FDTD simulations of far – infrared effective magnetic activity in microstructured TiO_2

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Motivation and Outline

Metamaterials and Left Handed Metamaterials (LHM)

- $n<0; \varepsilon<0; \mu<0$

- Wavelength much larger than the size of the scatterers (effective medium limit)
- Split ring resonators (SRR) – negative permeability

- Other routes
- Dielectric resonators, plasmonic systems

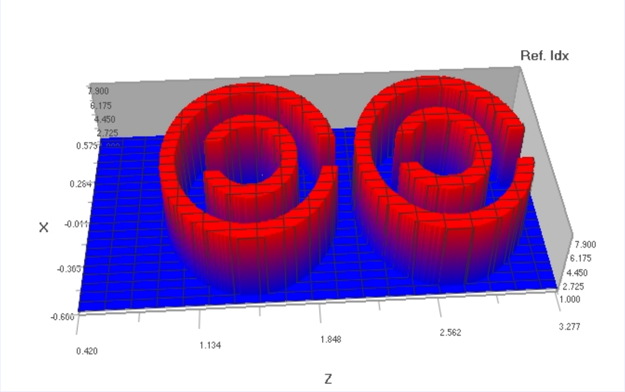
- FDTD simulations + S – parameter retrieval method
- Microstructured polar dielectric – strong magnetic response in far – infrared

- Composite system realized by to polar dielectrics - LHM

2 - dimensional magnetic metamaterial

SRR configuration

TM polarization
Eddy currents
Induced magnetic moment
Resonant behavior
Large magnetic response
Positive or negative magnetic moment
$\lambda >> a$
Effective medium $\mu<0$



Dielectric cylinders configuration

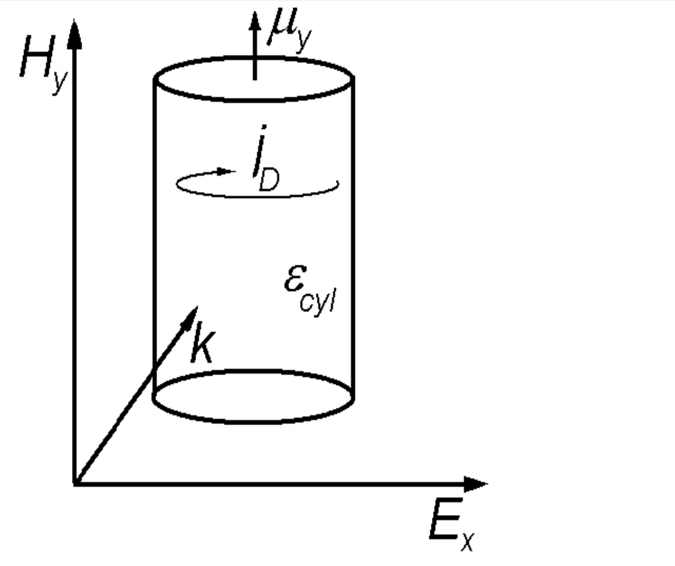
TM polarization
Polarization currents
Induced magnetic moment
Resonant behavior
Large magnetic response
Positive or negative magnetic moment
$\lambda >> a$
Effective medium $\mu<0$

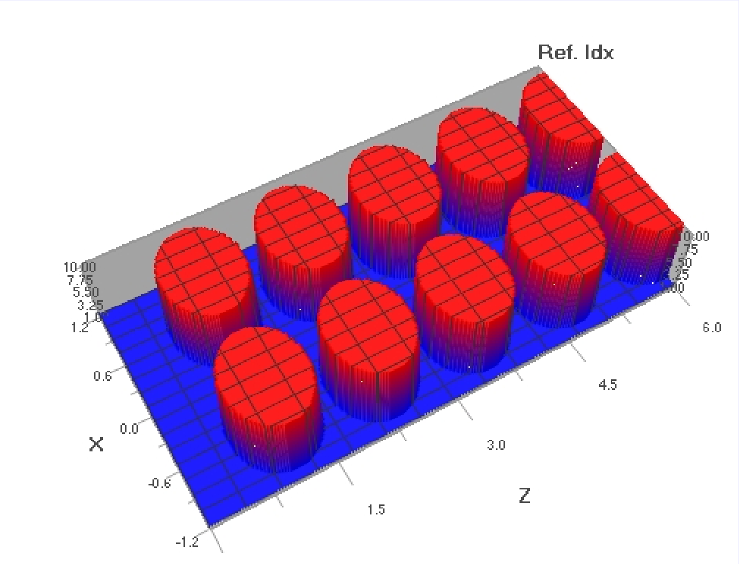
S. O'Brien and J. B. Pendry,
J. Phys. Condensed Matter, **14** 6383, (2002).

2 dimensional left handed material

RHM

$\mu<0$





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)

Microwaves

$SrTiO_3$ ε=300+0.8*i* 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 –

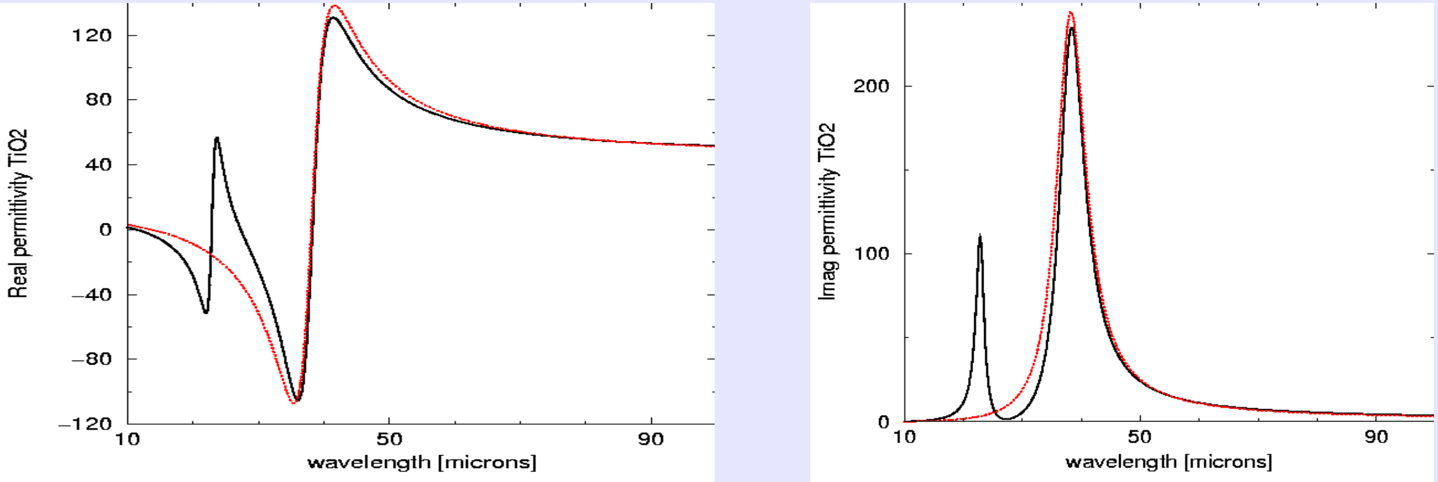
SiC, TiO_2, $LiTaO_3$

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)*

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.

$$\epsilon(\omega)=\epsilon_0+(\epsilon_0-\epsilon_\infty)\frac{\omega_{TO}^2}{\omega_{TO}^2-\omega^2+i\gamma_{TO}\omega}$$

E ⊥ 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

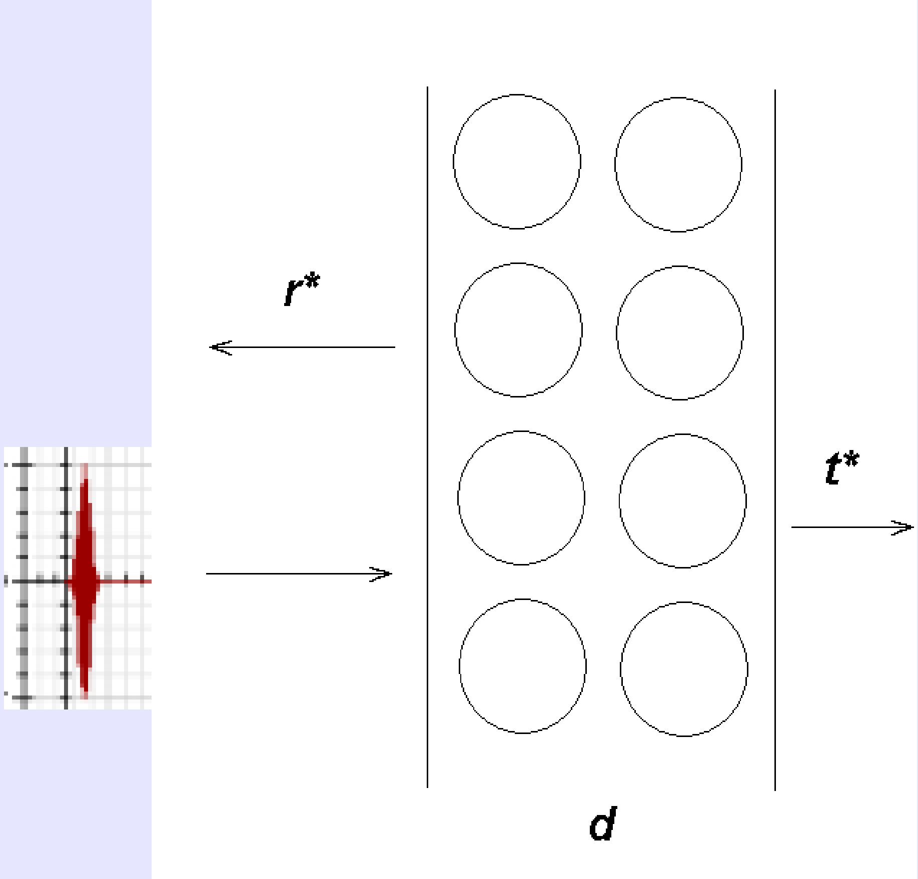
ε_{inf}= 5.82 high frequency dielectric constant

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).

S – parameter retrieval method



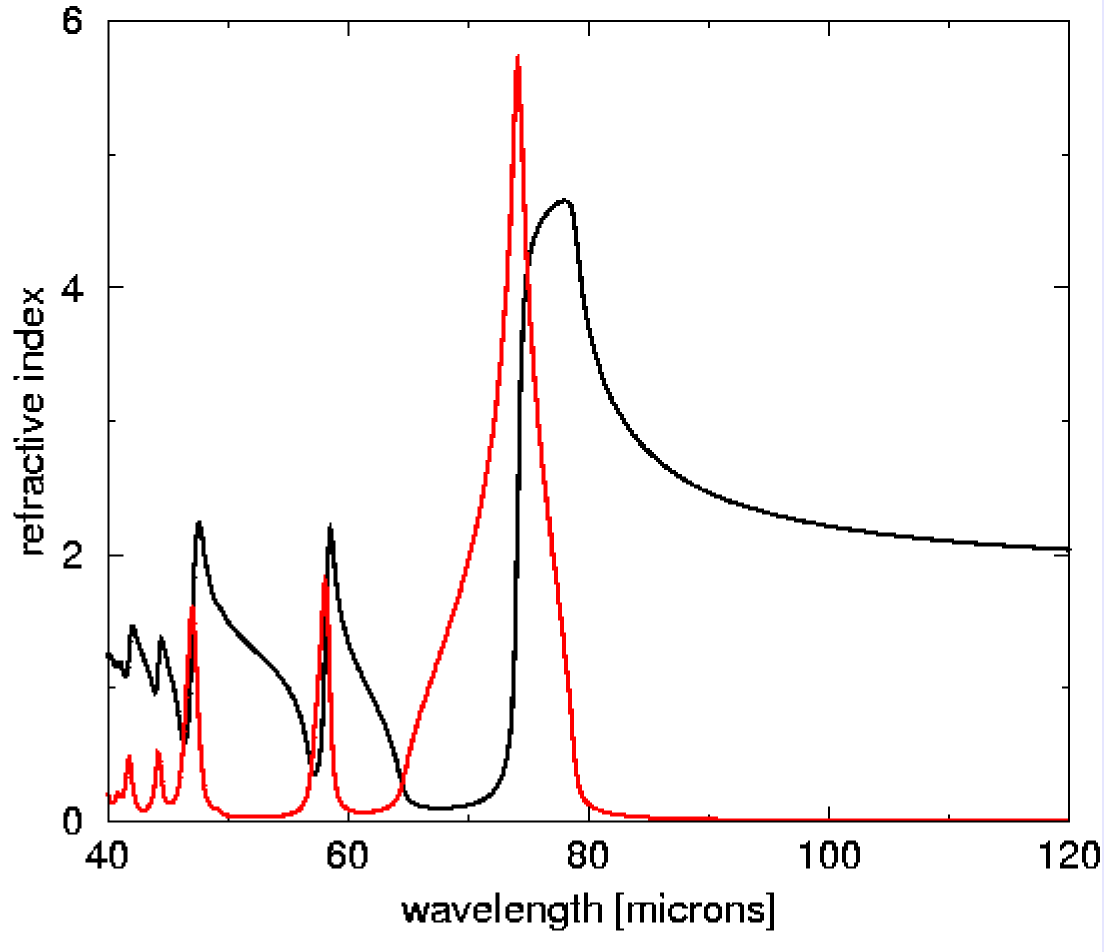
Z – surface impedace
n – effective refractive index
ε – effective permittivity
μ – effective permeability

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

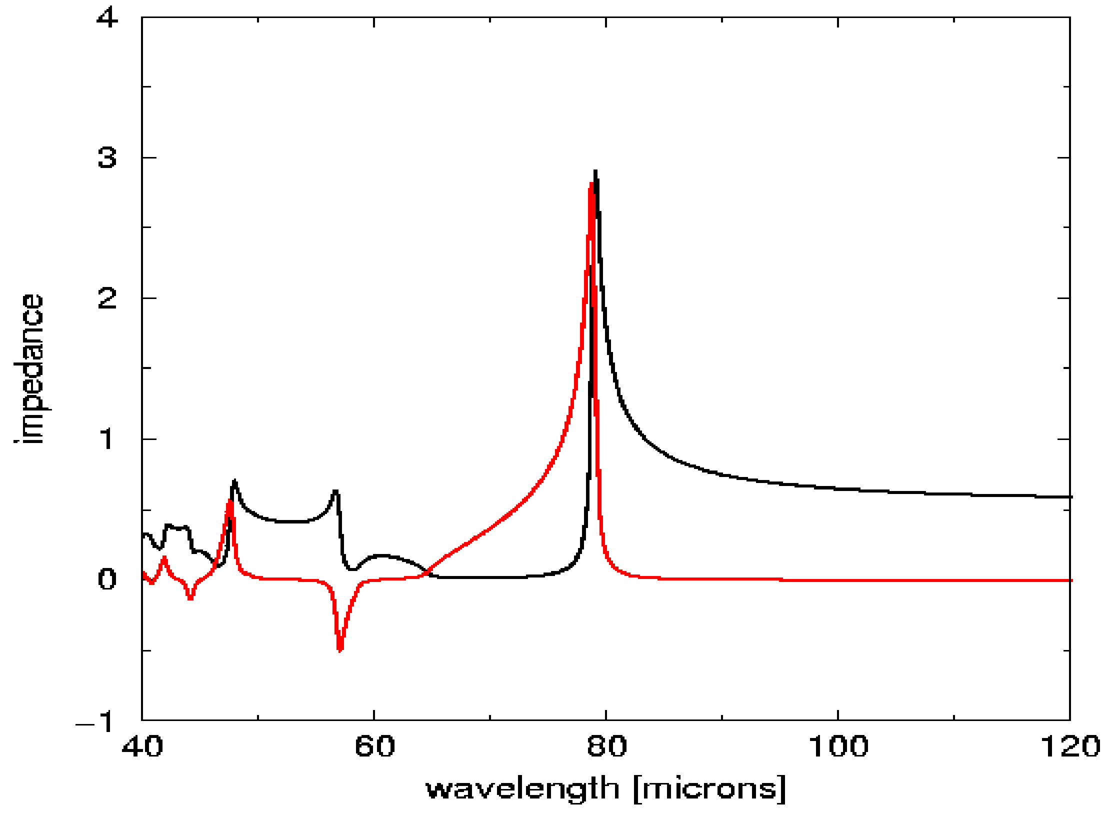
$$Z = \pm\sqrt{\frac{(1+r^*)^2 - t^{*2}}{(1-r^*)^2 - t^{*2}}}$$

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

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



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.



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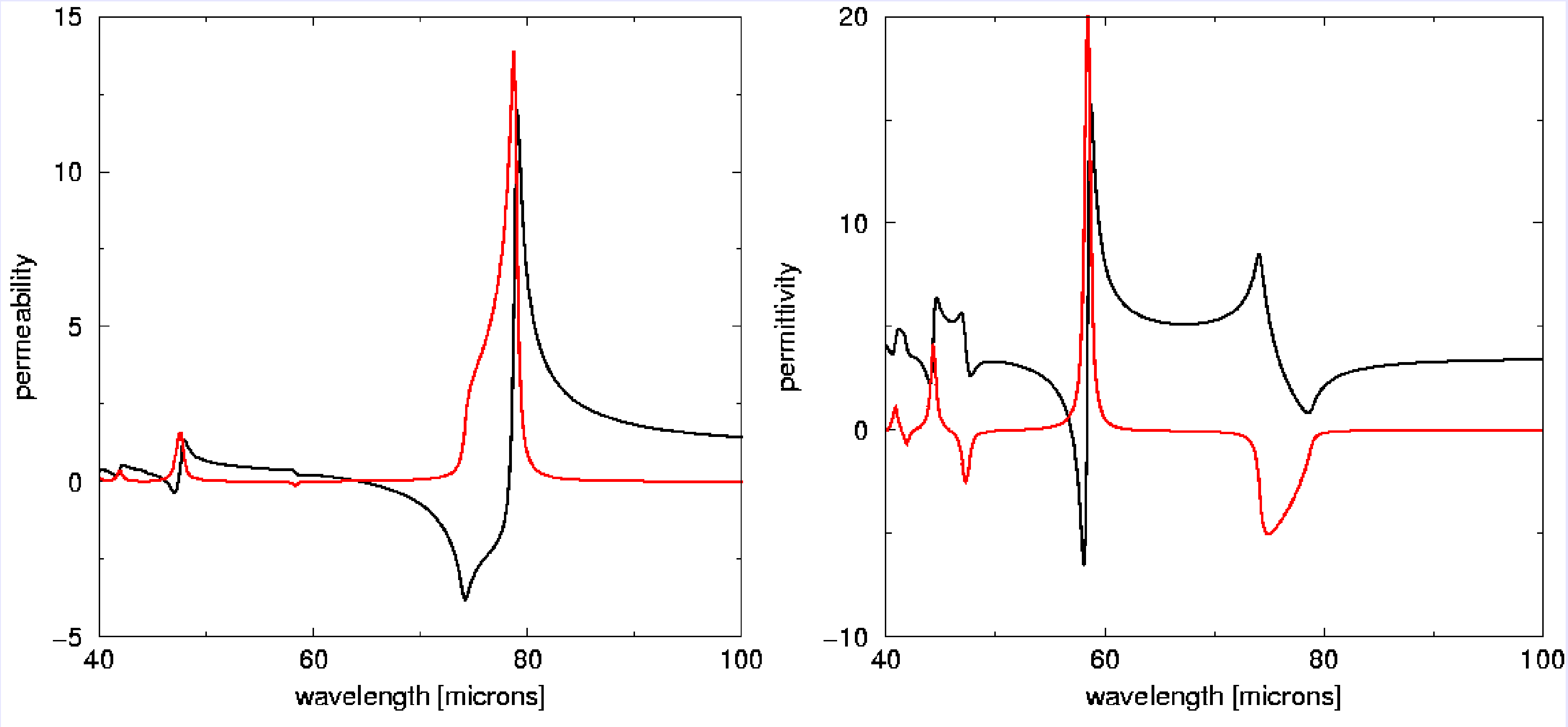

Negative effective permeability around zero order Mie resonance

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

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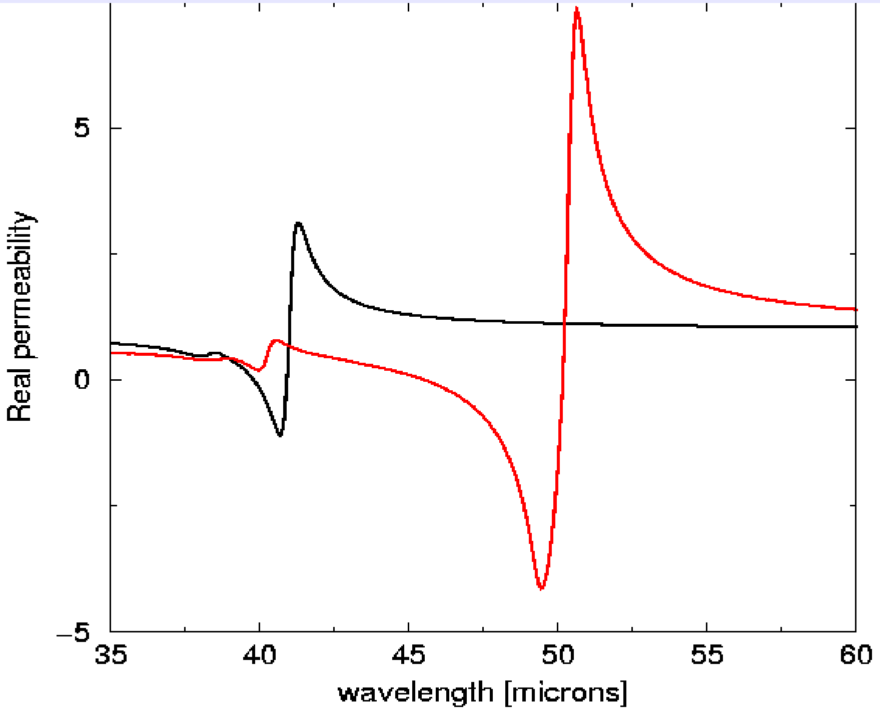
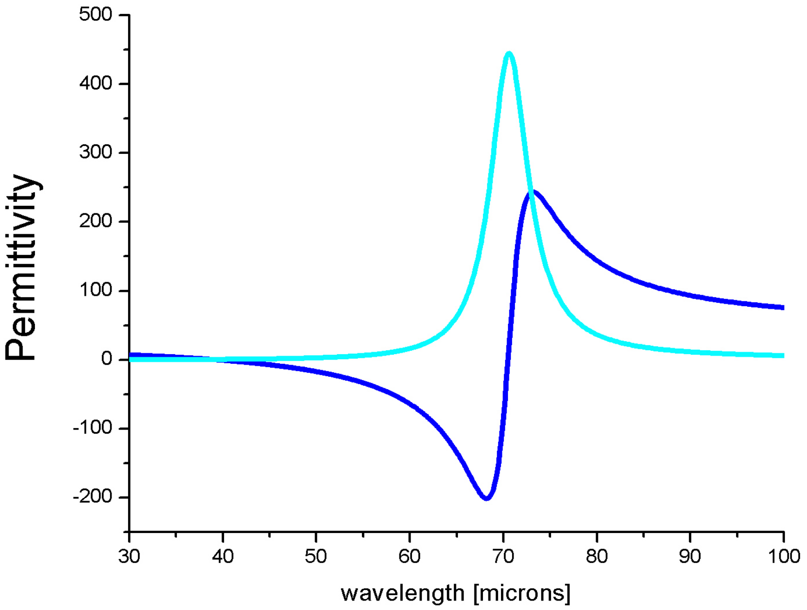


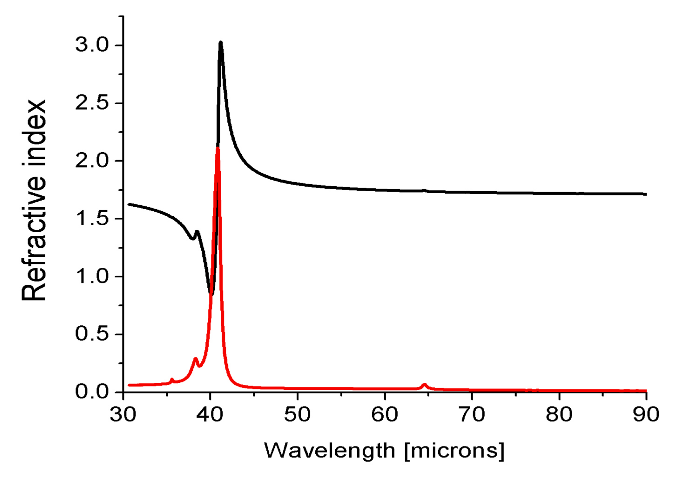
The real part of the effective μ for :
(black line) d=2.0 μm and a=2.5 μm,
(red line) d=4.0 μm and a=5.0 μm.

Microstructured TiO_2

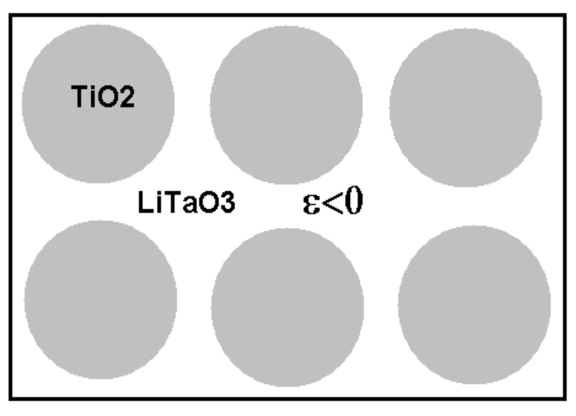


Bulk $LiTaO_3$

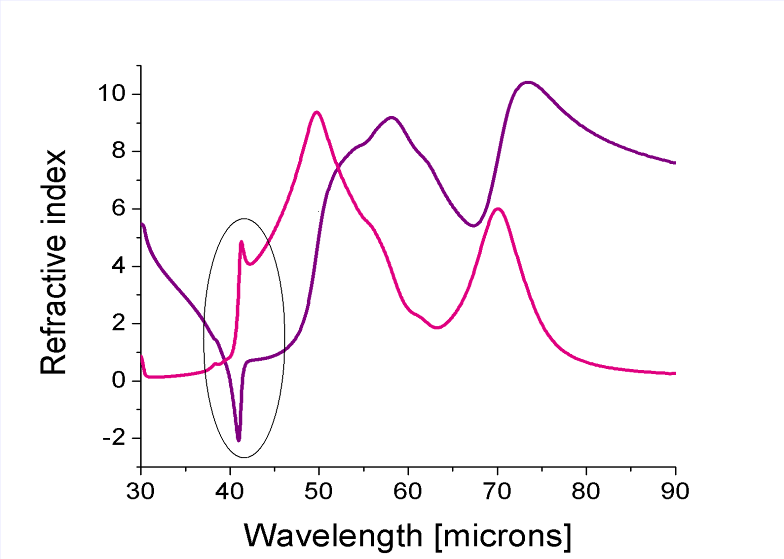
M. S. Wheeler, J. S. Aitchinson, and M. Mojahedi, Phys. Rev. B **73,** 045105 (2006).



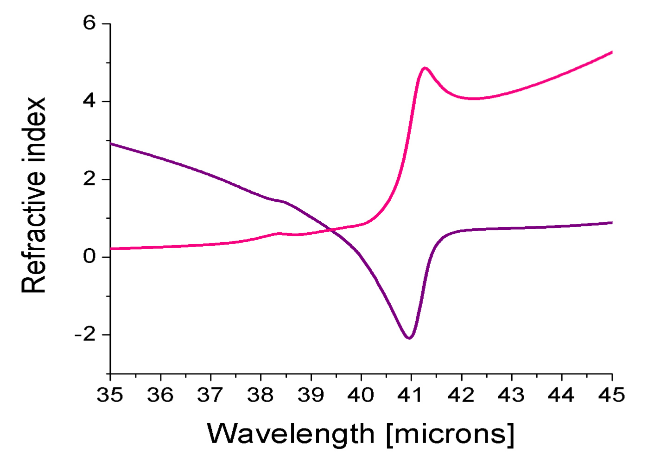
Microstructured TiO_2



n<0
negative index metamaterial NIM



Microstructured TiO_2 + $LiTaO_3$



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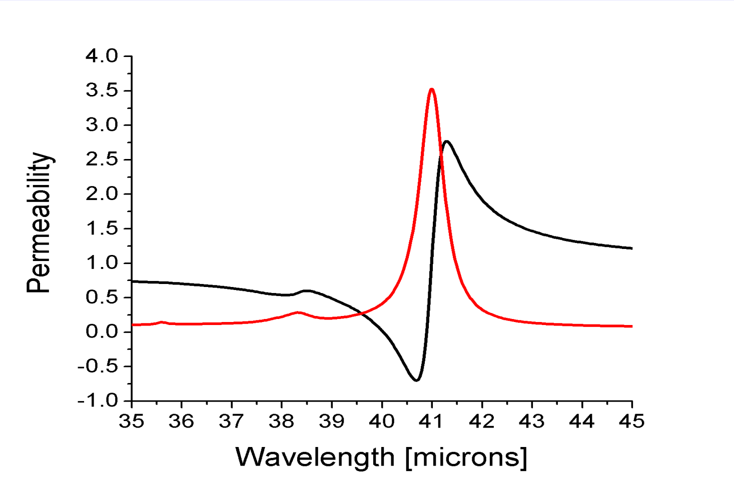

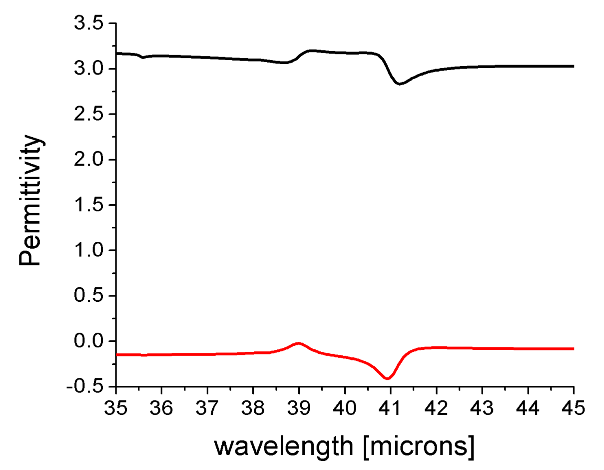

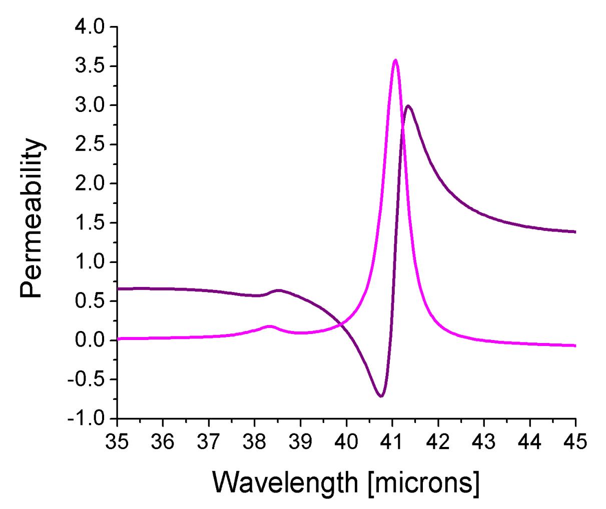

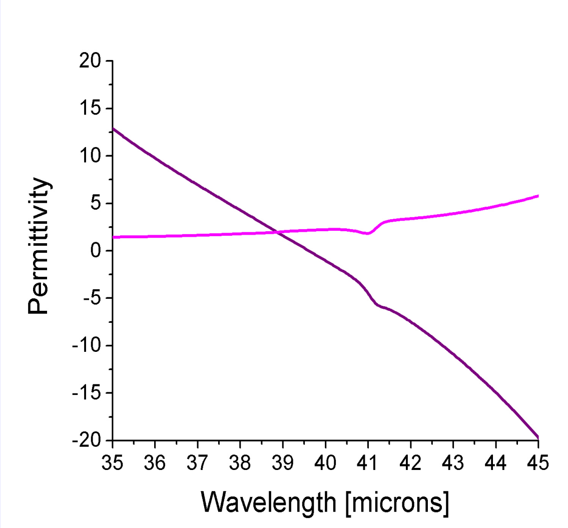

$\varepsilon<0; \mu<0$

Left handed metamaterial

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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

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