The Exciting World of Surface Plasmons

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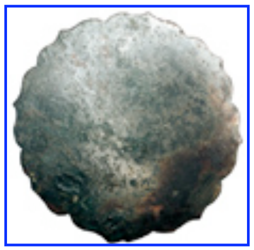
Outline:

- Surface plasmons in complex media: many-body problem in electromagnetism.
- Metamaterials and applications: negative index materials, magnetic plasmons, superlens, optical activity, sub-wavelength solitons and transmission lines.
- Current work and future prospective.
- Possible collaborations

Materials with controlled optical properties

"The heart of the sage is quiet;
it is a mirror of Heaven and Earth."

Zhuang Zi
Zhou Dynasty (770–256 BC)



Bronze mirror
Song Dynasty (960-1279)

Lycurgus cup
(4th cent. AD)

James Clerk Maxwell
(1831-1879)

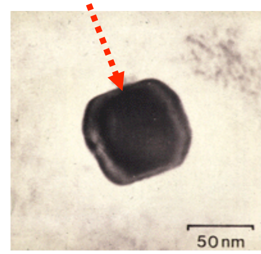
Stone Age
2 mil. - 6000BC

Bronze Age
5000 -1600BC

Iron Age
1600BC -

Middle Age
10th -16th cent. AD

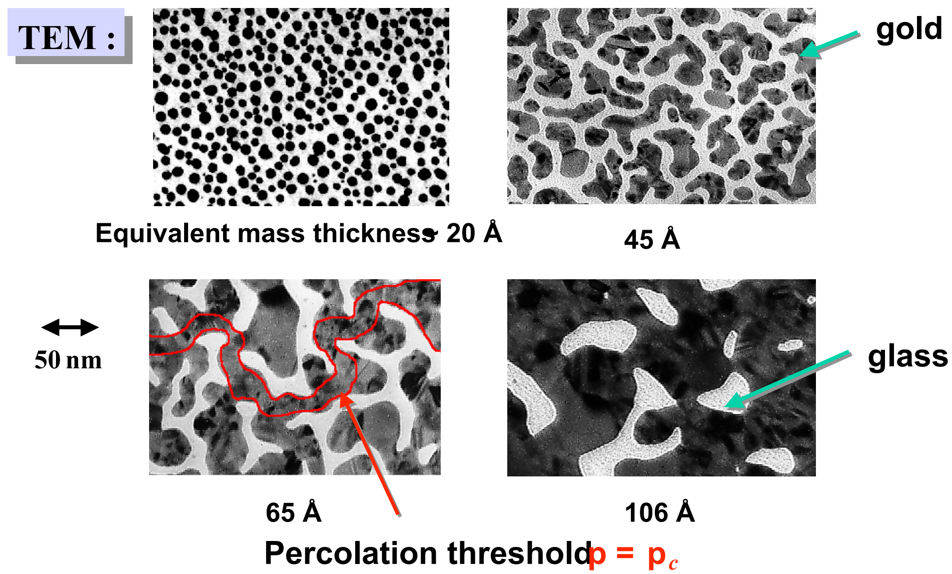
Photonics Age
20th cent. -present

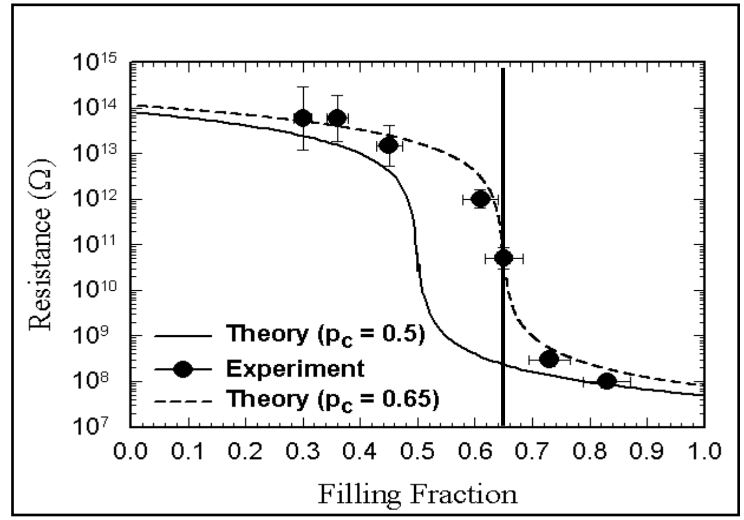


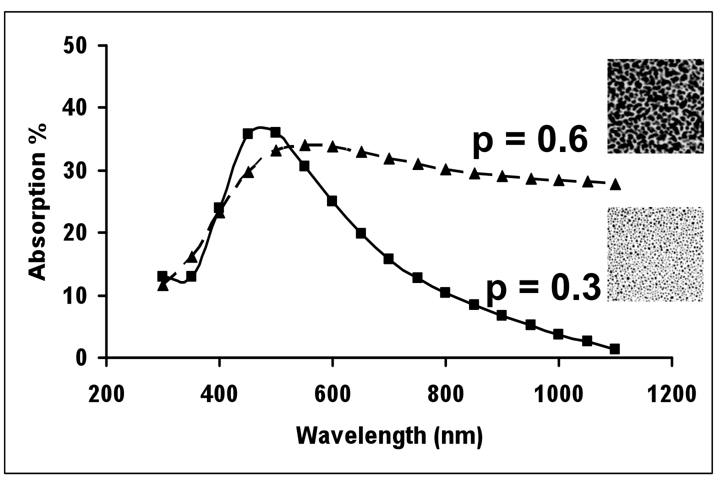
Nano-sized metal particles

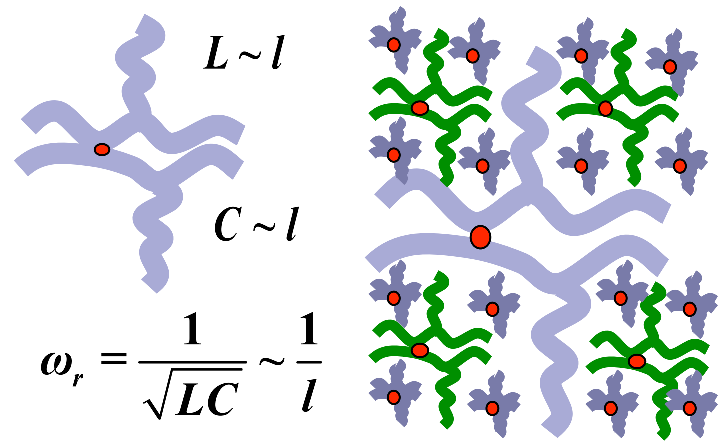
Stained glass

Inhomogeneous metal-dielectric films: extraordinary electromagnetic properties







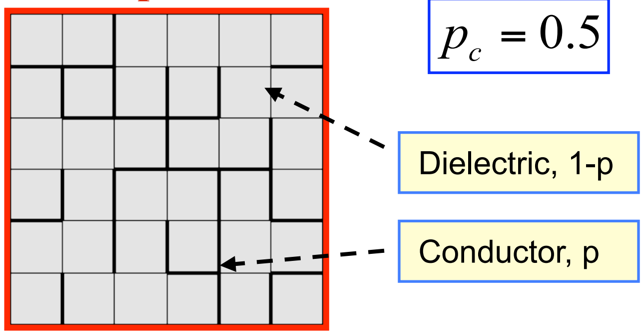


$$\omega_r = \frac{1}{\sqrt{LC}} \sim \frac{1}{l}$$

K. Seal, D. A. Genov, *et al.* PRB 67, 35318 (2003)

Local optical response – numerical results

Bond percolation



$p_c = 0.5$

Current conservation: $(\lambda >> h \approx a)$

$$\nabla \cdot \mathbf{j}(\mathbf{r}) = \nabla \cdot \{\sigma(\mathbf{r})[-\nabla \varphi_{loc}(\mathbf{r}) + \mathbf{E}_0]\} = 0$$

Kirchhoff's equations: $\hat{H}_{KH} \cdot \Phi = E$

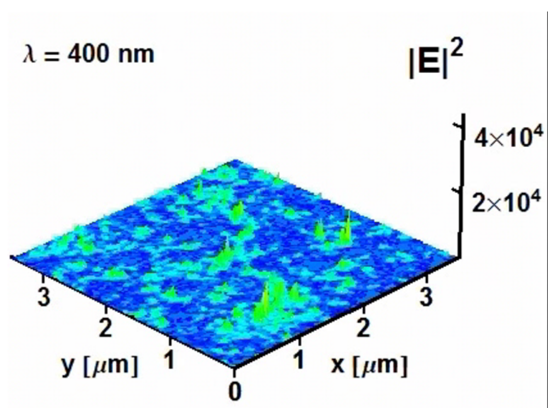
Many-body problem
3.5 µm X 3.5 µm ~ 100,000 particles

GE ~ 10 years

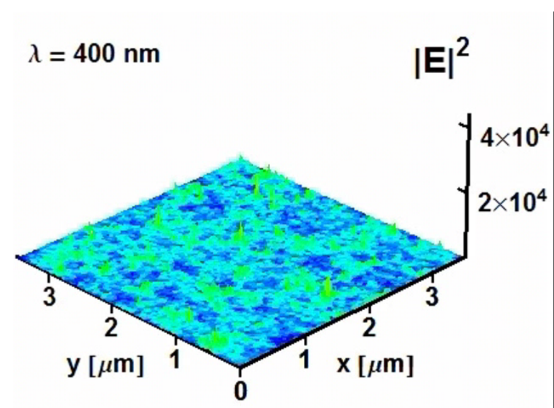
BE ~ 1 hours

- Exceptionally strong local field enhancement
- EM field localization in the nanoscale
- Broad optical response at percolation threshold

p = 0.2



p = 0.5



D. Genov *et al.* Phys. Rev. E 67, 56611 (2003)

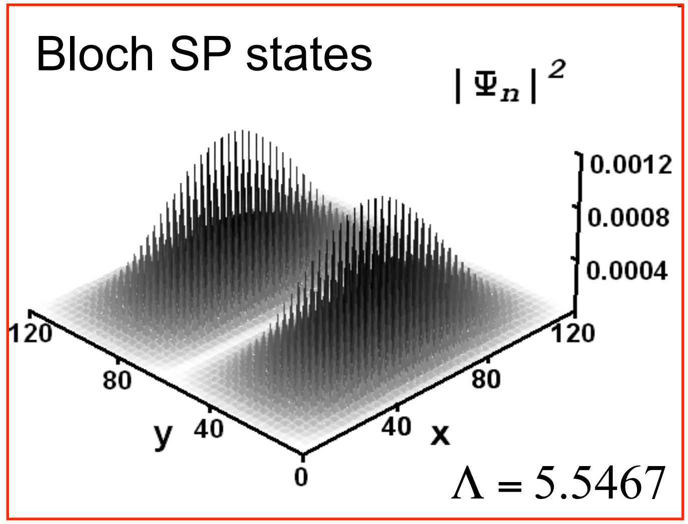
SP eigenstates: random vs. periodic systems

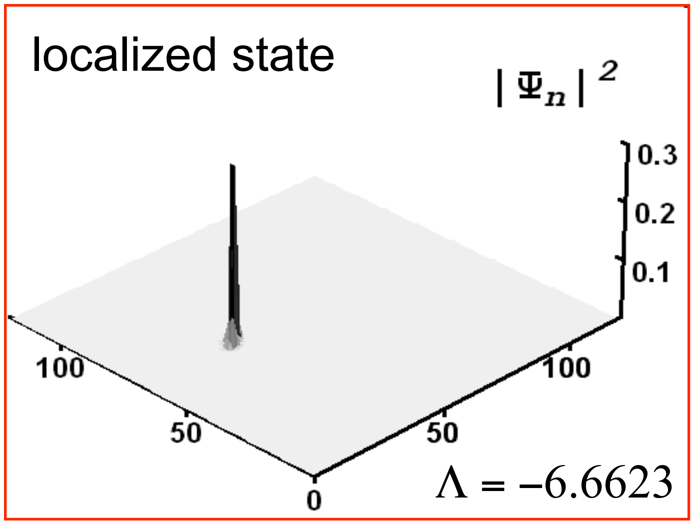
SP as a quasiparticles (localization):

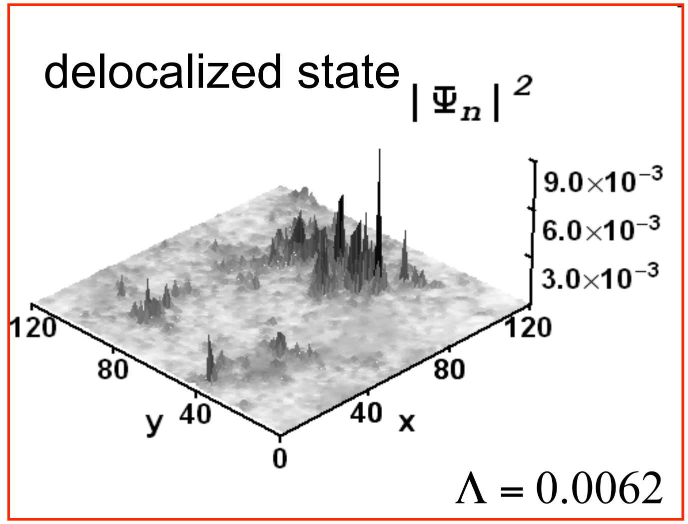
$$[-\frac{\hbar}{2m_{SP}^{*}}\nabla^2 + U_{KH}(\mathbf{r})]\Psi_{SP}(\mathbf{r}) = \Lambda^{(SP)}\Psi_{SP}(\mathbf{r})$$

$$\widehat{\mathrm{H}}_{KH} = \sum_{n} h_{nn}^{(KH)}|n\rangle\langle n| + \sum_{\substack{n,k \\ n\neq k}} h_{nn}^{(KH)}|n\rangle\langle k|$$

$$h_{nn}^{(KH)} = \sum_{\{m\}}\sigma_{nm}^{*}, \quad h_{nk}^{(KH)} = -\sigma_{nk}^{*}$$



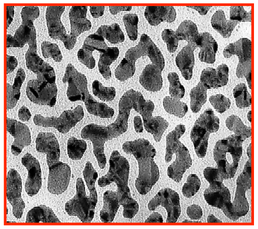




P.W. Anderson, Phys. Rev. 109, 1492 (1958)

D. A. Genov, *et. al.* PRB 72, 113102 (2005)

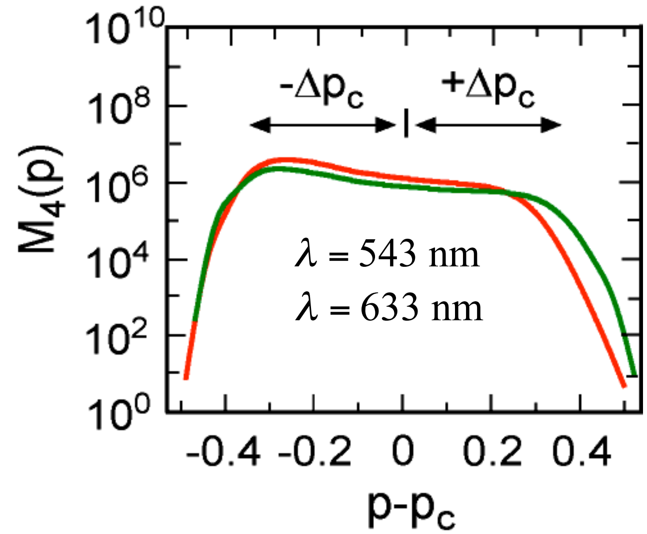
Surface Enhanced Raman Scattering

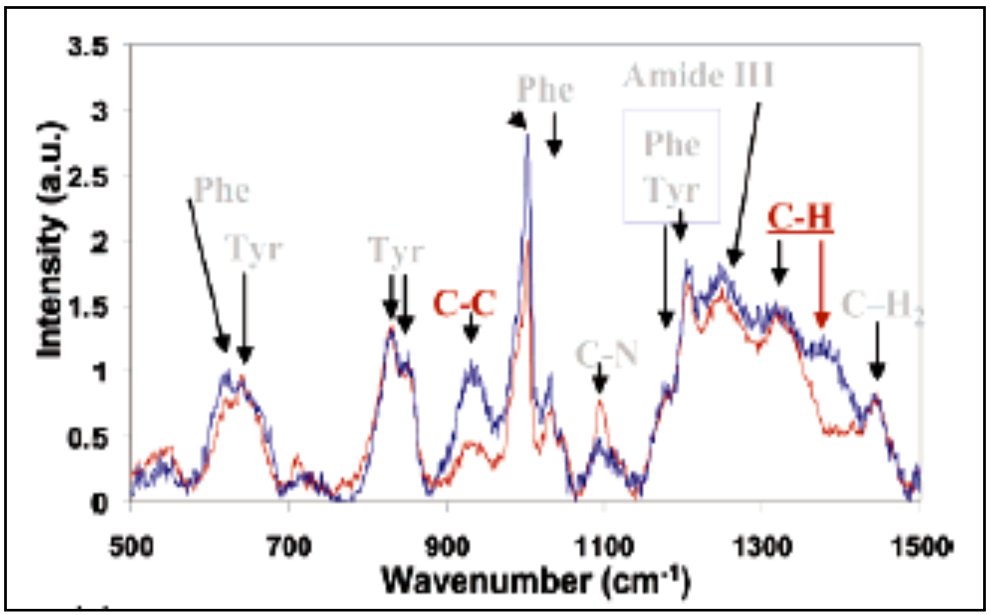


$$\Phi \sim I_0 \sigma^{SERS}, \quad \sigma^{SERS} = \overline{G}\sigma^{R}$$

$$\overline{G} = \overline{G}_{EM} \cdot \overline{G}_{Ch}, \quad \overline{G}_{EM} >> \overline{G}_{Ch}$$

$$\overline{G}_{EM} = \frac{|E(\omega)|^2 |E(\omega+\omega_R)|^2}{|E_0(\omega)|^4} \approx M_4(\omega)$$





Detected insulin surface density of about 80 fmol/mm^2, or sub-monolayer coverage. The measured average enhancement factor of the SERS-active silver structure is about 3 x10^6.

V. P. Drachev, *et al.*,
Journal of Phys. Chem. 108, 18046 (2004).

D. A. Genov, *et al.*, *Nano Letters* 4, 153, (2004).

D. A. Genov, *et al.*, *Phys. Rev. B*, 75, 201403, (2007).

Metamaterials: negative index media

Negative index media

$$n^2 = \varepsilon\mu, \quad n = \pm\sqrt{\varepsilon\mu}$$

$$\varepsilon < 0, \quad \mu < 0$$

H. Lamb "*On group-velocity*", Proc. London Math. Soc. 1, 473 (1904)

V. G. Veselago, Sov. Phys. Uspekhi 10 (1968)

J. B. Pendry Phys. Rev. Lett. 85, (2000)

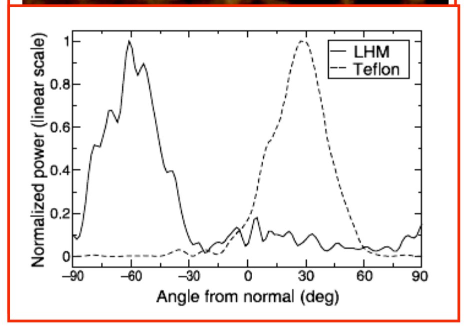
New optical phenomena:

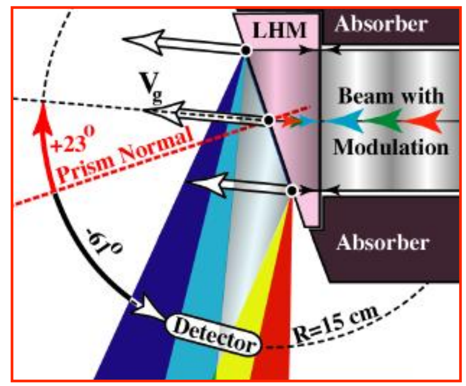
- reversed geometrical optics
- reversed Doppler shifts
- reversed Cerenkov radiation
- perfect lens

$$\sin\theta_1 = -|n|\sin\theta_2 = |n|\sin(-\theta_2)$$

$$f = 10 \text{ GHz}, \; n = -2.7$$

R. A. Shelby, *et. al.* Science 292, 77 (2001)

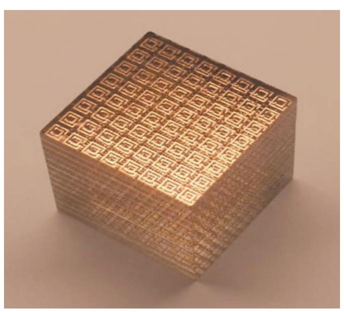




P. M. Valanju, *et al.* Phys. Rev. Lett. 88, (2002)

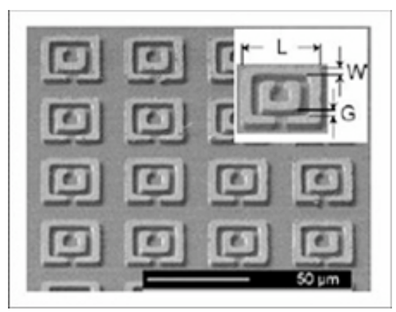
Magnetic resonance in microwave

Bulk materials (GHz)



C. Parazzoli, *et al.* Phys. Rev. Lett. 90, (2003)

Magnetic response (THz)



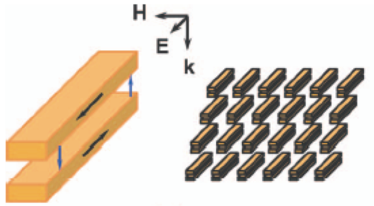
T. J. Yen, *et al.*, Science 303, (2004)

Magnetic response in optics

<u>Negative index</u>

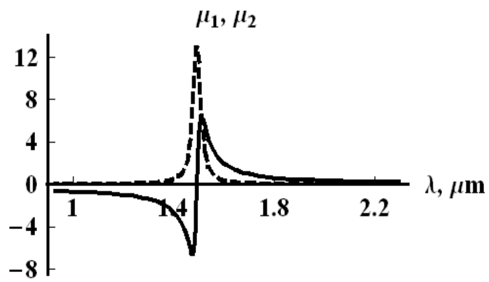
$$\varepsilon < 0, \quad \mu < 0$$

$$n = -\sqrt{\varepsilon\mu}$$

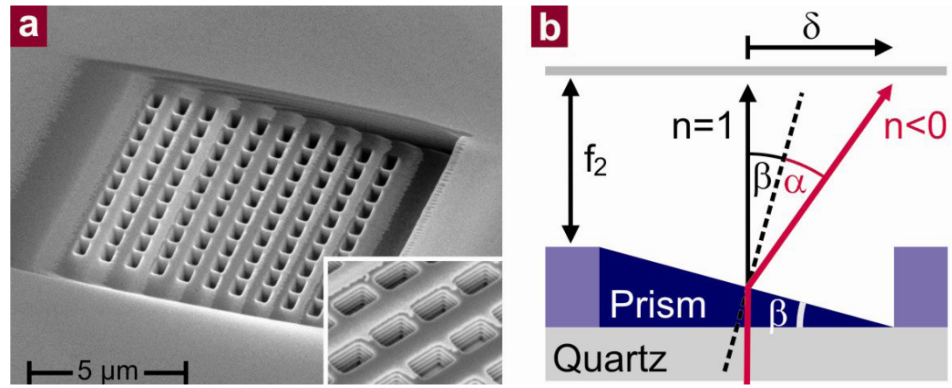


Metals

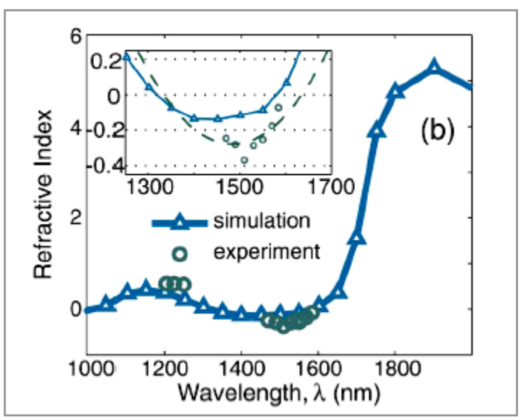
$$\varepsilon < 0$$



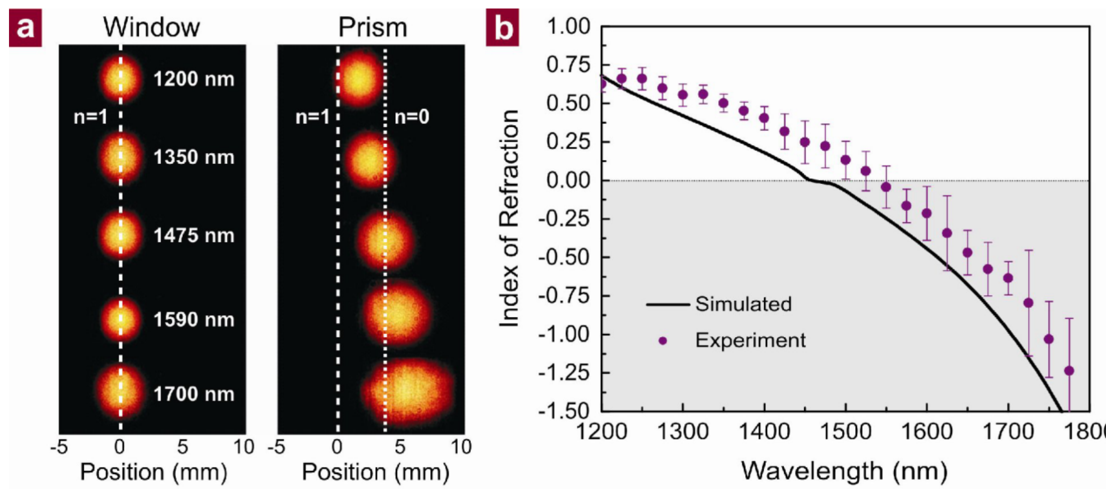
<u>First Bulk Negative index Media in Optics</u>



Magnetic plasmons:



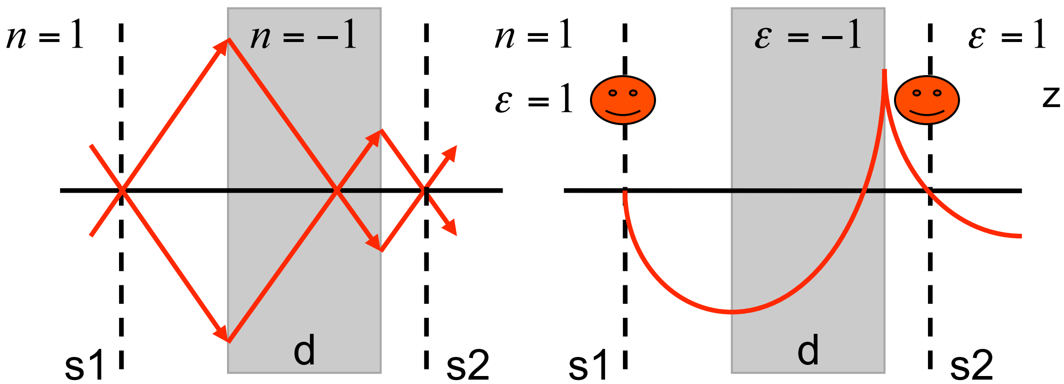
V.M. Shalaev, *et. al.*
OPTICS LETTERS, v. 30, 3358 (2004).



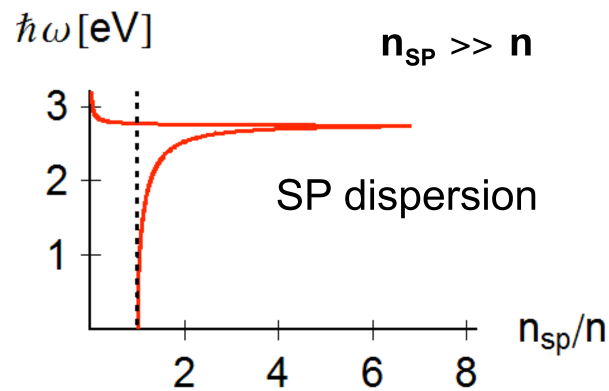
J. Valentine, *et. al.* <u>Nature</u>, v. 455, 376 (2008).

Optical imaging with super-resolution

Propagating waves **Evanescent wave**

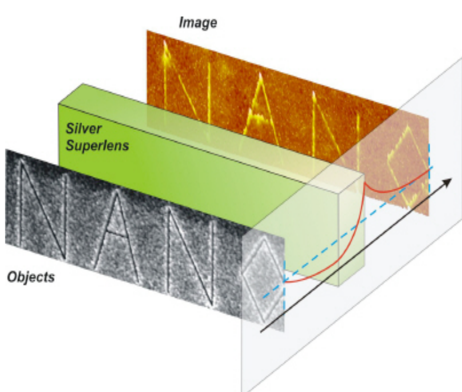


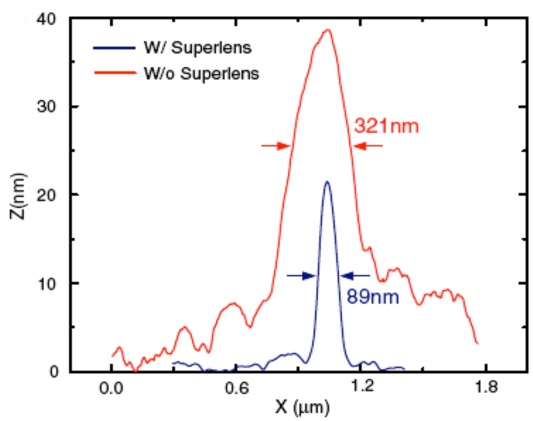
Perfect lens,…not really.
Loss and dispersion plays substantial role!



$$k_z = \sqrt{(\omega/c)^2 - k_\perp}$$

$$k_\perp = \frac{2\pi}{\Delta} > k = (\omega/c)^2$$



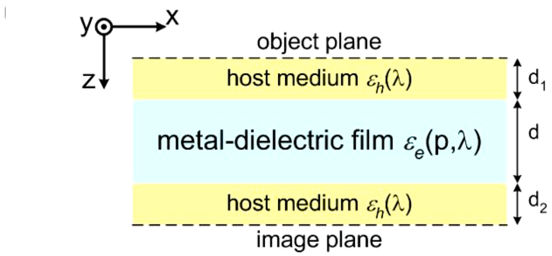


Resolution improvement by a factor of four (very close to the theoretical limit) has been experimentally demonstrated!

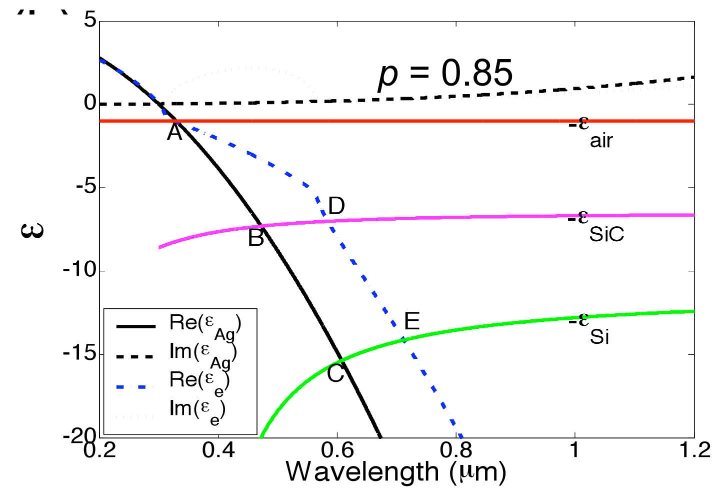
J. B. Pendry, Phys. Rev. Lett. 85, 3966 (2000)

Fang, N., *et al., Science* 308, 534 (2005)

Tunable superlens with composite materials

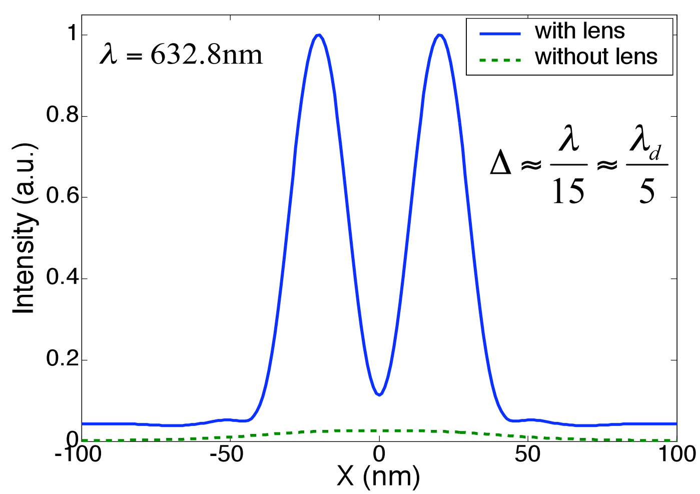


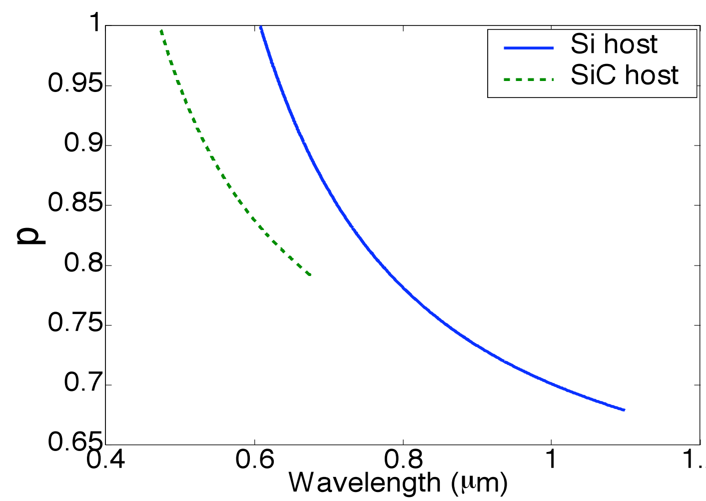
$$Ag - SiO_2$$



$$\text{Re}[\varepsilon_e(\lambda, p)] = -\varepsilon_d$$

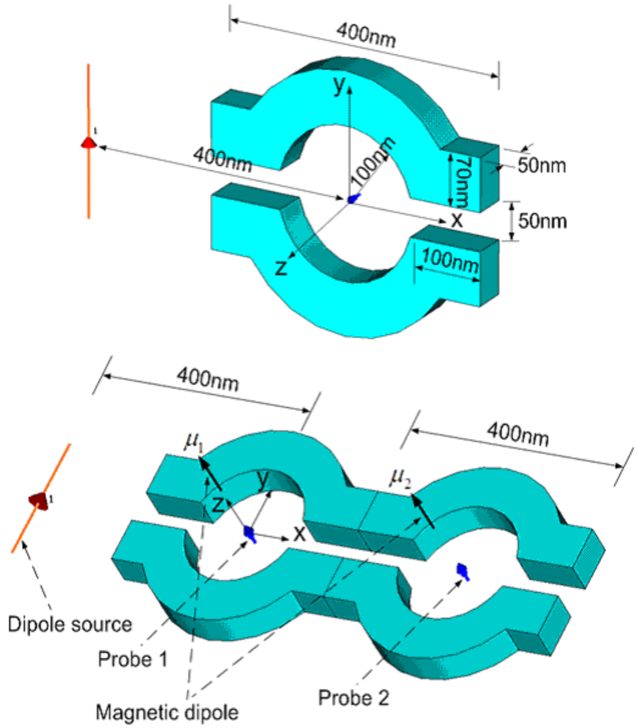
$$p\frac{\varepsilon_m - \varepsilon_e}{\varepsilon_m + (d-1)\varepsilon_e} + (1-p)\frac{\varepsilon_d - \varepsilon_e}{\varepsilon_d + (d-1)\varepsilon_e} = 0$$





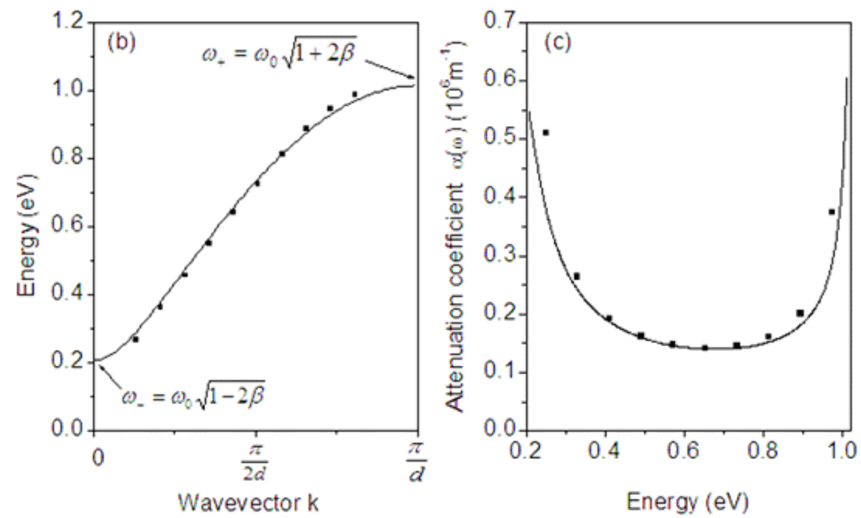
W. Cai, D. A. Genov, V. M. Shalaev, PRB B 72 (2005)

Magnetic plasmons transmission lines



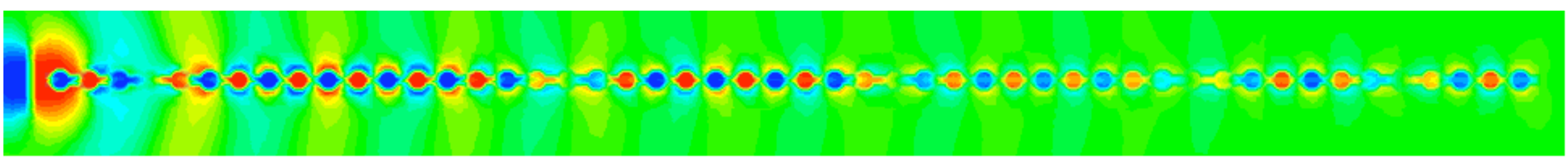
Coupled magnetic dipoles:

$$\ddot{\mu}_m = -(1+i\gamma_I)\omega_0^2\mu_m + \frac{\gamma_R}{\omega_0}\ddot{\mu}_m + \beta\omega_0^2(\mu_{m-1}+\mu_{m+1})$$



Highly efficient sub-wavelenght energy transfer:

v_g = 0.82c, α = 1200cm-1

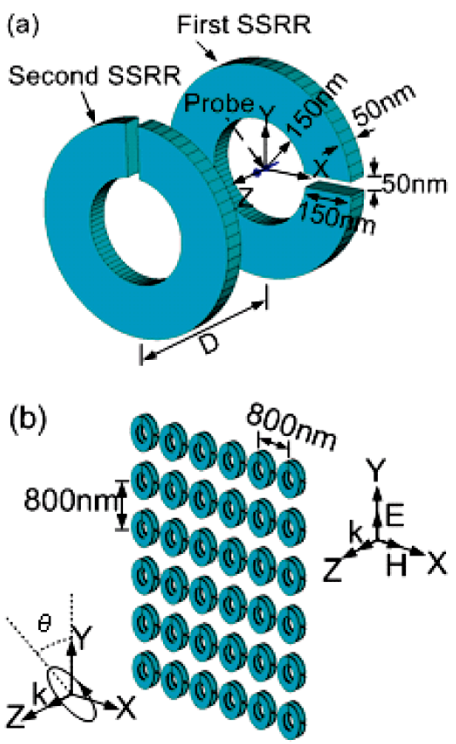


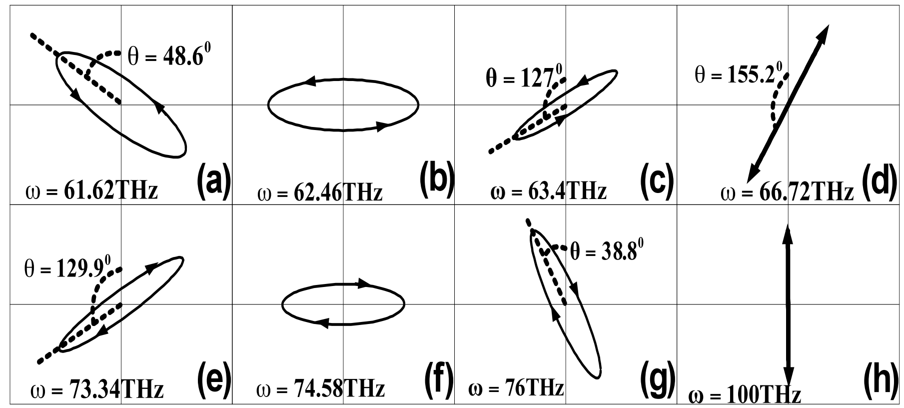
http://xlab.me.berkeley.edu/research/Magnetic_plasmon.htm

H. Liu, D. A. Genov, *et al,*
Phys. Rev. Lett., 97, 243902 (2006).

Chiral metamaterials, optical activity and EIT

A. Magnetic dimers

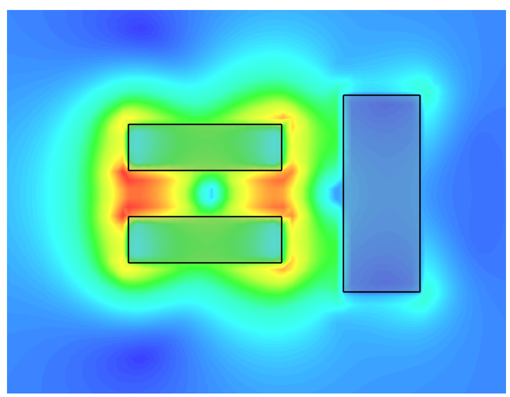


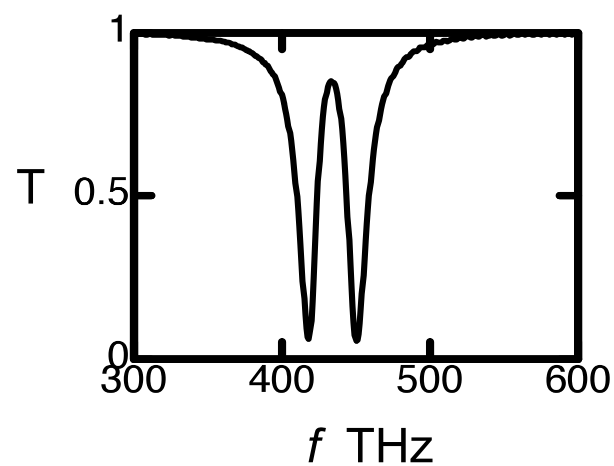


H. Liu, D. A. Genov, *et al*, Phys. Rev. B. 76, 073101 (2007).

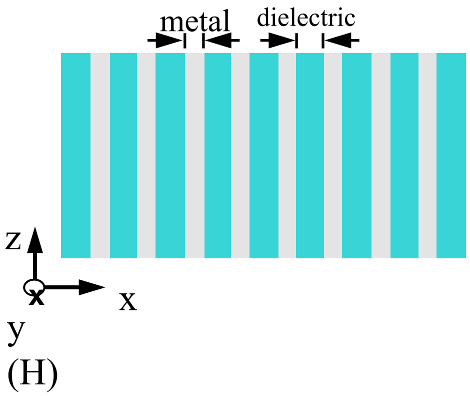
S. Zhang, D. A. Genov, *et al*, PRL 101, pp. 047401 (2008).

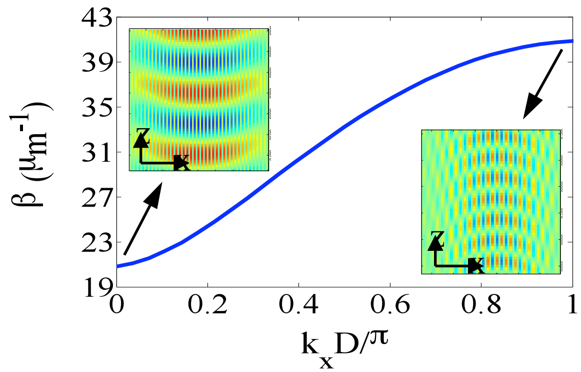
B. Plasmonic "molecule" for electromagnetically induced transparency (EIT)

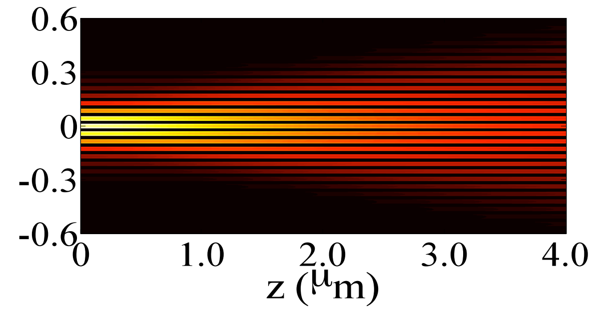


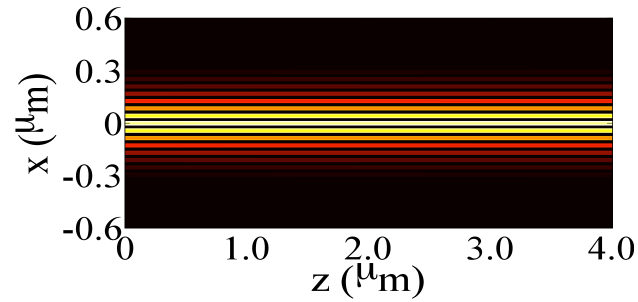


Sub-wavelength solitons in metal-dielectric arrays





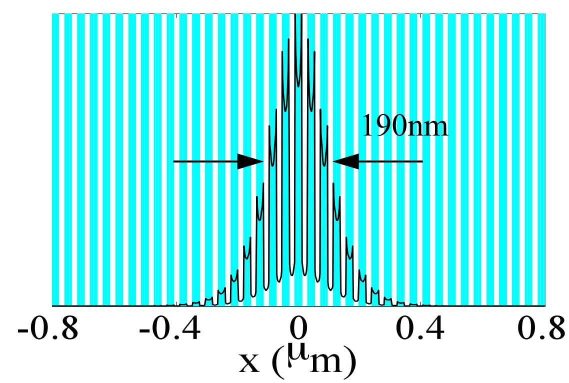




These solitons manifest unique features arising from the three-fold interplay between periodicity, nonlinearity, and SPPs tunneling, and display anomalous behaviors comparing to solitons in uniform dielectric media and conventional DWGAs.

$$\frac{\partial}{\partial z}\begin{pmatrix} H_y \\ E_x \end{pmatrix} = -\frac{i}{k_0}\begin{pmatrix} 0 & \varepsilon k_0^2 \\ \hat{H} & 0 \end{pmatrix}\begin{pmatrix} H_y \\ E_x \end{pmatrix} = -i\hat{M}(z)\begin{pmatrix} H_y \\ E_x \end{pmatrix}$$

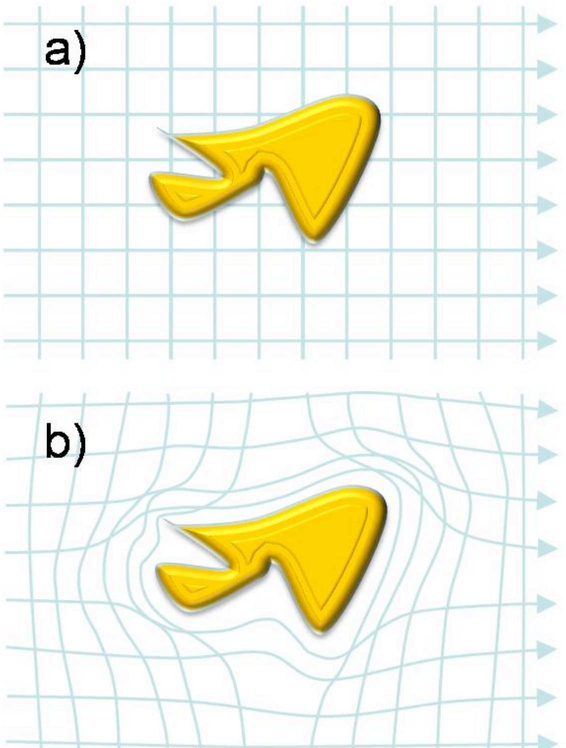
$$\hat{H}(x) = \frac{\partial}{\partial x}\left(\frac{1}{\varepsilon}\frac{\partial}{\partial x}\right) + k_0^2$$



Y. Liu, G. Bartal, D. A. Genov, X. Zhang,
Physical Review Letters **99, (2007)**

Highlighted in the December issue of Nature

Transformation optics



A. Invariance of the Maxwell's equations under coordinate transformation - conformal mapping

$$x' = \frac{kx}{z+is}, \quad y' = \frac{ky}{z+is}, \quad z' = k\,\frac{x^2+y^2+z^2+s^2-a^2}{2a(z+is)},$$

$$s' = k\,\frac{x^2+y^2+z^2+s^2+a^2}{2ia(z+is)},$$

which is quite different from an inversion or simple displacement. This corresponds to the real spherical wave transformation‡

$$x' = \frac{kx}{z-t}, \quad y' = \frac{ky}{z-t}, \quad z' = k\,\frac{x^2+y^2+z^2-a^2-t^2}{2a(z-t)},$$

$$-t' = k\,\frac{x^2+y^2+z^2+a^2-t^2}{2a(z-t)}.$$

An imaginary rotation in the four-dimensional space may be specified, in a particular case, by the equations

$$x' = x\cos iw + s\sin iw, \qquad y' = y,$$

$$s' = -x\sin iw + s\cos iw, \qquad z' = z.$$

Putting $\tanh w = v,$

B. EM fields in general relativity

$$D_a = E_a + \epsilon_{ab}E_b + \epsilon_{abc}g_bH_c,$$

$$B_a = H_a + \epsilon_{ab}H_b - \epsilon_{abc}g_bE_c,$$

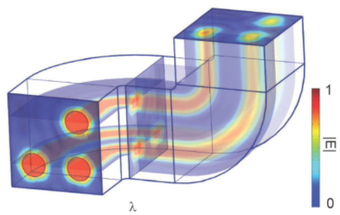
$$\epsilon_{ab} = -\frac{(-g)^{\frac{1}{2}}}{g_{00}}g^{ab} - \delta^{ab}, \quad g_a = \frac{g_{a0}}{g_{00}},$$

H. Bateman, "The transformation of the electrodynamical equations", *Proc. London Math. Soc.* 8, 223 (1910).

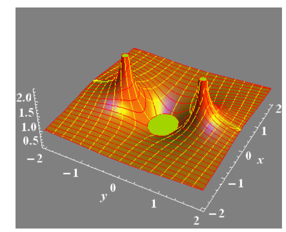
Plebanski, J. "Electromagnetic Waves in Gravitational Fields", *Phys. Rev*. 118, 1396 (1960).

Seeking collaborations within LI

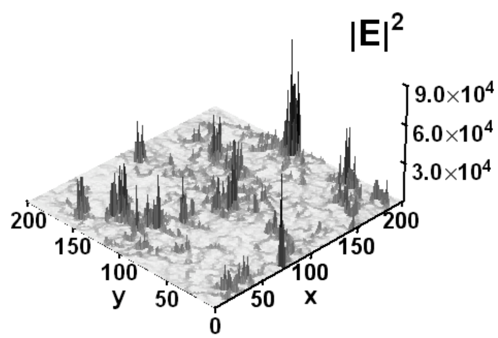
B. Parallelization of the FDFD and FDTD codes for fast calculations of transformable media

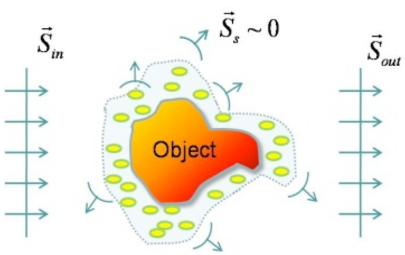


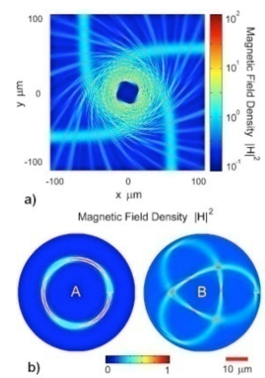
C. Analytical studies and experimental validation of the isotropic cloaking



A. SP localization in 3D, percolation threshold and critical exponents







D. Parallelization of the inverse design methods including MST and generic optimizations

E. Massively parallel calculations of The EM behavior near gravitational singularities and optical attractors