THz left –handed EM in composite polar dielectrics

Plasmonic excitations in nanostructured materials

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Motivation and Outline

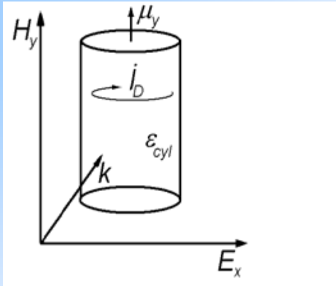
Metamaterials and Left Handed Metamaterials (LHM)

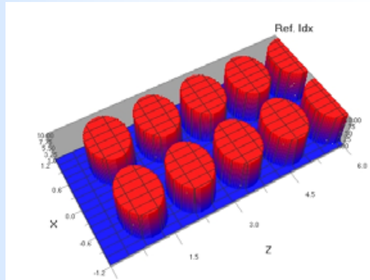
- n<0; ε<0; μ<0
- Wavelength much larger than the size of the scatterers (effective medium limit)
- Split ring resonators (SRR) – negative permeability
- Other routes
- Dielectric resonators, plasmonic systems
- FDTD simulations + S – parameter retrieval method
- Microstructured polar dielectric – strong magnetic response in far – infrared
- Composite system realized by to polar dielectrics – LHM
- THz spectral domain – novel applications (sensing, imaging, life sciences, condensed matter physics)

2 dimensional left handed material

RHM

μ<0





The unit cell of a two dimensional dielectric high contrast photonic crystal

cylinder with high permittivity ϵ_{cyl}

the system presents an *effective* magnetic permeability μy.
$\lambda >> a$

$$ka = a\frac{2\pi\sqrt{\varepsilon}}{\lambda}$$

Zero of a Bessel function

L. D. Landau and E. M. Lifshitz, Electrodynamics of Continuous Media

Z. Zhai, C. Kusko, N. Hakim, S. Sridhar, A. Viektine, and A. Revcolevski Rev. Sci. Instr. 70, 3151 (2000)

23/09/2008 NUSOD 2008 3

Microwaves

$SrTiO_3$ ε=300+0.8i 22 GHz

G. Ruppercht and R. O. Bell, Phys. Rev. 125, 1915 (1962)

Tunnability

Nonlinear effects

Higher frequencies - infrared

Wheeler et al Phys Rev B 72, 193103 (2005)

Effective medium approach – LiTaO3 spheres
Clausius Mossotti

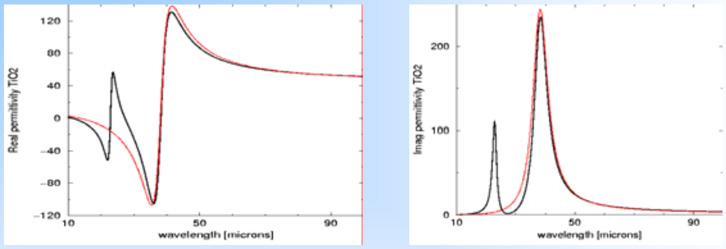
Polar materials –
SiC, TiO_2, $LiTaO_3$
Phonon modes

*J. A. Schuller, R. Zia, T. Taubner, and M. L. Brongersma, Phys. Rev. Lett **99,** 107401 (2007)*

*L. Peng, L. Ran, H. Chen, H. Zhang, J. Au Kong, and T. M. Grzegorczyk, Phys. Rev. Lett **98,** 157403 (2007)*

23/09/2008 4

Polar dielectrics $-TiO_2$ far - infrared phonon modes



The real part (left panel) and the imaginary part (right panel) of the permittivity for the TiO_2 anatase (solid black line). The dotted red line represents the one resonance fit used in the FDTD simulations.

$E \perp c$ – axis two vibrational modes
TO_1 262 cm^{-1} LO_1 366 cm^{-1}
TO_2, 435 cm^{-1} LO_2 876 cm^{-1}

ε_0=44.5 low frequency dielectric constant

ε_{inf} = 5.82 high frequency dielectric constant

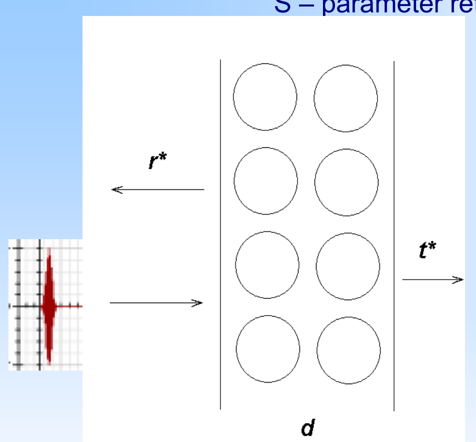
ω_{TO} = 262 cm^{-1} = 5.10^{13} rad/s mode resonant frequency

ω_{TO} =12.10^{11} rad/s damping frequency

R.J. Gonzales, R. Zallen and H.Berger, *Phys. Rev. B 55*, **7014**, (1997).

23/09/2008 5

S – parameter retrieval method



Z – surface impedace
n – effective refractive index
ε – effective permittivity
μ – effective permeability

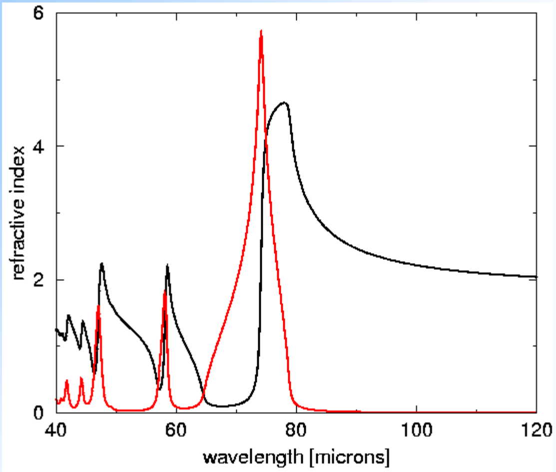
$$Z = \pm\sqrt{\frac{(1+r^*)^2 - t^{*2}}{(1-r^*)^2 - t^{*2}}}$$

$$n = \frac{1}{kd}\arccos\left(\frac{1}{2r^*}\left(1 - r^{*2} + t^{*2}\right)\right) + \frac{m\pi}{kd}$$

$$\mu = n_{eff}\, Z \qquad \varepsilon = \frac{n_{eff}}{Z}$$

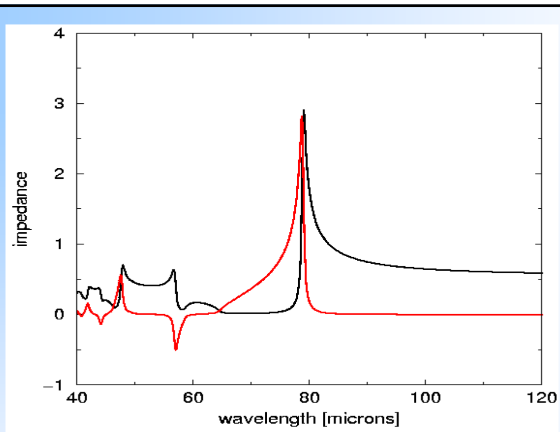
D. R. Smith, S. Scultz, P. Markos and C. M. Soukoulis, Phys. Rev. B ***65,*** *195104 (2002)*

23/09/2008 6



The effective refractive index for a metamaterial consisting in a square periodic array of cylinders made of TiO2, with the diameter d=8microns and lattice constant a=10microns.
The black line represents the real part of the refractive index, whereas the red line represents the imaginary part.

23/09/2008 NUSOD 2008 7



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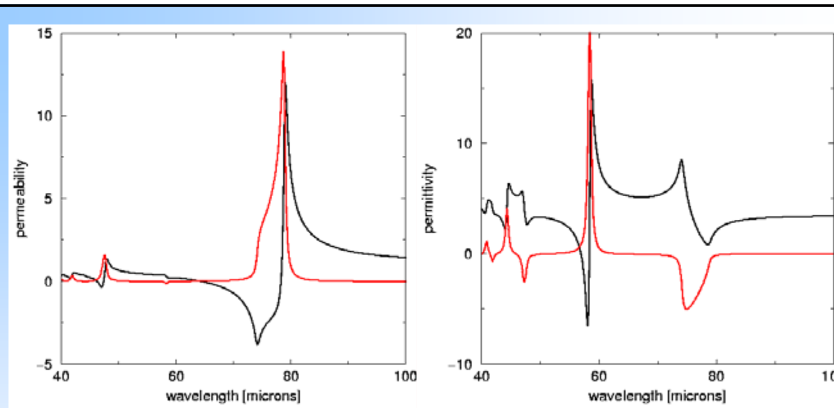
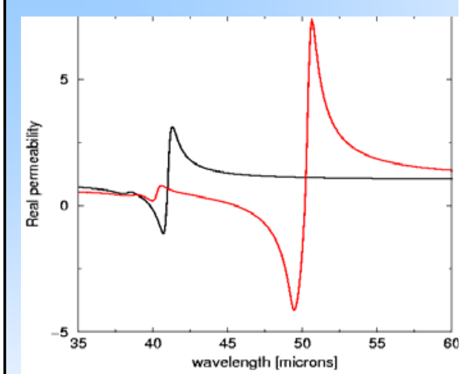
23/09/2008 8



Negative effective permeability around zero order Mie resonance

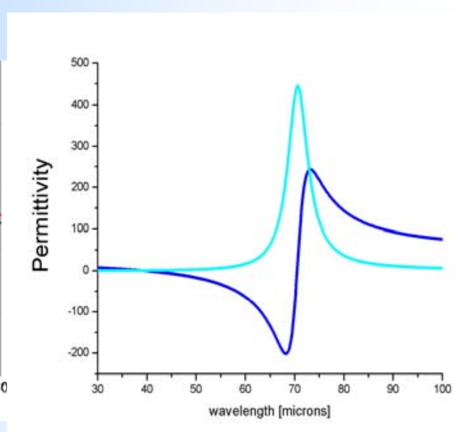
Negative effective permittivity around first order Mie resonance
Antiresonant behavior for permittivity around zero order Mie resonance
(negative imaginary part of the permittivity)

23/09/2008 9



The real part of the effective μ for :
(black line) d=2.0 μm and a=2.5 μm,
(red line) d=4.0 μm and a=5.0 μm.

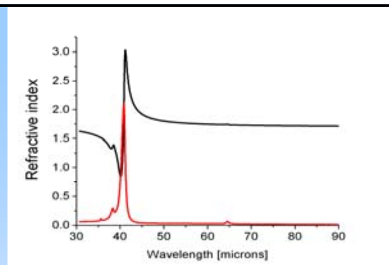
Microstructured TiO_2

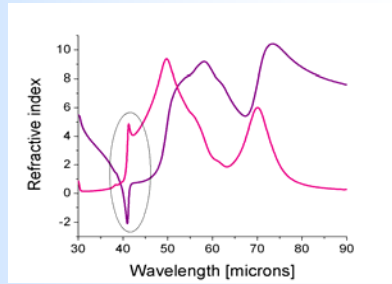


Bulk $LiTaO_3$

M. S. Wheeler, J. S. Aitchinson, and M. Mojahedi, Phys. Rev. B **73,** 045105 (2006).

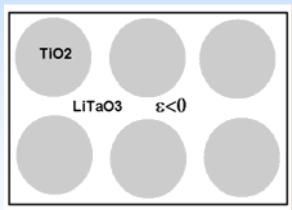
23/09/2008 NUSOD 2008 10

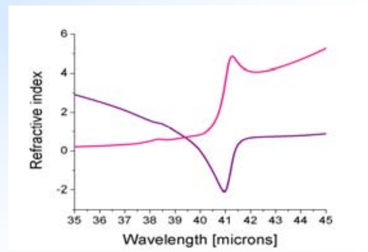




Microstructured TiO_2

Microstructured TiO_2 + $LiTaO_3$

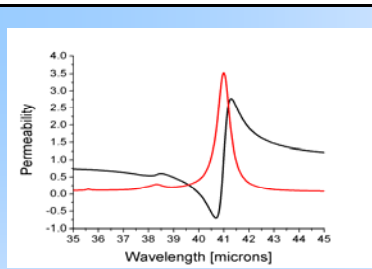


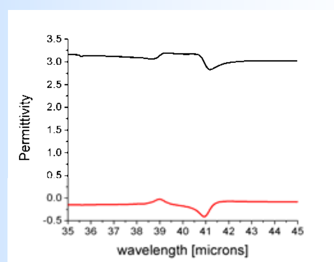


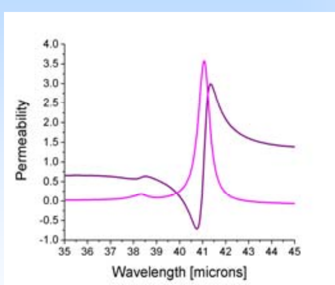
n<0

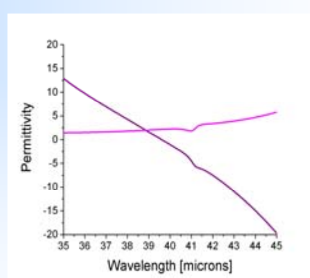
negative index metamaterial NIM

23/09/2008 11









$\varepsilon<0$; $\mu<0$

Left handed metamaterial

23/09/2008 12

Summary

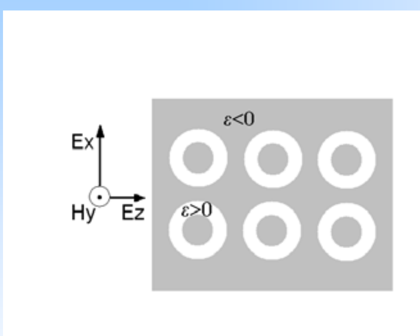
- A metamaterial realized from titanium TiO2 mimics strong magnetic activity at terahertz frequencies.
- TiO2 anatase polar material active phonon modes in the far infrared wavelengths (or terahertz frequencies)
- high dielectric constant ε_0=50 – 120 λ=100 – 40 microns.
- Mie resonances in a periodic array of cylinders
- strong effective magnetic response.
- FDTD computations and S – parameter formalism
- microstructured TiO2 anatase, negative permeability in the range of wavelengths λ=80 – 40 mm.
- LHM metamaterial – combination of TiO2 and LiTaO3

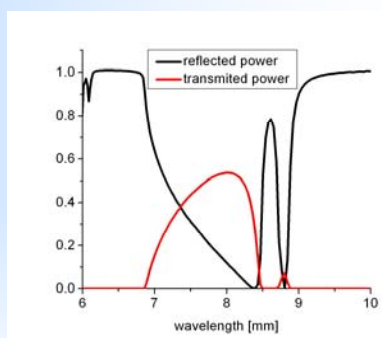
23/09/2008 13

Plasmonic excitations in nanostructured materials

Electromagnetic response of a structured Drude material

Complementary structure



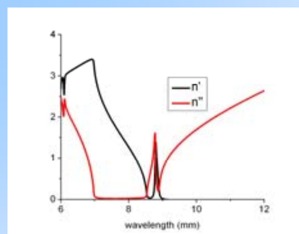


a plasma frequency of 8.10 ^{11} rad/s

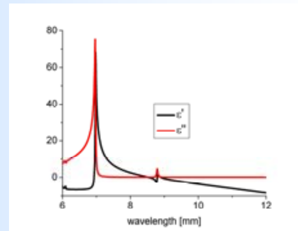
Wavelength 3mm

C. Rockstuhll and F. Lederer, Phys. Rev. B, 125426 (2007)

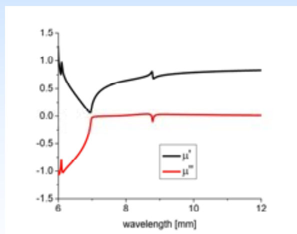
R. Liu et al Phys. Rev. Lett. **100** 023903, (2008)



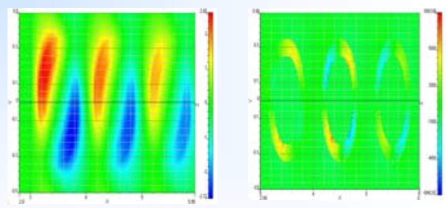
The real (black line) and the imaginary (red line) of the refractive index.



The real (black line) and the imaginary (red line) of the permittivity.



The real (black line) and the imaginary (red line) of the permeability.



The electromagnetic fields configuration

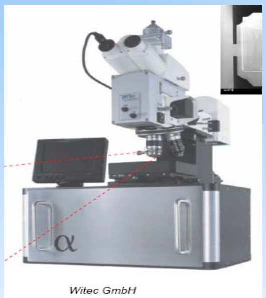
Summary

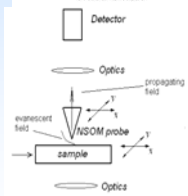
- A metamaterial realized from a structured Drude material mimics positive refractive index for frequencies below the plasma frequency
- Spectral range with a monotonic behavior of the refractive index
- Sub unitary permeability
- Localised plasmonic excitations
- FDTD computations and S – parameter retrieval formalism
- spectral domain mm waves extension to THz ; infrared ; visible polar dielectrics, metals

CEEX II Reintegration grant

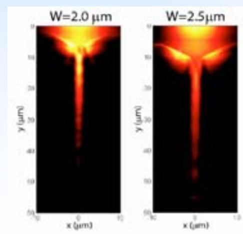
Future activities – experimental work

Witec GmbH, Germany
Alpha 300 SNOM





Simulation → **Nanofabrication** → **Characterization** → **Simulation**



R. Zia, J. A. Schuller, and
M. L. Brongersma
Phys. Rev B **74**, 165415 2006

MIMOMEMS FP7