Nanoplasmonics and plasmon-polariton metamaterials

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4th International Sakharov Conference on Physics
19 May 2009, Moscow

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OUTLINE

1. Introduction: localized and surface plasmons, nanoplasmonics; polaritonic photonic crystals

2. Polaritonic photonic crystals: controlling optical properties and near fields

3. Metamaterials based on polaritonic photonic crystals: unit-cell-shape-controlled effective electromagnetic response

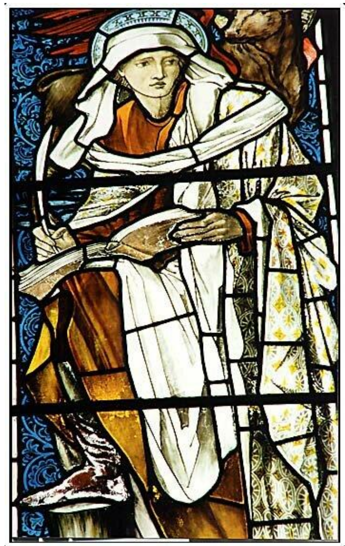
4. Conclusions

Plasmons:

surface & localized (size << λ)

Lorenz 1890
Hertz 1892
Rayleigh 1897
Maxwell Garnett 1904
Mie 1908

Drude 1900
Wood 1902
Fano 1941
Richie 1968



$$\frac{E_{\alpha,\mathrm{in}}}{E_{\alpha,\mathrm{out}}} = \frac{1}{1 + N_\alpha[(\varepsilon_{\mathrm{in}}(\omega))/\varepsilon_{\mathrm{out}} - 1]}$$

$$\frac{\varepsilon_{\mathrm{in}}(\omega)}{\varepsilon_{\mathrm{out}}} = 1 - N_\alpha^{-1} = \begin{cases} -2 \ , & \text{sphere} \\ -1 \ , & \text{cylinder} \end{cases}$$

Stained-glass
Giant Raman scattering
Photoluminescence control, nanoantennas
Single molecule spectrometry (including that of DNA)
Scanning near-field microscopy and nanophotolythography with subwavelength resolution
Metallic-dielectric plasmon-polariton photonic crystals and metamaterials, nanoplasmonics

Plasmons:

surface & **localized (size << λ)**

surface	localized (size << λ)
	Lorenz 1890
	Hertz 1892
Drude 1900	***Rayleigh 1897***
Wood 1902	***Maxwell Garnett 1904***
Fano 1941	***Mie 1908***
Richie 1968	

$$k^2 = \frac{\omega^2}{c^2}\frac{\varepsilon_1\varepsilon_2(\omega)}{\varepsilon_1+\varepsilon_2(\omega)}$$

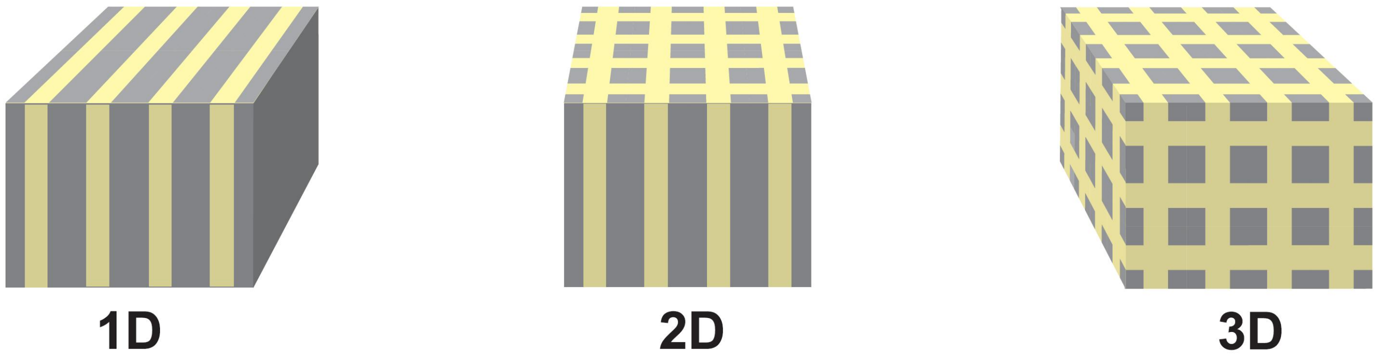
Wood-Fano anomalies in the optical spectra of metallic gratings
Nanophotolythograpy with subwavelength spatial resolution
Metallic-dielectric plasmon-polariton photonic crystals

• Photonic crystal = media with periodically modulated dielectric susceptibility

V.P. Bykov 1972

E. Yablonovitch 1987

S. John 1987



Photonic Crystal Slabs: layers of 1D or 2D PhCs with complex (or simple) vertical structure

•Diffraction grating = 1D photonic crystal slab

Rittenhouse 1786
Fraunhofer 1821
Wood 1902
Lord Rayleigh 1907
Fano 1941
Shestopalov 1970
Neviere 1980

Polaritonic photonic crystals: Interacting electronic and photonic resonances

Exciton polaritons in periodic arrays of semiconductor quantum wells
Ivchenko et al, 1994; Kochereshko et al, 1994

Plasmon polaritons in photonic crystals with nanosructured metals
Ebbesen et al, *1998;* Linden et al, 2001; Christ et al, 2003
Teperik et al, 2006

Metamaterials – short period photonic crystals with controlled electromagnetic response
Pendry 2000; Smith et al 2000; Podolskiy, Sarychev, Shalaev 2003; Zhang et al 2005; Pendry et al 2006, Shalaev 2007, Liu & Giessen 2008,2009

Giant magneto-optical effects in plasmon-polaritonic crystals and metamaterials
Inoue et al (incl. Aktsipetrov, Fedyanin, Murzina), 2006; Belotelov et al, 2007; Zharov and Kurin, 2007

Nanoplasmonics was known and used by mankind for centuries.

However, the recent development of nanotechnology brings new interesting possibilities

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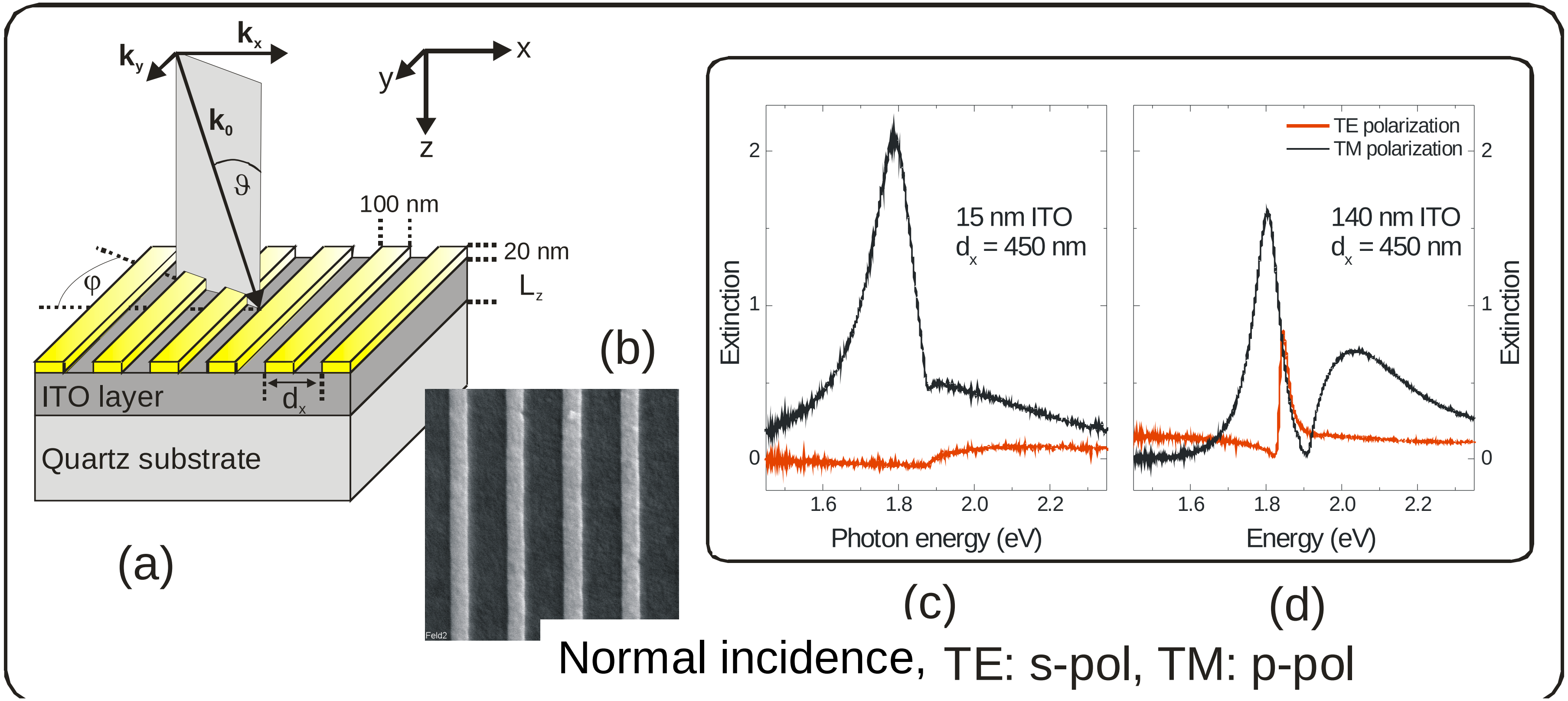
2. **Polaritonic photonic crystals: controlling optical properties and near fields**

3. **Metamaterials based on polaritonic photonic crystals: unit-cell-shape-controlled effective electromagnetic response**

4. **Conclusions**

1D grating of gold nanowires on top of a dielectric waveguide



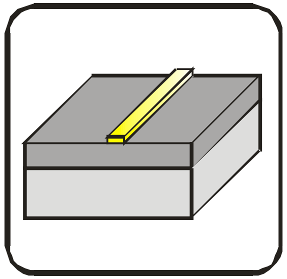
Schematics (a) and real structure (b), extinction (-ln T) spectra in a structure without (c) and with (d) guided modes

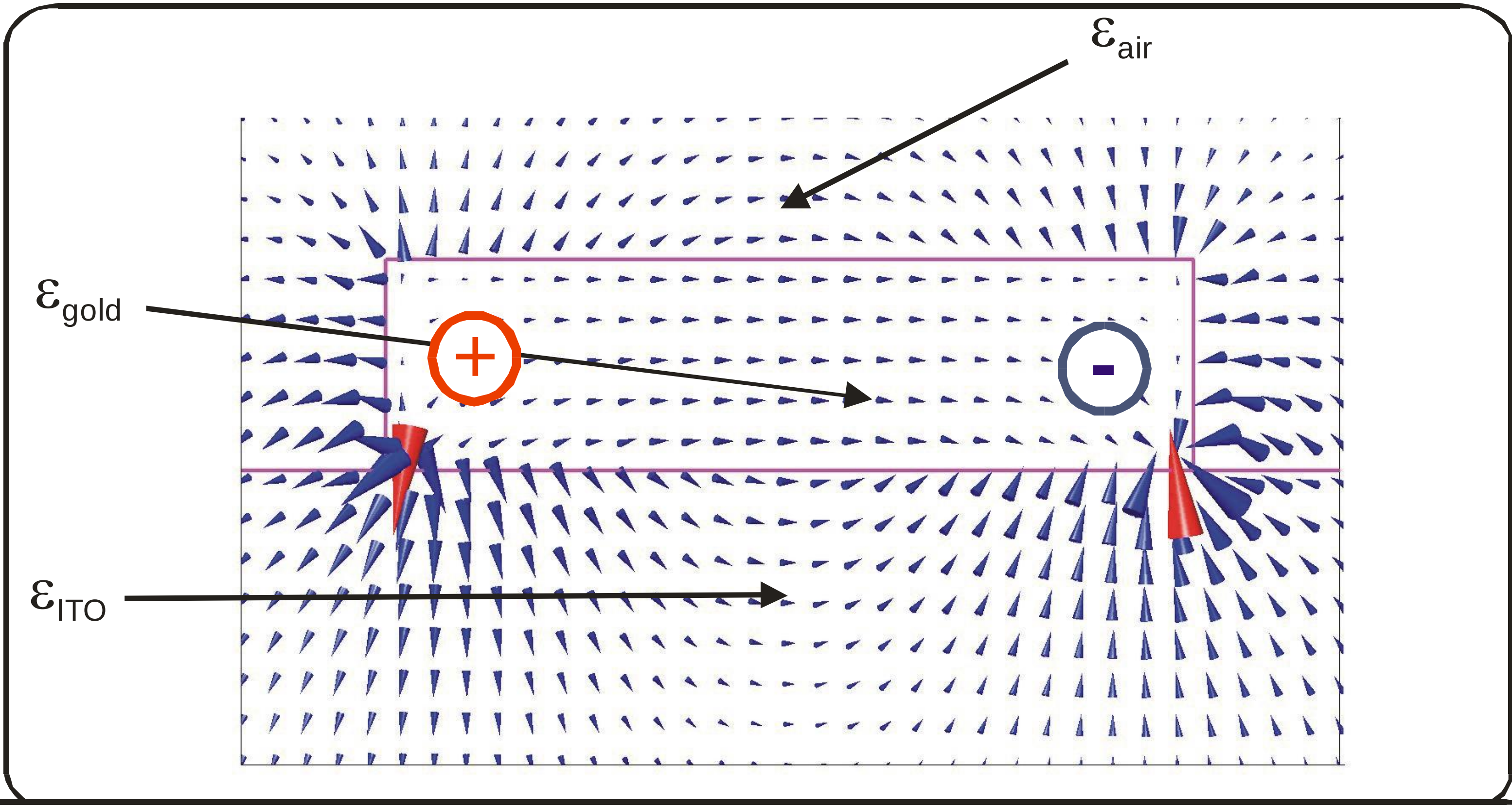
A. Christ, S. G. Tikhodeev, N. A. Gippius, J. Kuhl, and H.Gissen, *PRL* **91**, 183901, (2003), *PRB* **70**, 125113 (2004); T. Zentgraf, A. Christ, J. Kuhl, S. G. Tikhodeev, N. A. Gippius, and H.Gissen, *PRB* **73** 115103 (2006)

Interesting MO effects in case of ferromagnetic wires or waveguide, V. I. Belotelov et al, *Phys. Rev. Lett*. **98**, 077401 (2007)

Localized plasmon in metallic nanowire

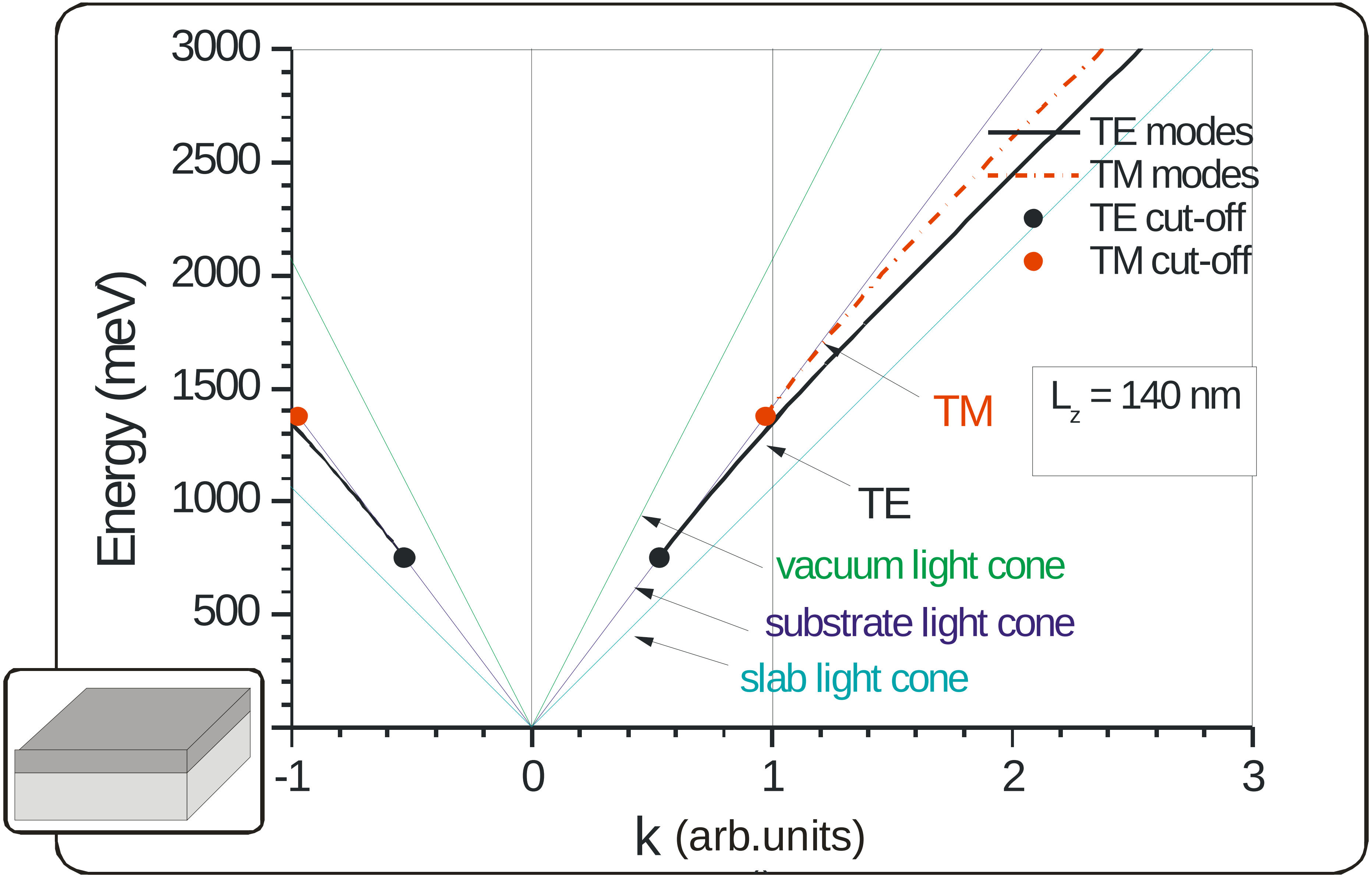
Electric field normal to the wire axis, resonance frequency depends on the metal nanoparticle shape and ε of metal and surrounding



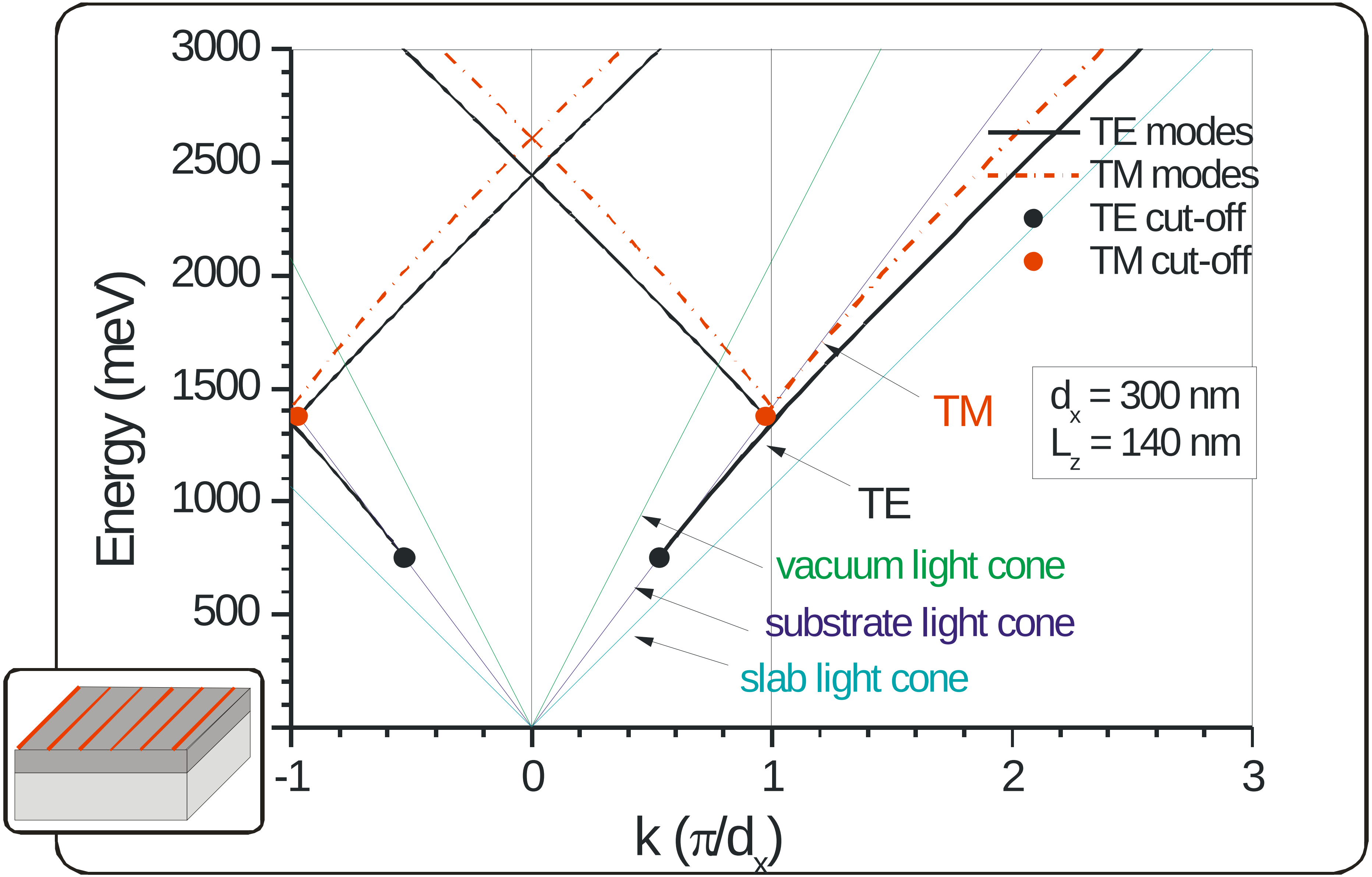


Electric field inside is modified

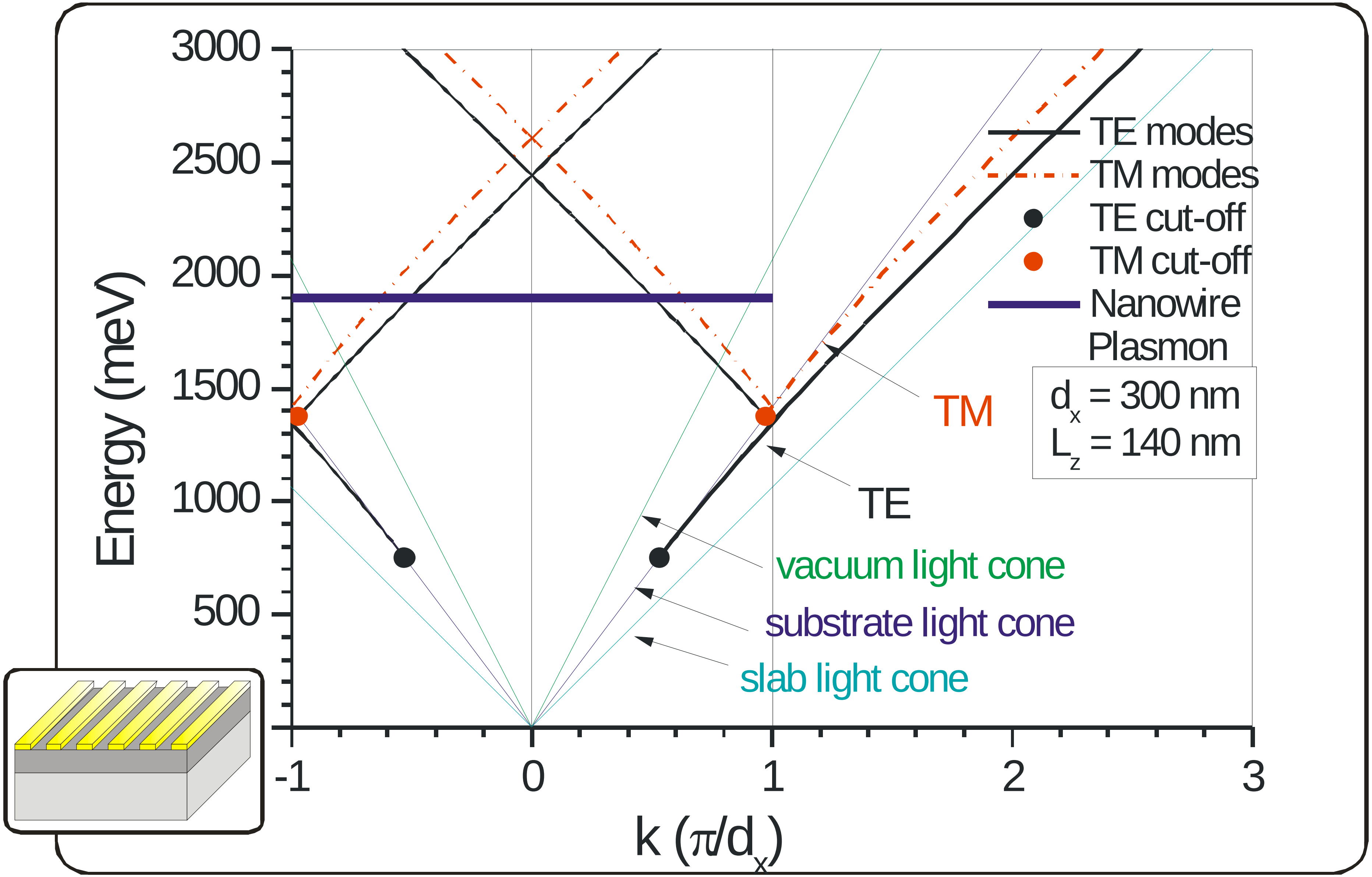
$$F_\alpha(\omega) \equiv \frac{E_{\alpha,\mathrm{in}}}{E_{\alpha,\mathrm{out}}} = \frac{1}{1 + N_\alpha\left[(\varepsilon_m(\omega)/\varepsilon_{\mathrm{out}} - 1\right]}, \quad \alpha = a, b, c,$$



TE(0) and TM(0) modes in waveguide



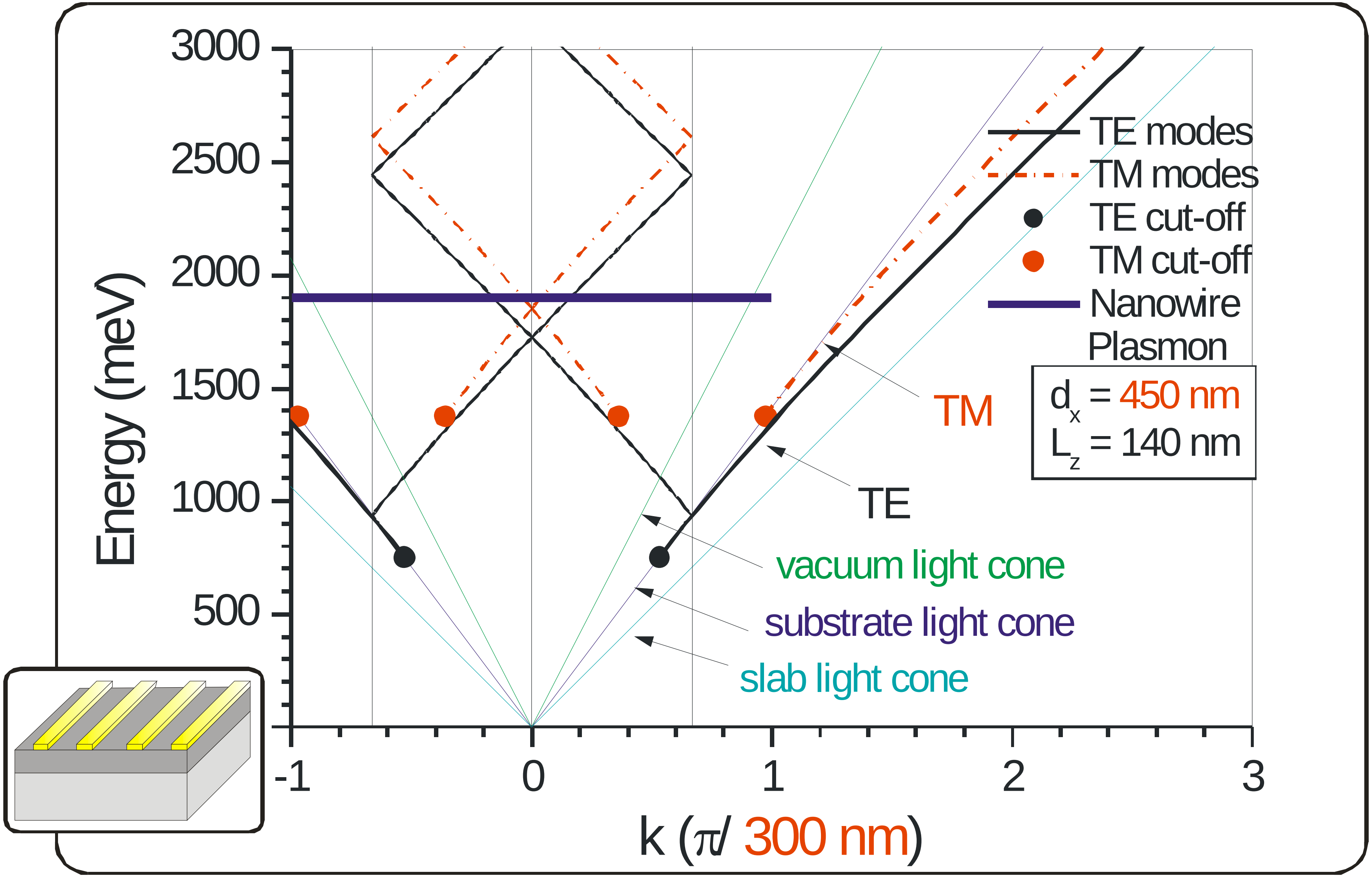
TE(0) and TM(0) modes in waveguide
folded into 1BZ of the grating, period 300 nm



TE(0) and TM(0) modes in waveguide

folded into 1BZ of the grating, period 300 nm

Blue horizontal line is the localoized plasmon on a single wire



TE(0) and TM(0) modes in waveguide

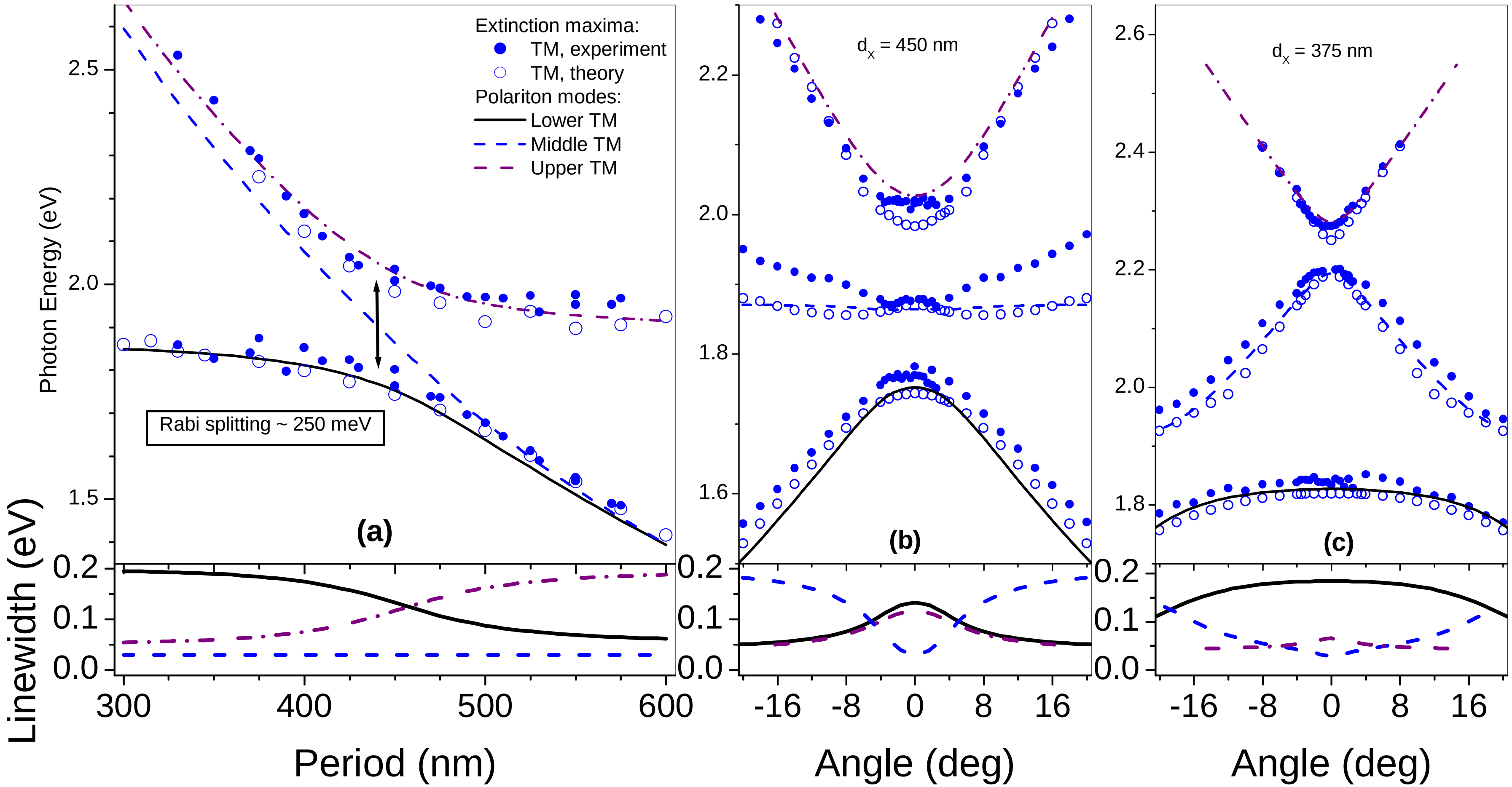
folded into 1BZ of the grating, period 450 nm

Blue horizontal line is the localoized plasmon on a single wire

Waveguide-plasmon polariton

A. Christ, S.G.Tikhodeev, N.A.Gippius, J.Kuhl, and H. Giesen,

*B. PRL **91,** 183901 (2003)*

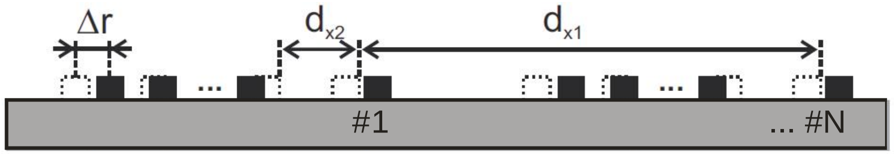


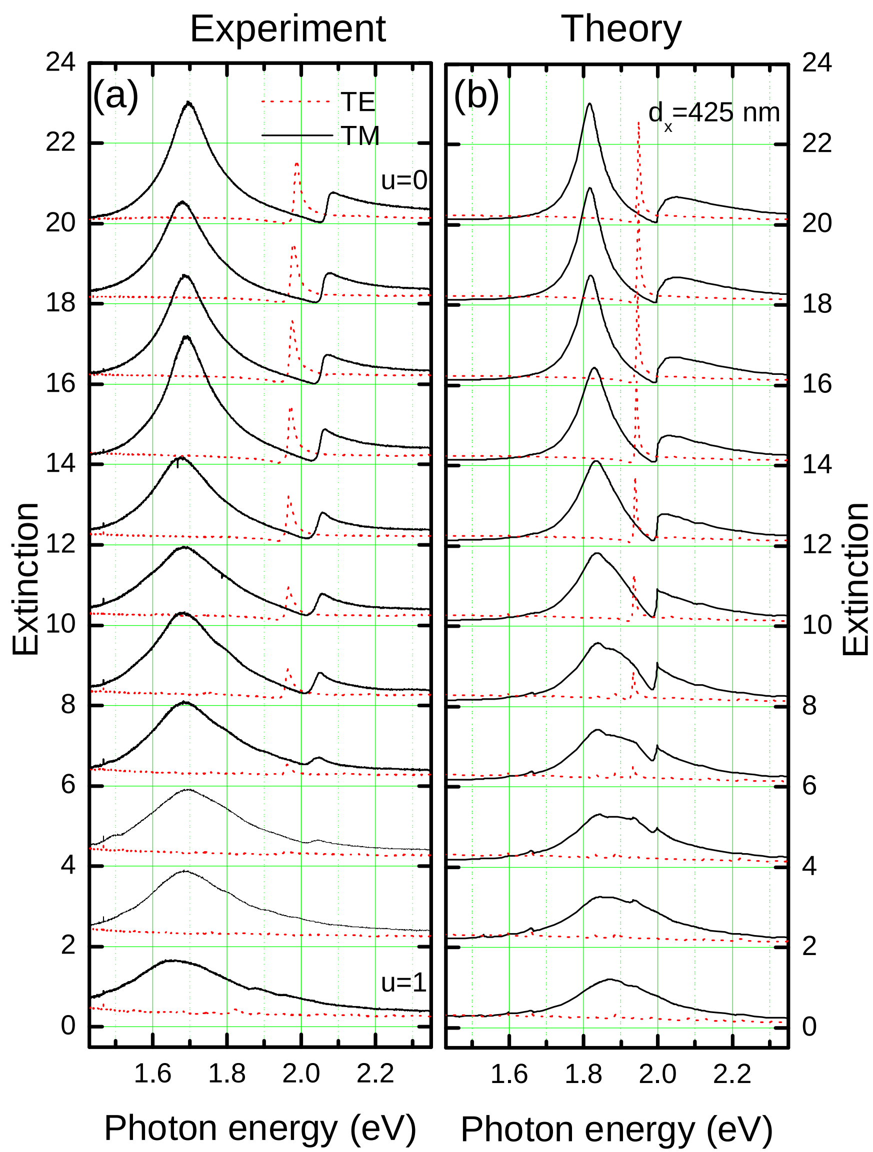
Extinction maxima: calculated (filled symbols) and calculated (empty symbols); lines are the polariton model

Introducing disorder kills the waveguide-plasmon polariton

$$\Delta r_i = u\, d_{x2}\, \mathrm{rnd}(i)$$

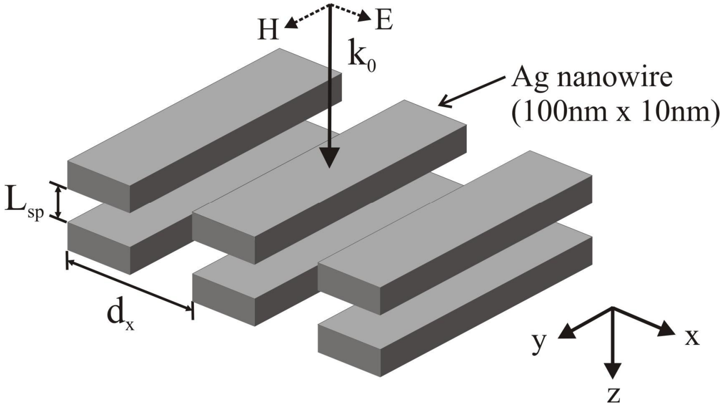
$$0 < \mathrm{rnd}(i) < 0.5, \;\; 1 < i < N$$



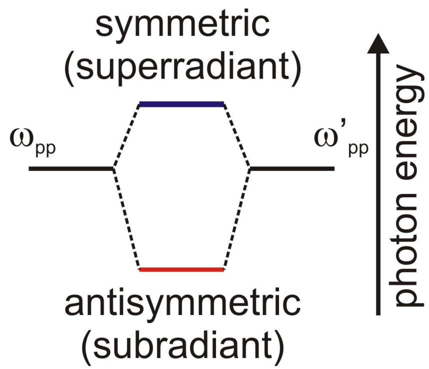


Plasmonic metamaterials

Nanostructurting ⇒ modification of the optical response

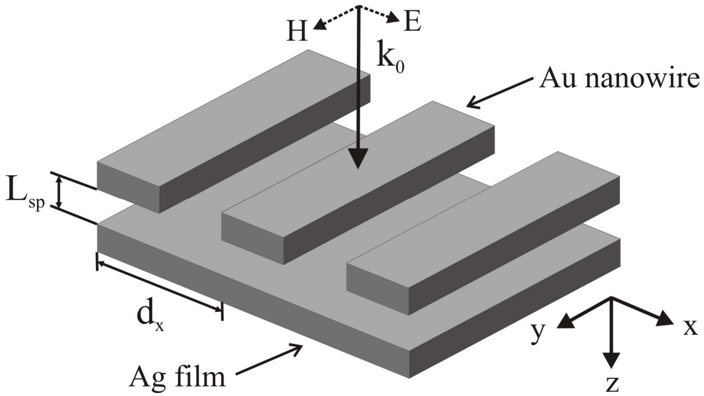


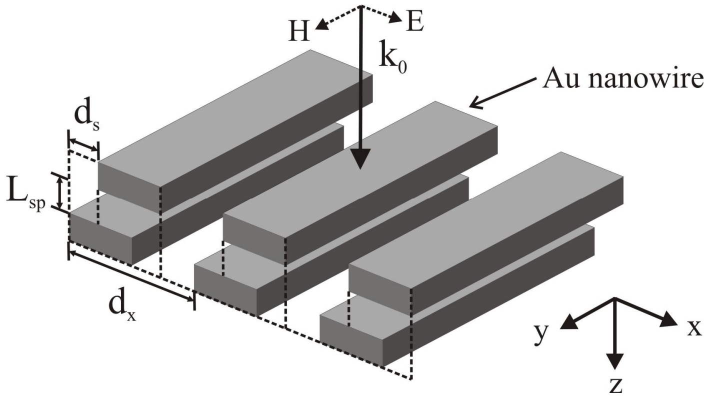
Localized plasmons hybridization



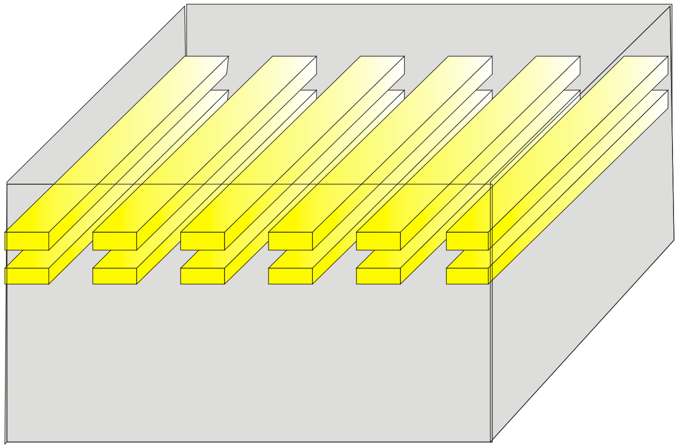
Interaction with image charges

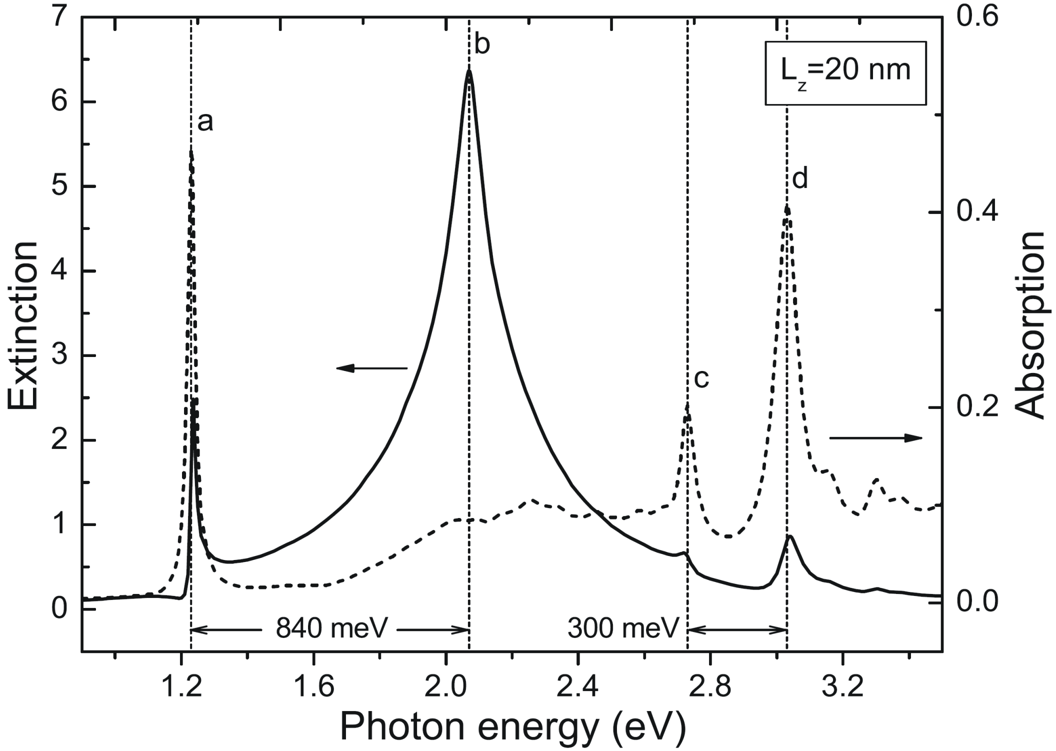
Near-field coupling





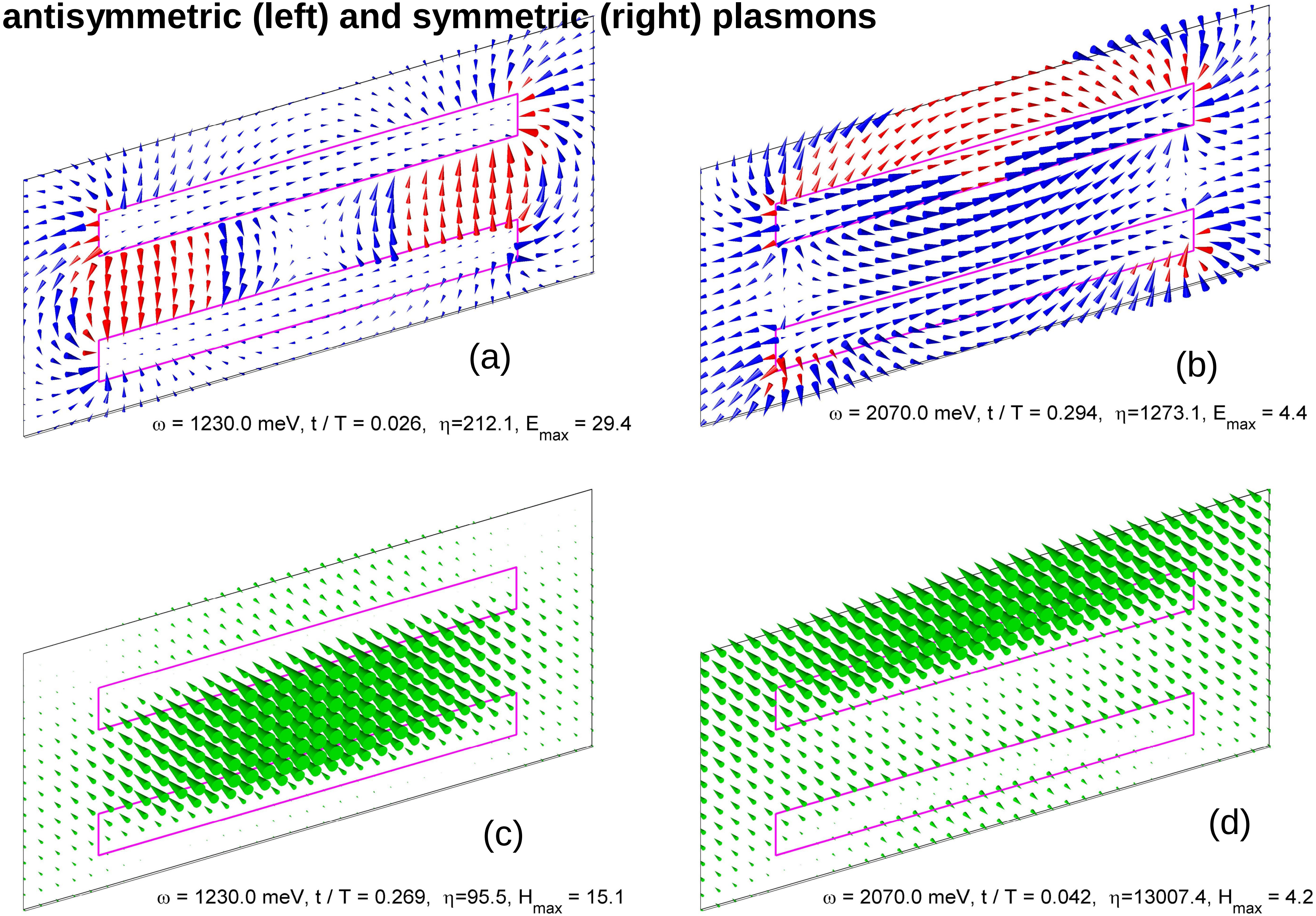
Plasmons in pairs of metallic nanowires: symmetric and antisymmetric





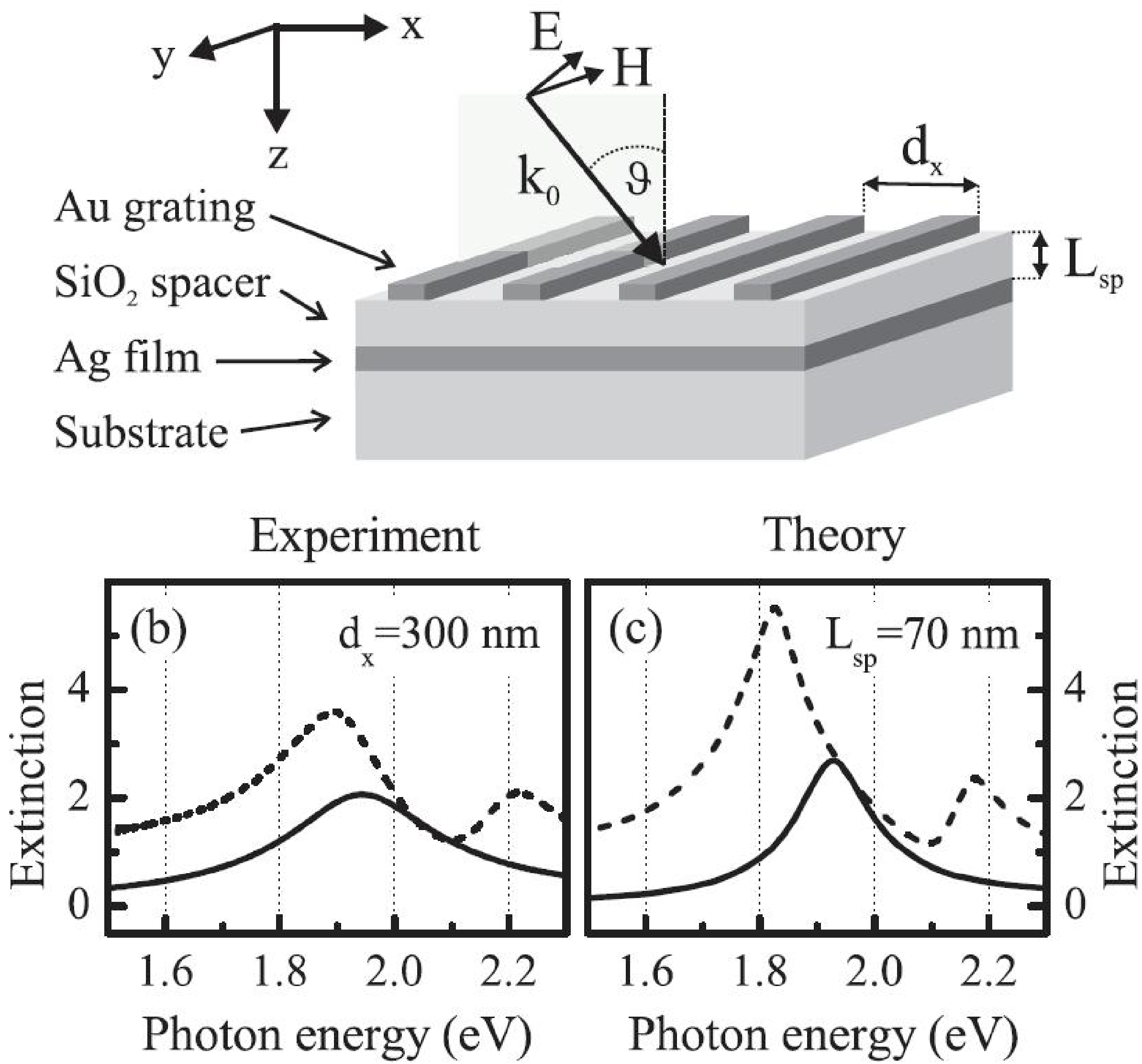
Extinction (- ln T) and absorption calculated for 20-nm vertical distance between gratings

Electric (top) and magnetic (bottom) near field distributions in antisymmetric (left) and symmetric (right) plasmons

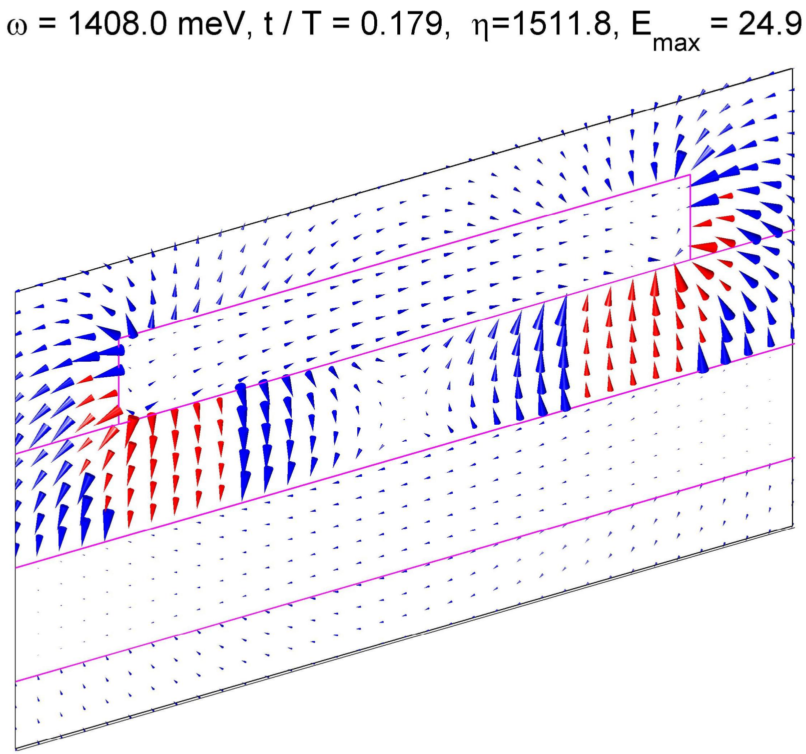


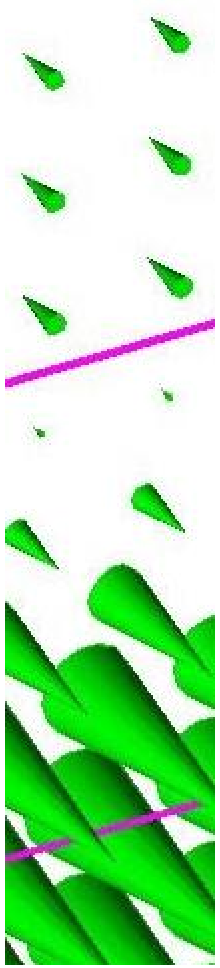
1D grating of metal nanowires near metal film: interacting localized and surface plasmons

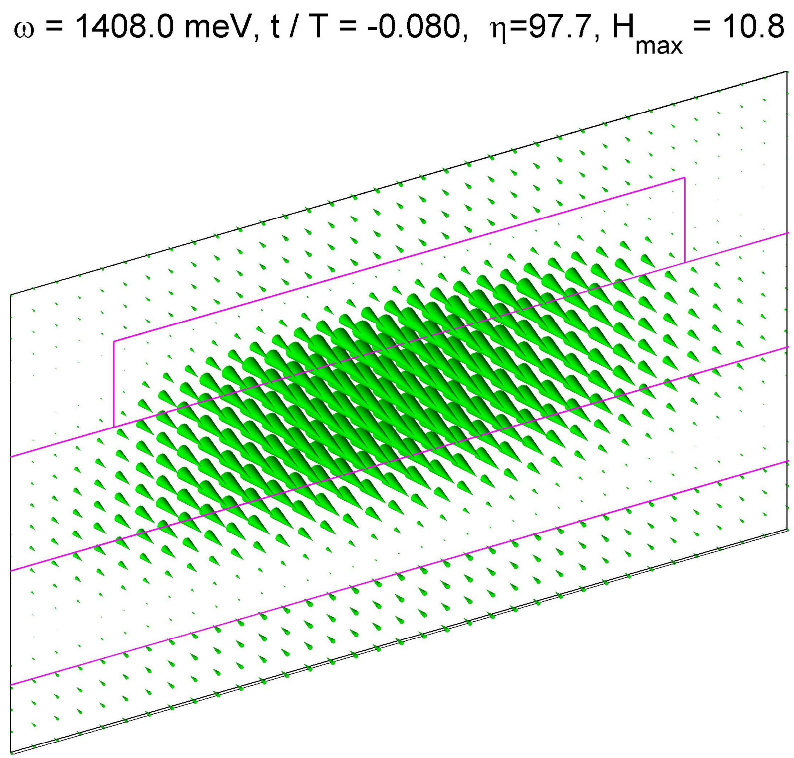
A. Christ, T. Zentgraf, S. G. Tikhodeev, N. A. Gippius, J. Kuhl, and H. Giessen, *Phys.Rev.* B **74**,155435 (2006)



Near field distributions of the electric (left) and magnetic (right) fields near the low-energy resonance



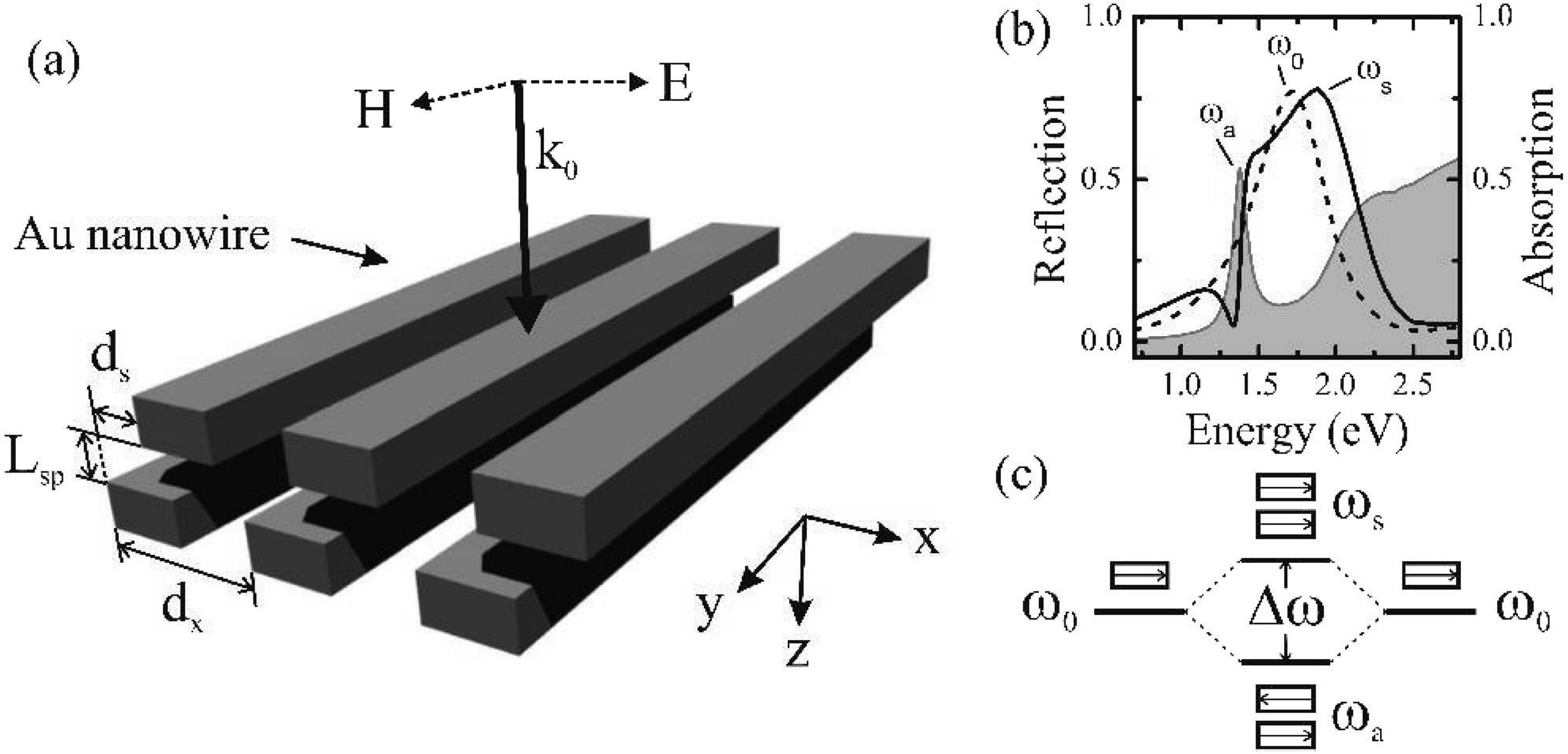




Strong near field modification: diamagnetism at optical frequencies (effective $\mu \neq 1$ and possibility of $\mu < 0$)

Symmetry-breaking allows to control the localized plasmons properties

A.Christ, O.J.F.Martin, Y. Ekinci, N. A. Gippius, and S. G. Tikhodeev**,** *Nano Lett* **8**, 2171 (2008)



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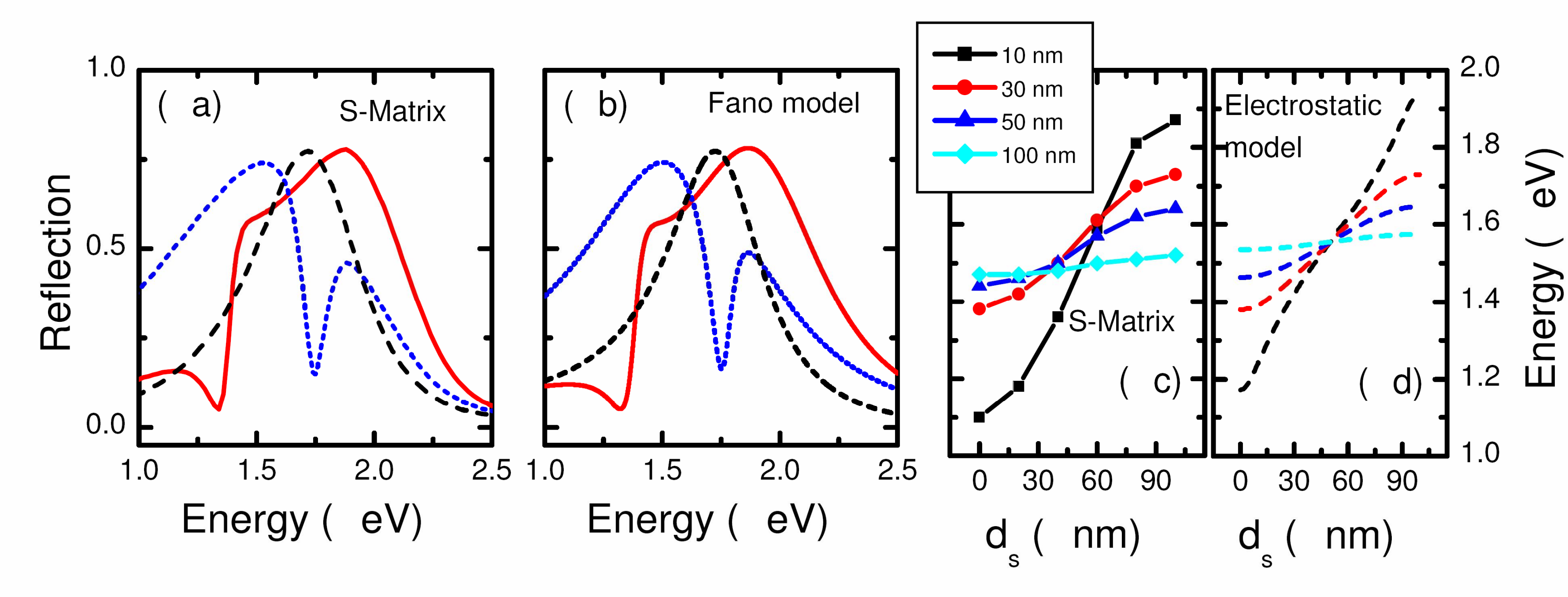

a,b: Red lines: wires are aligned vertically; Blue lines: top wires are in the middle between the bottom wires.

Narrow dip is the antisymmetric plasmon, broad maximum os the symmetric plasmon.

c,d: position of the antisymmetric plasmon as a function of the horizontal displacement

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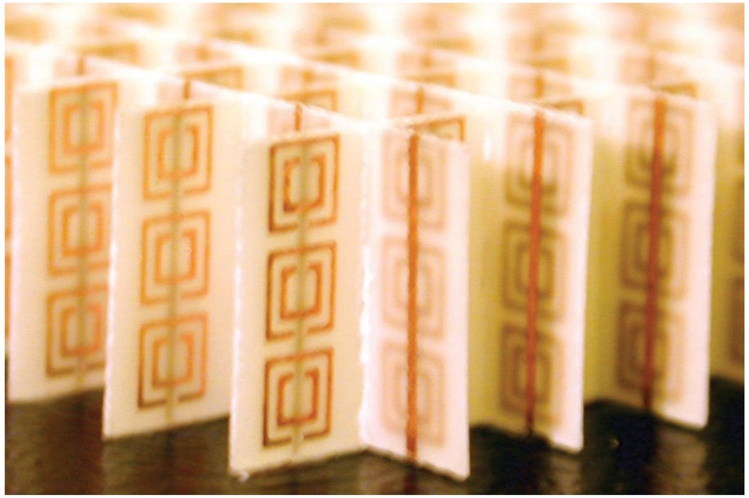
Metamaterials: nanostructured artificial materials, e.g. short-period plasmon-polaritonic crystals, period $\ll \lambda$.

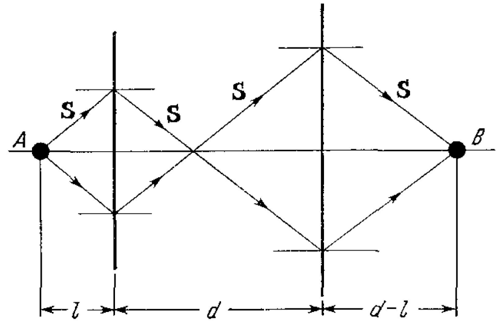
Goal: to control the electromagnetic response by nanostructuring (incl. unit cell shape) and material choice (metal/dielectric, metal/semiconductor)

Motivation: engineering of new unusual optical systems (Veselago lens, cloaking, transformation optics, structures with strong optical chirality)

Metamaterials



Shuster 1909
Мандельштам 1940
Веселаго 1967
Pendry 2000
Smith et al 2000
Shelby et al 2001



D. R. Smith et al 2000;
R. A. Shelby et al, 2001
$n(\omega) < 0$, $\omega \sim 10$ ГГц

Metamaterials are artificial electromagnetic (multi-) functional materials engineered to satisfy the prescribed requirements. The prefix meta means after, beyond and also of a higher kind. Superior properties as compared to what can be found in nature are often underlying in the spelling of metamaterial. These new properties emerge due to specific interactions with electromagnetic fields or due to external electrical control.

http://www.metamorphose-eu.org, December 2006.

Effective ε and μ do not describe fully the optical response of a general asymmetric and chiral media.

Chirality connects **D** with **H** and **B** with **E** directly:

$$\mathbf{D} = \hat{\varepsilon}\mathbf{E} + \hat{\chi}^{EH}\mathbf{H},\ \mathbf{B} = \hat{\mu}\mathbf{H} + \hat{\chi}^{HE}\mathbf{E}$$

In a more symmetric non-chiral media: bianisotropy. For example, if there is a preferential direction, **n**, then

$$\mathbf{D} = \hat{\varepsilon}\mathbf{E} + i\left(\mathbf{n} \times \beta^{EH}\mathbf{H}\right),\ \mathbf{B} = \hat{\mu}\mathbf{H} + i\left(\mathbf{n} \times \beta^{HE}\mathbf{E}\right)$$

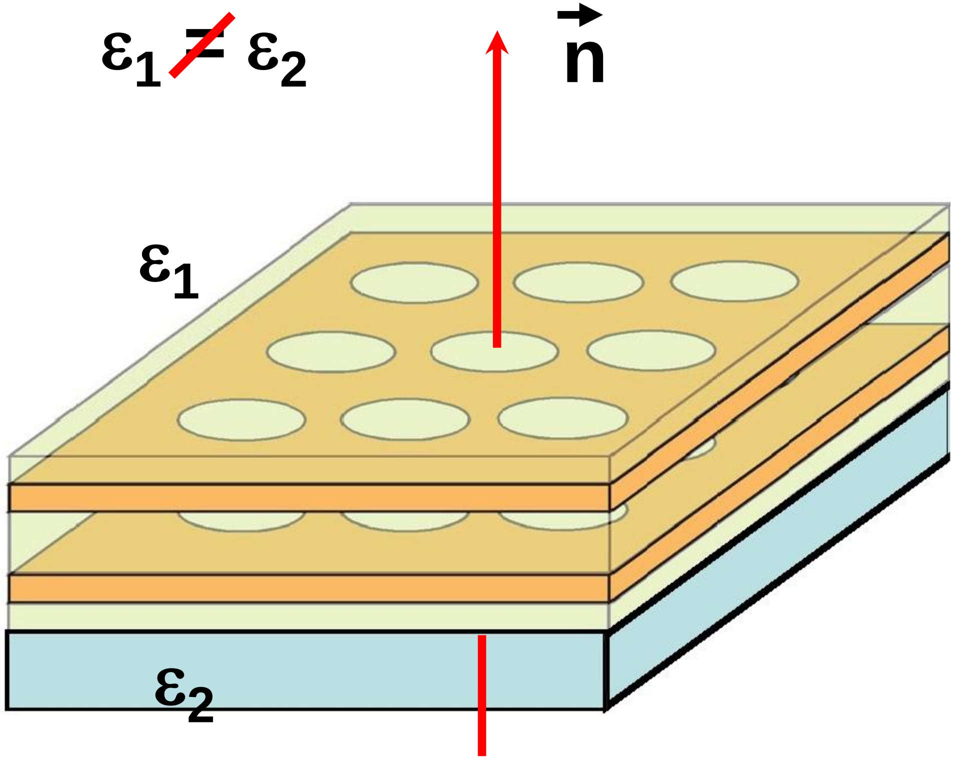
I. V. Lindell, A. H. Sihvola, S. A. Tretyakov, and A. J. Viitanen, *Electromagnetic Waves in Chiral and Bi-Isotropic Media* (Artech House, Boston, 1994).

In the metamaterials: shape-induced chirality and bianisotropy **which appear to be nonlocal**

Even if the shape itself is symmetric, the metamaterial slab is bianisotropic in case of the asymmetric dielectric background

Example: bi-fishnet structure on substrate

S. Zhang et al, *PRL* **95,** 137404 (2005)



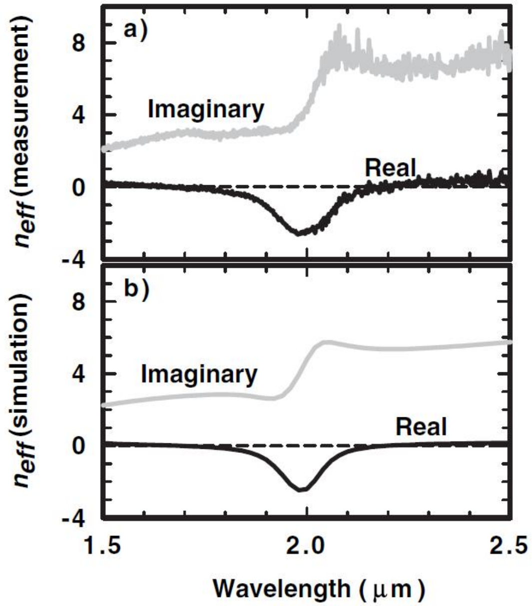
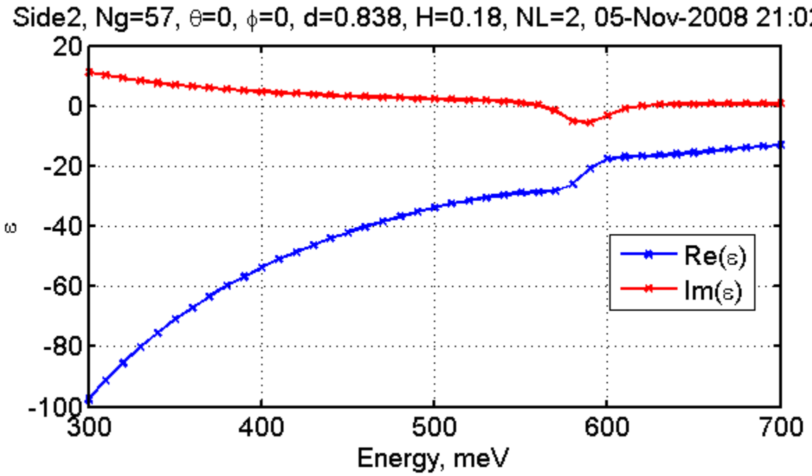


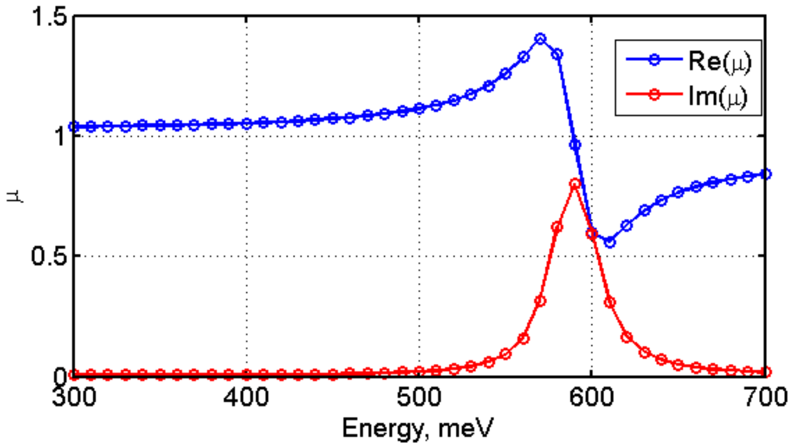
FIG. 5. The effective refractive index extracted from measurement (a) and from modeling (b) showing a resonance and a negative real part at ~2.0 μm.

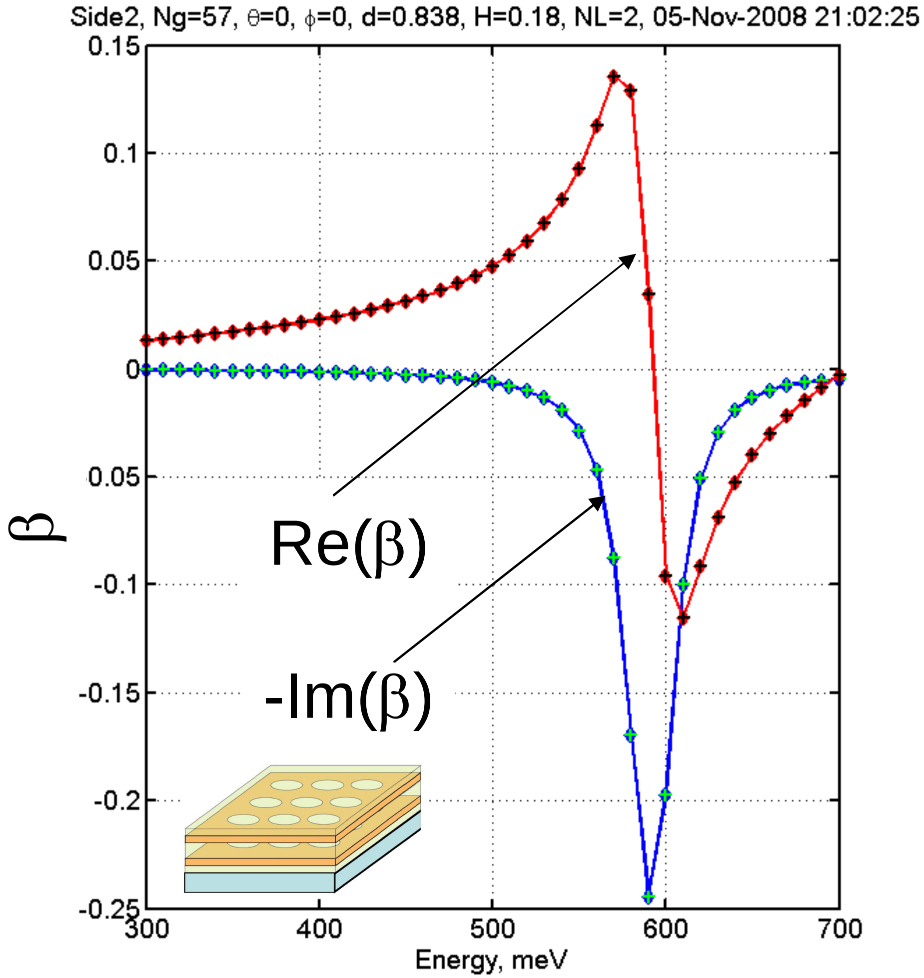
Passive (absorbing) media is left-handed if

$$\mathrm{Im}(n) > 0, \mathrm{Re}(n) < 0$$

The retrieved permittivity, permeability, and bianistoropy



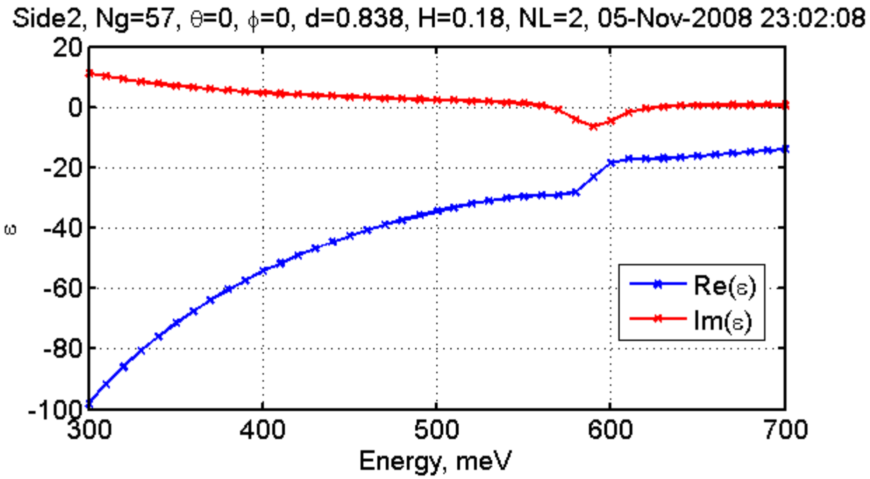


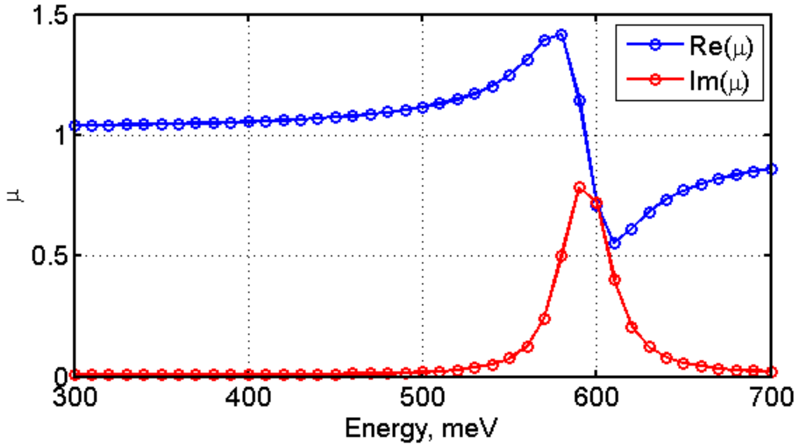


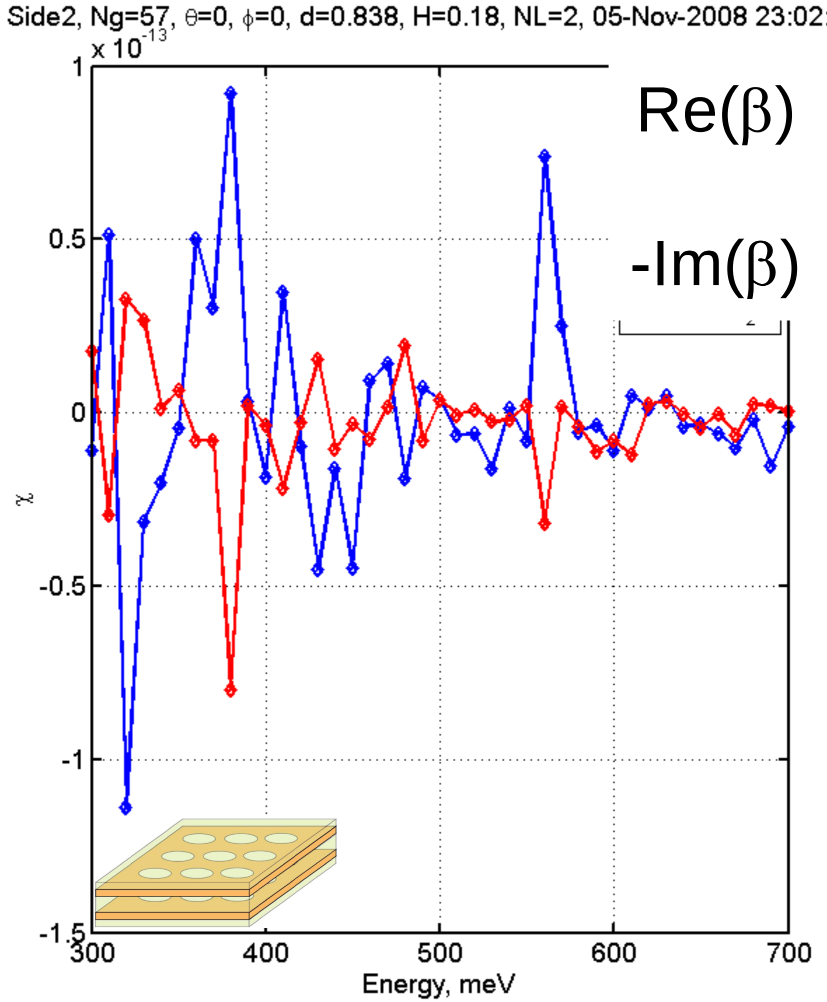
The retrieved bianisotropy is not small near the magnetic resonance

BUT: it disappears if the dielectric surrounding becomes symmetric

The retrieved permittivity, permeability, and no bianisotropy in a symmetric background







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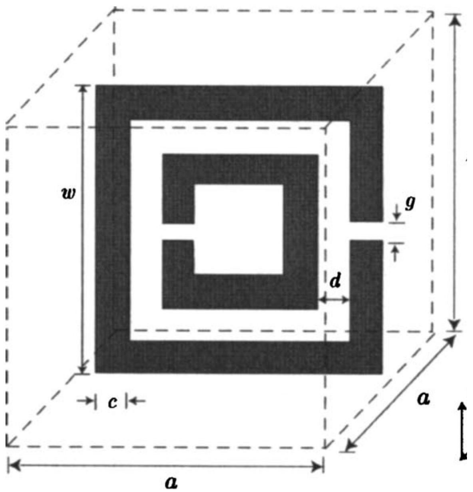
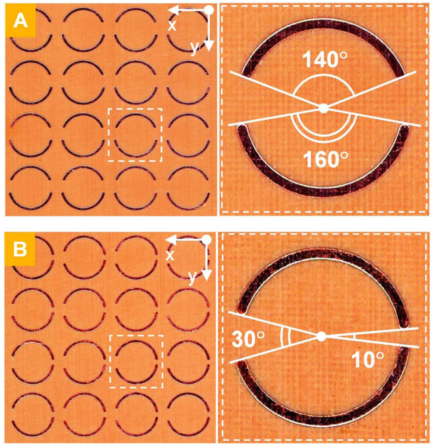
BUT: it disappears if the dielectric surrounding becomes symmetric

A direct demonstration of the effective response NONLOCALITY

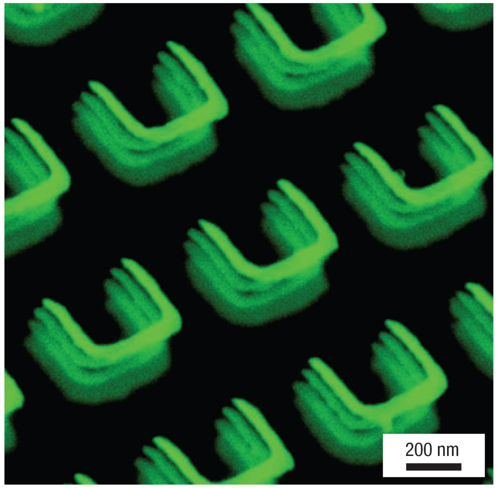
Examples of bi-anysotropic non-chiral metamaterials



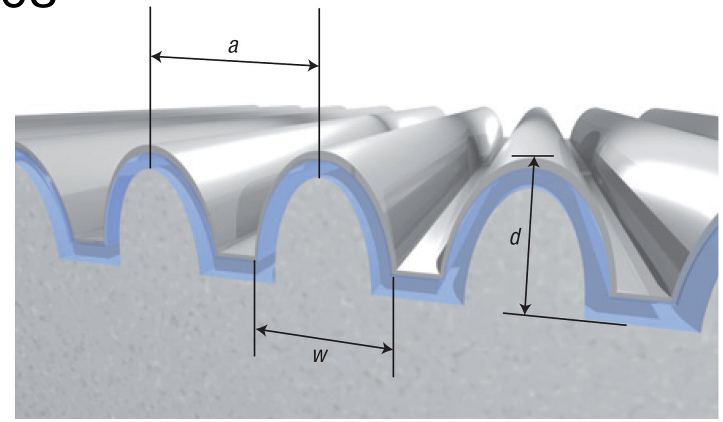
X. Chen et al, *PRE,* 2005



Fedotov et al, PRL, 2007

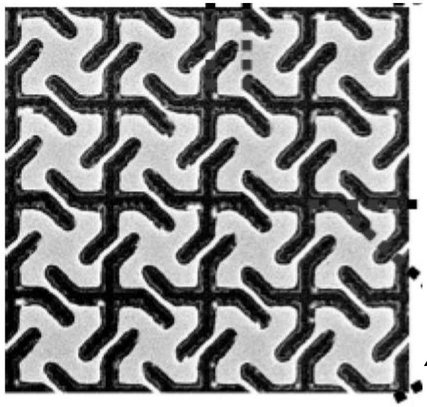


Na Liu et al, Nat. Mater. 2008

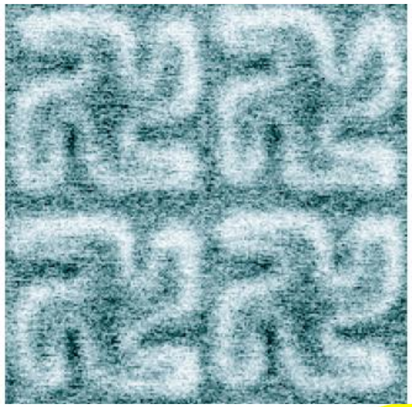


M.S. Rill et al, Nat. Mater. 2008

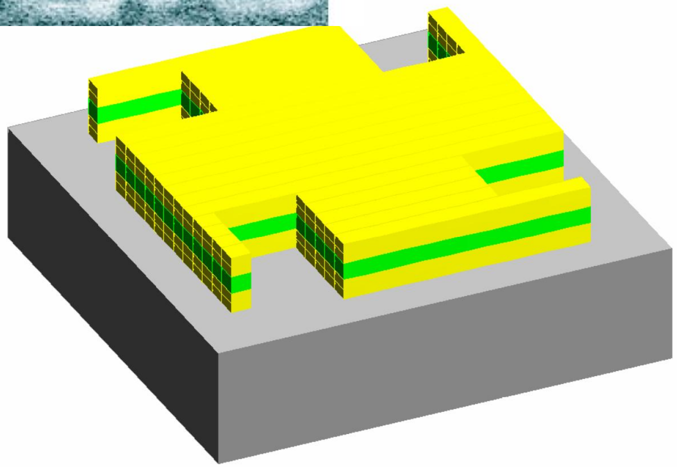
Examples of chiral metamaterials



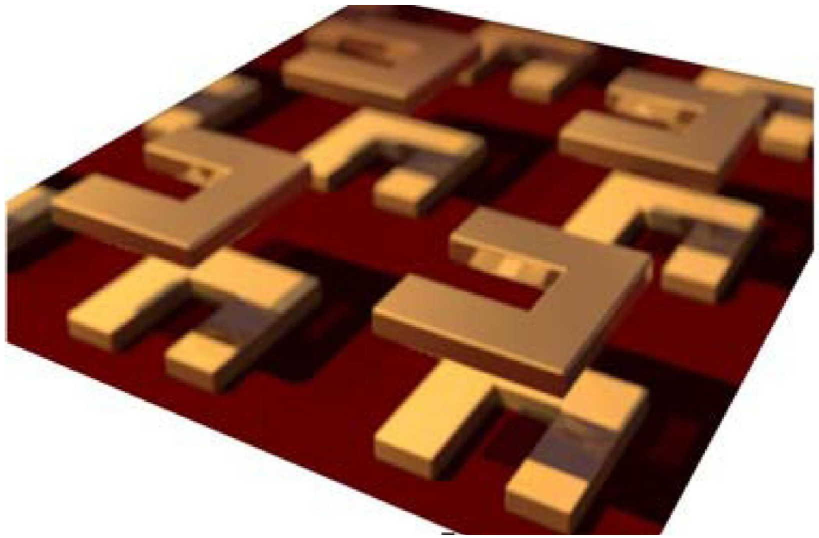
A. Papakostas et al, PRL, 2003



M. Kuwata-Gonokami et al, PRL, 2005

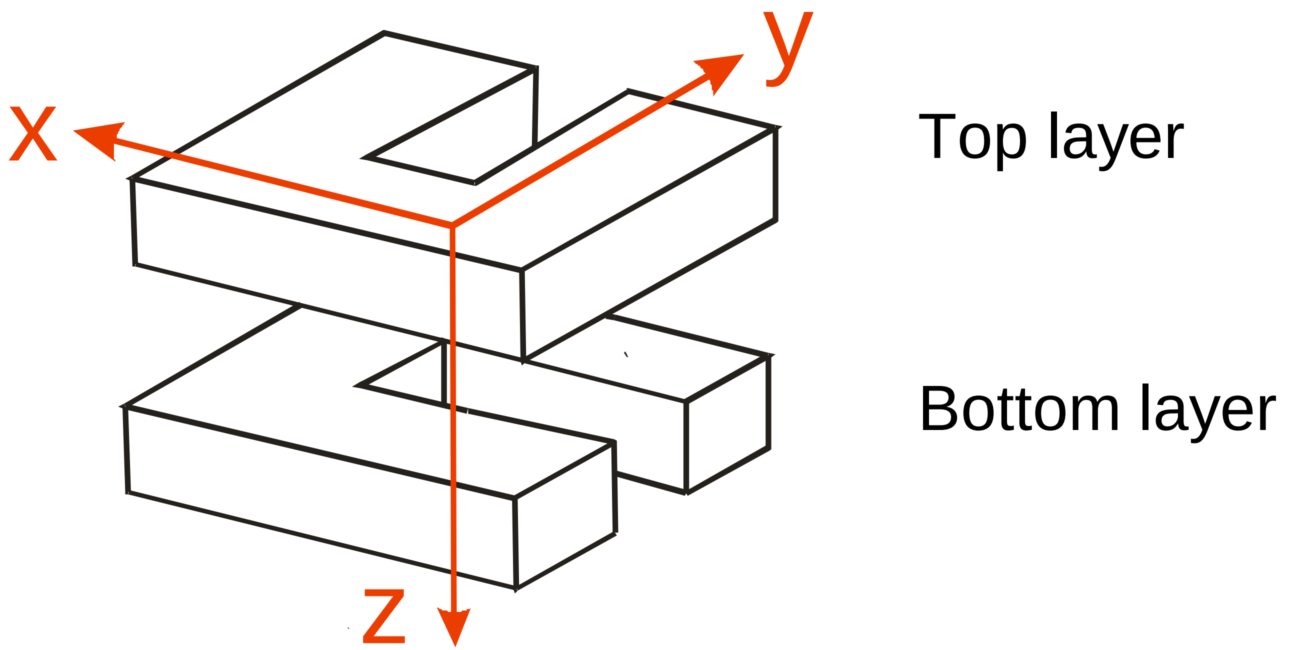


D.-H. Kwon et al, Opt Express, 2008



«Стереометаматериал»
Na Liu et al, *Nat. Photonics* 2009

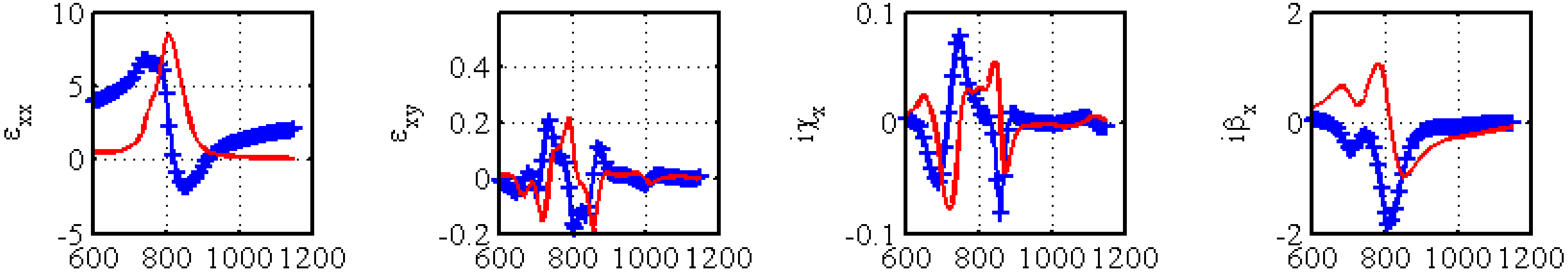
Example: 90 deg rotated pair of SRRs layers

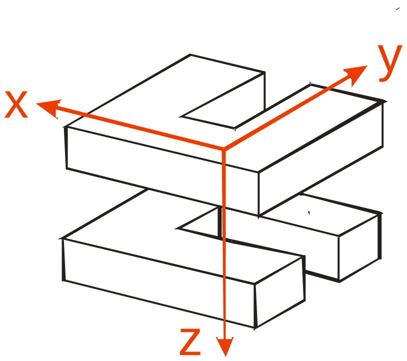


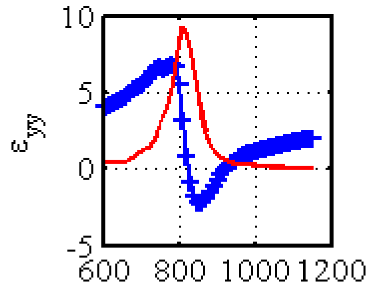
Unit cell of 2D periodic (in XY plane) metamaterial with square lattice

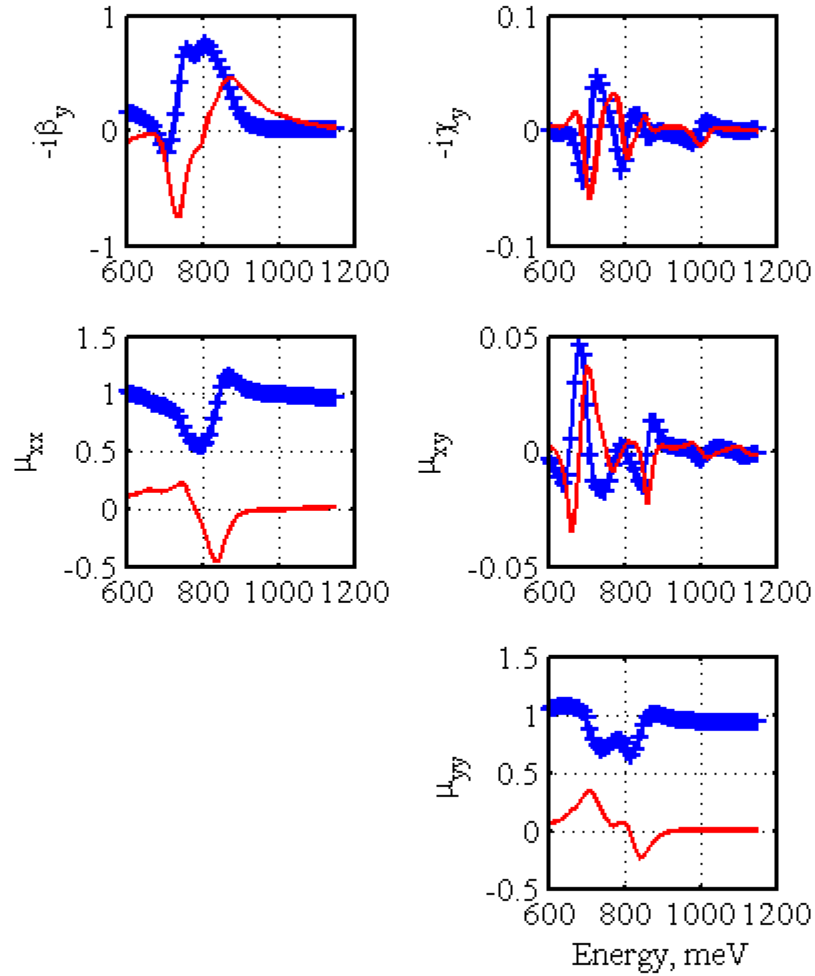
“Stereometamaterials”

Na Liu, Hui Liu, and Harald Giessen, 2009



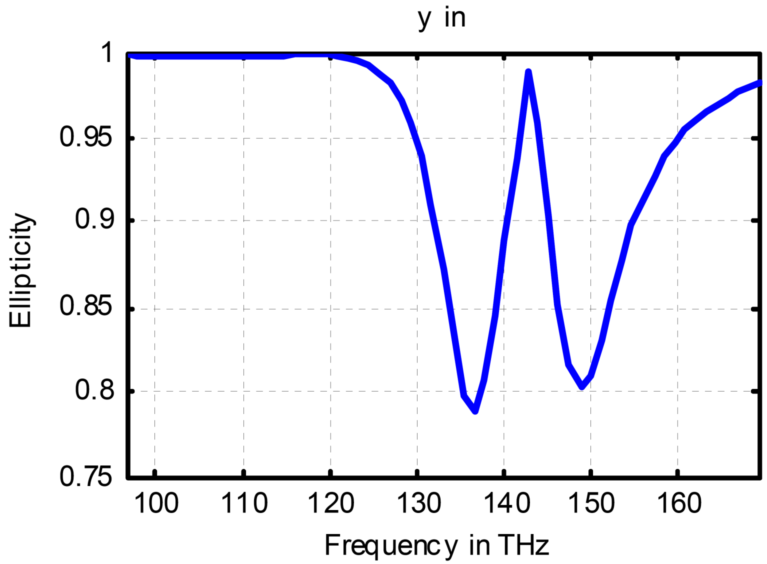


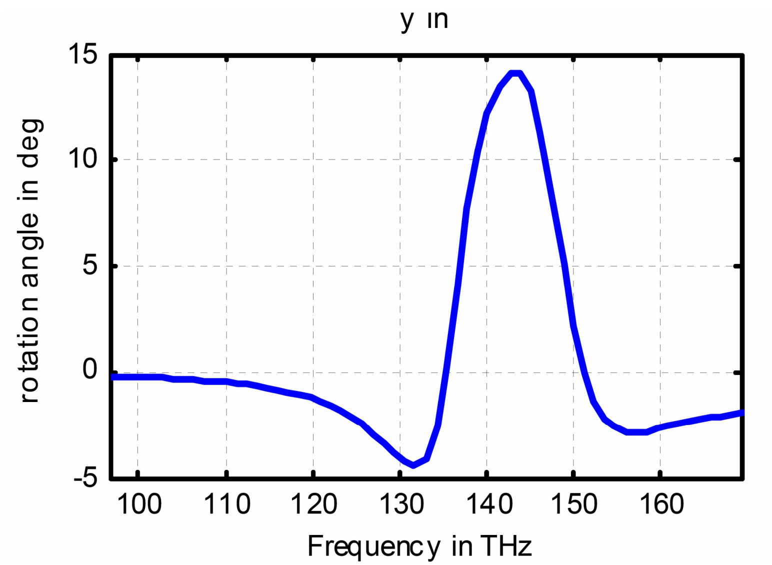


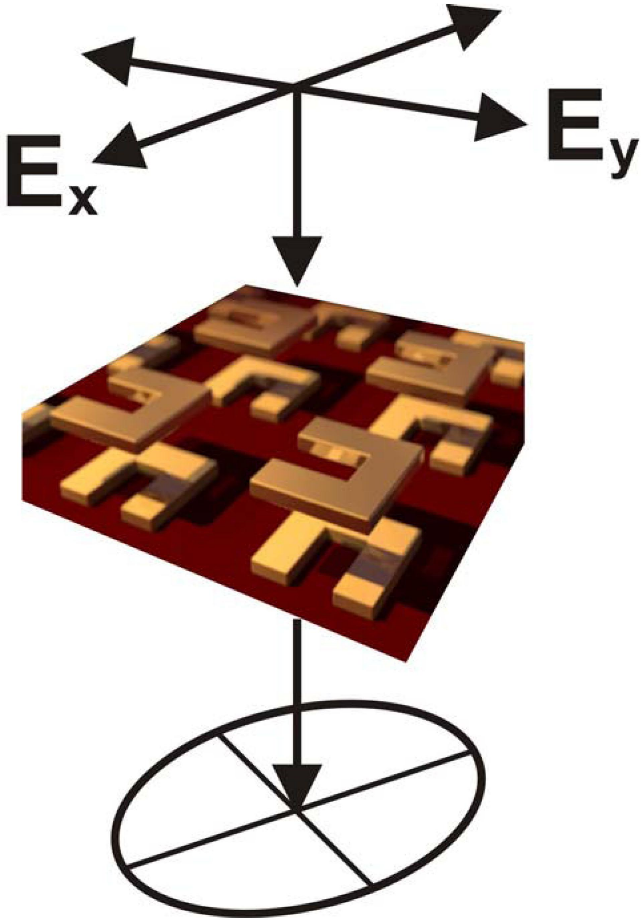


Retrieved response matrix

Giant natural optical activity







Conclusions

- Nanoplasmonics was known and used by mankind for centuries. **However, the recent development of nanotechnology brings new interesting possibilities**
- **Polaritonic photonic crystals** are systems with interacting electronic and photonic resonances**. New possibilities to control the optical properties and local electromagnetic fields**

3. As **metamaterials** (in short-period case) they demonstrate negative refraction behavior (in far field) and giant chiral properties.
4. Important property of the electromagnetic response is its **nonlocality**