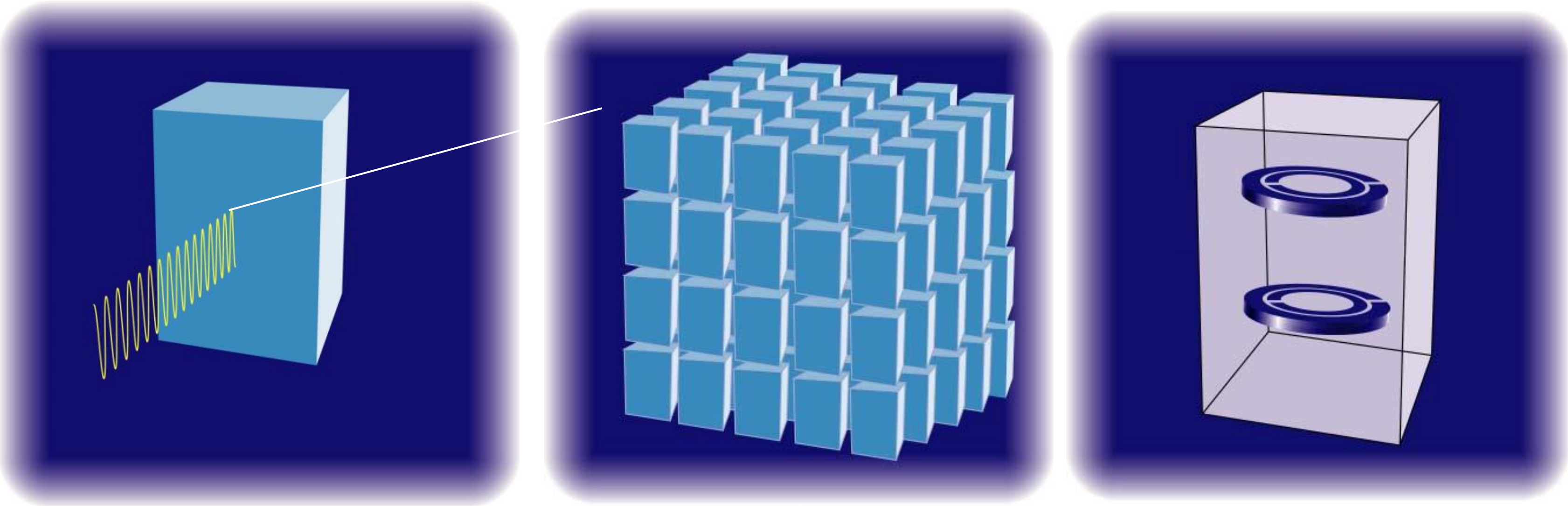
Structures with sizes less then EM wave similary like podobnie widzi materiał jednorodny.
Structures have properties like "magnetic atom" but with $\mu<0$



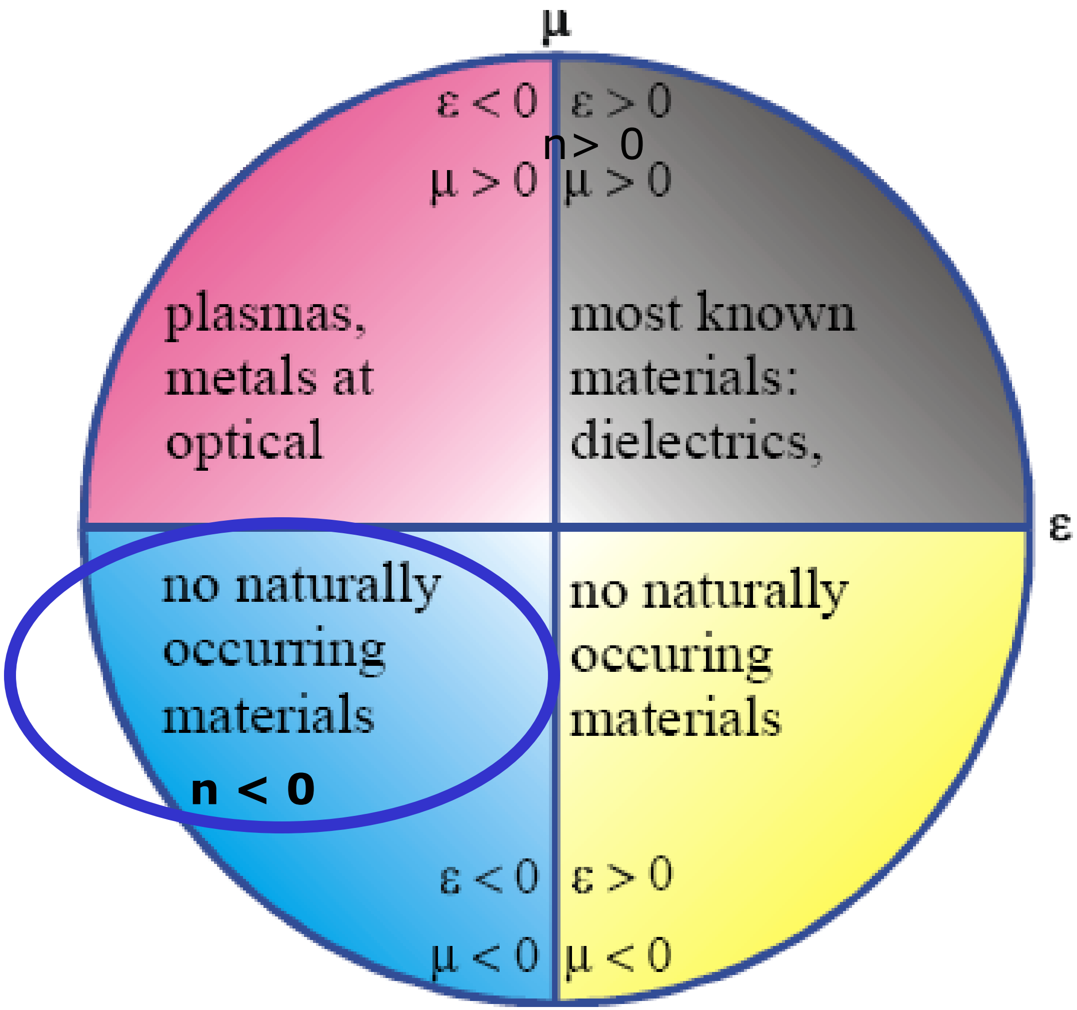
and properties of dielectric atom dielektric atom but with $\varepsilon<0$.

Electromagnetic Metamaterials

Example: Metamaterials based on repeated cells…



Material with negative refractive index ?

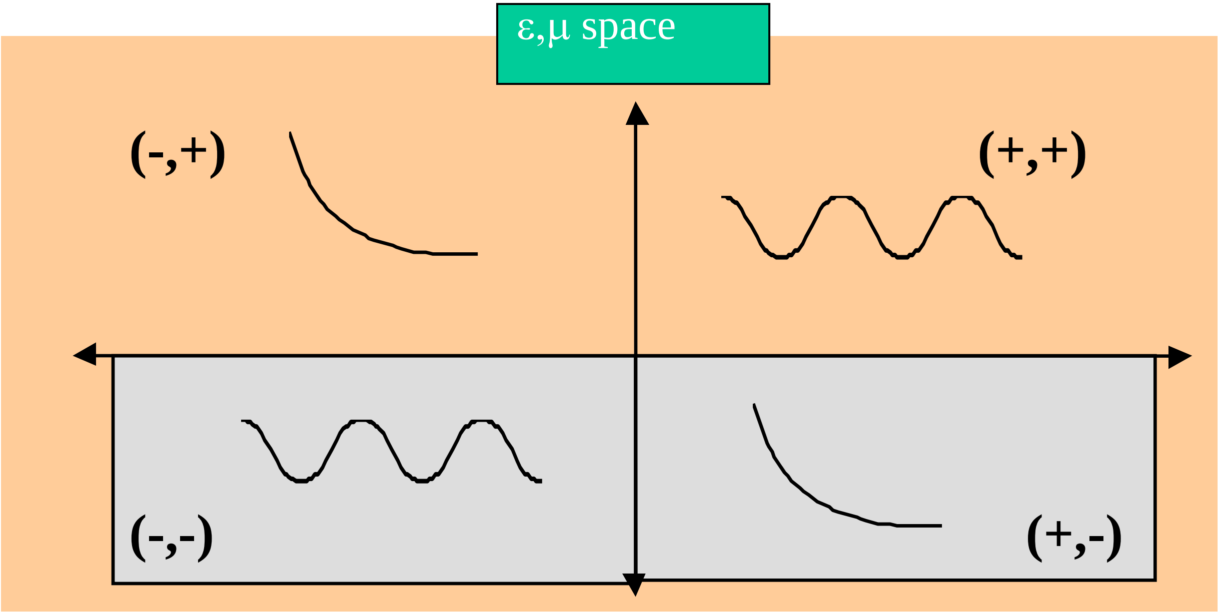


Veselago

We are interested in how waves propagate through various media, so we consider solutions to the *wave equation*.

$$\nabla^2 \mathbf{E} = \varepsilon\mu \frac{\partial^2 \mathbf{E}}{\partial t^2} \qquad n = \pm\sqrt{\varepsilon\mu}$$

$$k = \omega\sqrt{\varepsilon\mu}$$

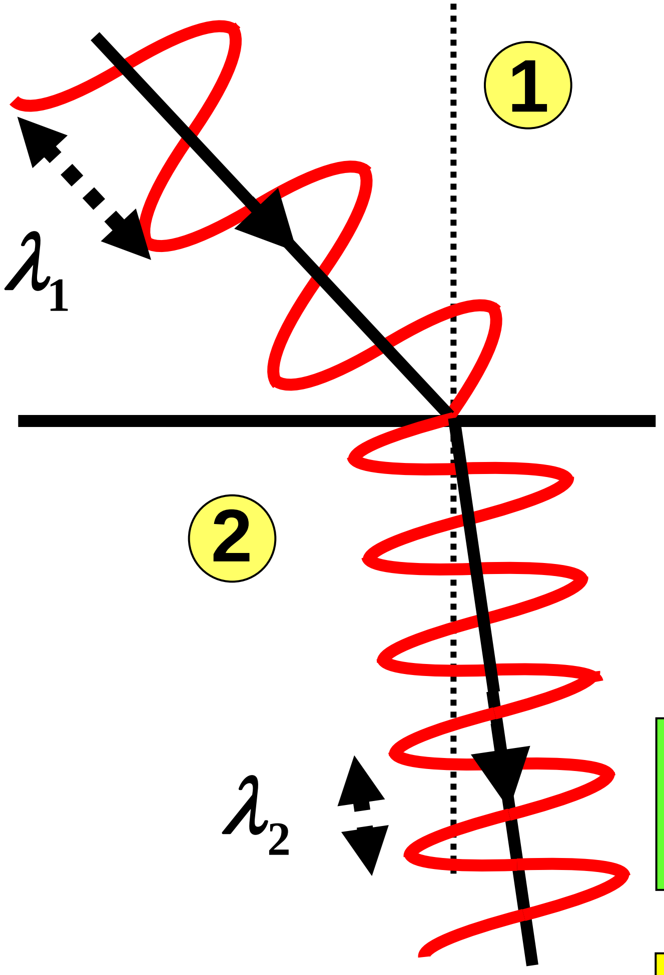


$$\boxed{k^2 = \frac{\omega^2}{c^2}\varepsilon}$$

$$\boxed{k = \pm\frac{\omega}{c}\sqrt{\varepsilon}}$$

Sov. Phys. Usp. 10, 509 (1968)

Wavelenght (λ) or wave vector (k)?



$$v = \frac{c}{n_1}$$

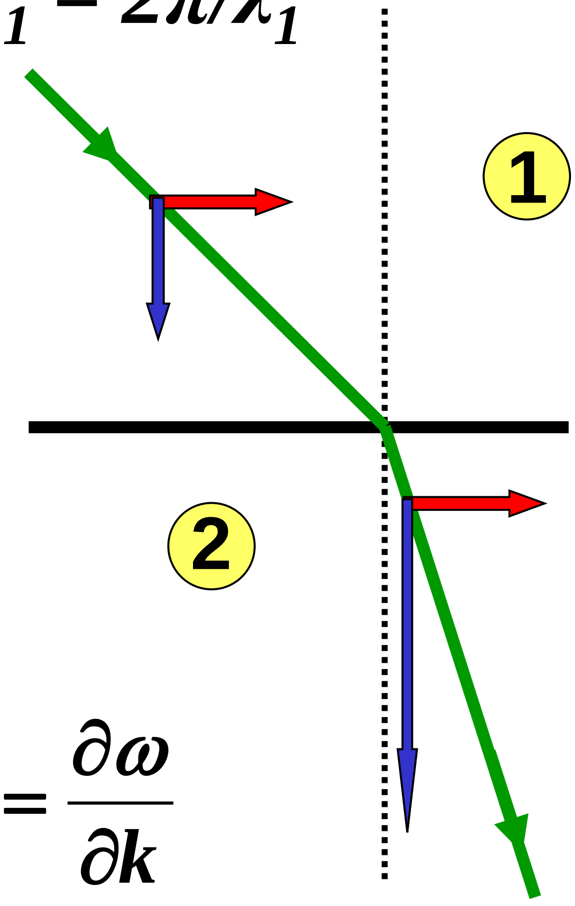
$$v = \frac{c}{n_2}$$

$$\mathbf{v}_p = \frac{\omega}{k}$$

$$\mathbf{v}_g = \frac{\partial \omega}{\partial k}$$

c = light velocity
$n_{1,2}$ = refractive index

$$k_1 = 2\pi/\lambda_1$$



$$k_2 = 2\pi/\lambda_2$$

Refraction

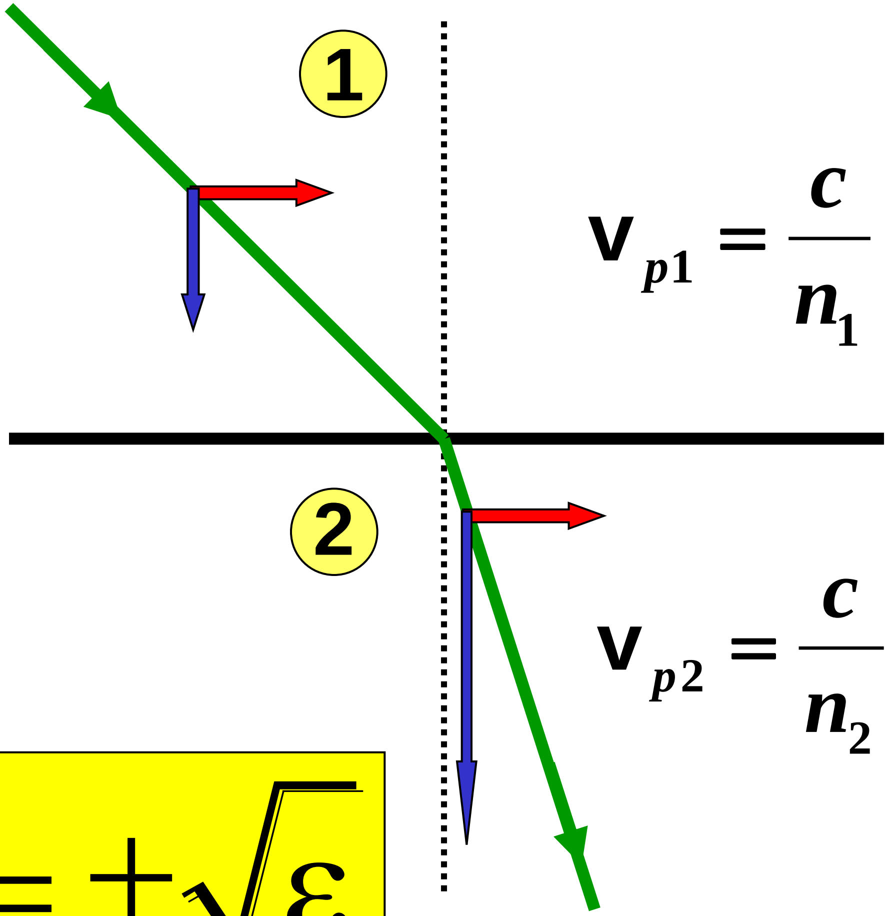
From theory EM

ω, k, ε, c

$$\boxed{k^2 = \frac{\omega^2}{c^2}\varepsilon}$$

$$\boxed{k = \pm\frac{\omega}{c}\sqrt{\varepsilon}}$$

Paralell components must be the same



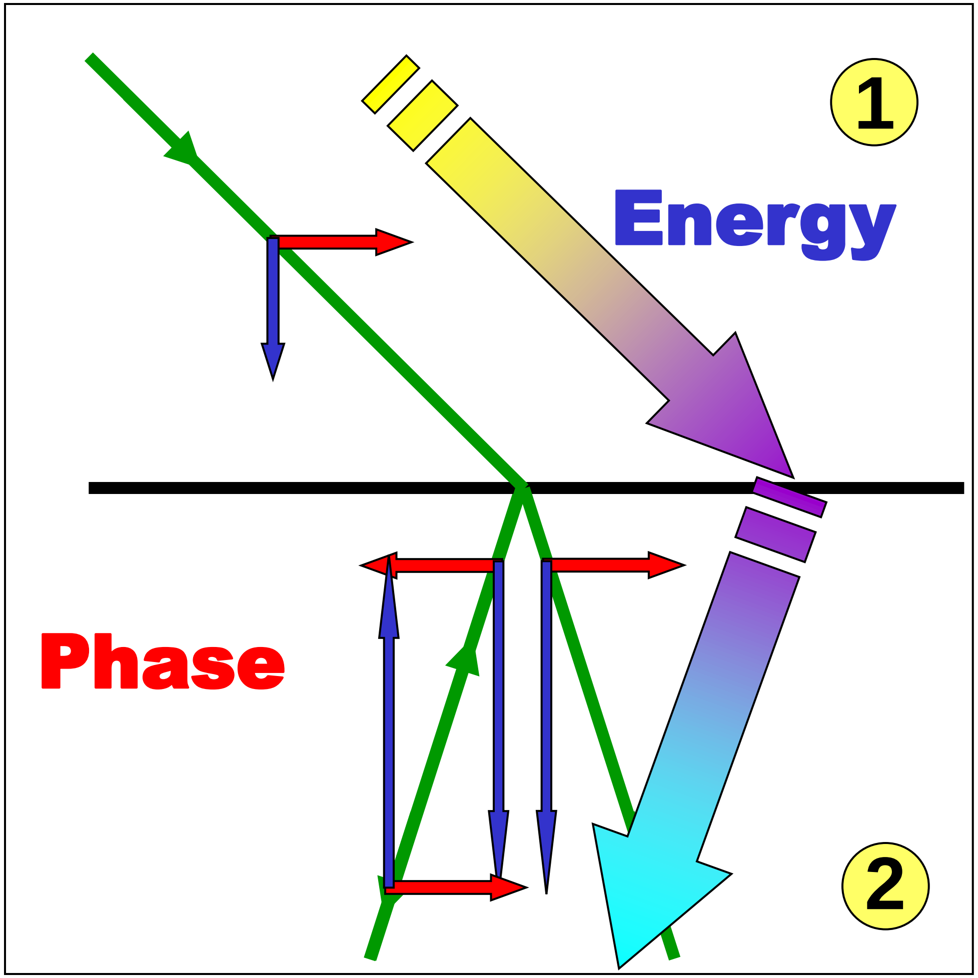
$$v_{p1} = \frac{c}{n_1}$$

$$v_{p2} = \frac{c}{n_2}$$

Def. of refractive index

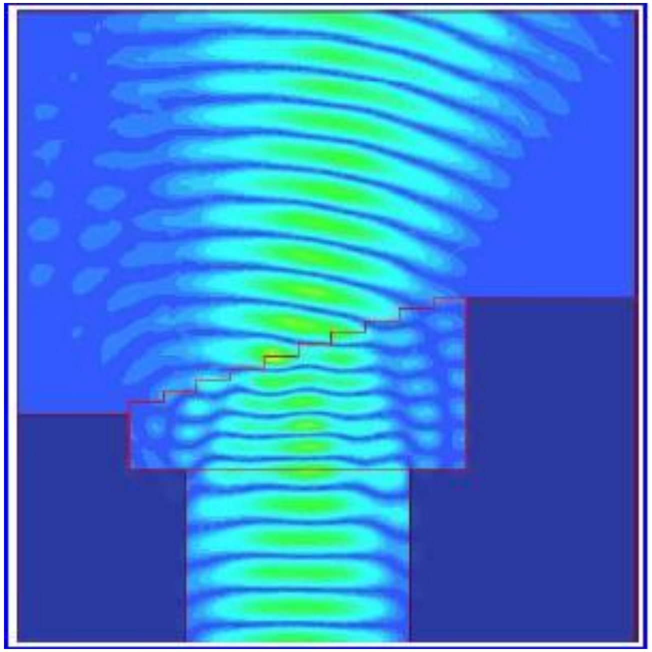
$$\boxed{n = \pm\sqrt{\varepsilon}}$$

I it possible?

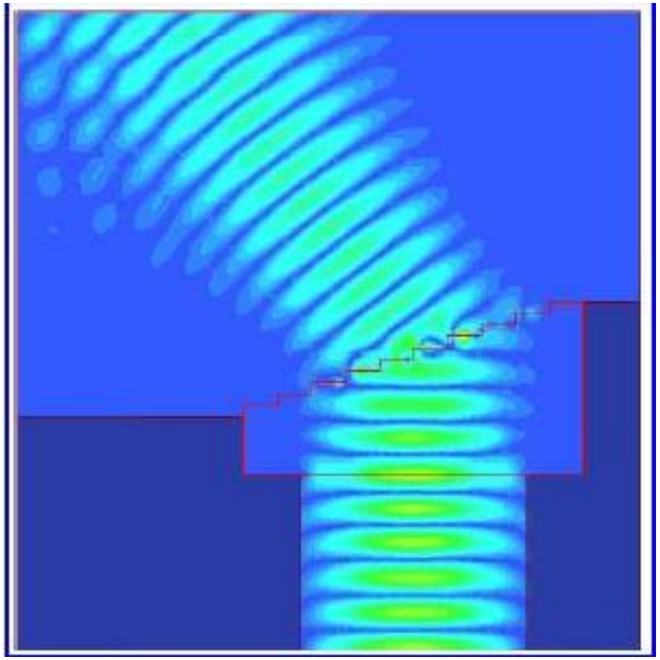


Yes as a revers wave

Załamanie na pryzmacie



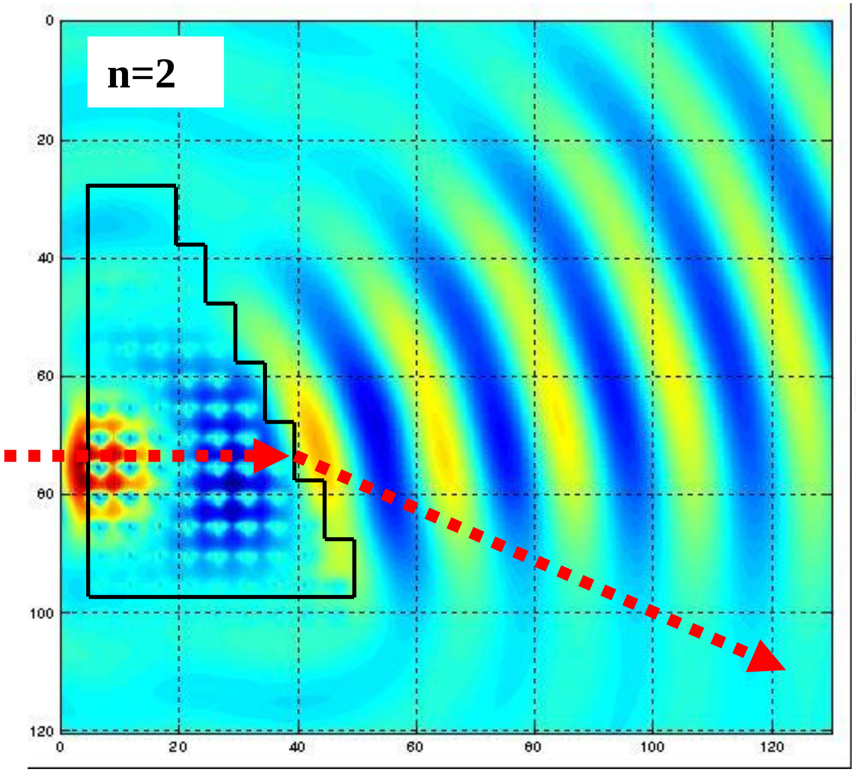
n>0

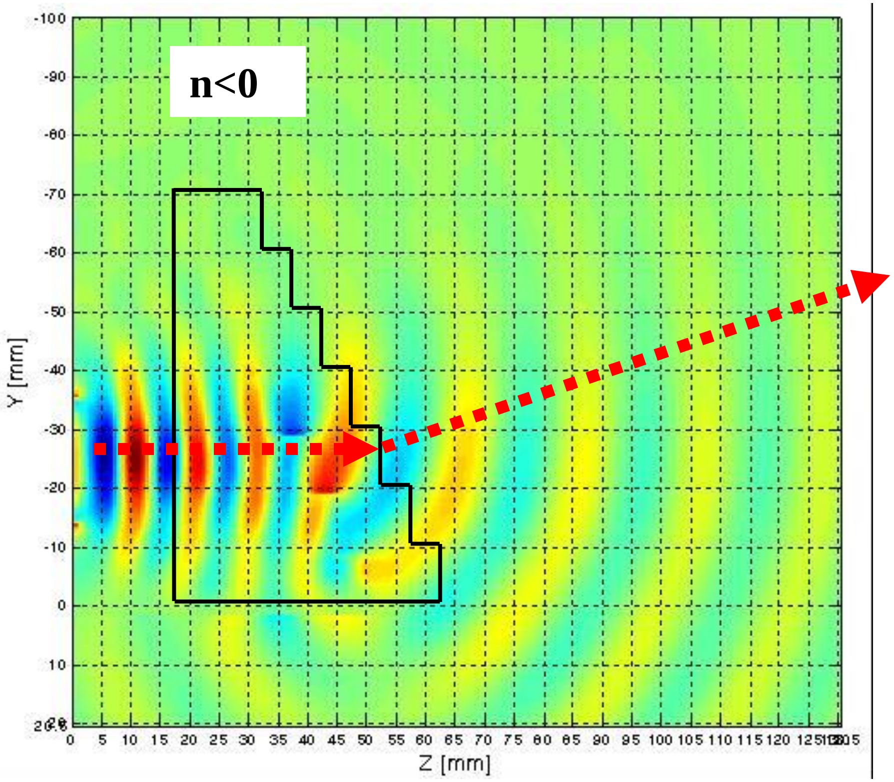


n<0

Raj Mittra, A Critical Look at the Performance Enhancement of Small Antennas using Metamaterials,

PRACE WŁASNE – ZAŁAMANIE NA PRYZMACIE

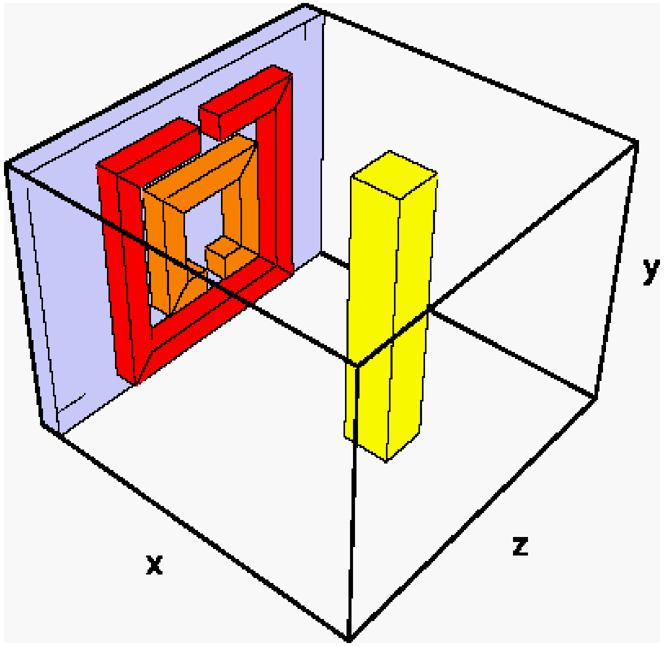




Structure of the unit cell

EM wave propagates in the *z* -direction

Periodic boundary conditions
are used in transverse directions



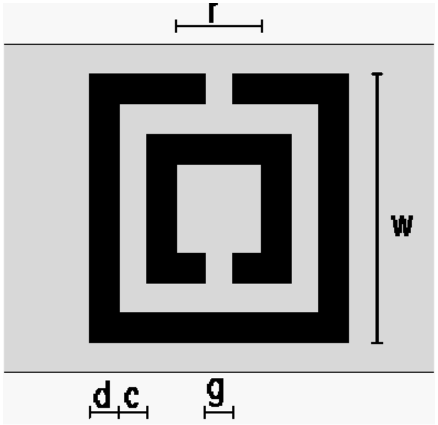
Polarization: *p* wave: **E** parallel to *y*
s wave: **E** parallel to *x*

For the *p* wave, the resonance frequency interval exists, where with Re μ_{eff} <0, Re ε_{eff}<0 and Re n_p <0.
For the *s* wave, the refraction index $n_s = 1$.

Typical size of the unit cell: 3.3 x 3.67 x 3.67 mm

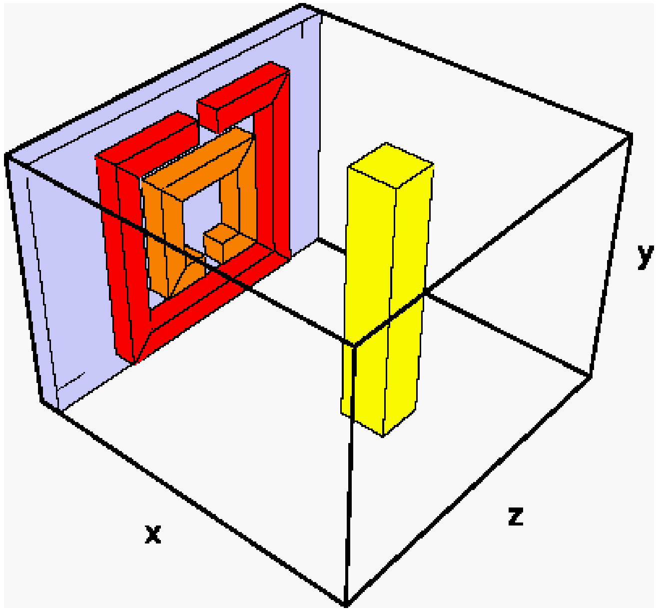
Typical permittivity of the metallic components: $e_{metal} = (-3+5.88\ i) \times 10^5$

Structure of the unit cell:



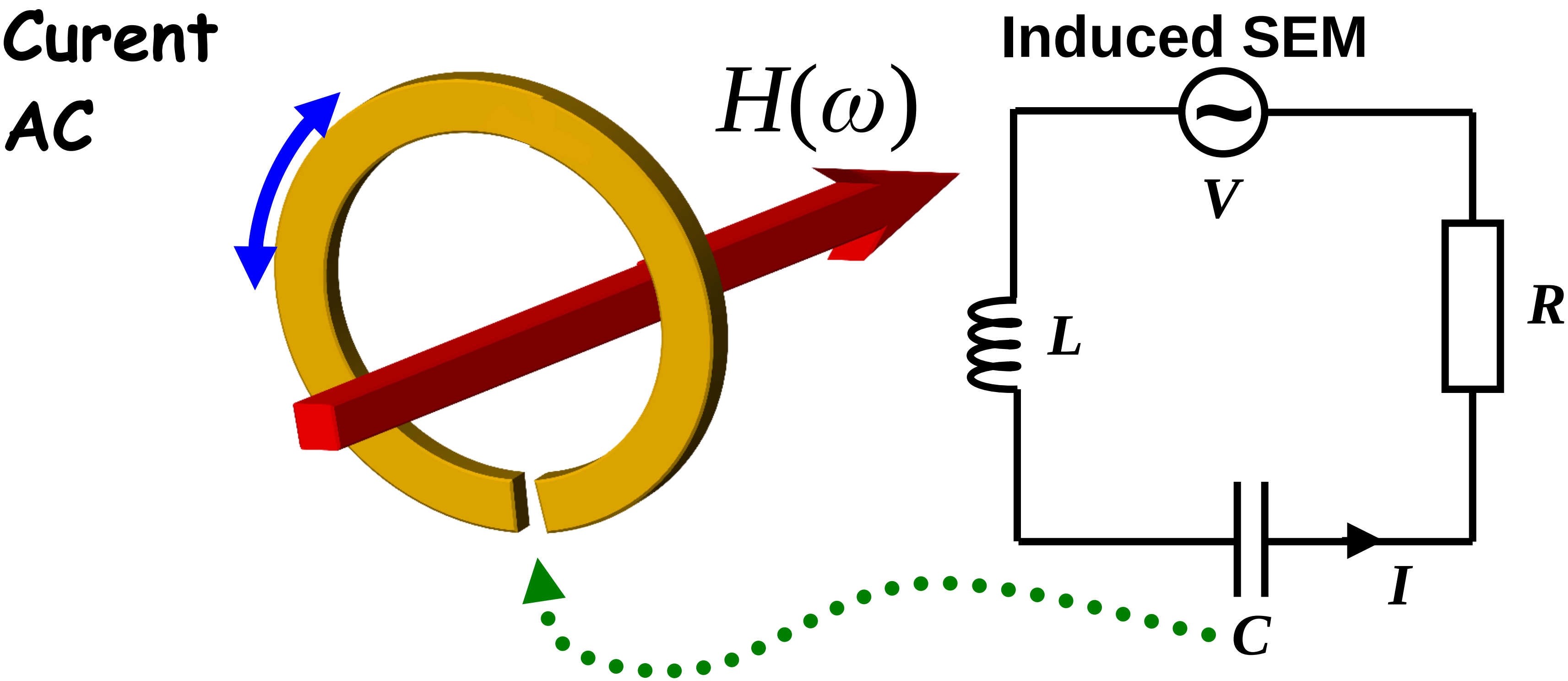
SRR

EM waves propagate in the *z*-direction. Periodic boundary conditions are used in the *xy*-plane



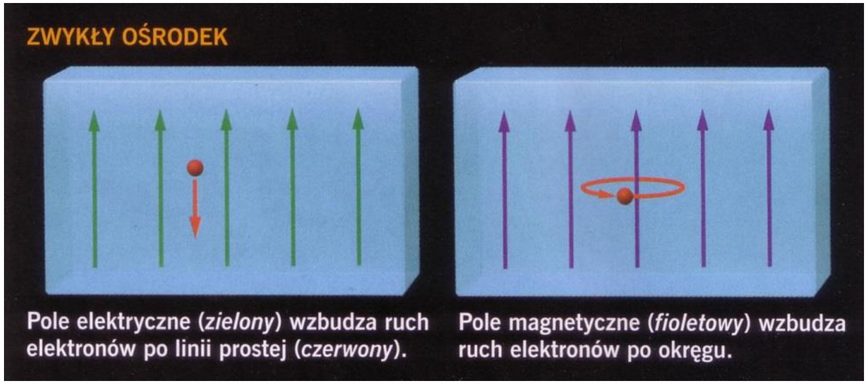
LHM

Ring with space as a magnetic resonans element



$$\boxed{V = L\frac{dI}{dt} + IR + \frac{Q}{C}}$$

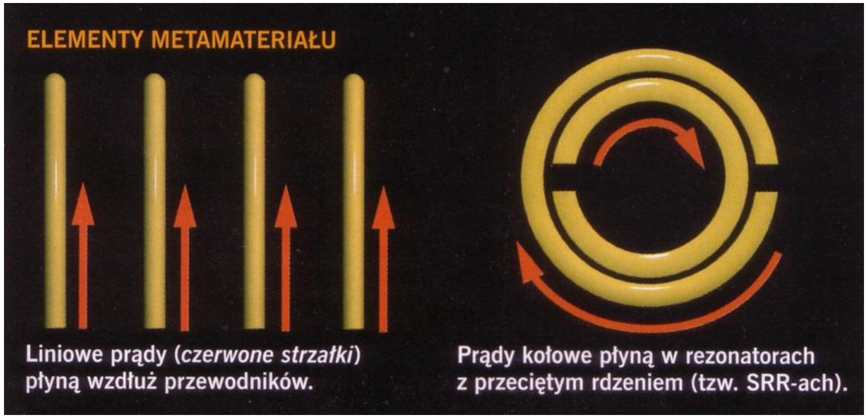
$$\Rightarrow \mu(\omega)$$



ZWYKŁY OŚRODEK

Pole elektryczne (*zielony*) wzbudza ruch elektronów po linii prostej (*czerwony*).

Pole magnetyczne (*fioletowy*) wzbudza ruch elektronów po okręgu.



ELEMENTY METAMATERIAŁU

Liniowe prądy (*czerwone strzałki*) płyną wzdłuż przewodników.

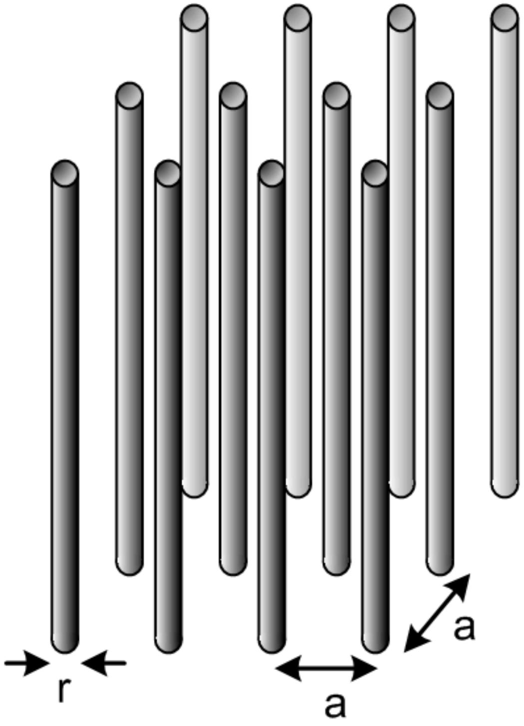
Prądy kołowe płyną w rezonatorach z przeciętym rdzeniem (tzw. SRR-ach).

NOWA STRUKTURA

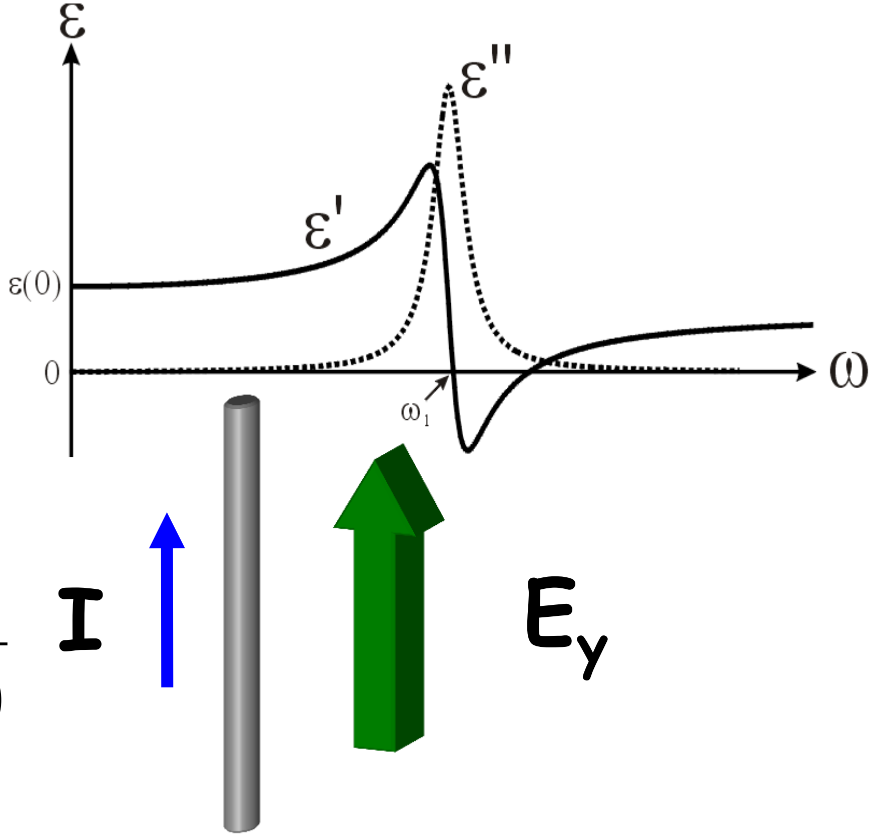
Metamateriał jest zbudowany z sieci przewodników i SRR-ów o rozmiarach mniejszych niż długość fali elektromagnetycznej, której używa się w tym ośrodku.

Resonans phenomena

Rezonans in thin wires goes to negative ε

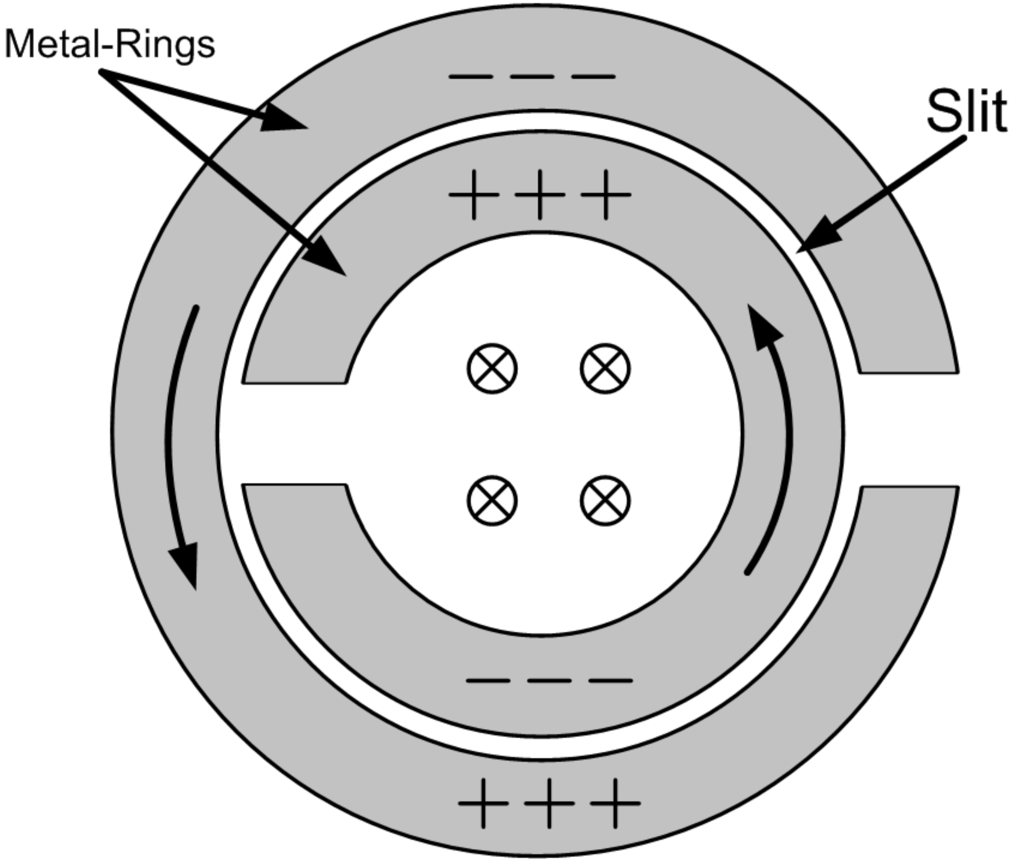


$$\omega_P = \frac{2\pi c^2}{a^2 \ln(a/r)}$$

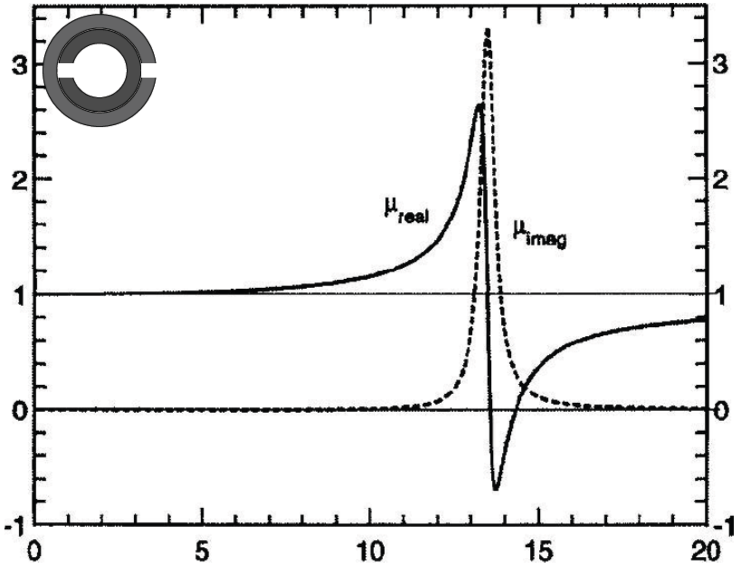


Electrical rezonans (negative ε)

Resonans phenomena



Magnetic resonans in SRR goes to negative μ



J.B.Pendry et al., 1999

Frequency dispersion of LH medium

- Energy density in the dispersive medium

$$W = \frac{\partial(\varepsilon\omega)}{\partial\omega}E^2 + \frac{\partial(\mu\omega)}{\partial\omega}H^2$$

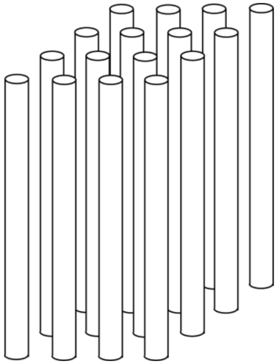
- Energy density ***W*** must be positive and this requires

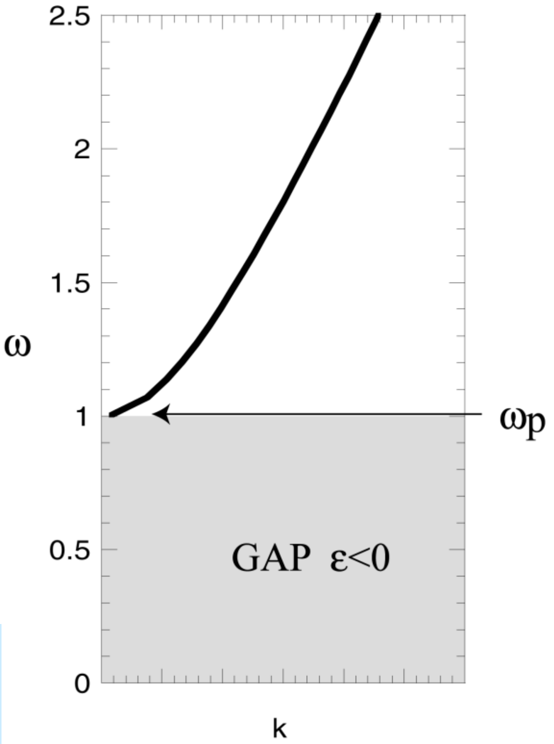
$$\frac{\partial(\varepsilon\omega)}{\partial\omega} > 0\,; \qquad \frac{\partial(\mu\omega)}{\partial\omega} > 0$$

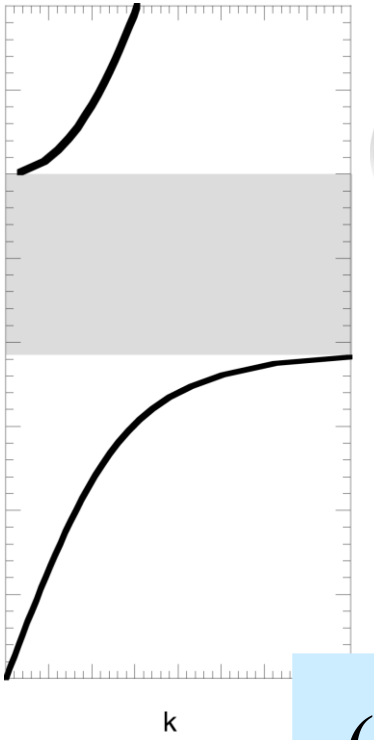
- *LH medium is always dispersive*

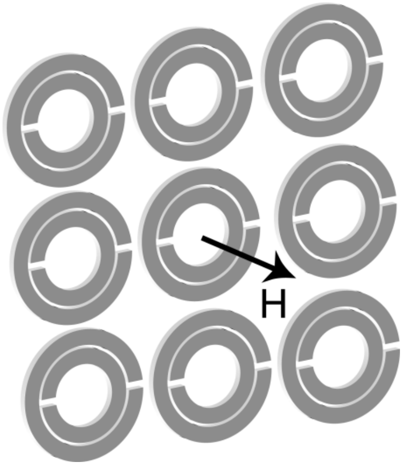
- According to the Kramers-Kronig relations –
  it is *always dissipative*

Metamaterials Extend Properties









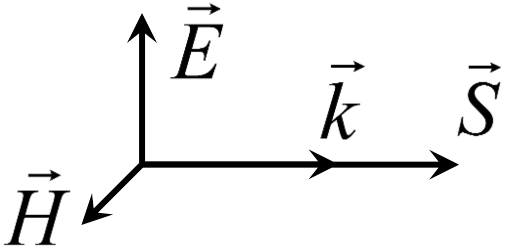
$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$

$$\mu(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - \omega_0^2}$$

J. B. Pendry

Energy flux in plane waves

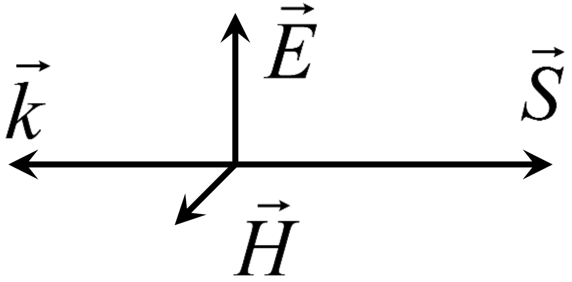
- Energy flux (Pointing vector): $\vec{S} = \frac{c}{4\pi}\left[\vec{E} \times \vec{H}\right]$
  - Conventional (right-handed) medium



$$\vec{S} \uparrow\uparrow \vec{k}$$

$$\vec{V}_{gr} \uparrow\uparrow \vec{V}_{ph}$$

  - Left-handed medium



$$\vec{S} \uparrow\downarrow \vec{k}$$

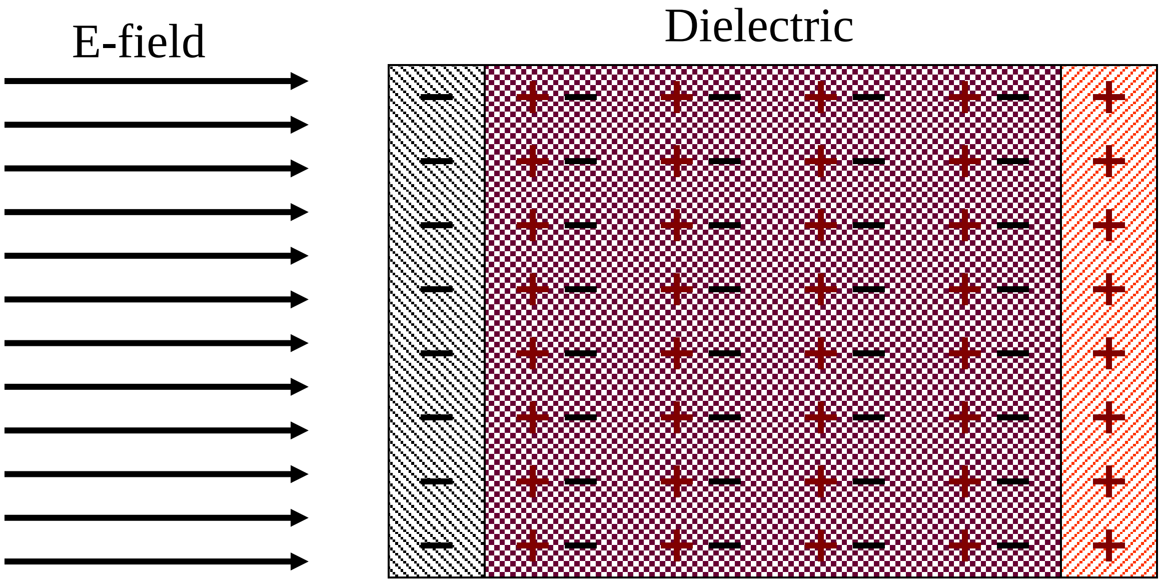
$$\boxed{\vec{V}_{gr} \uparrow\downarrow \vec{V}_{ph}}$$

Dielectrics

- Electric field is reduced inside dielectric
  - Space charge partly cancels
  - $E / E_v = \varepsilon / \varepsilon_0$
- Also possible for magnetic field
  - but usually $B = B_v$ and $\mu = \mu_0$

Index of refraction: n

- Result: light speed reduced $v = c \sqrt{(\varepsilon_0 / \varepsilon)} = c/n < c$
- Wavelength also reduced $\lambda = \lambda_0 / n$



Conventions

- **Polarization of materials**
- **Separate into material and vacuum parts**
  - $\varepsilon \mathbf{E} = \varepsilon_0 \mathbf{E} + \mathbf{P}$
  - **linear material:** $\mathbf{P} = \varepsilon_0 \chi \mathbf{E}$
- **Material part is due to small charge displacement**

- **Similar equation for magnetic polarization**
  - $\mathbf{B} / \mu = \mathbf{B} / \mu_0 + \mathbf{M}$
- **Most optical materials have** $\mu = \mu_0$

Refractive index

- $n^2 = (\varepsilon/\varepsilon_0)(\mu/\mu_0) = [1 + \mathbf{P} / (\varepsilon_0 \mathbf{E})] / [1 + \mu_0 \mathbf{M}/\mathbf{B}]$
- **Drop magnetic part**
- $n^2 = [1 + \mathbf{P} / (\varepsilon_0 \mathbf{E})]$

Material part of polarization

- **Polarization due to small displacements**
- **Examples:**
    - **Polar molecules align in field**
    - **Non-polar molecules – electron cloud distorts**
- **Optical frequencies**
    - **Nucleus cannot follow fast enough**
        - **Too heavy**
    - **Consider mainly electron cloud**

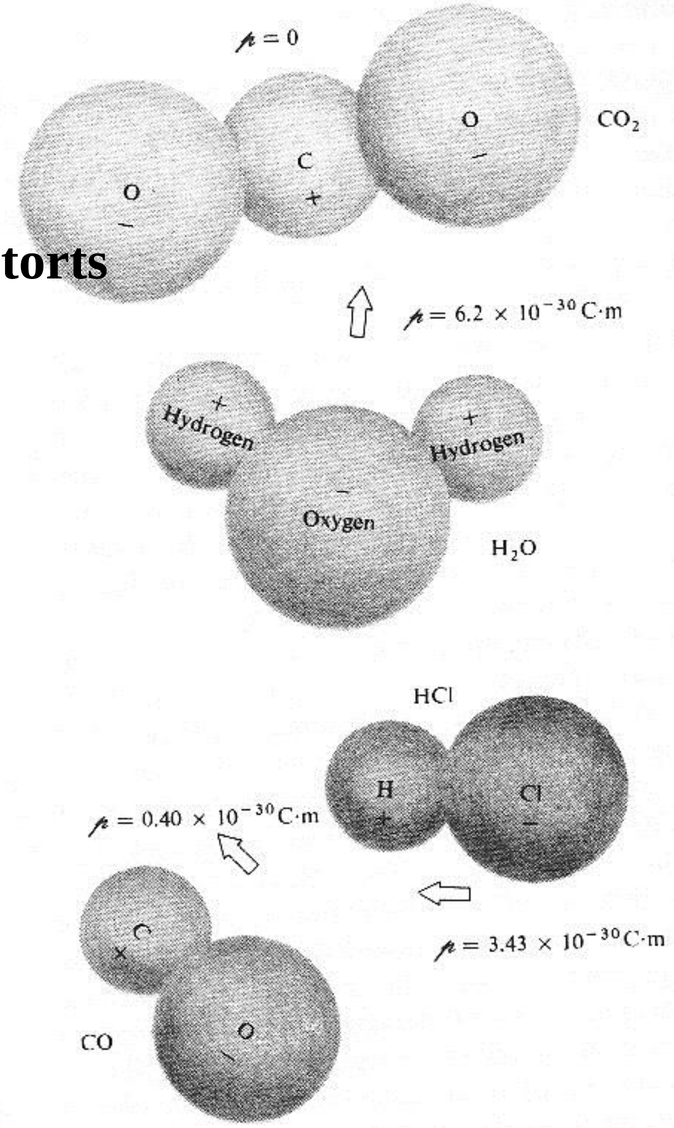
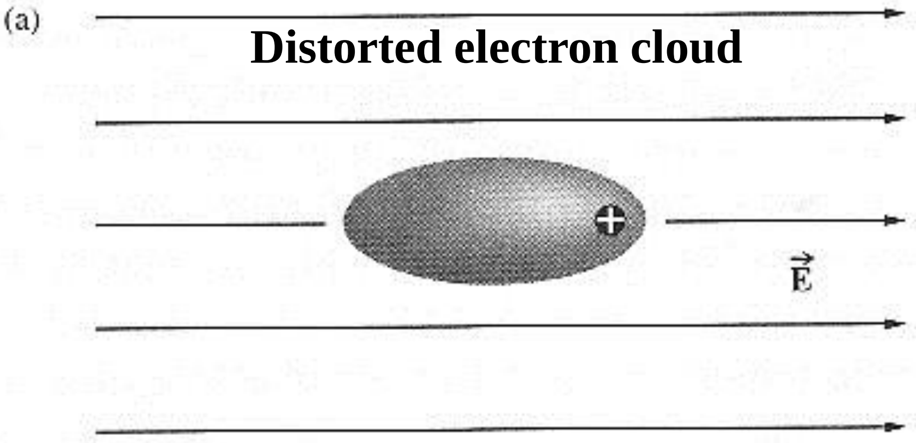


Figure 3.37 Assorted molecules and their dipole moments.



Distorted electron cloud

Model of atom

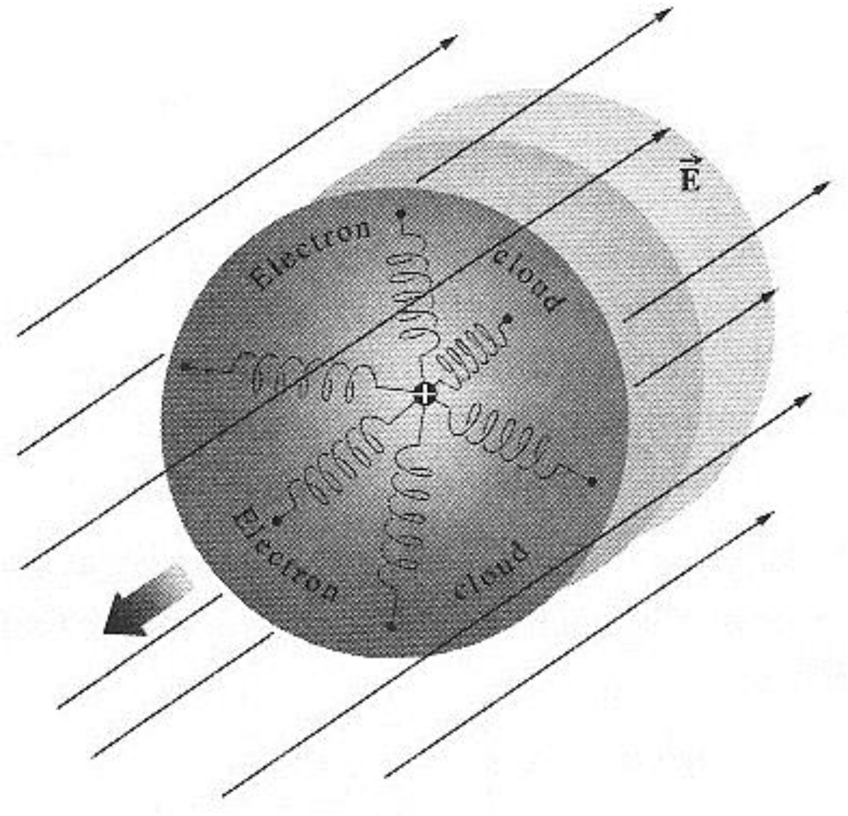
- **Lowest order – everything is harmonic oscillator**

Model atom as nucleus and electron connected by spring

- **Newton's law: $F = m a$**
- **Spring restoring force: $F_R = - k x = - m \omega_0^2 x$**
  - **Resonant freq of mass-spring: $\underline{\omega_0 = \sqrt{k/m}}$**
- **Driving force: $F_D = q_e E$**
- **Damping force: $F_\gamma = - m \gamma v$**

Resultant equation:

- **$q_e E - m \gamma dx/dt - m \omega_0^2 x = m d^2x/dt^2$**
- **Free oscillation: $(E=0, \gamma=0)$**
  - **$d^2x/dt^2 + \omega_0^2 x = 0$**
- **Use complex representation for E**
  - **$E = E_0 e^{i \omega_0 t}$**
- **Forced oscillation:**
  - **motion matched drive frequency**
  - **$x = x_0 e^{i \omega t}$**
- **Result: $x_0 = (q/m) E_0 / [\omega_0^2 - \omega^2 + i\gamma\omega]$**



Refractive index & dispersion

- **Drude model**
- **Polarization of atom**
  - **Define as charge times separation**
  - **$P_A = q_e x$**
- **Material has many atoms: N**
- **Material polarization:**
- **$P = q_e x N$**

Recall previous results

- **$n^2 = [1 + P / (\varepsilon_0 E)]$**
- **$x_0 = (q/m) E_0 / [\omega_0^2 - \omega^2 + i\gamma\omega]$**

Result is dispersion equation:

$$n^2 = 1 + \frac{Nq_e^2}{\varepsilon_0 m_e}\left(\frac{1}{\omega_0^2 - \omega^2 + i\gamma\omega}\right)$$

Correction for real world complications:

$$\frac{n^2 - 1}{n^2 + 2} = \frac{Nq_e^2}{3\varepsilon_0 m_e}\sum_j\left(\frac{f_j}{\omega_{0j}^2 - \omega^2 + i\gamma\omega}\right)$$

Sum over all resonances in material

f **is oscillator strength of each transition**

~ 1 for allowed transition

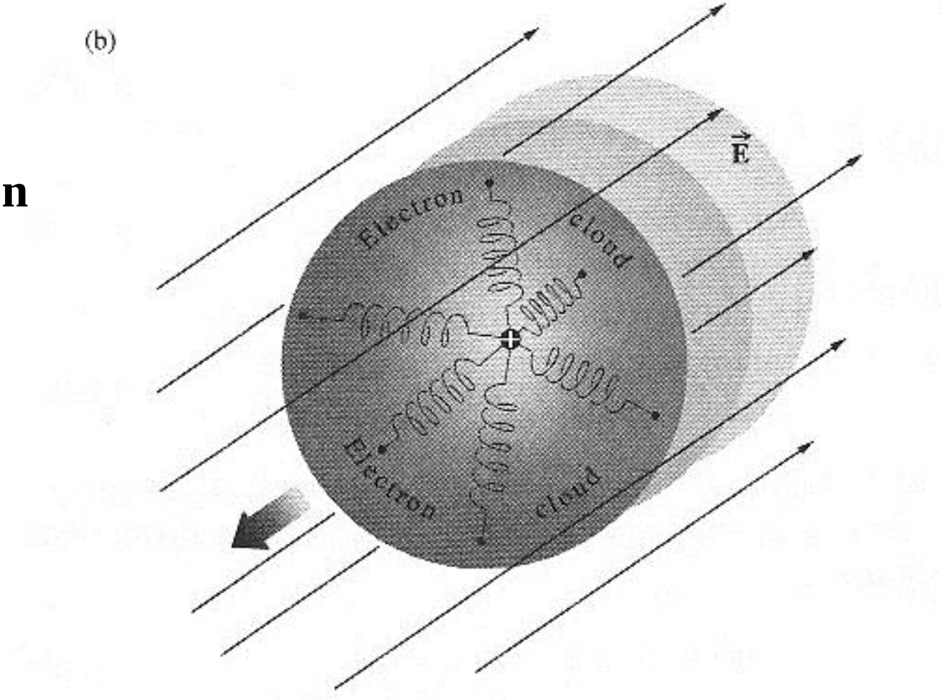


Figure 3.38 (*a*) Distortion of the electron cloud in response to an applied $\vec{E}$-field. (*b*) The mechanical oscillator model for an isotropic medium—all the springs are the same, and the oscillator can vibrate equally in all directions.

Anomalous dispersion

Above all resonance frequencies

- **Dispersion negative**
- **Refractive index < 1**
- **v > c**

X-ray region

$$\frac{n^2-1}{n^2+2}=\frac{Nq_e^2}{3\varepsilon_0 m_e}\sum_j\left(\frac{f_j}{\omega_{0j}^2-\omega^2+i\gamma\omega}\right)$$

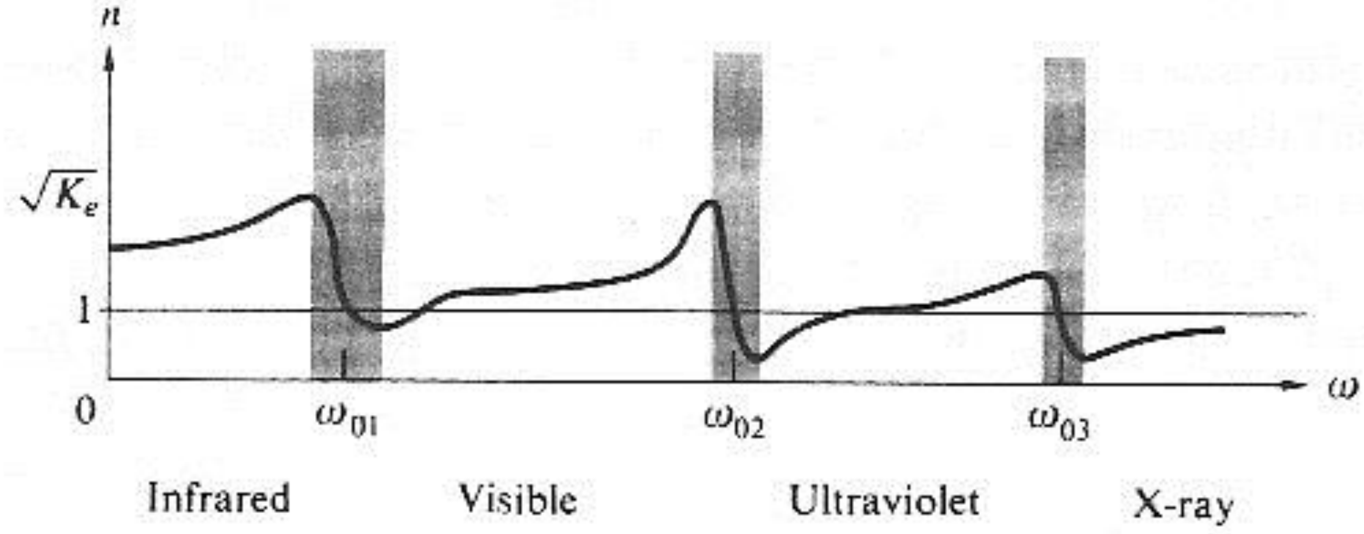


Figure 3.41 Refractive index versus frequency.

Plasmons

- **Assume ω_0 = 0 for conduction electrons -- keep damping** $\nabla^2\vec{E} = \varepsilon\mu\frac{\partial^2\vec{E}}{\partial t^2} + \mu\sigma\frac{\partial\vec{E}}{\partial t}$

$$n^2 = 1 + \left(\frac{\omega_{plasma}^2}{\omega_0^2 - \omega^2 + i\gamma\omega}\right) \quad \rightarrow n^2 = 1 - \frac{\omega_{plasma}^2}{\omega(\omega - i\gamma)} \qquad \gamma = \nu_{collision}$$

- **Transition occurs when optical frequency exceeds collision frequency**
  - **depends on dc resistivity**
  - **lower resistivity = higher frequency transition**
- **Above collision frequency -- Plasmons**

- **Plasmons quenched at plasma frequency**
- **Example -- silver**
  - **σ = 6.17 x 10^7 /Ω-m, ω_{plasma} = 9.65 x 10^{14} Hz (311 nm, 4 eV)**
  - **ν_e = 1/(13 fs) = 7.7 x 10^{13} Hz**
  - **plasmons shorter than ~ 23.5 microns wavelength**

Metals and plasma frequency

- **“Free” conduction electrons – resonance at zero $\omega_0 = 0$**

Plasma frequency

$$\omega_{plasma}^2 = \frac{Nq_e^2}{\varepsilon_0 m_e}$$

$$n^2 = 1 + \frac{Nq_e^2}{\varepsilon_0 m_e}\left(\frac{1}{\omega_0^2 - \omega^2 + i\gamma\omega}\right) \rightarrow 1 - \omega_{plasma}^2\left(\frac{1}{\omega^2 - i\gamma\omega}\right)$$

- **Metals become transparent at very high frequency – UV -- X-ray**
- **Neglect damping**

$$\rightarrow n^2 = 1 - \frac{\omega_{plasma}^2}{\omega^2}$$

- **At low frequency $n^2 < 0$**
  - **refractive index complex**
  - **absorption**
- **At high frequency**
  - **n becomes real**
  - **like dielectric**
  - **transparency**

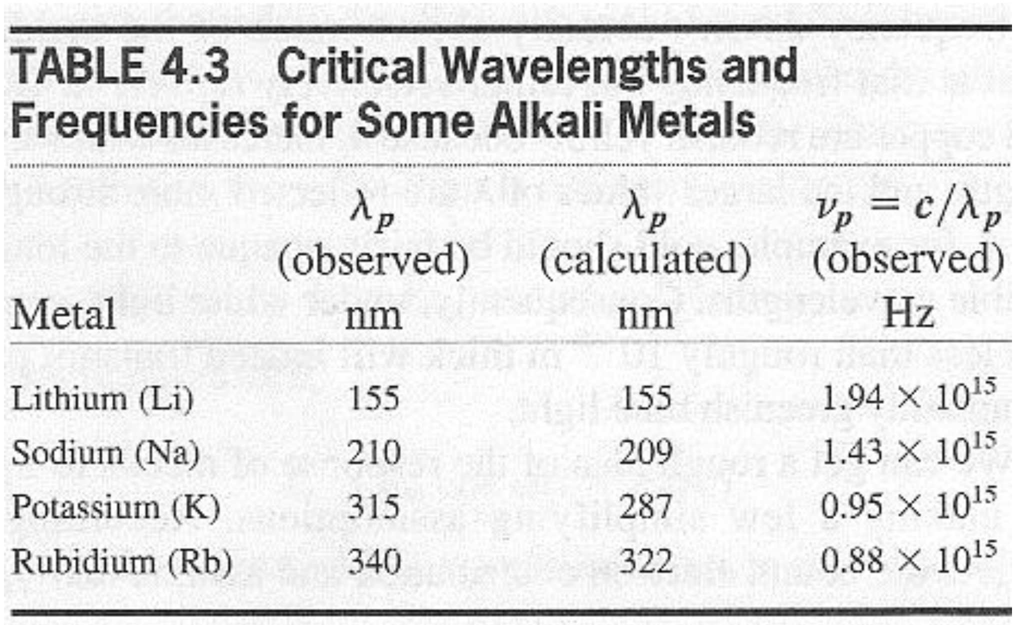


TABLE 4.3 Critical Wavelengths and Frequencies for Some Alkali Metals

Metal	λ_p (observed) nm	λ_p (calculated) nm	$\nu_p = c/\lambda_p$ (observed) Hz
Lithium (Li)	155	155	1.94×10^{15}
Sodium (Na)	210	209	1.43×10^{15}
Potassium (K)	315	287	0.95×10^{15}
Rubidium (Rb)	340	322	0.88×10^{15}

Skin depth in metals

Electrons not bound

- **Current can flow**
- **Conductance σ ~ 1/R causes loss**
- **Maxwell's equations modified**

$$\nabla^2 \vec{E} = \varepsilon\mu \frac{\partial^2 \vec{E}}{\partial t^2} + \sigma\mu \frac{\partial E}{\partial t}$$

- **Wave solution also modified**
  - **Express as complex refractive index**
  - **$n_{complex} = n_R - i\,\alpha\, c / (2\omega)$**
  - **$E = E_0\, e^{-\alpha z/2}\, e^{i(kz-\omega t)}$**
- **Result for propagation in metal:**
- **$I = I_0\, e^{-\alpha z}$, $1/\alpha$ = skin depth**

Metals: $1/\alpha \ll \lambda$

- **Example copper:**
  - **λ = 100 nm, $1/\alpha$ = 0.6 nm = λ / 170**
  - **λ = 10 μm, $1/\alpha$ = 6 nm = λ / 1700**
  - **λ = 10 mm, $1/\alpha$ = 0.2 μm = λ / 50,000**
  - **$1/\alpha \sim \sqrt{\lambda}$**
- **Similar to n >> 1**
- **Strong reflection – not much absorption**

Metal	**Density**	**Ro** (microOhm cm)	**f** (GHz)	**skin depth** (microns)
Aluminum	2.70 g/cc	2.824;	478.59	0.12
Copper	8.89 g/cc	1.7241;	409.1	0.1033
Gold	19.3 g/cc	2.44;	403.8	0.12
Mercury	13.546 g/cc	95.783;	10,975.	0.15
Silver	10.5 g/cc	1.59;	260	0.12

Drude -- low frequency limit ω → 0

$$n^2 = 1 - \omega_{plasma}^2 \left(\frac{1}{\omega^2 - i\gamma\omega} \right) \to i\,\frac{\omega_{plasma}^2}{\gamma\omega}$$

$$k = \frac{2\pi n}{\lambda} = \frac{2\pi}{\lambda}\frac{(1+i)}{\sqrt{2}}\frac{\omega_{plasma}}{\sqrt{\gamma\omega}}$$

$$\alpha = \omega_{plasma}\sqrt{\frac{\pi}{\lambda\gamma c}}$$

Plasmons and nano optics

- **Small metal particles can act like inductors, capacitors**
- **Maxwell's equation for current density:**
  - **Separate into vacuum and metal parts**

$$\sigma' = i\omega\varepsilon_0\left(1 + \frac{P}{\varepsilon_0 E}\right)$$

Vacuum metal

- **Vacuum (or dielectric) part is capacitor**

$$\sigma_v = i\omega\varepsilon_0 = i\omega C$$

- **Metal part is inductor plus series resistor**

$$\sigma_m = \frac{-i\varepsilon_0\omega^2_{plasma}}{\omega - i\nu_{collision}} = \frac{1}{R + i\omega L}$$

- **RLC circuit parameters**
  - **Resonance frequency ω_0=1/sqrt(LC) = ω_{plasma}**
  - **Resonance width $\Delta\omega$ = R/L = $\nu_{collision}$**

- **Structure geometry can increase L and C**
  - **Strong local field enhancement possible in capacitor**

conductivity

$$J = \sigma E + \varepsilon\frac{\partial E}{\partial t} = \sigma' E$$

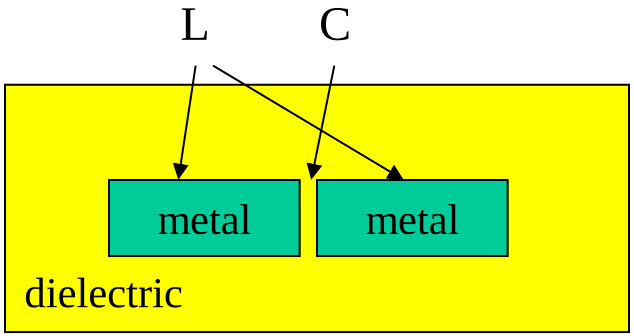
Displacement current

$$L = \frac{1}{\varepsilon_0\omega^2_{plasma}}$$

$$R = \frac{\nu_{collison}}{\varepsilon_0\omega^2_{plasma}}$$

$$C = \varepsilon_0$$

Nano optic RLC circuit



Properties of metals

Optical properties of conductive materials are desribed by interaction EM wave with free electrons

$$\boxed{\omega_p = \sqrt{\frac{Ne^2}{\varepsilon_0 m}}}$$

Plazma frequency ~ 10^{16} Hz

Complex permittivity $$\varepsilon = \varepsilon' - j\varepsilon'' = 1 - \boxed{\frac{\omega_p^2\tau}{\omega^2\tau - j\omega}}$$ **Drude model**

Relaxetion time ~ 10^{-14} s

Complex refractive index:

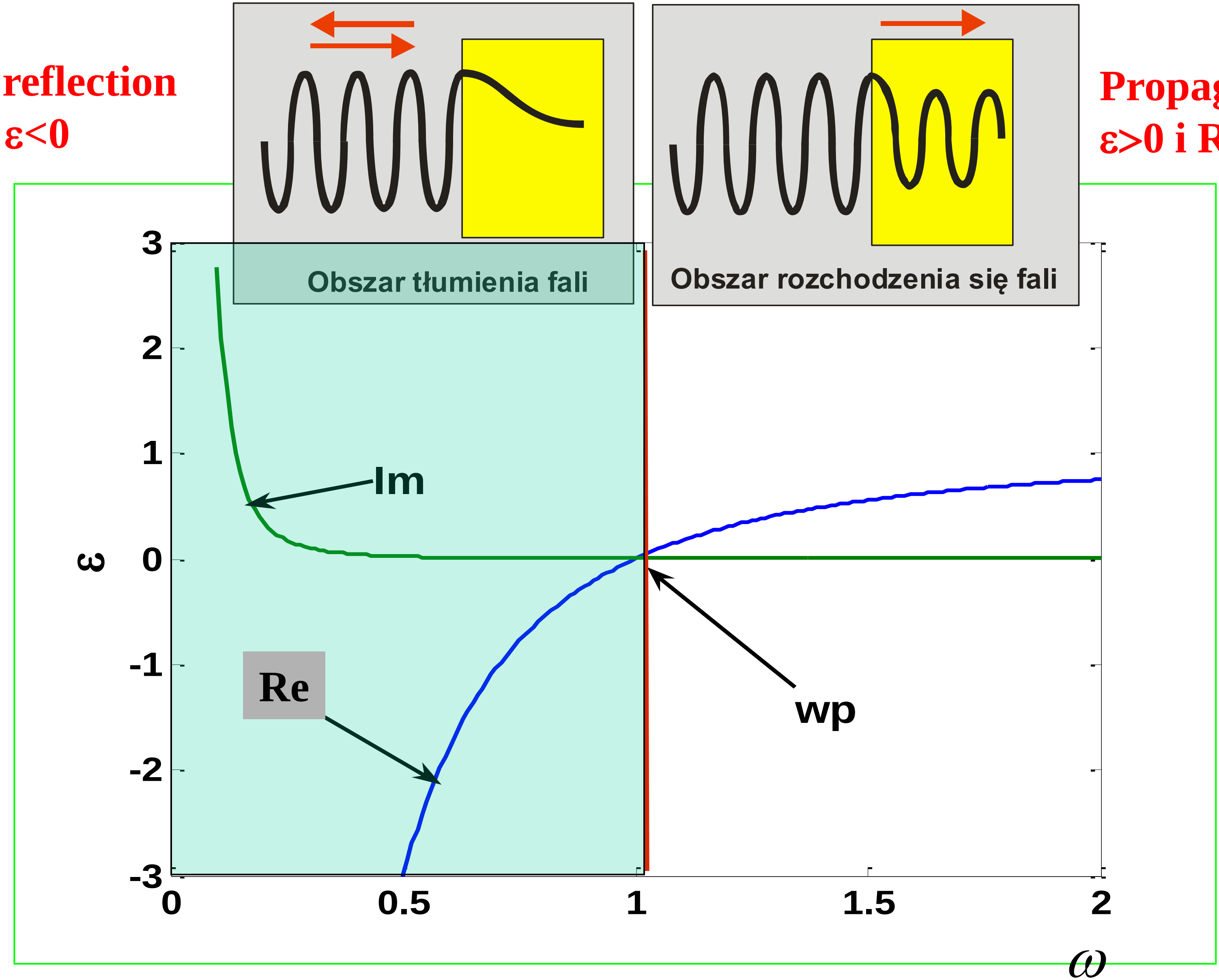
$$n = n' - jn''$$

$$\boxed{n = \sqrt{\varepsilon}}$$

DRUDE MODEL

Total reflection
ε<0

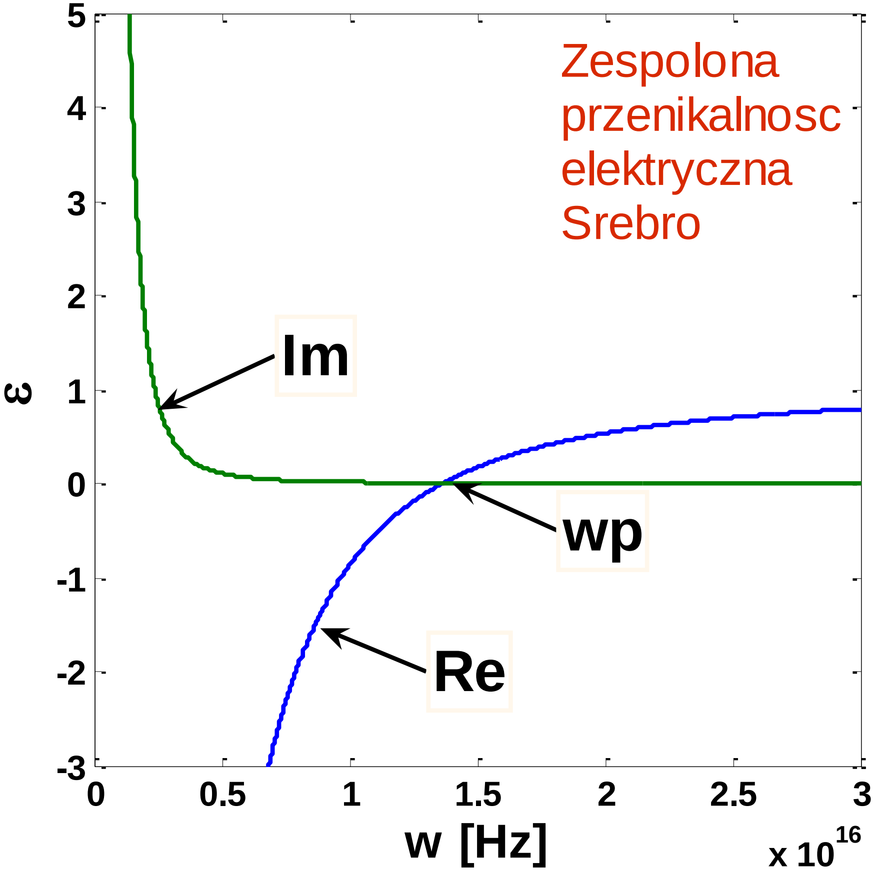
Propagation
ε>0 i Re(ε)=0

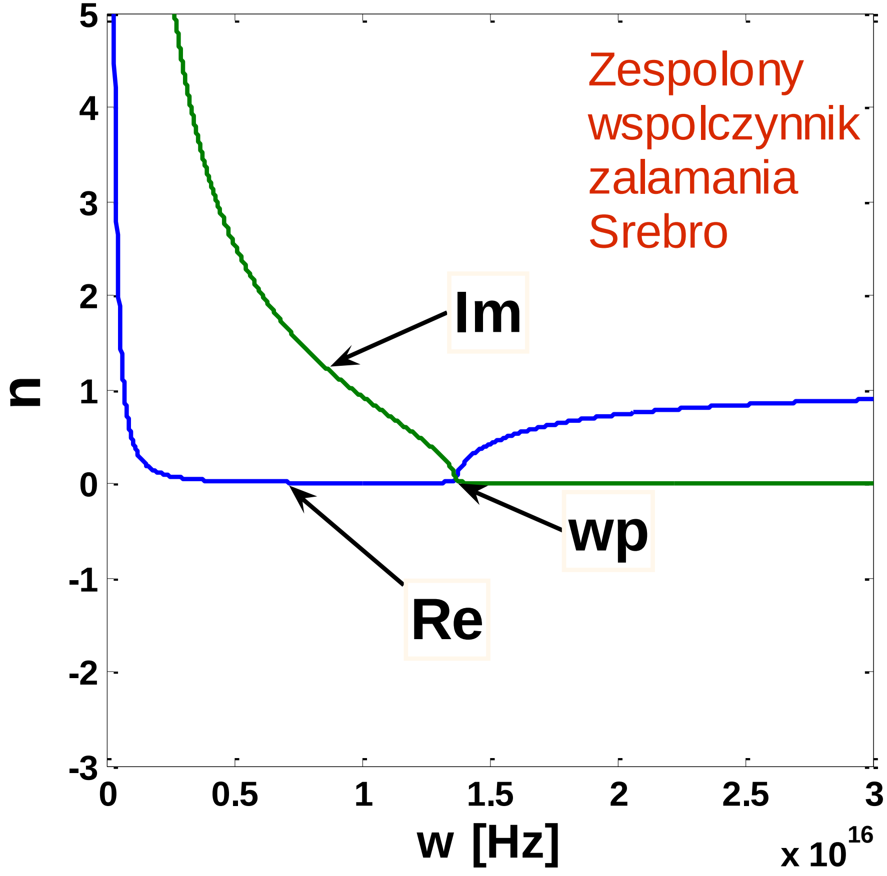


Mikrowave Infrared Visible Ultraviolet

$\frac{\omega}{\omega} \rightarrow$

Material constants - silver





ω_p=1.36884 10^16 Hz (~ 150 nm)

τ=1.37752 10^-14 s

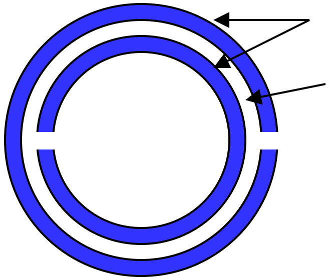
$$\boxed{n=\sqrt{\varepsilon}}$$

Left handed materials - fabrication

Need sign of ε and μ both negative

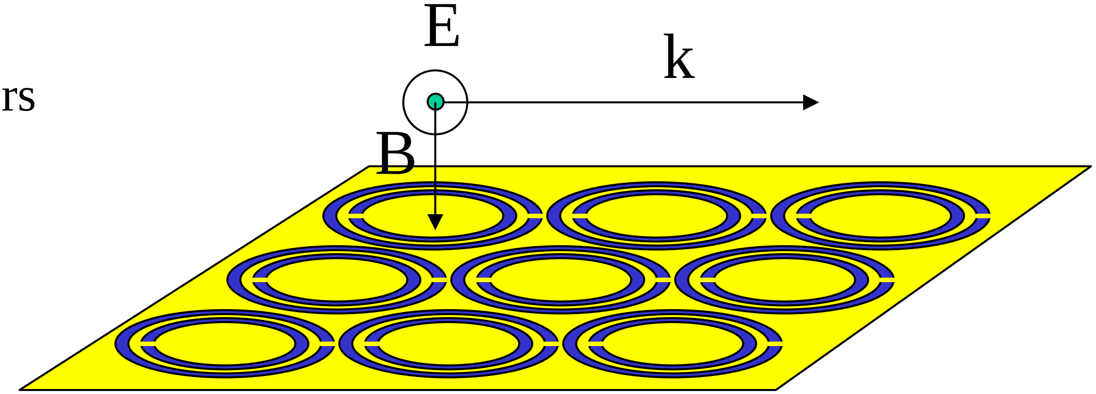
- Problem: magnetic part usually ~1
- Solution: Fool the EM field
  - LC circuit – material in capacitor gap indirectly modifies magnetic material

LC circuit



Loops are inductors

Gap is capacitor



Artificial “left-hand” material

First Left-Handed Test Structure for GHz range

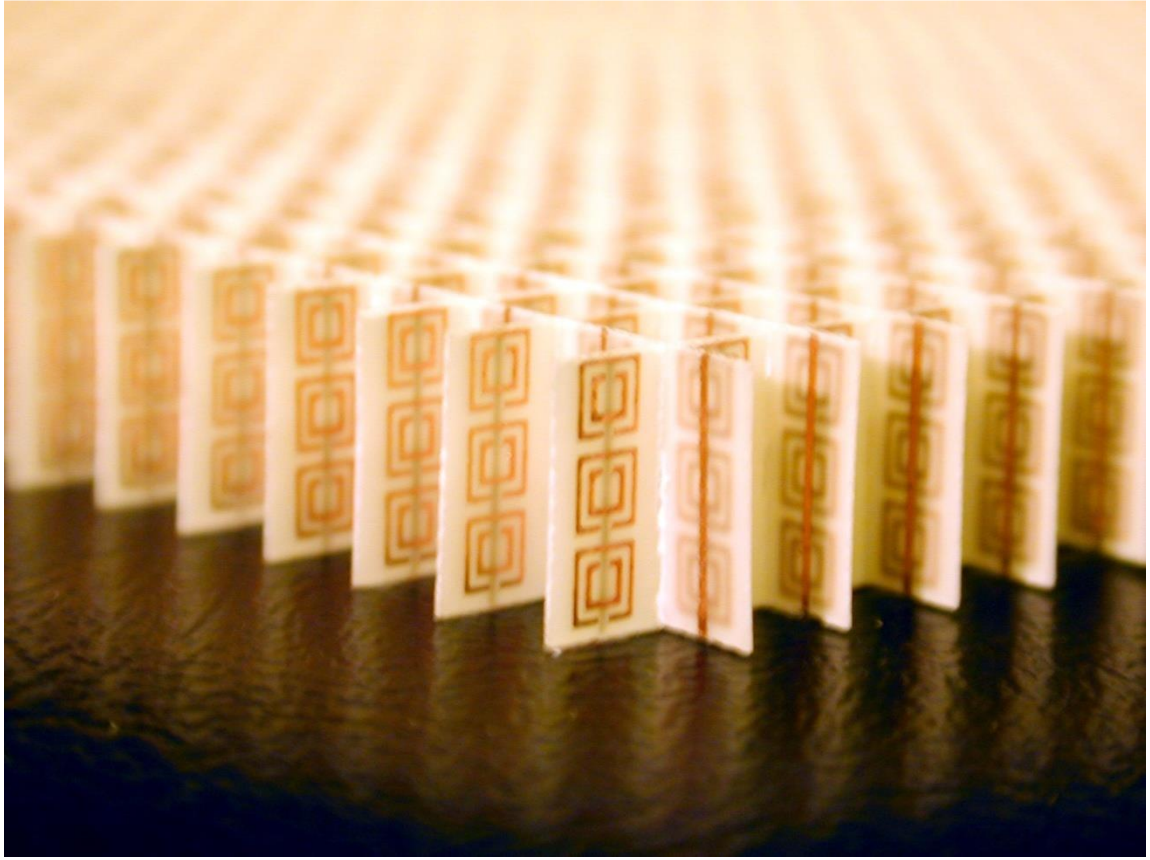
UCSD, PRL 84, 4184 (2000)

First results

λ = 6 cm)

*Smith et al: Phys. Rev. Lett. **84**, 4184 (2000)*

A 2-D Isotropic Structure

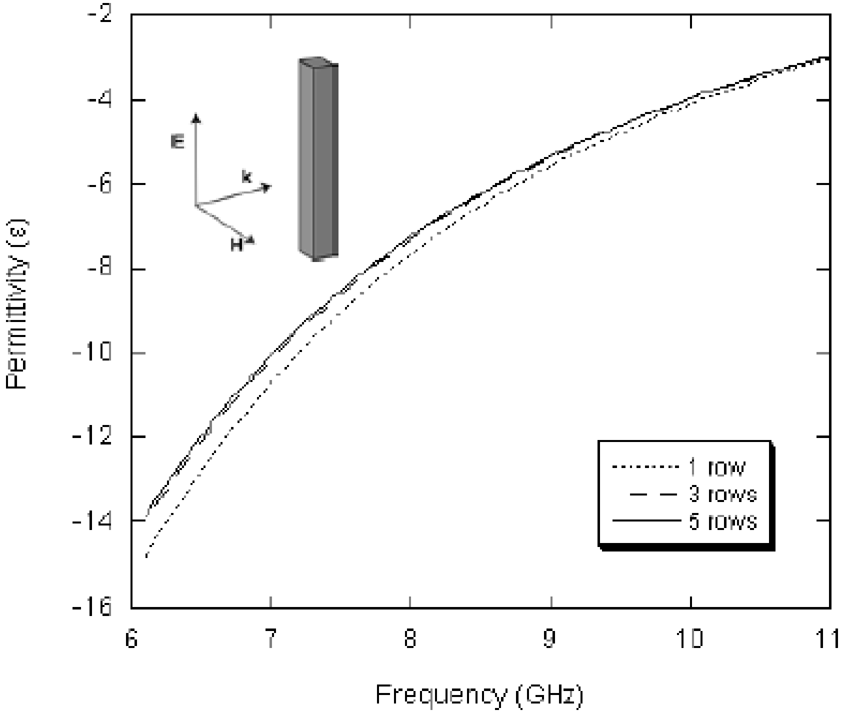


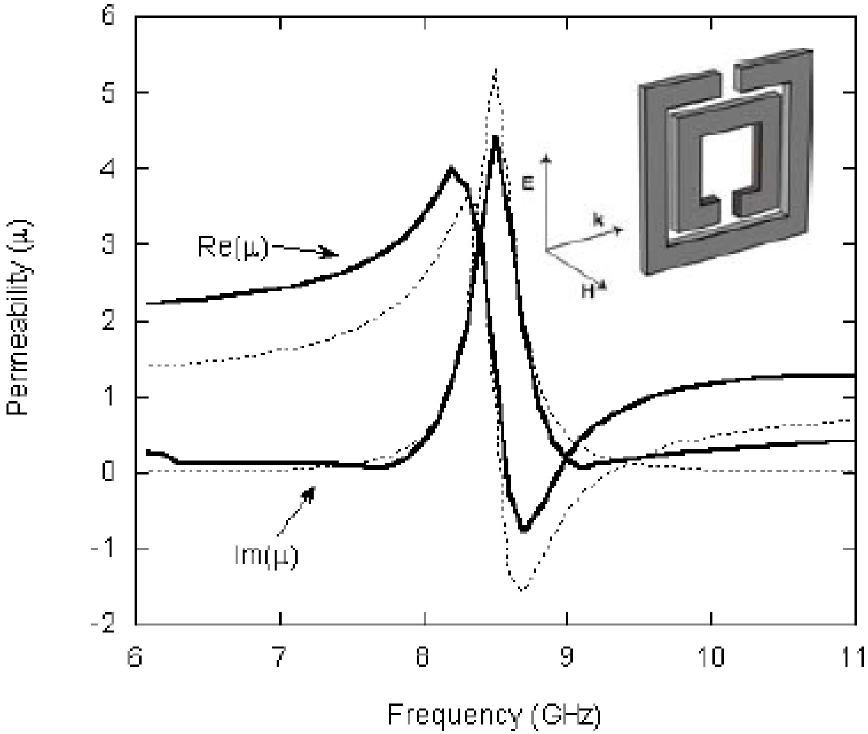
UCSD, APL 78, 489 (2001)

First results

D. Schurig et al.. Science ***314*** *(2006) 577 (λ = 3,5 cm, Duke University)*

Permittivity and Permability



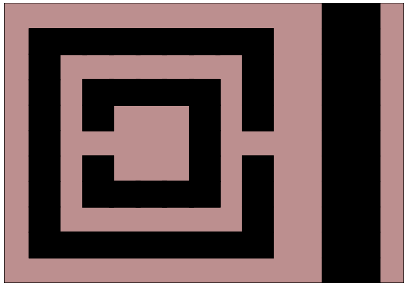


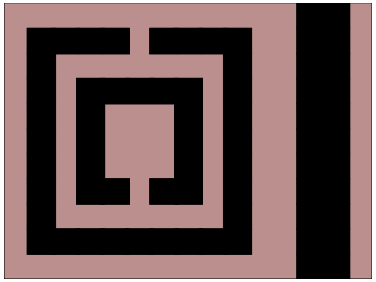
Efective permittivity of wires ε(ω)

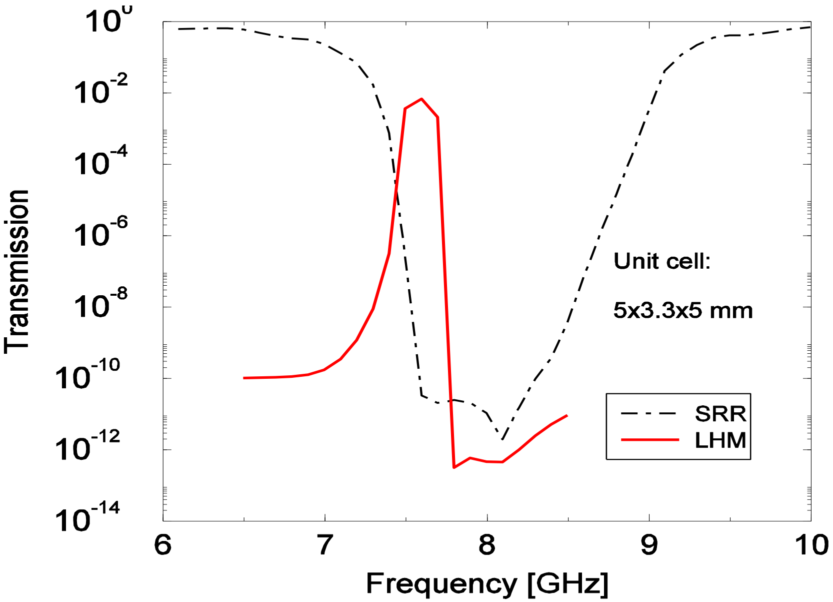
Efective permability of SRR μ(ω)

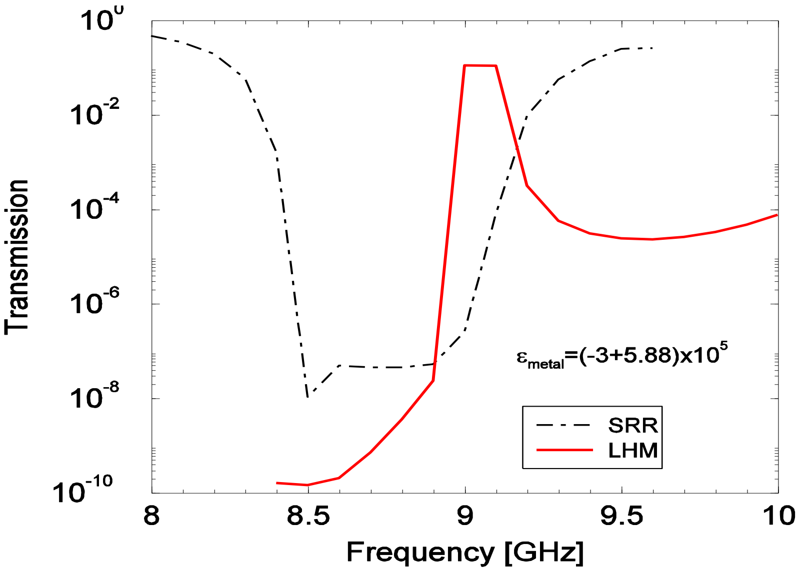
UCSD and ISU, PRB, 65, 195103 (2002)

Another 1D left-handed structure:









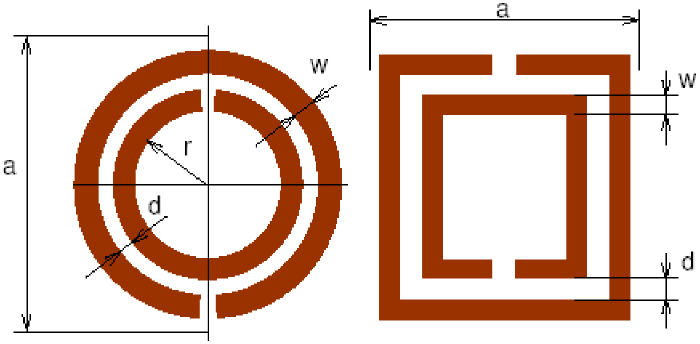
Both SRR and wires are located on the same side of the dielectric board.

Transmission depends on the orientation of SRR.

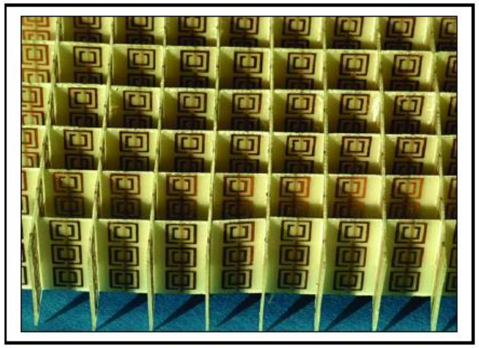
Bilkent & ISU APL 2002

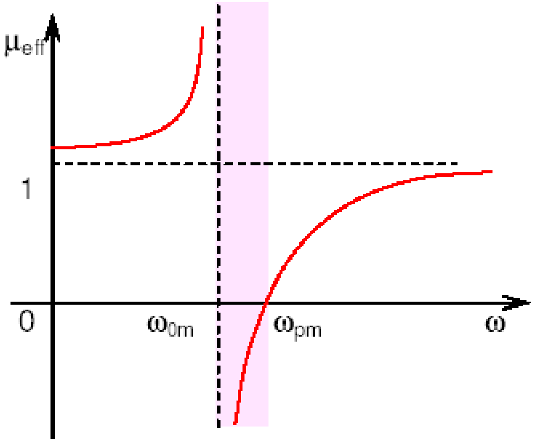
Metamaterial design- negative μ

SRR-split ring resonator



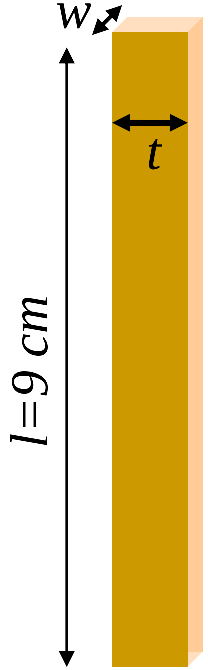
$$\mu_{eff} = 1 - \frac{\pi r^2 / s}{1 + \dfrac{2\sigma i}{\omega \tau \mu_0} - \dfrac{3d}{\pi^2 \mu_0 \omega^2 \varepsilon_0 r^3}}$$





From Dana V. Radović etc. XII telecom Forum

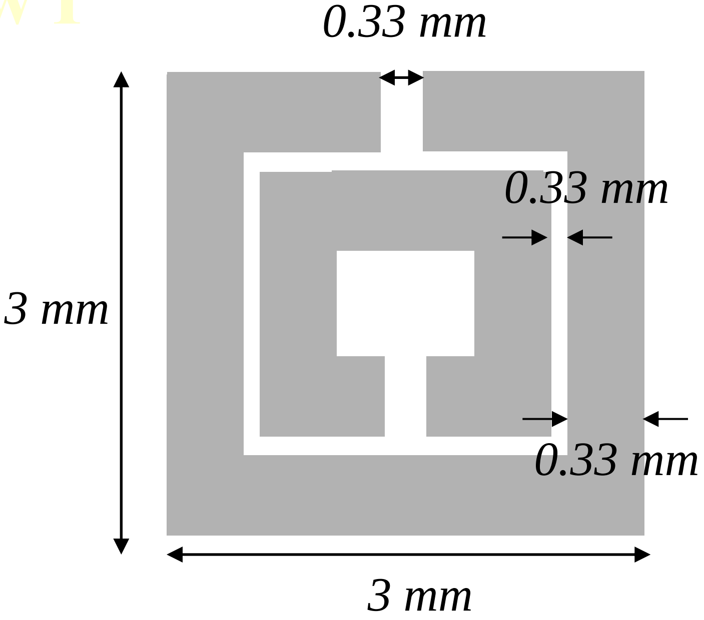
Przykłady struktur metamateriałów I

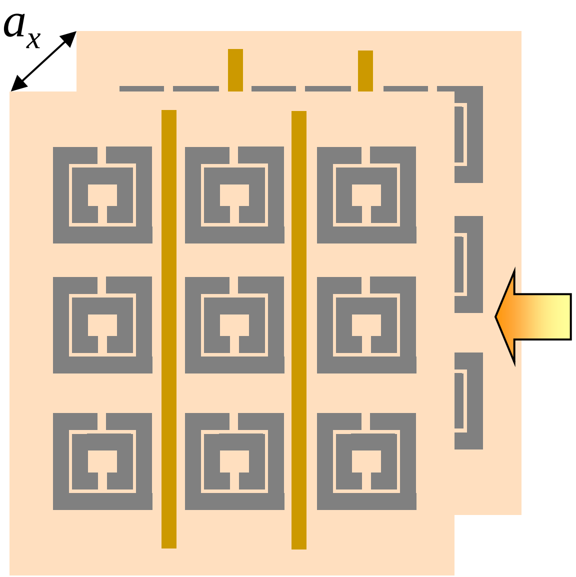


t»w

t=0.5 or 1 mm

w=0.01 mm





Periodicity:

a_x=5 or 6.5 mm

a_y=3.63 mm

a_z=5 mm

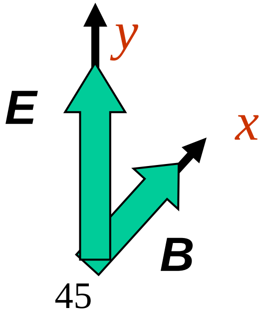
Quantity of SRR

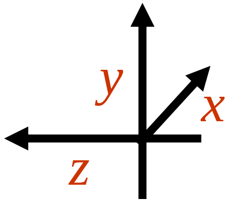
N_x=20

N_y=25

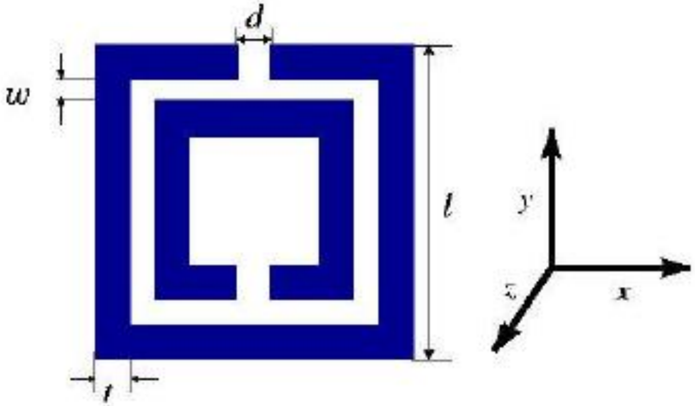
N_z=25

Polarization: TM





New designs for left-handed materials



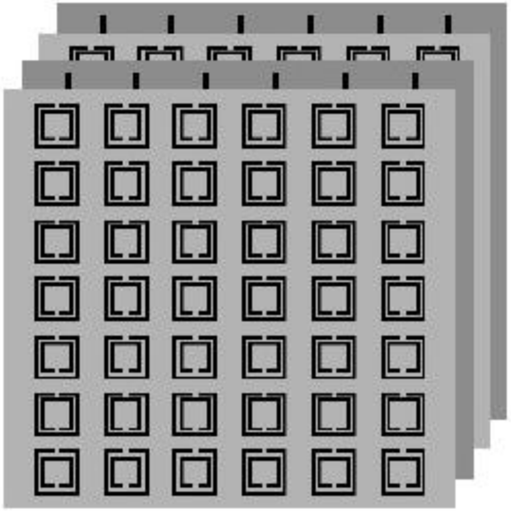
Parameters:

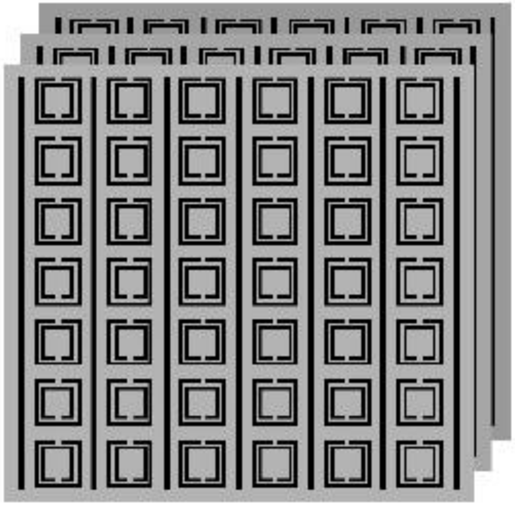
$l=3$ mm, $d=t=w=0.33$ mm

Depositing metal (Sn or Cu) on dielectic board

$\varepsilon_b=4.4$

Thickness of board =0.45 mm

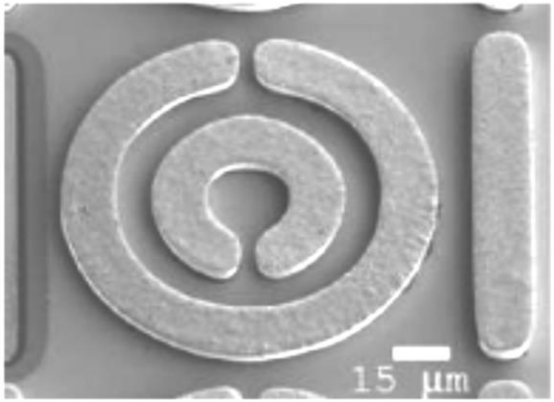




Bilkent and ISU, APL 81, 120 (2002)

Zmiany wymiarów Rezonatorów

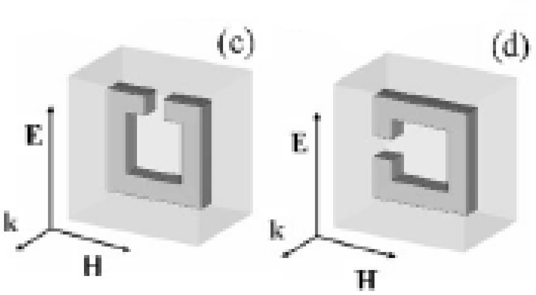
Moser et al. PRL 90 063901 (2005)

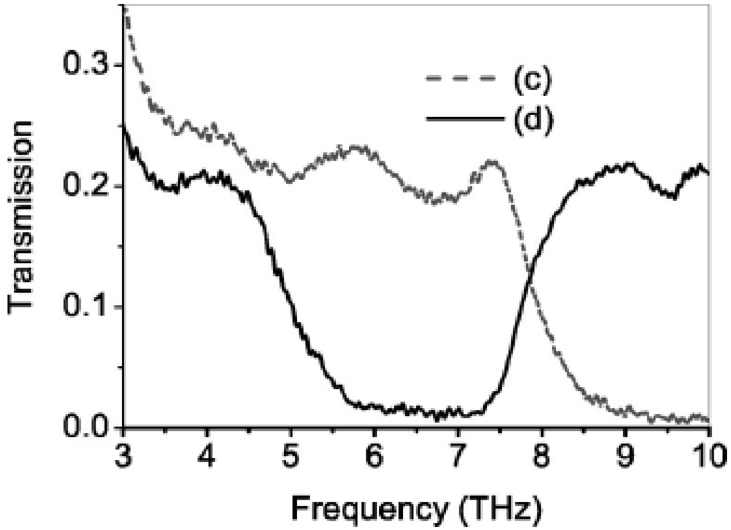


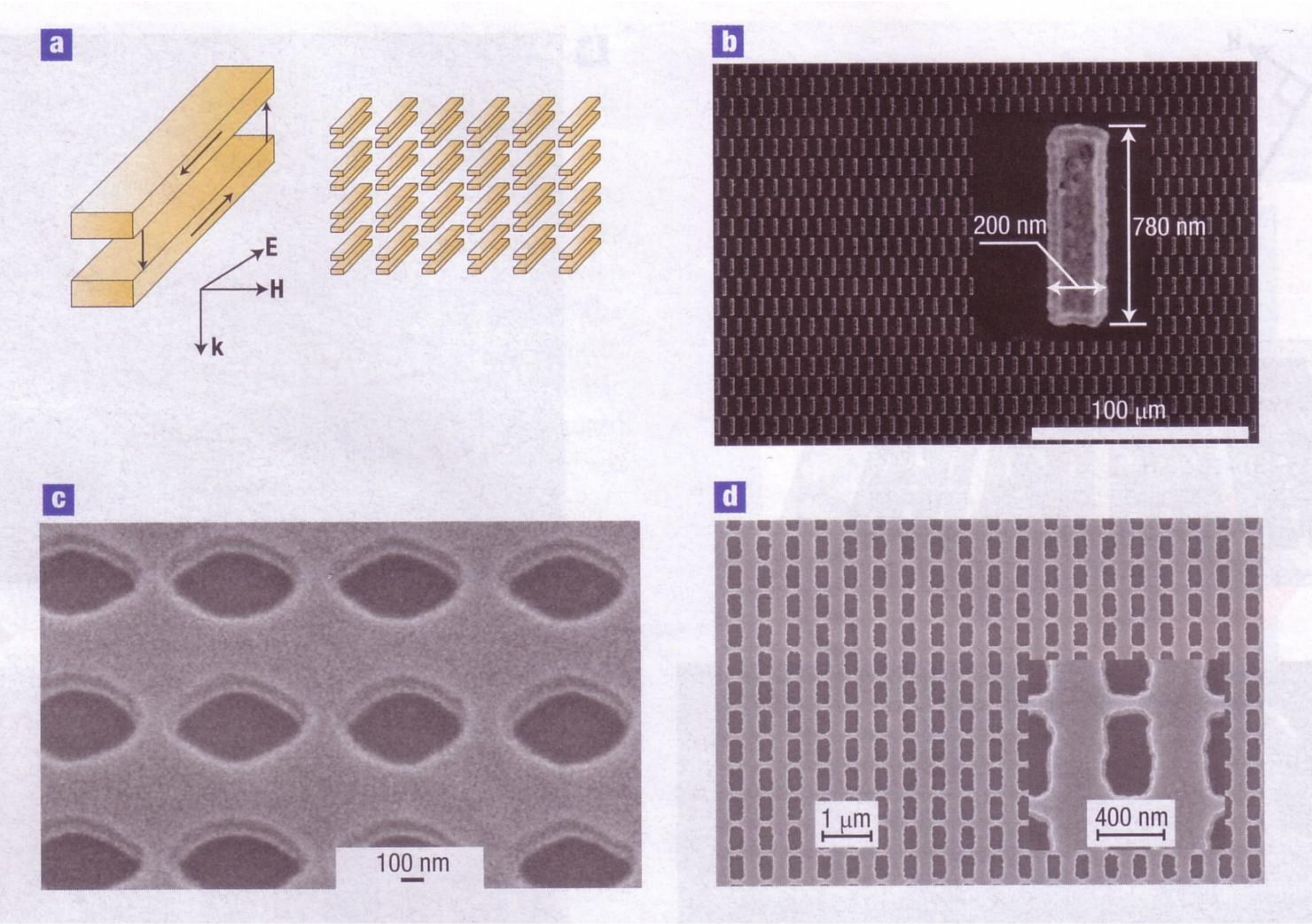
1-2.7 THz

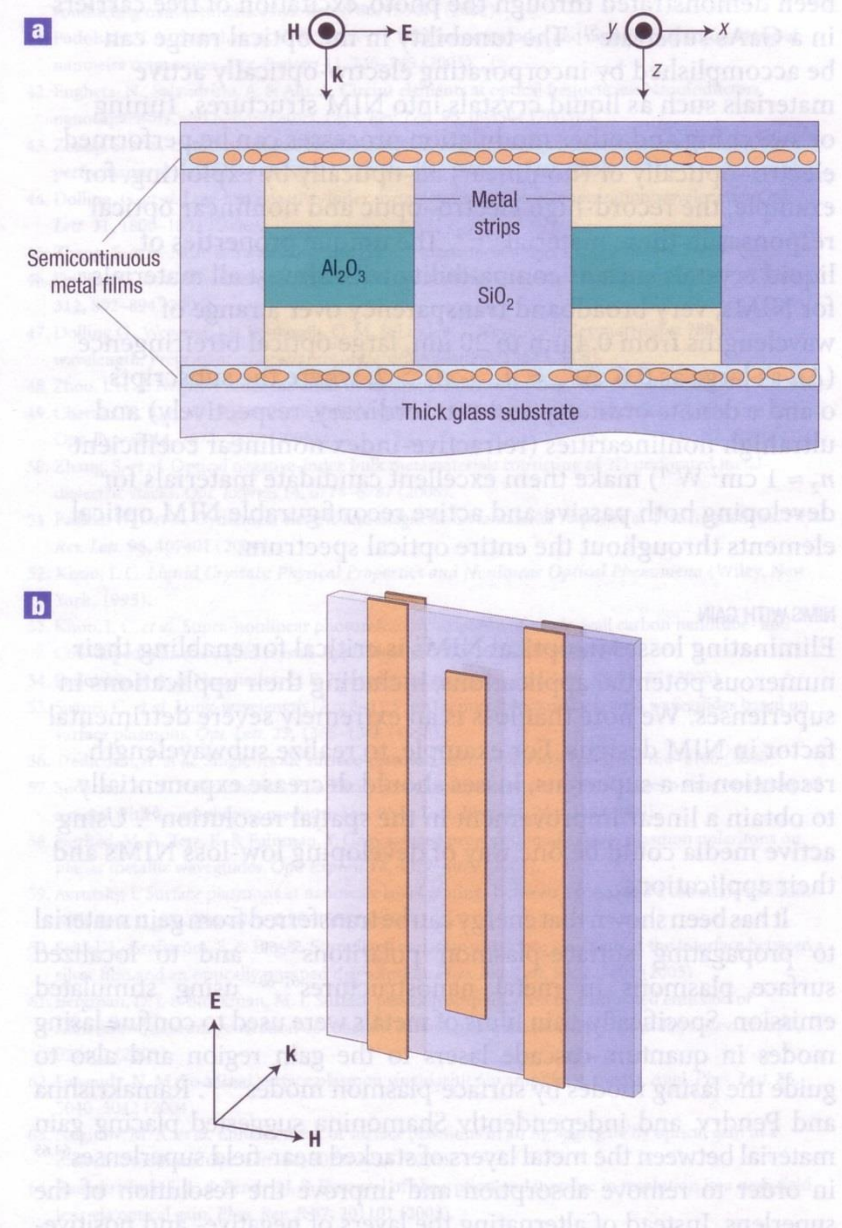
Katsarakis et al. Opt Lett 30(11) 1348 (2005)

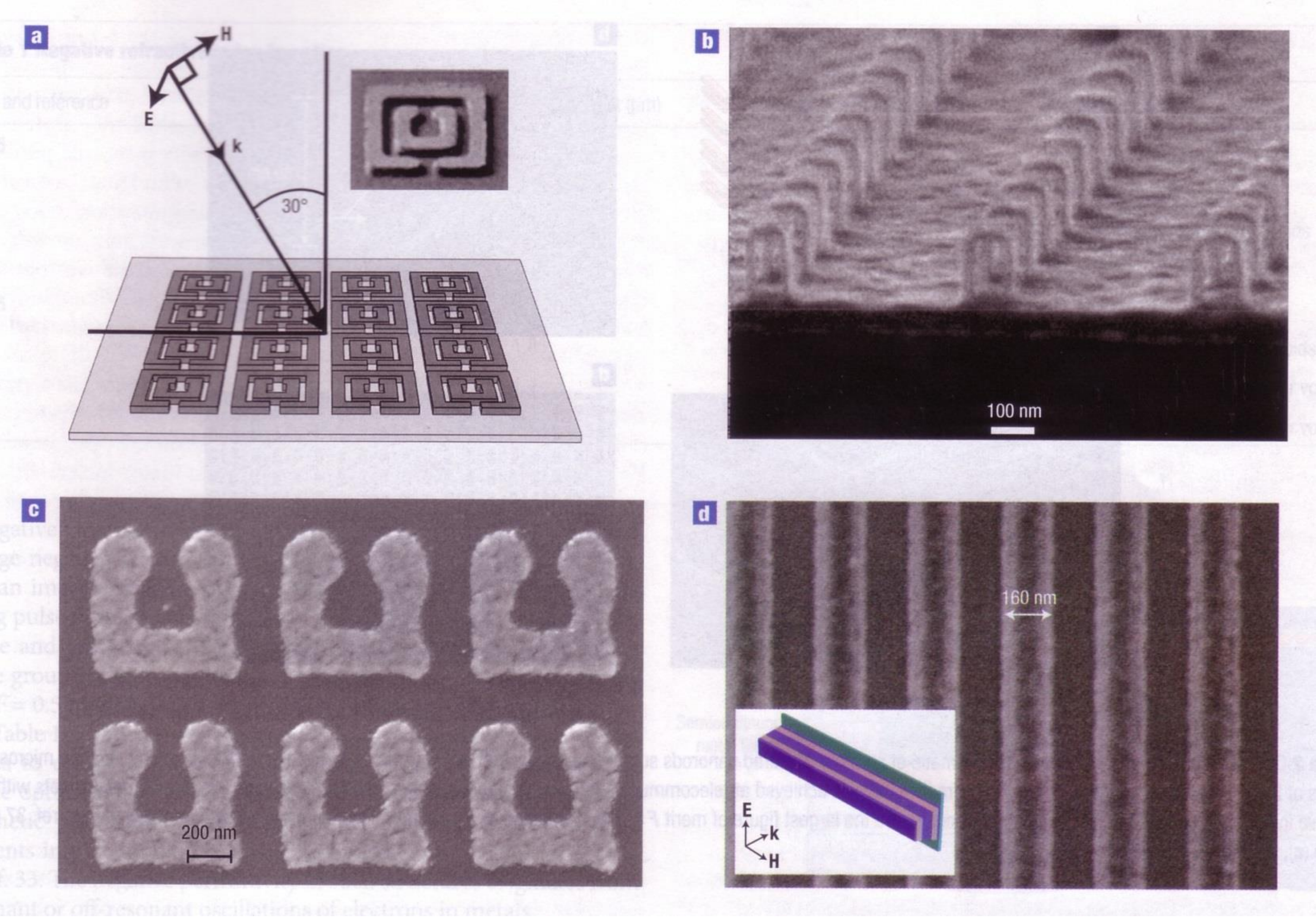
6 THz






a
E
H
k
b
200 nm
780 nm
100 μm
c
100 nm
d
1 μm
400 nm


a
H
E
k
y
x
z
Metal strips
Semicontinuous metal films
Al_2O_3
SiO_2
Thick glass substrate
b
E
k
H


a
H
E
k
30°
b
100 nm
c
200 nm
d
160 nm
E
k
H

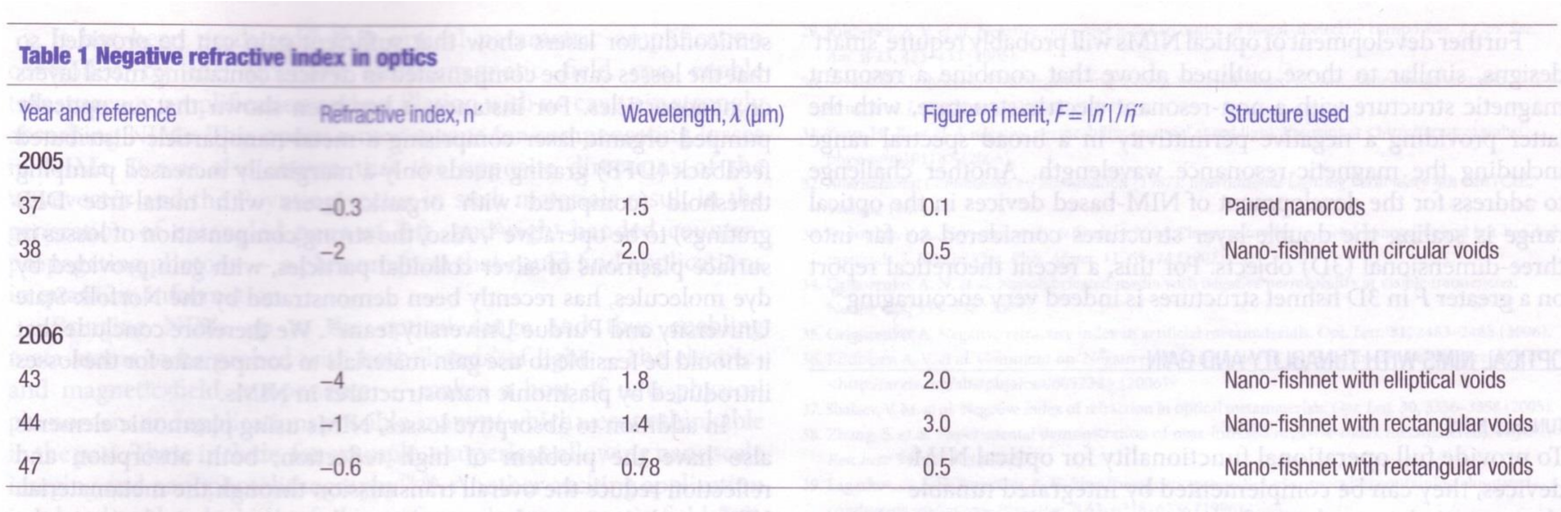
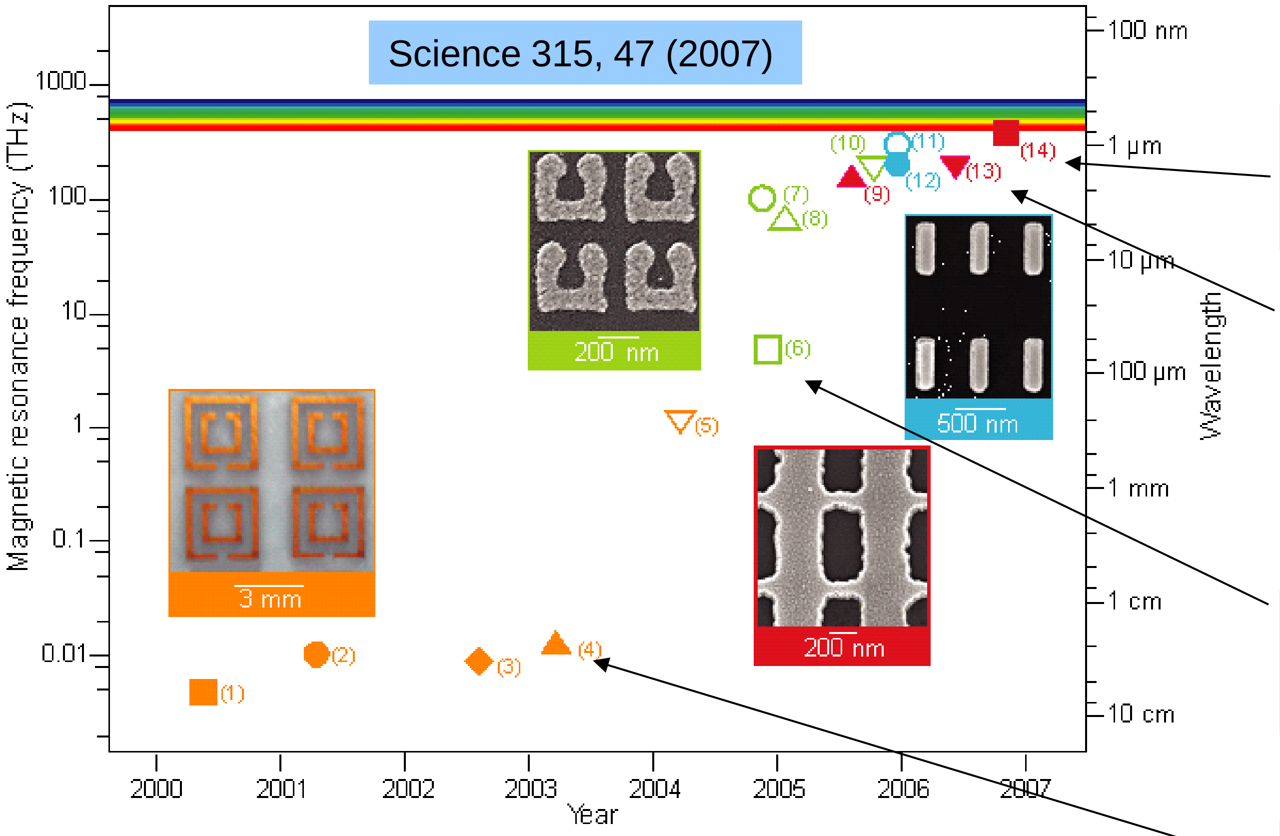


Table 1 Negative refractive index in optics

Year and reference	Refractive index, n'	Wavelength, λ (μm)	Figure of merit, $F = \lvert n' \rvert / n''$	Structure used
2005				
37	−0.3	1.5	0.1	Paired nanorods
38	−2	2.0	0.5	Nano-fishnet with circular voids
2006				
43	−4	1.8	2.0	Nano-fishnet with elliptical voids
44	−1	1.4	3.0	Nano-fishnet with rectangular voids
47	−0.6	0.78	0.5	Nano-fishnet with rectangular voids

A Brief History of Left-handed Metamaterials

Since the first demonstration of an artificial LHM in 2000, there has been rapid development of metamaterials over a broad range of frequencies.



n<0 for 780 nm
(ISU & Karlsruhe)
Opt. Lett. 32, 53 (2007)

n<0 for 1.5 µm
(ISU & Karlsruhe)
Science 312, 892 (2006)

µ<0 for 6 THz
(ISU & Crete)
Opt. Lett. 30, 1348 (2005)

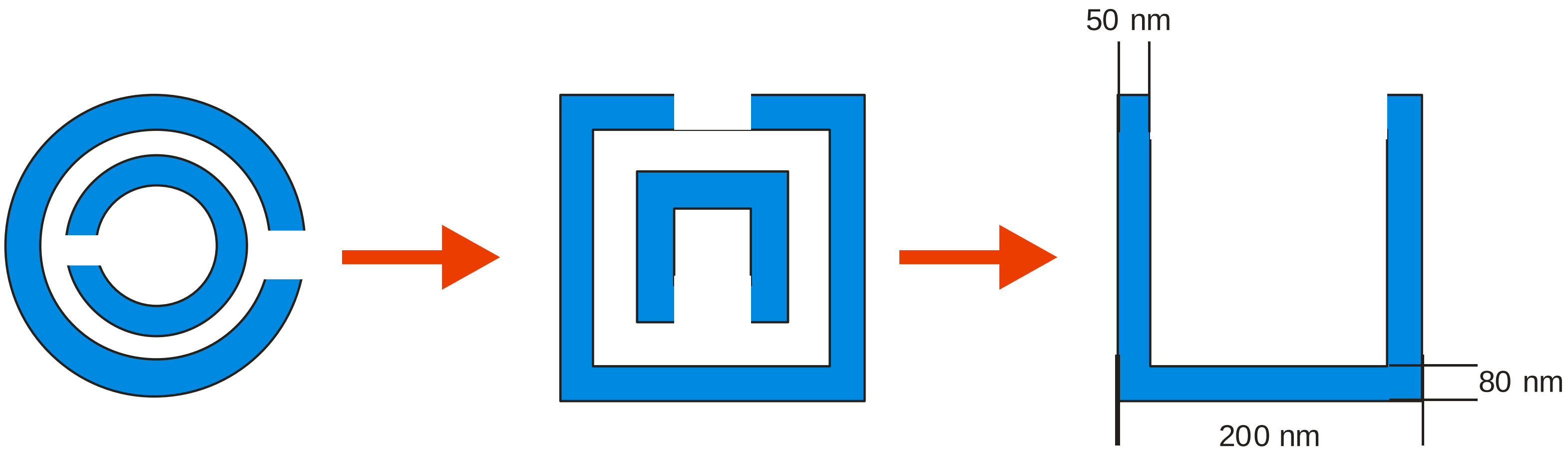
n<0 for 4 GHz
(ISU & Bilkent)
Opt. Lett. 29, 2623 (2004)

Solid symbol: n<0

Open symbol: µ<0

Iowa State University involved in designing, fabrication and testing of LHMs from GHz to optical frequencies.

Modyfication of SRR to structure U

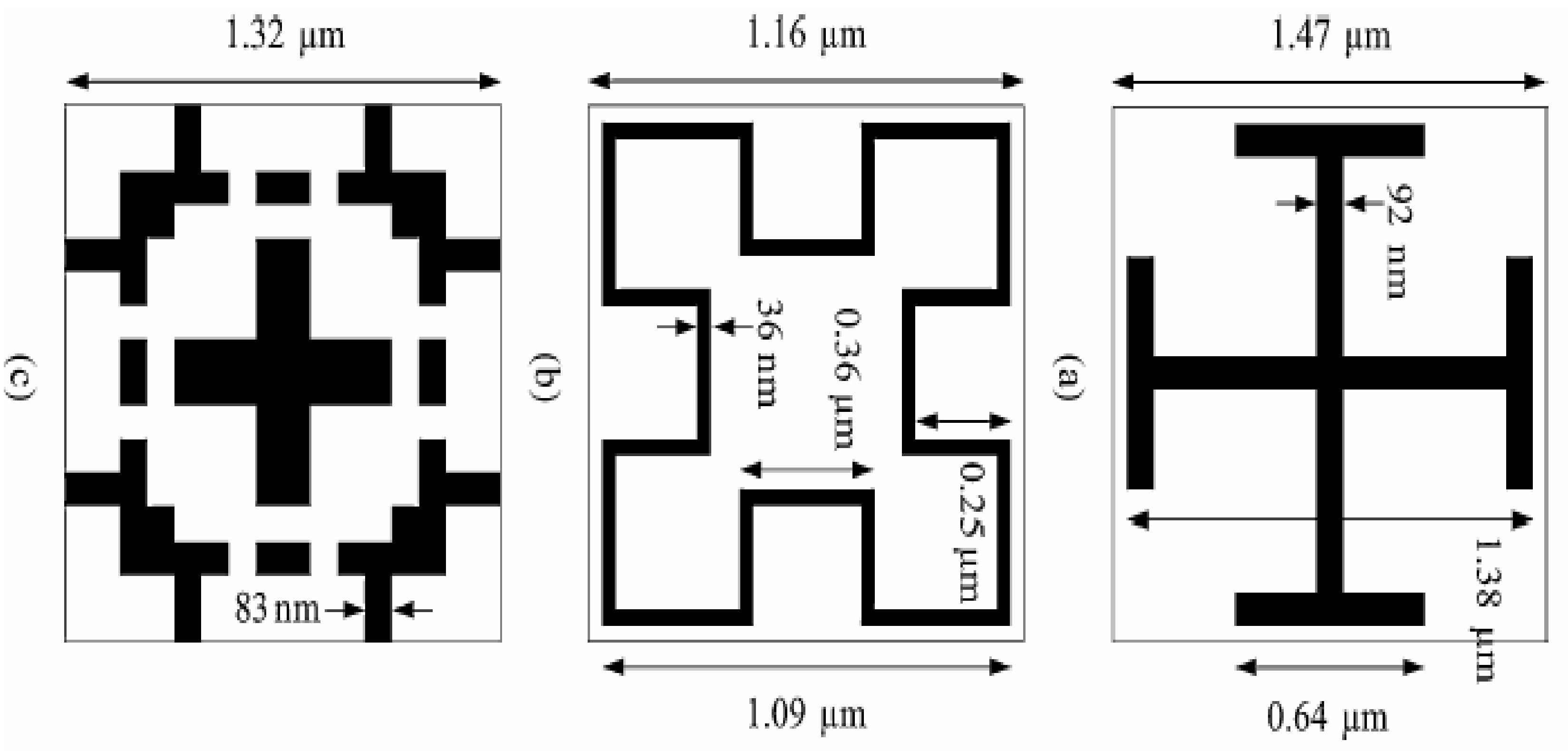


Nanotechnology :

- Standard elektron lit., lift – of method, or interference lit. on glass: 1mm, 5 nm warstwą ITO – *Indium-Tin-Oxide* with Au layer – 30 nm,.
-.

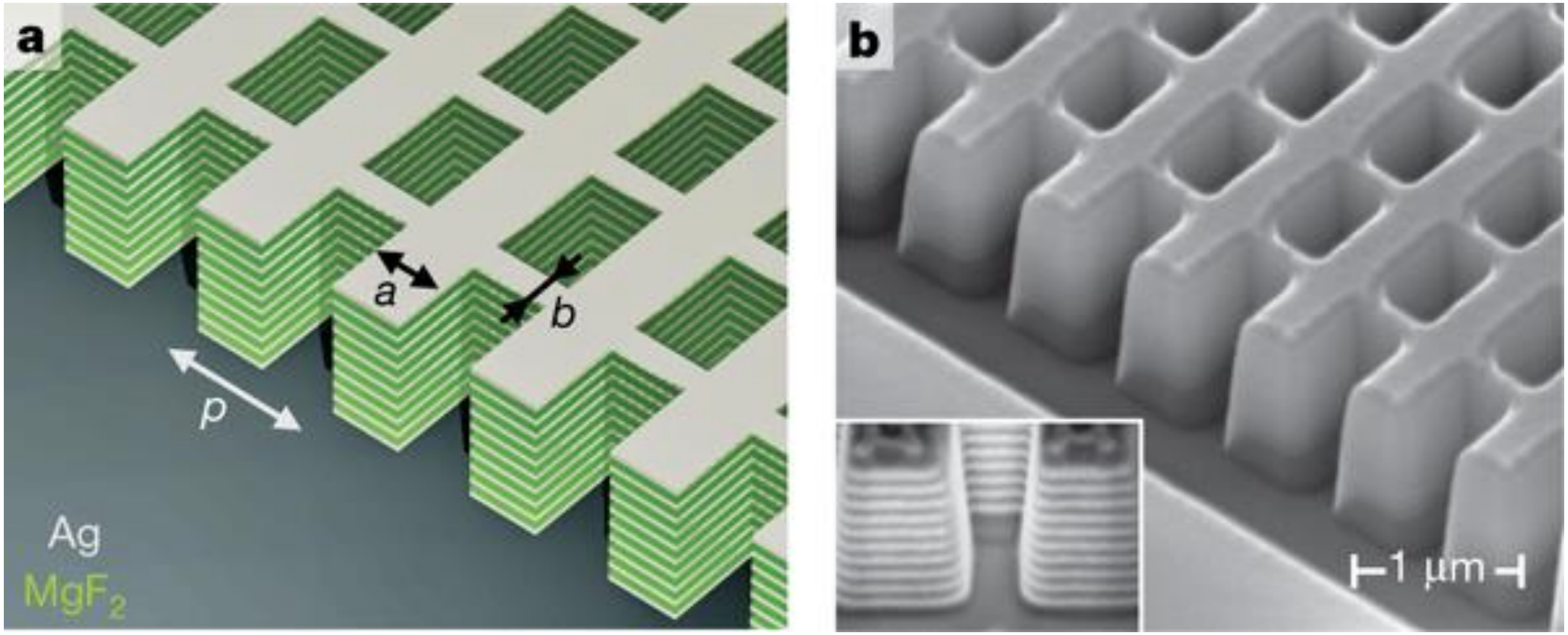
8. C. Enkrich et al., PRL 95, 203901 (2005)

Different struktures of metamaterials:



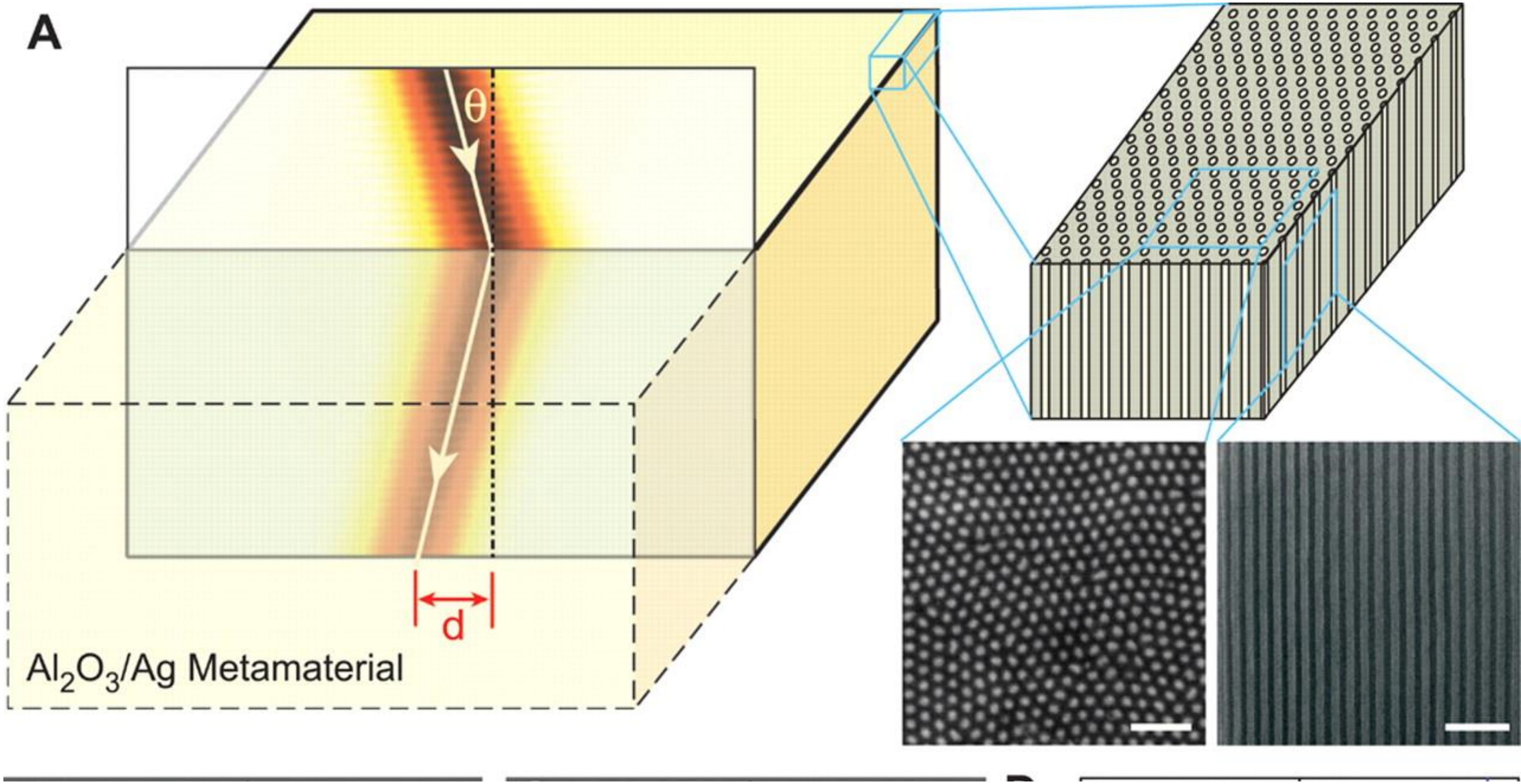
Geometry of metamaterial sructure; (a) Jeruzalem element; (b) Minkowski fraktal; (c) double element

J.A. Bossard, X. Liang, L. Li, S. Yun, D. H. Werner, B. Weiner, T. S. Mayer, P. F. Cristman, A Diaz and I. C. Khoo – Tunable Frequency Selective Surfaces and Negative-Zero-Positive Index Metamaterials Based on Liquid Crystals, IEEE, Vol. 56, No.5, May 2008



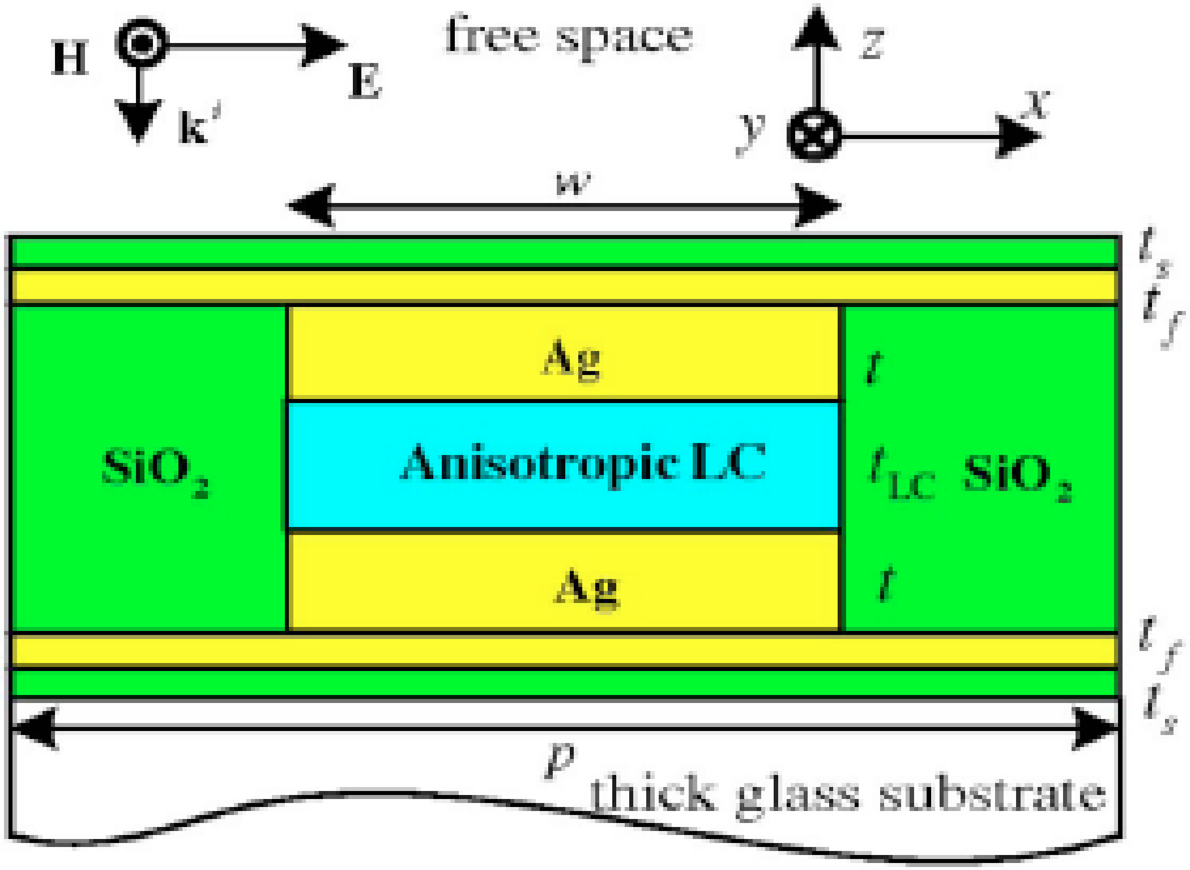
a, 21- layers, *p* = 860 nm, *a* = 565 nm, *b* = 265 nm. **b**, Ag (30 nm) i MgF_2 (50 nm)

*J Valentine et al. Nature **455**, 376 - 379 (11 Aug 2008),*



Al_2O_3/Ag

J. Yao et al., Science ***321****, 930 (2008) , University of California, Berkeley.*



p=600 nm,

w= 300 nm,

t = 30 nm,

t_f =20 nm

t_{LC} = 200 nm.

Geometry of metamaterial cell with thin layer of liquid crystal
X.Wang, D.H. Kwon, D.H. Werner, I.C. Khoo, A.V. Kildishev, V.M. Shalaev - Tunable optical negative-index metamaterials employing anisotropic liquid crystals. Appl. Phys. Lett. 91, 143122(2007)

Metamaterial stucture is limited in ± y direction and periodic with with period p – in ± x direction

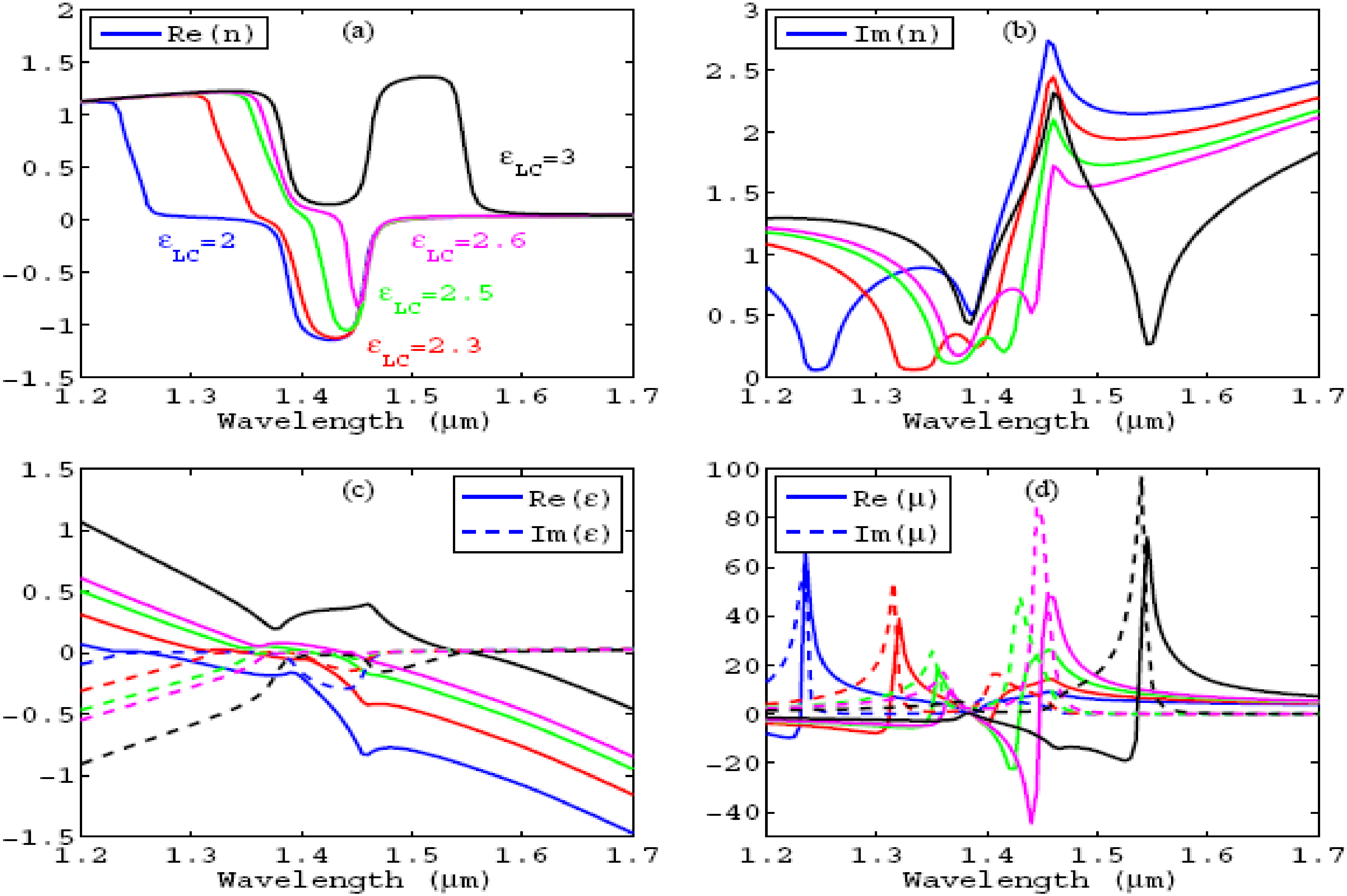
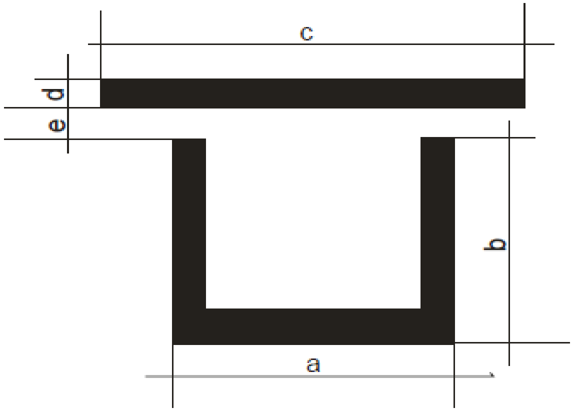


Fig. 2. Effective parameters of the reconfigurable near-IR metamaterial for different values of ε_{LC}: (a) n', (b) n'', (c) ε, and (d) μ with respect to wavelength.

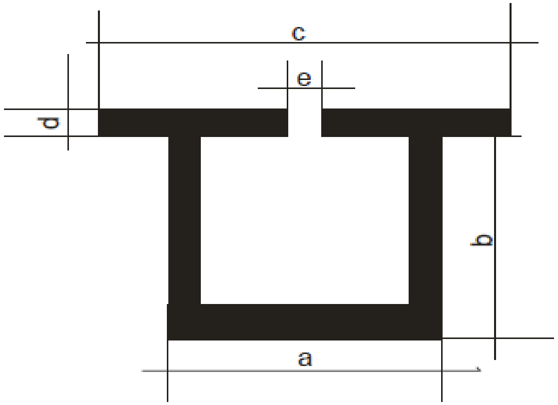
Our configuration of SRR

Przyjmujemy 3 poniższe konfiguracje meta struktury:

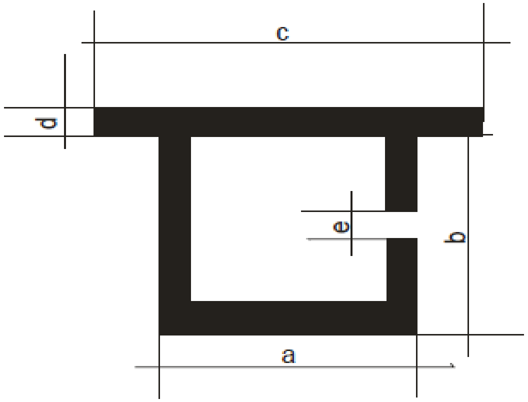
MODEL A



MODEL B

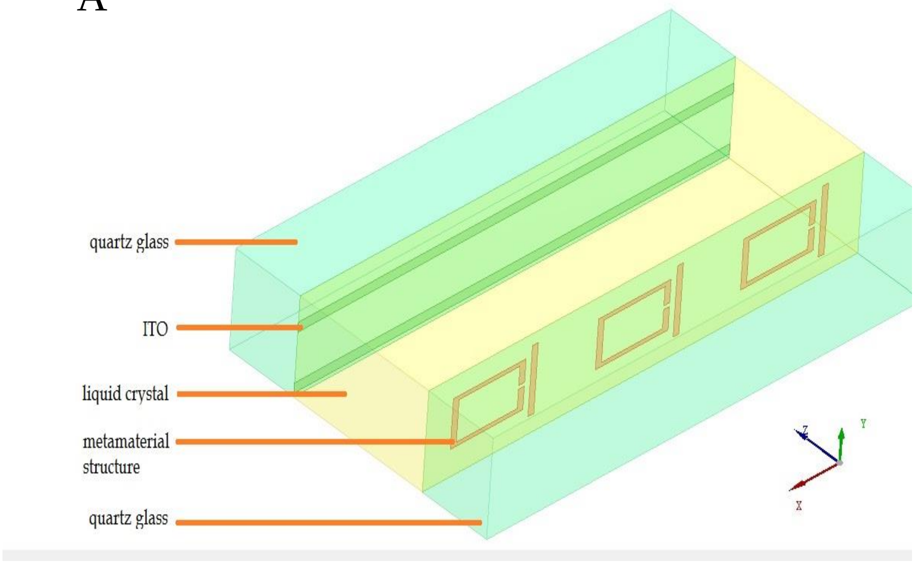


MODELC

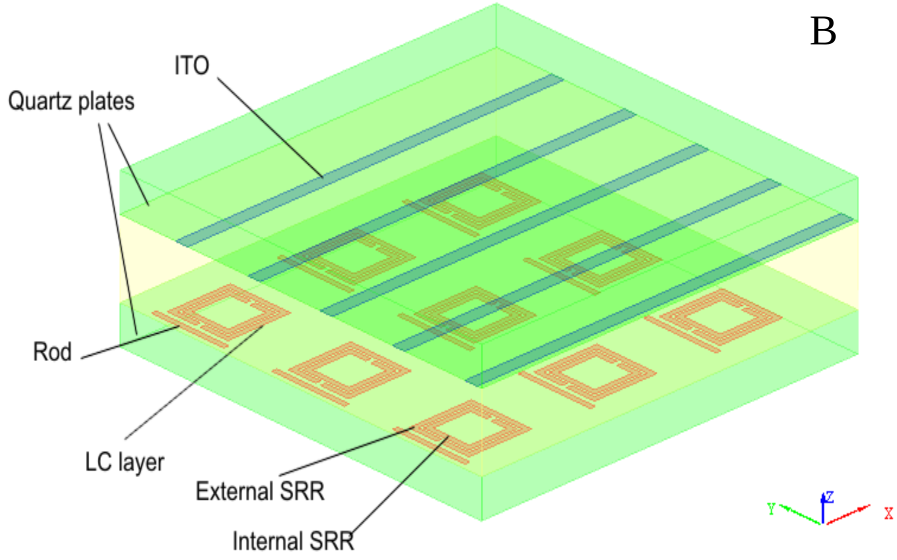


Models of metamaterials transducers

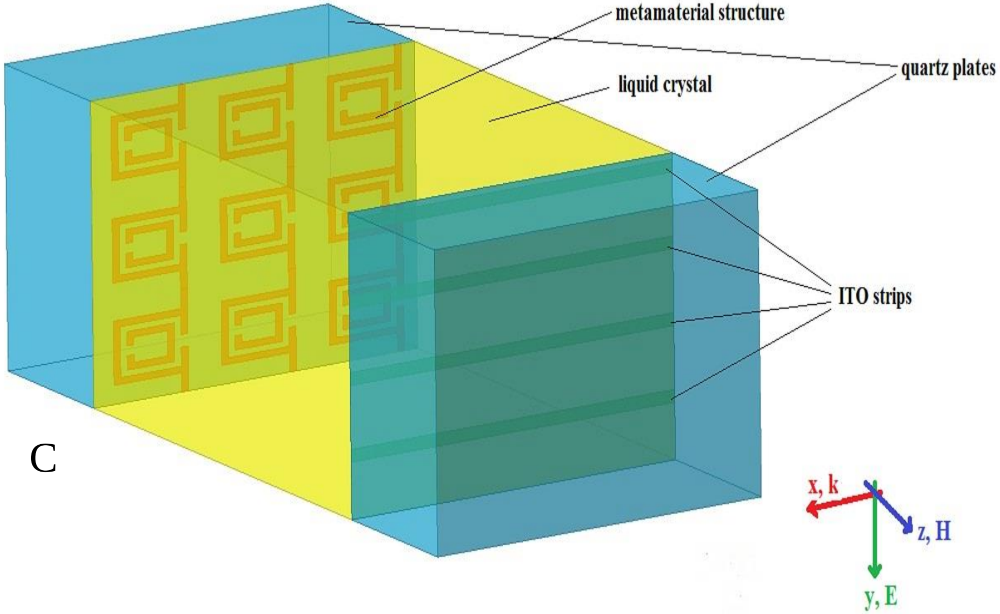
A



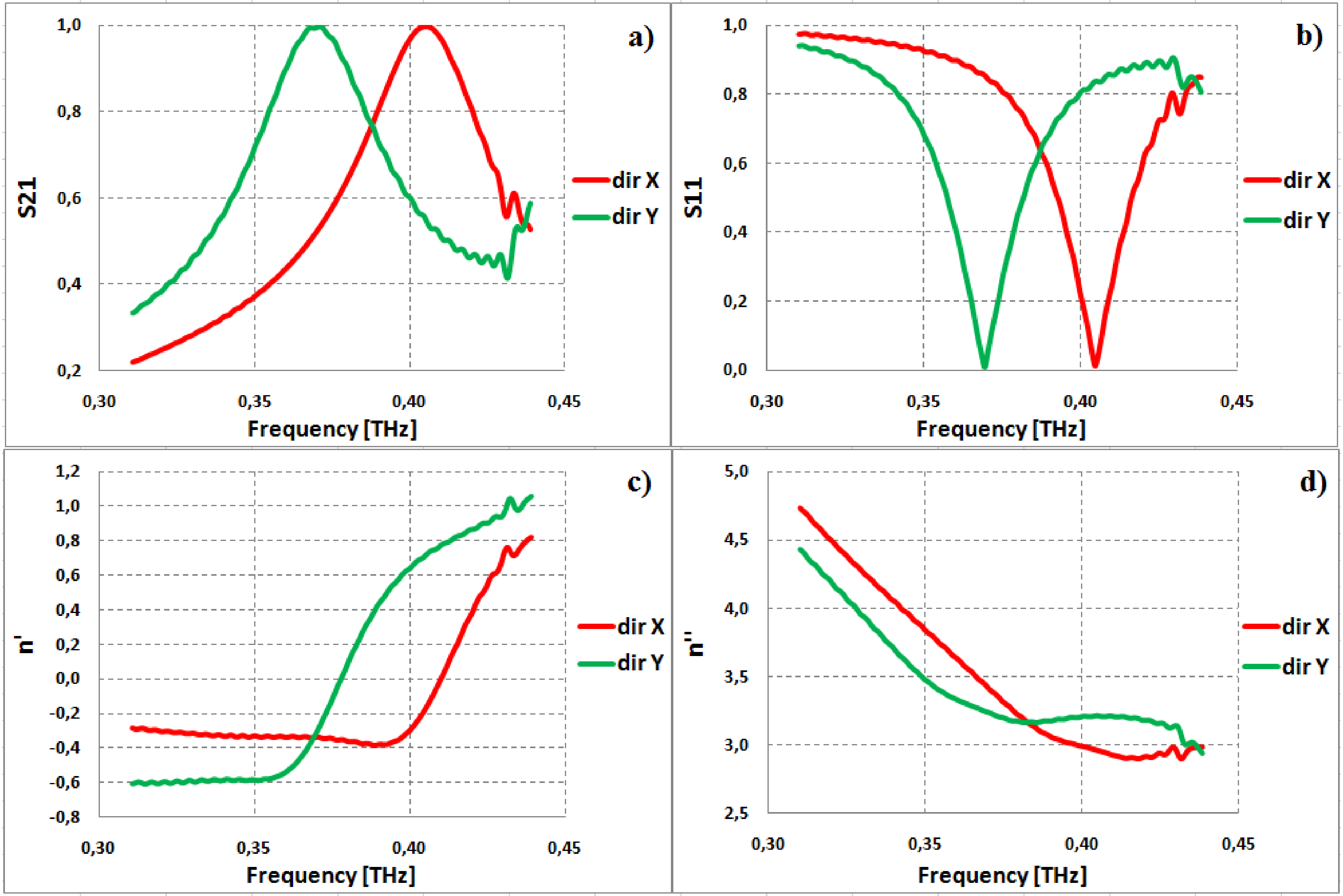
B



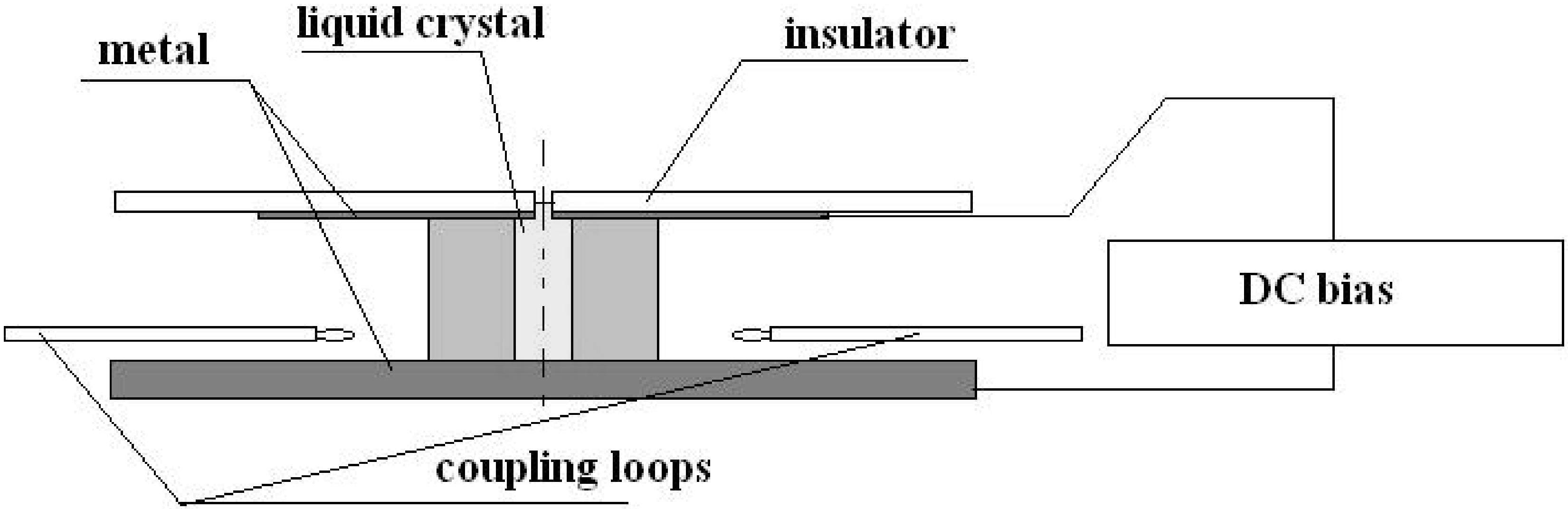
C



Parametry rozproszenia oraz efektywny współczynnik załamania (model C)



Proposed resonant structure



Schematic diagram of resonant structure used for measurements of the complex permittivity of liquid crystals.

The dielectric loss tangents are then determined from the following formula:

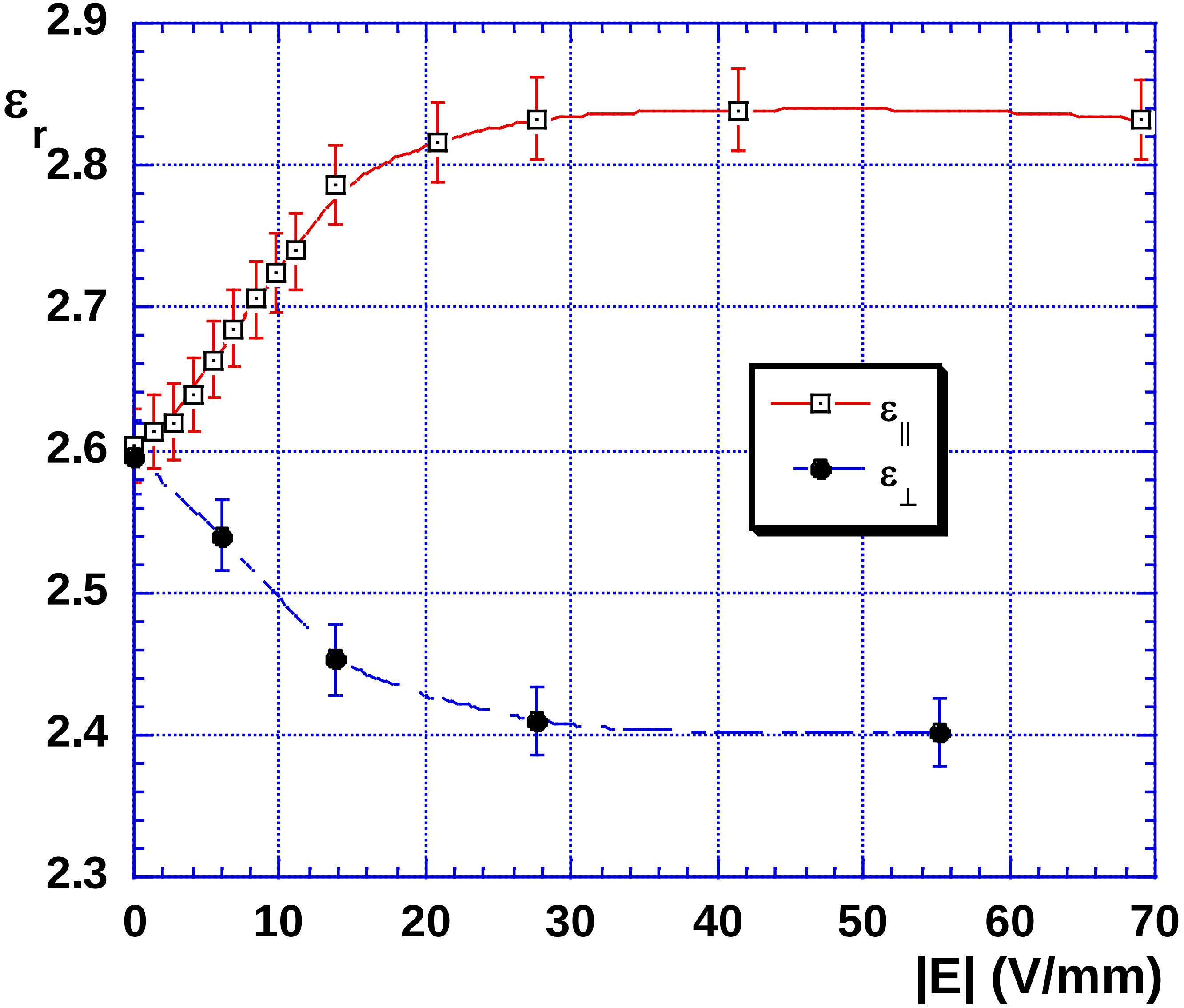
$$\tan\delta = p_e^{-1}\left(\frac{1}{Q_u} - \frac{1}{Q_0}\right)$$

where: Qu denotes the measured value of the unloaded Q-factor of the appropriate mode containing the sample under test, Q0 denotes the Q-factor due to parasitic losses (resonator without liquid crystal) and pe denotes the electric energy filling factor in the sample.

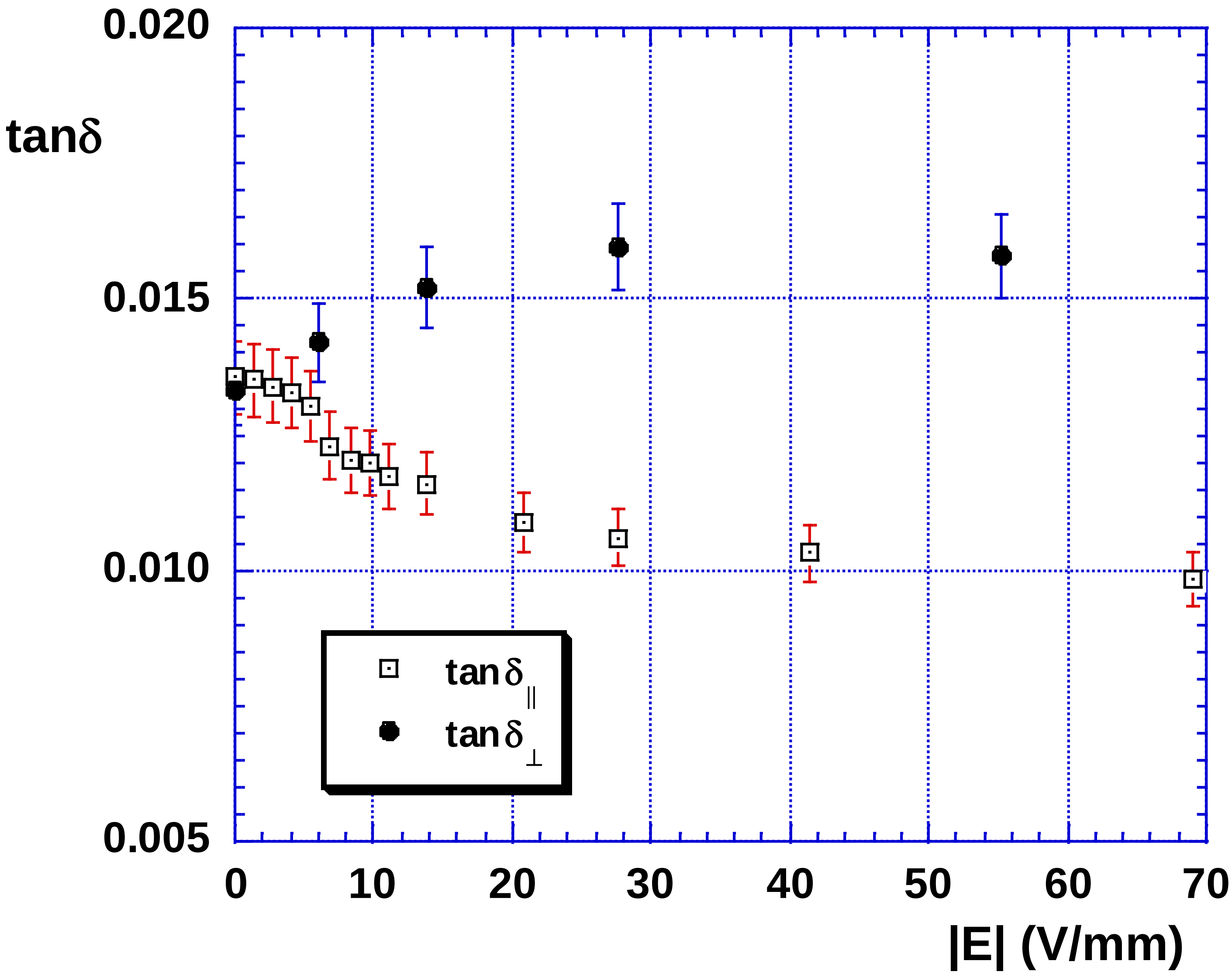
Parameters of the dielectric resonator used in measurements

Parameter	Value
Dint	2.18 mm
Dext	13.86 mm
L	7.24 mm
f_0 (TE_{011})	13.712 GHz
f_0 (TM_{011})	15.125 GHz
Q_0 (TE_{011})	8100
Q_0 (TM_{011})	3450

Permittivity of liquid crystal versus static electric field bias of liquid crystal (6HCBT)



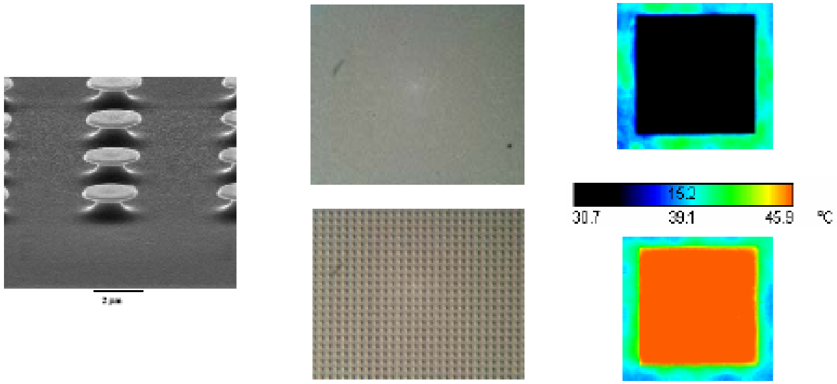
Dielectric loss tangent of liquid crystal (6HCBT) versus static electric field bias



Meta-Material Structures for Super-Radiant Emitters and Sensors

Program Year Started: 2001 **Program Manager: G. Pomrenke (AFOSR)**

Metamaterials With Enhanced IR Emission Characteristics



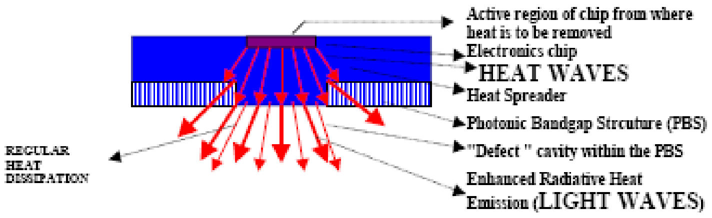
Program Objectives

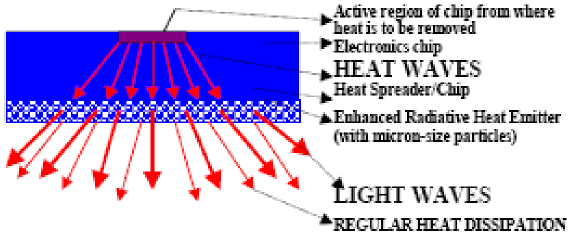
- Explore and demonstrate new physics of meta-materials for enhanced IR emission / absorption
- Develop characterization techniques to measure the properties of the meta-materials
- Develop improved implementation methodologies for the fabrication meta-materials
- Evaluate prototype meta-materials and their devices in thermal management and IR-sensing applications

DOD Relevance

Revolutionary advances in thermal management in a variety of military systems and Improved IR sensing applications

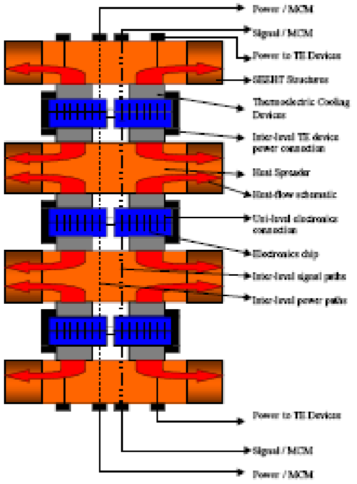
Approach





Prototyping and Technology Impact

Multi-chip module



Improved IR Sensors

MINIATURIZED ANTENNAS WITH ELECTROMAGNETIC METAMATERIALS

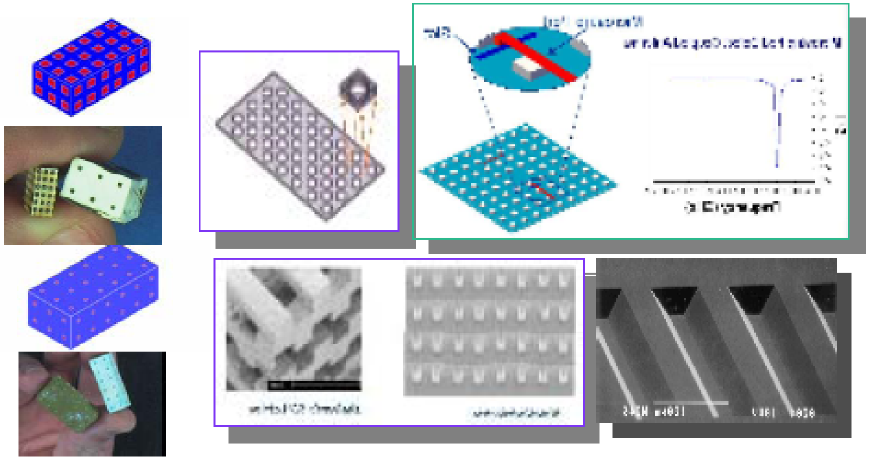
Multidisciplinary Approach

The University of Michigan and Harris Corporation will miniaturize antennas using magnetodielectric metamaterials created by topology design and automated fabrication methods

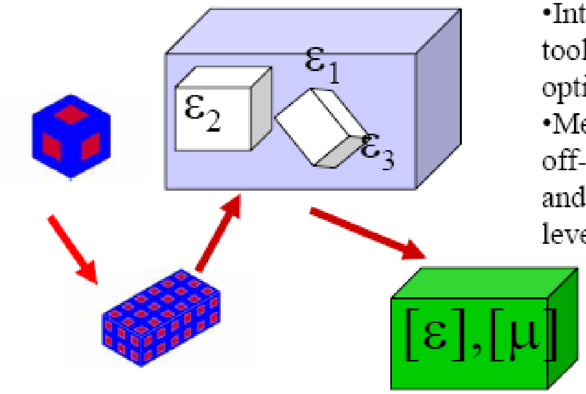
Fabrication:J. Halloran, Materials Science and Engineering
Electromagnetics: L. Katehi, K. Sarabandi, J. Volakis, Electrical Engineering
Optimal Design: Noboru Kikuchi, Mechanical Engineering
Integration, Design, Commercial Implementation: Harris Corporation

University (U. of Michigan) → **Industry** (Harris Corp) → **Military** (DARPA, etc.)

Solid Freeform Fabrication of Metamaterials



Electromagnetic Metamaterials Design Method

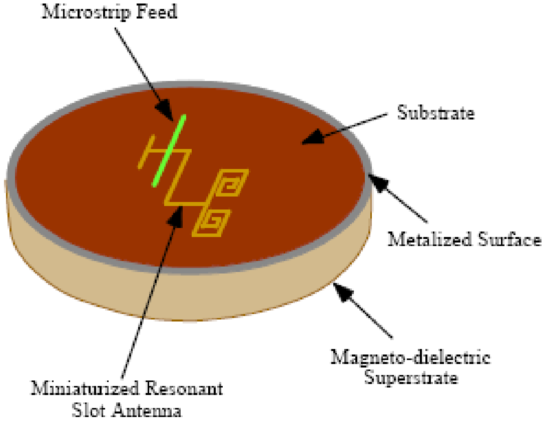


- Integrate full wave EM tools with topology optimization
- Metamaterials from off-the-shelf dielectrics and ferrites at several levels of granularity

Design with Periodic Microstructure allowing Spatially varying composition and properties

Objectives

- Metamaterials with unprecedented properties
- Optimal Design of Electromagnetic Metamaterials
- High efficiency miniaturized antennas and Microwave devices
- Lab and commercial scale fabrication



DoD Relevance

Revolutionary advance in antenna miniaturization, reduced cost and complexity

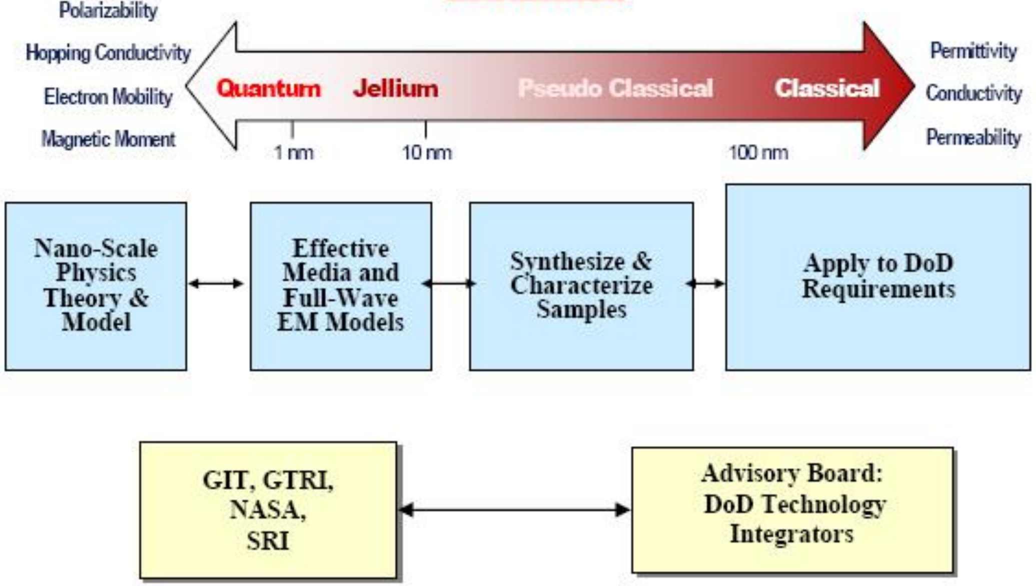
Science and Application of Meta Materials (SAMM)

Objectives:

- Develop design tools to span scale between quantum mechanics and macroscopic behavior
- Improve understanding of nano-scale effects on bulk material properties
- Apply SAMM process to develop DoD materials (microwave, IR, and optical) and antennas

Georgia Tech Research Institute

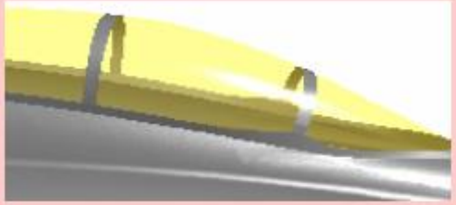
Approach



Nano-Scale Physics Theory & Model ↔ Effective Media and Full-Wave EM Models ↔ Synthesize & Characterize Samples ↔ Apply to DoD Requirements

GIT, GTRI, NASA, SRI ↔ Advisory Board: DoD Technology Integrators

Target Applications



IR and Optical Coatings

Compact, Rugged Antennas

Periodic structures in electromagnetic applications

Phased array antenna

application in radar system and satellite TV or communication

Leaky wave antenna

leaky wave antenna changes a wave-guiding structure into a radiating structure

Frequency selective surface

FSS as band-pass, band-stop filters, and application in radomes, thermovoltaic system

What is Phased Array antenna

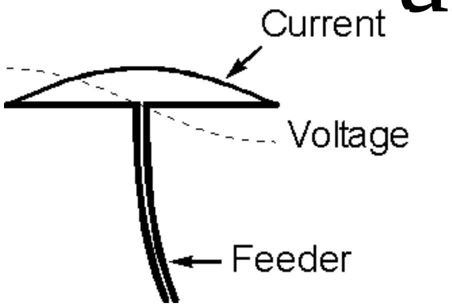
- Phased-array antennas contain a multitude of radiating elements, typically arranged in a rectangular or triangular tessellation.

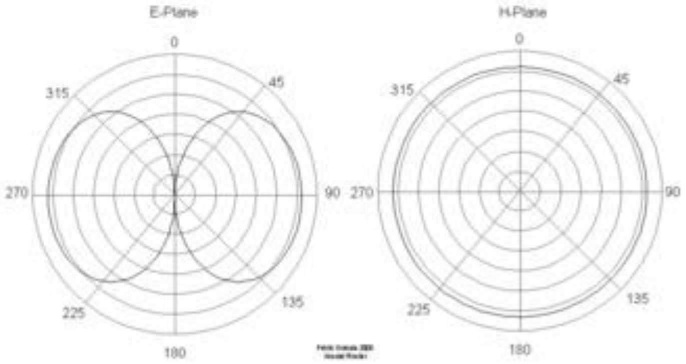
- Array of antenna element with phase (and sometimes, the amplitude) of each element being a variable.

- Phased array antenna can control the radiation beam direction and pattern shape including side lobes.

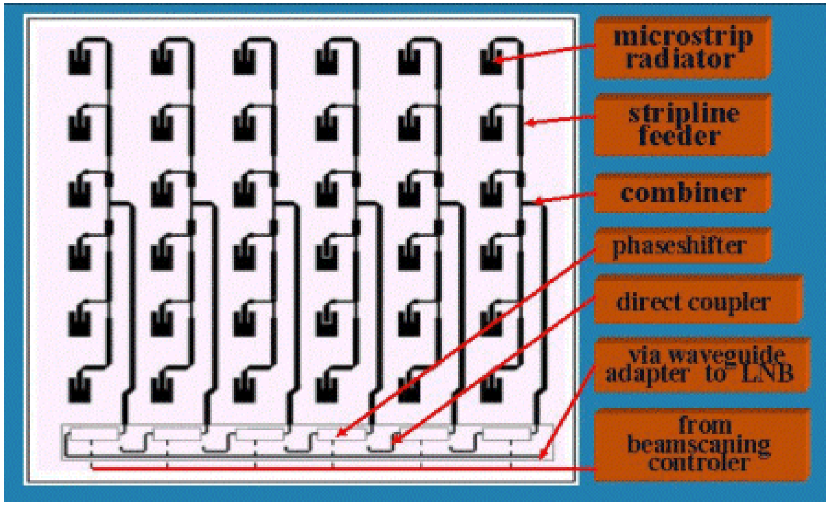
- When the phase change is accomplished by varying the frequency, it’s called frequency scanning arrays.

The structure of Phased array antenna





Single antenna element and its radiation pattern



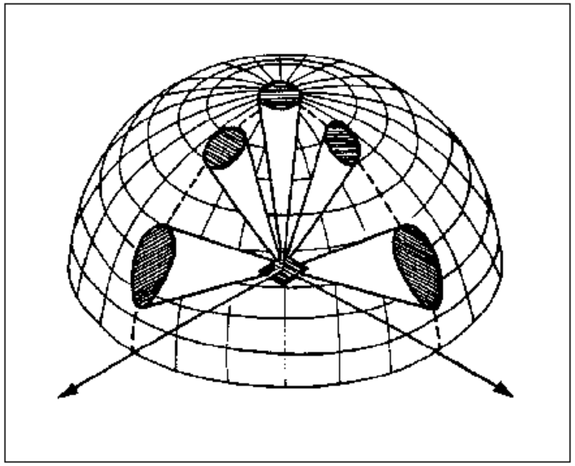


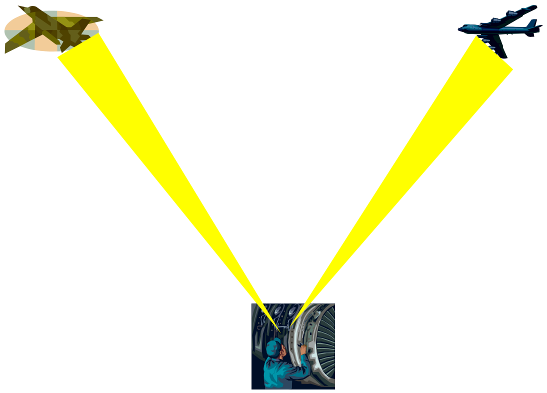
Figure 4. Beam Distortion

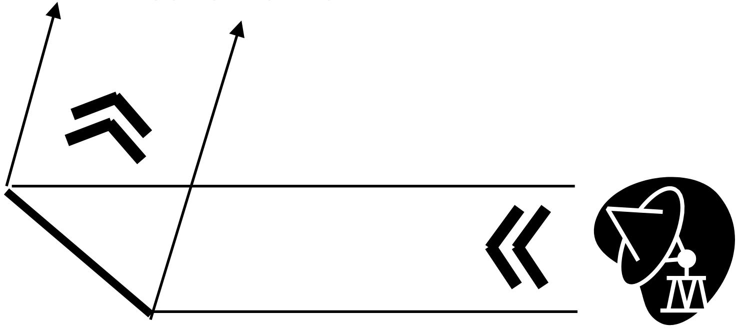
Phased array antenna and its radiation pattern

Phased array antenna in radar application

- Extreme beam agility

  Mechanical scanning takes 1 second while electronic scanning takes less than 1 ms.
- Reducing antenna radar cross section
- Advanced beam forming capabilities
- High reliability and less structural intrusion





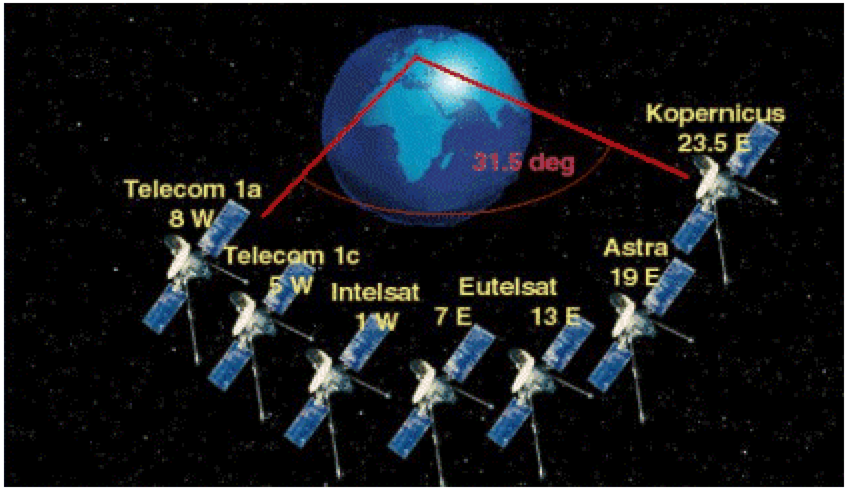
Radiation deflected from threat antenna

Stationary phased array antenna

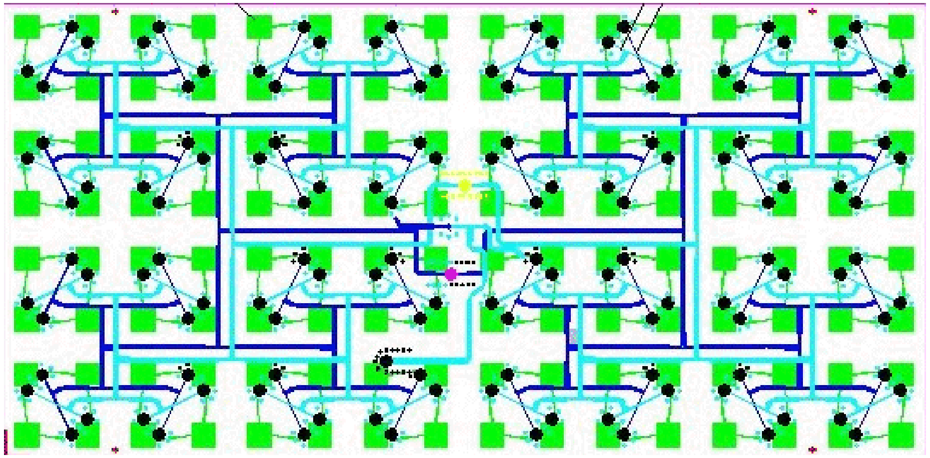
Phased array antenna application in radar system

Phased array antenna Application in DBS

Big Ugly dish(BUD)

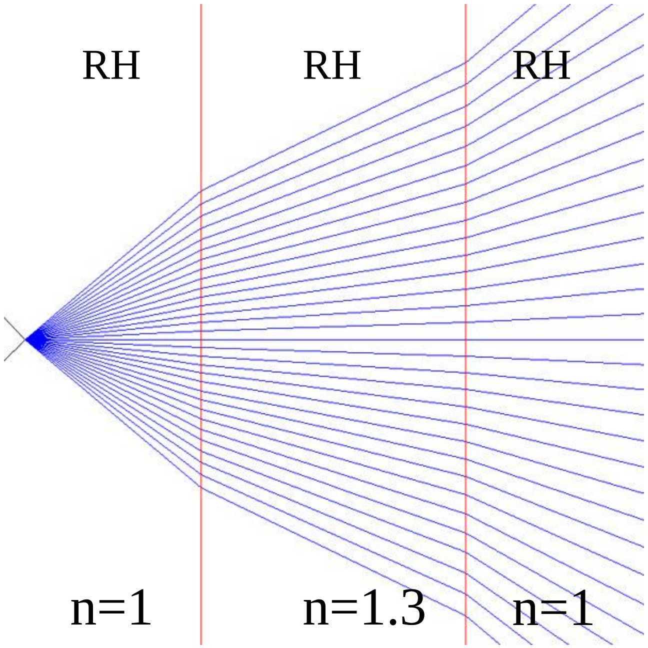


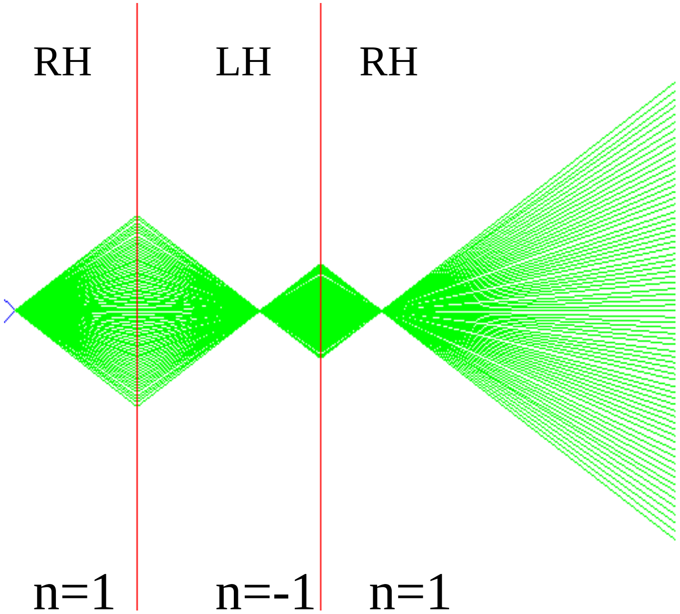
Direct broadcast satellites



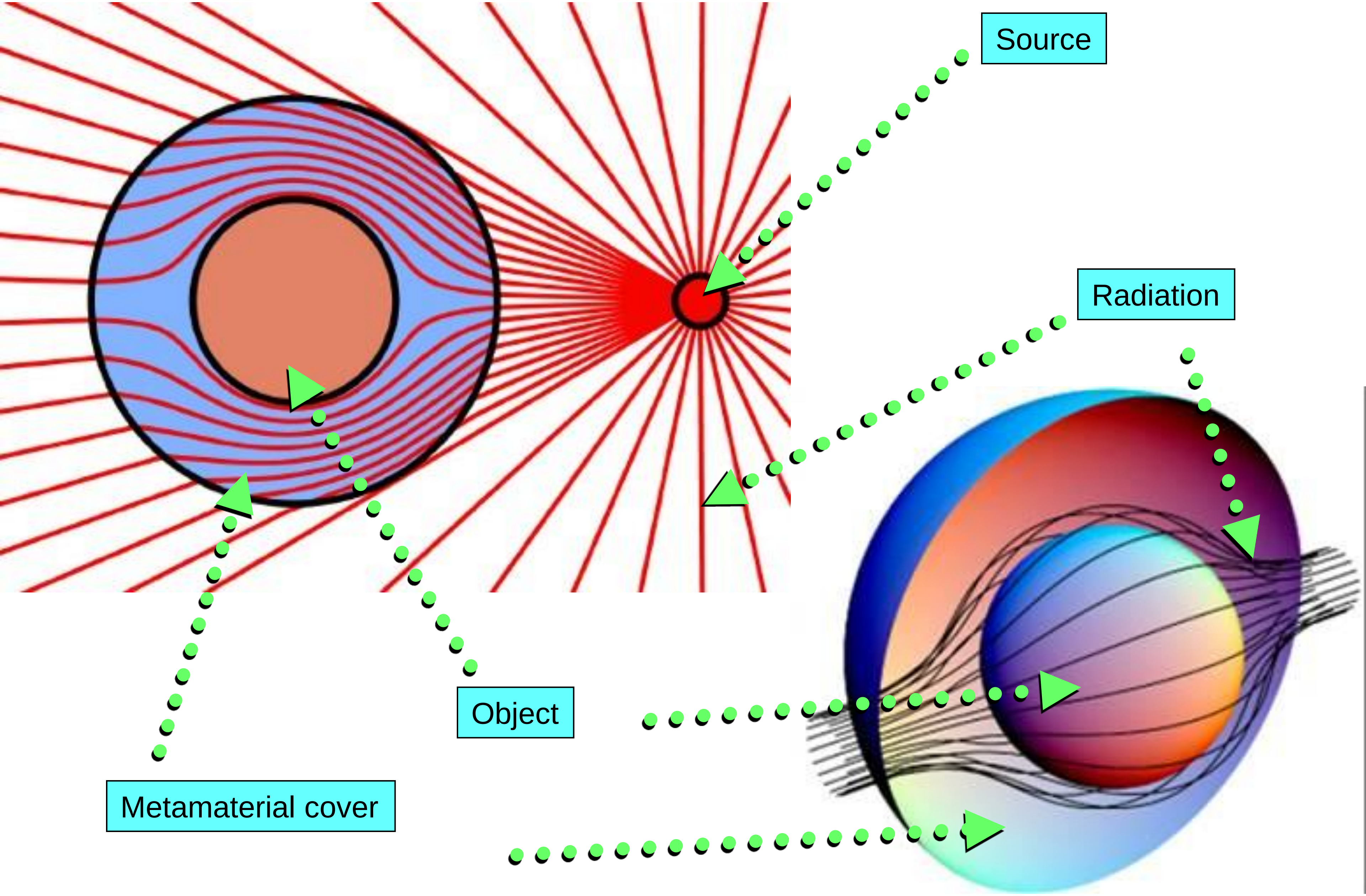
The planar microstrip antenna array

Focusing in a Left-Handed Medium





Application of metamaterials for cloaking



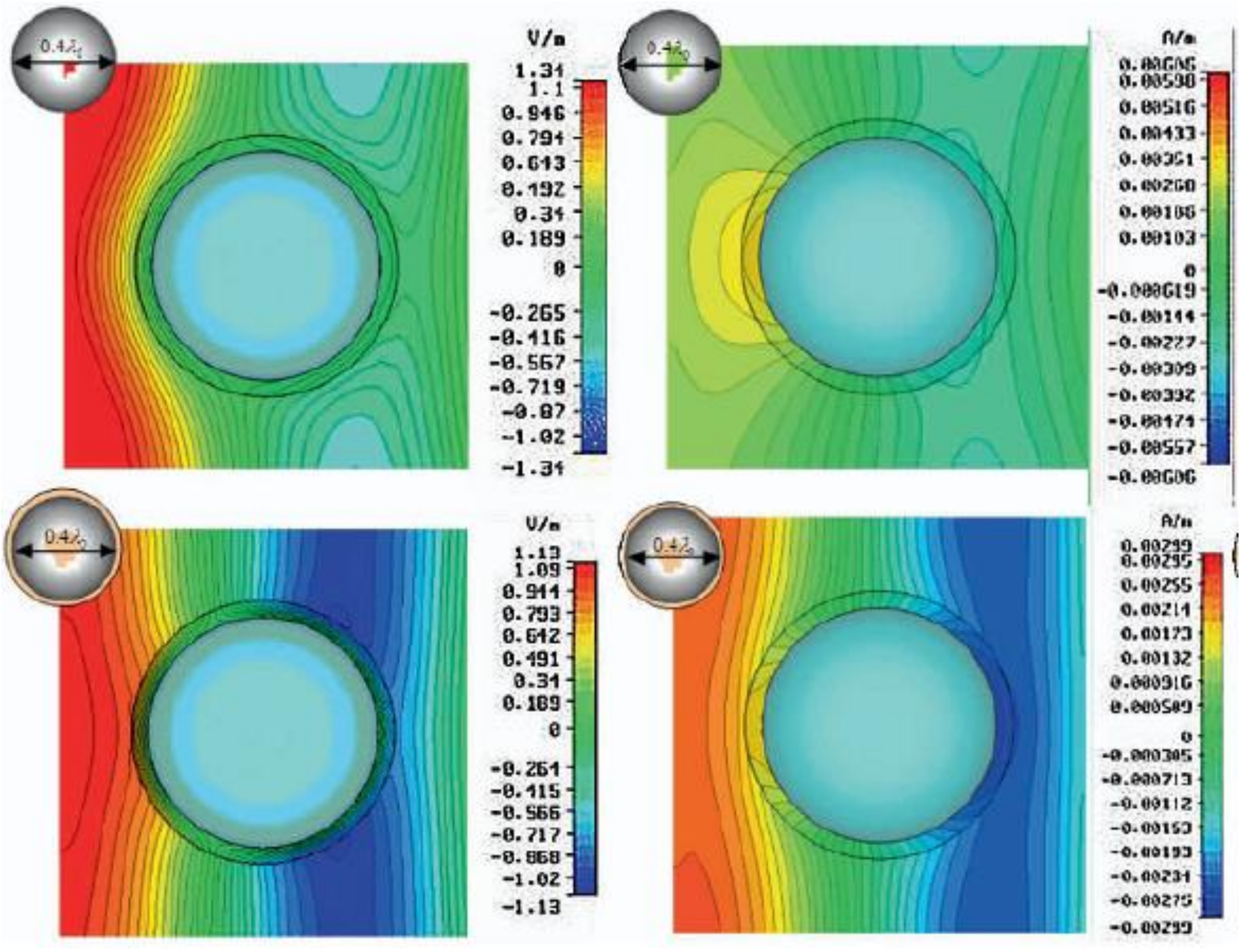
Source

Radiation

Object

Metamaterial cover

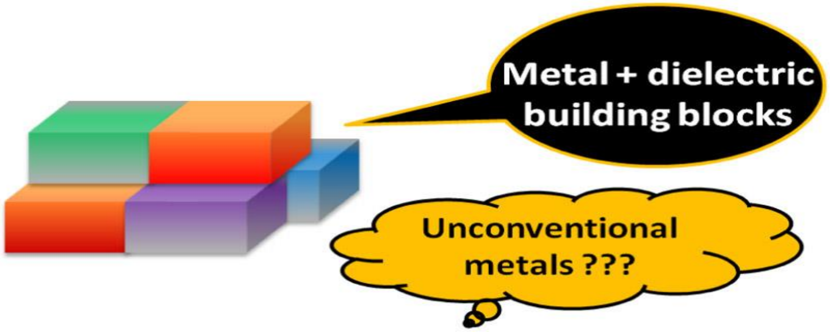
Application of metamateials for cloaking, c.d.

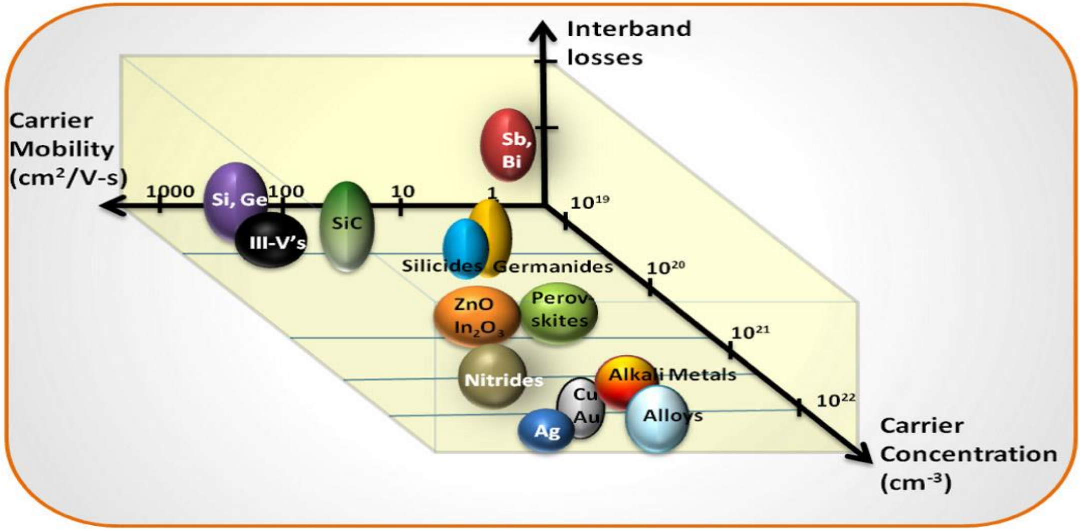


SPASER

SPASER (*Surface Plasmon Amplification of Stimulated Emission of Radiation)*

and many, many other interesting applications!!!!!!!





Metamaterials are made out of natural materials such as metals and dielectrics that are patterned to sizes much smaller than the operating wavelength and arranged in special geometries to provide extreme control over their response to light.

An ideal plasmonic material would provide zero interband losses, the highest possible mobility, and a carrier concentration of $10^{21-22}cm^{3}$.

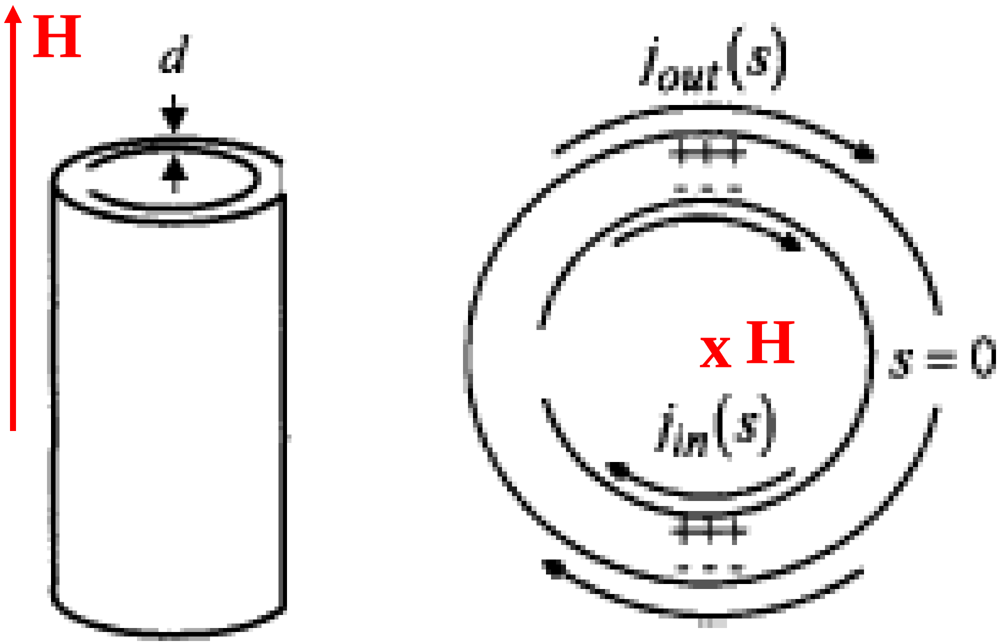
Materials possess lower carrier concentration and result in weaker interaction with light. The weaker interaction reduces loss, but still provides an overall metallic property

- R. KOWERDZIEJ, **J. PARKA**, P. NYGA, B. SALSKI, *Simulation of tunable metamaterial with nematic liquid crystal layers*, Liquid Crystals, 38 (3), pp. 377-379, (2011),
- R. KOWERDZIEJ, **J. PARKA**, J. KRUPKA, *Experimental study of thermally controlled metamaterial with liquid crystal layer at microwave frequencies*, Liquid Crystals, 38(06), pp. 743 – 747, (2011),
- R. KOWERDZIEJ, **J. PARKA**, P. NYGA, *Tunable Liquid Crystalline Metamaterial Structure in GHz Range*, Mol. Cryst. Liq. Cryst. Vol. 545, pp. 91-95, (2011),
- M. SUTKOWSKI, W. PIECEK, T. GRUDNIEWSKI, **J. PARKA,** E. NOWINOWSKI, *"Light driven optical switching of the surface stabilized antiferroelectric liquid crystals"*, Optics and Lasers in Engineering , Vol. 49, Issue 11, pp. 1330-1334, November (2011),
- J. KRUPKA, **J. PARKA**, P. ŁOŚ, J. G. HARNETT, K. NAGUSZEWSKA, *Silver-gelatine metal-dielectric composites made from developed X-Ray films*, IEEE Antennas and Wireless Propagation Letters, 10, pp. 1602 – 1604, (2011),
- M. OLIFIERCZUK, R. KOWERDZIEJ, L. JAROSZEWICZ, M. CZERWIŃSKI, **J. PARKA**, *Numerical analysis of THz metamaterial with high birefringence liquid crystal*, Liq. Cryst., 39(06), pp. 739-744, (2012),
- R. KOWERDZIEJ, M. OLIFIERCZUK, B. SALSKI, **J. PARKA**, *Tunable negative index metamaterial employing in-plane switching mode at terahertz frequencies*, Liq. Cryst, 39(07), pp. 827-831, (2012),
- R. KOWERDZIEJ, **J. PARKA**, M. OLIFIERCZUK, L. JAROSZEWICZ, *Simulation of tunable metamaterial with nematic liquid crystal layers*, 9th International Conference on Microwaves, Radar and Wireless Communications, MIKON 2012 1, art. no. 6233502, pp. 343-345, (2012),
- U. CHODOROW, **J. PARKA**, O. CHOJNOWSKA, *Liquid Crystal Materials in THz Technologies*, Photonics Letters of Poland, 10.4302/vol.2, (2012),
- U. CHODOROW, **J. PARKA**, K. GARBAT, N. PAŁKA, K. CZUPRYŃSKI, L. JAROSZEWICZ, *Spectral Properties of Nematic Liquis Crystal Mixtures Composed with Long and Short Molecules in THz Frequency Range*, Liquid Crystals, 39 (10) , pp. 1237-1242, (2012),
- U. CHODOROW**, J. PARKA**, N. PAŁKA, K. CZUPRYŃKI, *Spectral investigation of nematic liquid crystals with high optical anisotropy at THz frequency range***,** Phase Transitions, 85 (4) , pp. 337-344, (2012),
- R. KOWERDZIEJ, J. KRUPKA, E. NOWINOWSKI-KRUSZELNICKI**,** M. OLIFIERCZUK, **J. PARKA,** *Microwave complex permittivity of voltage-tunable nematic liquid crystals in high resistivity silicon transducers*, Applied Physics Letters, 102, pp. 2904-2907, 2013,

Thank you for your attention

UJEMNA PRZENIKALNOŚĆ MAGNETYCZNA I

J. Pendry et al, *Magnetism from Conductors and Enhanced Nonlinear Phenomena*, IEEE Trans. on microwave, VOL. 47, (1999)



1. **Pole elektryczne E indukuje ładunki w SRR.**
2. **Dzięki skończonej pojemności układu pojawiają się prądy.**
3. **Pole H równoległe do osi SRR powstrzymuje przepływ prądu.**

SRR - Split Ring Resonator

PAPERS

R. KOWERDZIEJ, J. PARKA, P. NYGA, B. SALSKI, *Simulation of tunable metamaterial with nematic liquid crystal layers*, Liquid Crystals, 38 (3), pp. 377-379, (2011),

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M. OLIFIERCZUK, R. KOWERDZIEJ, L. JAROSZEWICZ, M. CZERWIŃSKI, J. PARKA, Numerical analysis of THz metamaterial with high birefringence liquid crystal, Liq. Cryst., 39(06), pp. 739-744, (2012),

R. KOWERDZIEJ, M. OLIFIERCZUK, B. SALSKI, J. PARKA, *Tunable negative index metamaterial employing in-plane switching mode at terahertz frequencies*, Liq. Cryst, 39(07), pp. 827-831, (2012),

R. KOWERDZIEJ, J. PARKA, M. OLIFIERCZUK, L. JAROSZEWICZ, Simulation of tunable metamaterial with nematic liquid crystal layers, 9th International Conference on Microwaves, Radar and Wireless Communications, MIKON 2012 1, art. no. 6233502, pp. 343-345, (2012),

- **Metamaterialy: Osiaganie ujemnego e i m**
- **W osrodkach izotropowych równanie dyspersyjne ma postac k2 = n2 w2 /c2,**
- **gdzie n2 = em.**
- **Jesli wspólczynnik zalamania n osrodka, jego przenikalnosc dielektryczna**
- **e i magnetyczna m sa rzeczywiste - co oznacza osrodek bez pochlaniania -**
- **to jednoczesna zmiana znaku e i m nie zmienia powyzszego równania.**
- **Jesli uda sie wytworzyc osrodek, w którym obie przenikalnosci sa**
- **zespolone, z ujemna czescia rzeczywista i niezerowa czescia urojona - co**
- **oznacza osrodek z pochlanianiem, to powinien miec inne wlasnosci od**
- **osrodków znanych.**
- **Gdy e i m sa ujemne to wektory indukcji D oraz B sa przeciwnie**
- **skierowane niz wektory pól E i H.**

Acknowledgement

Ph. D E. Nowinowski – Kruszelnicki, Ph. D. M. Olifierczuk,
Prof. R. Dąbrowski and team – MUT

prof. J. Krupka, prof. W. Gwarek, dr J. Piotrowski - WUT

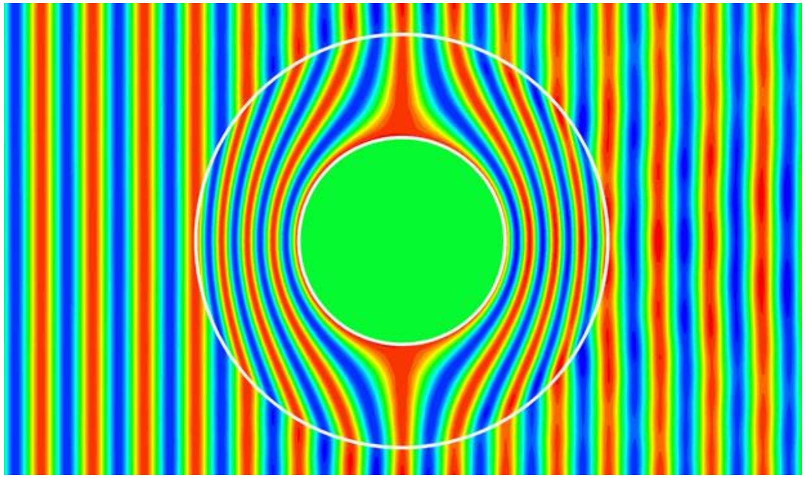
Prof. W. Salejda – WUT

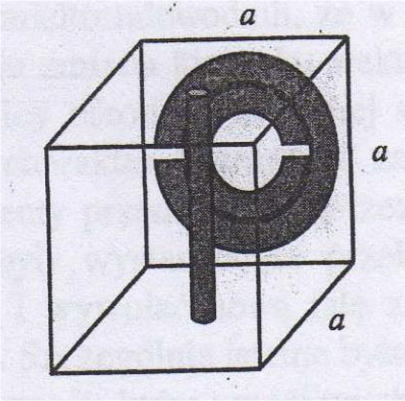
Prof. J. Wróbel – IP PAS Warsaw

Ph. D. students : R. Kowerdziej and U. Chodorow

Financial support- project NCBR nr 0114/RIT00/2010/12
„Liquid crystal tunable transducers for THz i GHz range”

QWED QuickWave
software for electromagnetic design

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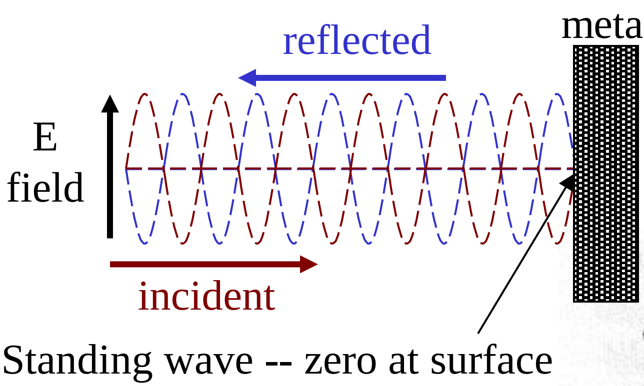
Invisibility
Cloak

Reflectivity of metals

- **Assume perfect conductor**
- **No electric field parallel to interface**

Normal incidence reflection from metal



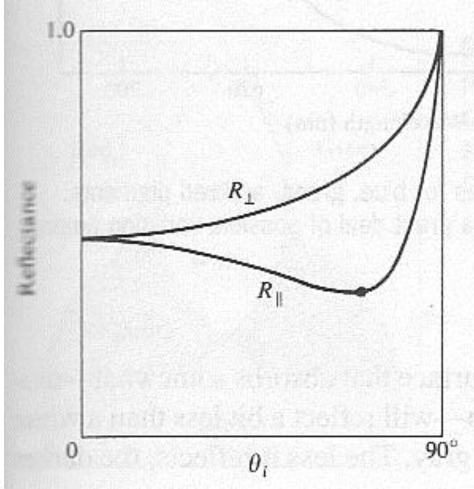


Figure 4.58 Typical reflectance for a linearly polarized beam of white light incident on an absorbing medium.

- **Reflectivity at normal incidence**
- **(assume n_i = 1)**

$$r = \frac{n_{complex} - 1}{n_{complex} + 1}$$

- **Power reflected**
- **R = r r* → 1 for large absorption**

$$R = \frac{(n_{real} - 1)^2 + (\alpha c / 2\omega)^2}{(n_{real} + 1)^2 + (\alpha c / 2\omega)^2}$$

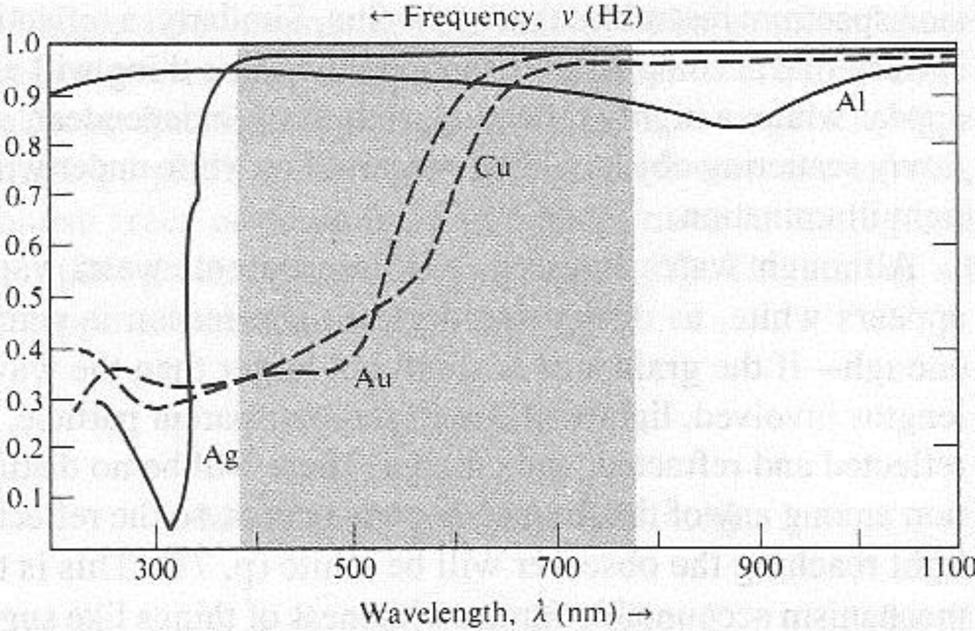


Figure 4.59 Reflectance versus wavelength for silver, gold, copper, and aluminum.

O wlasnosciach elektromagnetycznych materialów decyduje:

E H k

r r r

´ = -

*n*2 = *em*

W równaniu Helmholtza wspólczynnik zalamania n wystepuje w kwadracie (2) 0

0

Ñ2 + *n*2 *k* Y =

Klasyczny osrodek izotropowy

Klasyczny osrodek anizotropowy

Metamaterial izotropowy

E

D

E

D

E

D

HB

Sample materials

- **Refractive index approx. follows formula**
- **Resonances in UV**
- **Polar materials also have IR resonances**
  - **Nuclear motion – orientation**

$$\frac{n^2-1}{n^2+2} = \frac{Nq_e^2}{3\varepsilon_0 m_e}\sum_j\left(\frac{f_j}{\omega_{0j}^2-\omega^2+i\gamma\omega}\right)$$

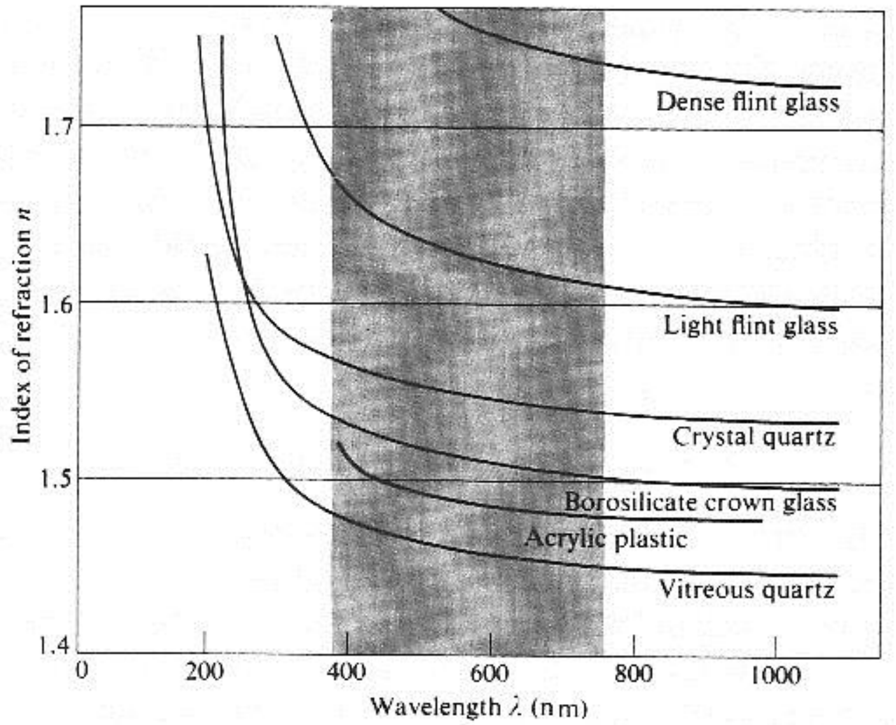


Figure 3.40 The wavelength dependence of the index of refraction for various materials.

Polar materials

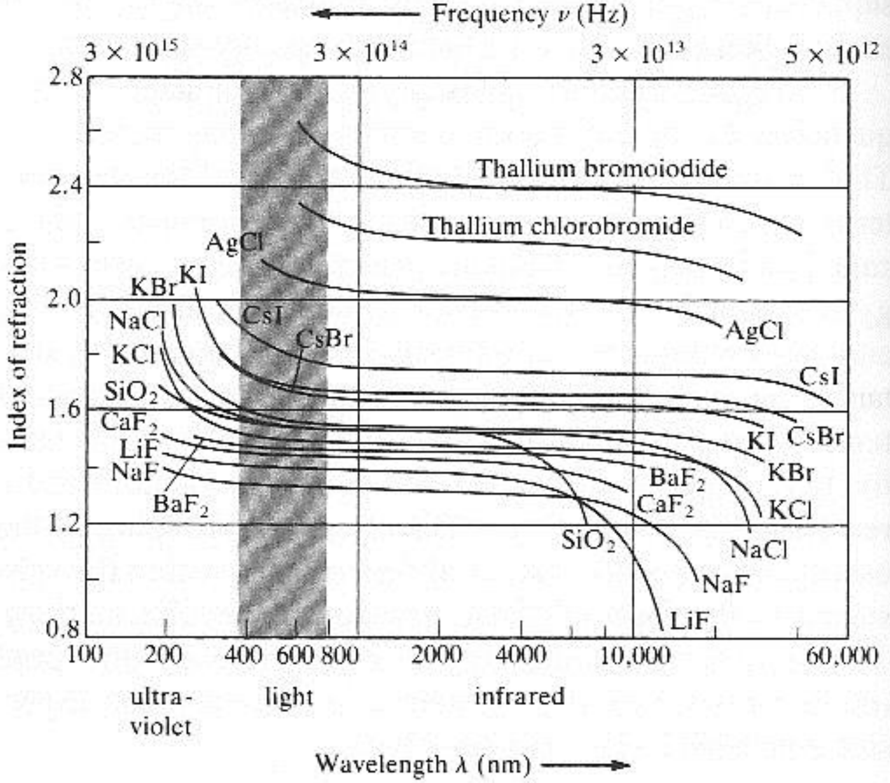


Figure 3.42 Index of refraction versus wavelength and frequency for several important optical crystals. (Adapted from data published by The Harshaw Chemical Co.)