Engineering Space for Light with Metamaterials

Part 1: Electrical and Magnetic Metamaterials

Part 2: Negative-Index Metamaterials, NLO, and super/hyper-lens

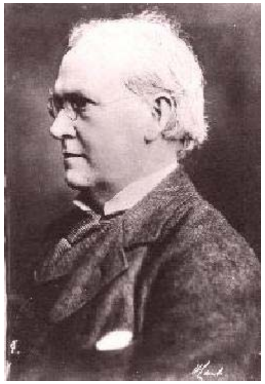
Part 3: Cloaking and Transformation Optics

Outline

- What are metamaterials?
- Early electrical metamaterials
- Magnetic metamaterials
- Negative-index metamaterials
- Chiral metamaterials
- Nonlinear optics with metamaterials
- Super-resolution
- Optical cloaking

Negative refractive index: A historical review

Sir Arthur Schuster



Sir Horace Lamb

… energy can be carried forward at the group velocity but in a direction that is anti-parallel to the phase velocity…

Schuster, 1904

Negative refraction and backward propagation of waves

Mandel'stam, 1945

L. I. Mandel'stam

V. G. Veselago

Left-handed materials: the electrodynamics of substances with simultaneously negative values of ε and μ

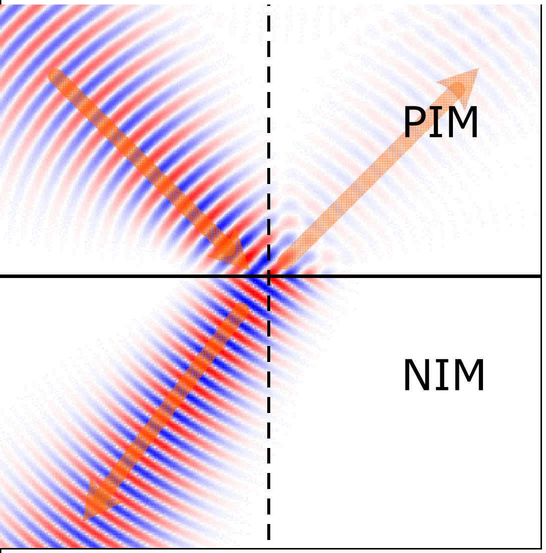
Veselago, 1968

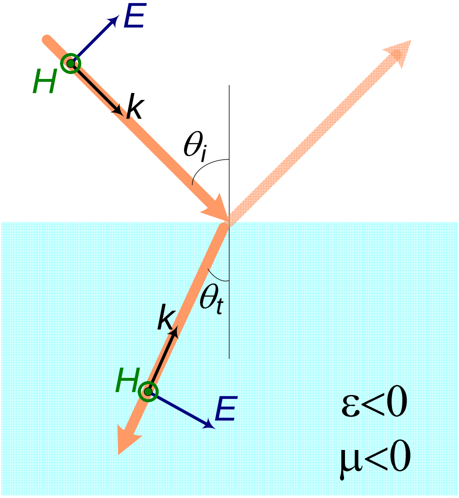
Pendry, the one who whipped up the recent boom of NIM researches

Perfect lens (2000)
EM cloaking (2006)

Sir John Pendry

Metamaterials with Negative Refraction





Refraction:

$$n^2 = \varepsilon\mu$$

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

Warning! ***Negative refraction ≠ negative refractive index***

(e.g. see Peccianti & Assanto: OE, 2007)

n < 0, if **$\varepsilon'|\mu| + \mu'|\varepsilon| < 0$**

Single-negative:

n<0 when $\varepsilon' < 0$ whereas $\mu' > 0$
(F is low)

Figure of merit
$F = |n'|/n''$

Double-negative:

n<0 with both $\varepsilon' < 0$ and $\mu' < 0$
(F can be large)

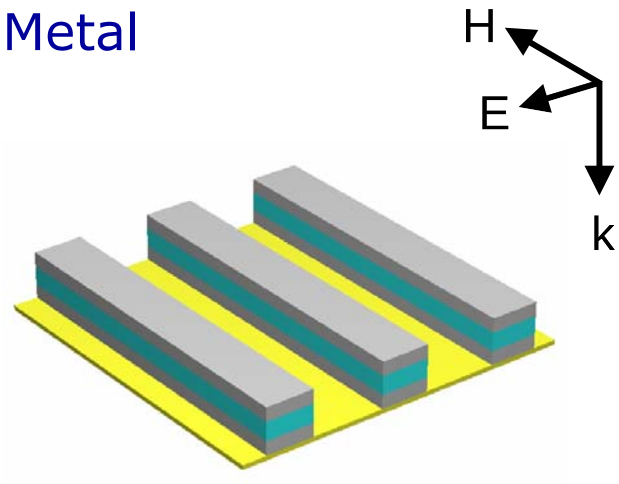
Negative Refractive Index in Optics: State of the Art

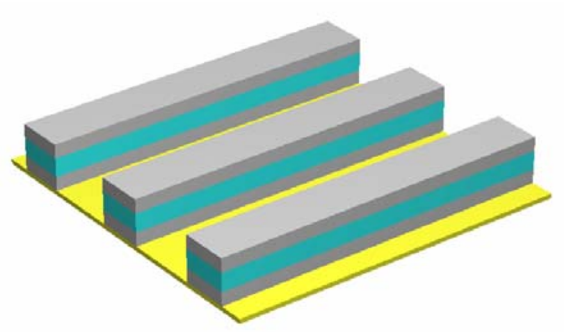
Year and Research group	*1st time posted and publication*	*Refractive index, n'*	*Wavelength λ*	*Figure of Merit $F=\lvert n'\rvert/n''$*	*Structure used*
<u>2005:</u>					
Purdue	**April 13 (2005) arXiv:physics/0504091 Opt. Lett. (2005)**	**–0.3**	**1.5 μm**	**0.1**	**Paired nanorods**
UNM & Columbia	**April 28 (2005) arXiv:physics/0504208 Phys. Rev. Lett. (2005)**	**–2**	**2.0 μm**	**0.5**	**Nano-fishnet with round voids**
<u>2006:</u>					
UNM & Columbia	**J. of OSA B (2006)**	**–4**	**1.8 μm**	**2.0**	**Nano-fishnet with round voids**
Karlsruhe & ISU	**OL. (2006) OL (2007)**	**–1 –1**	**1.4 μm 1.4 μm**	**3.0 2.5**	**Nano-fishnet 3-layer nanofishnet**
Karlsruhe & ISU	**OL (2006)**	**–0.6**	**780 nm**	**0.5**	**Nano-fishnet**
Purdue	**OL (2007)**	**–0.9 -1.1**	**770 nm 810nm**	**0.7 1.3**	**Nano-fishnet**

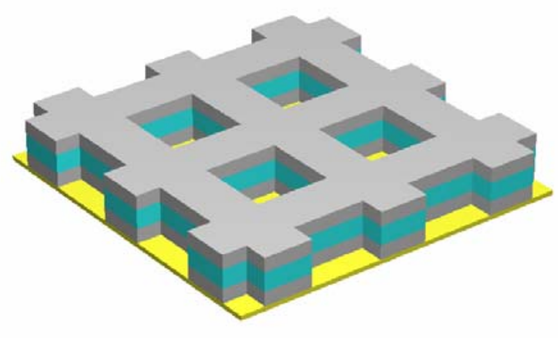
see review: Nature Photonics v. 1, 41 (2007)

Negative permeability and negative permittivity

- 🟦 Dielectric
- ⬜ Metal







Nanostrip pair (TM)

$\mu < 0$ (resonant)

Nanostrip pair (TE)

$\varepsilon < 0$ (non-resonant)

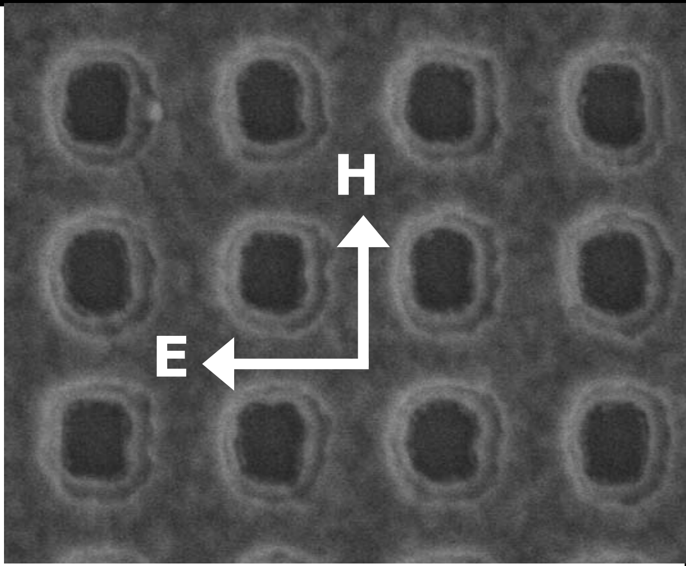
Fishnet

ε and $\mu < 0$

S. Zhang, et al., PRL (2005)

Sample Geometry (Fishnet Structure)

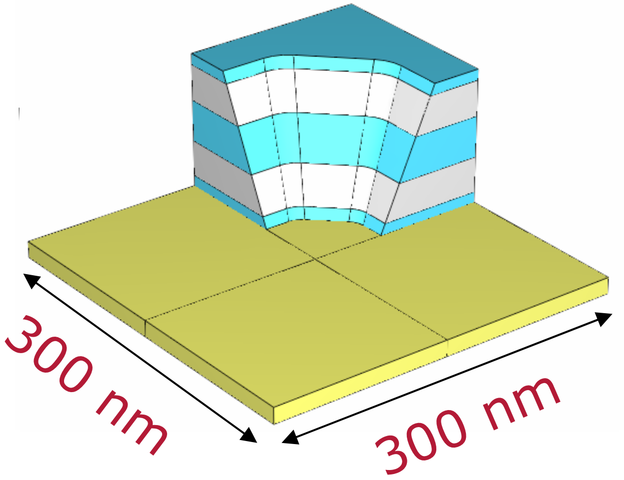
- E-beam lithography
- Period = 300 nm along both axis
- Average width of strips along H = 130 nm
  Average width of strips along E = 95 nm



SEM image and primary polarization

Stacking:

10 nm of Al_2O_3
33 nm of Ag
38 nm of Al_2O_3
33 nm of Ag
10 nm of Al_2O_3



🟦 Alumina

⬜ Silver

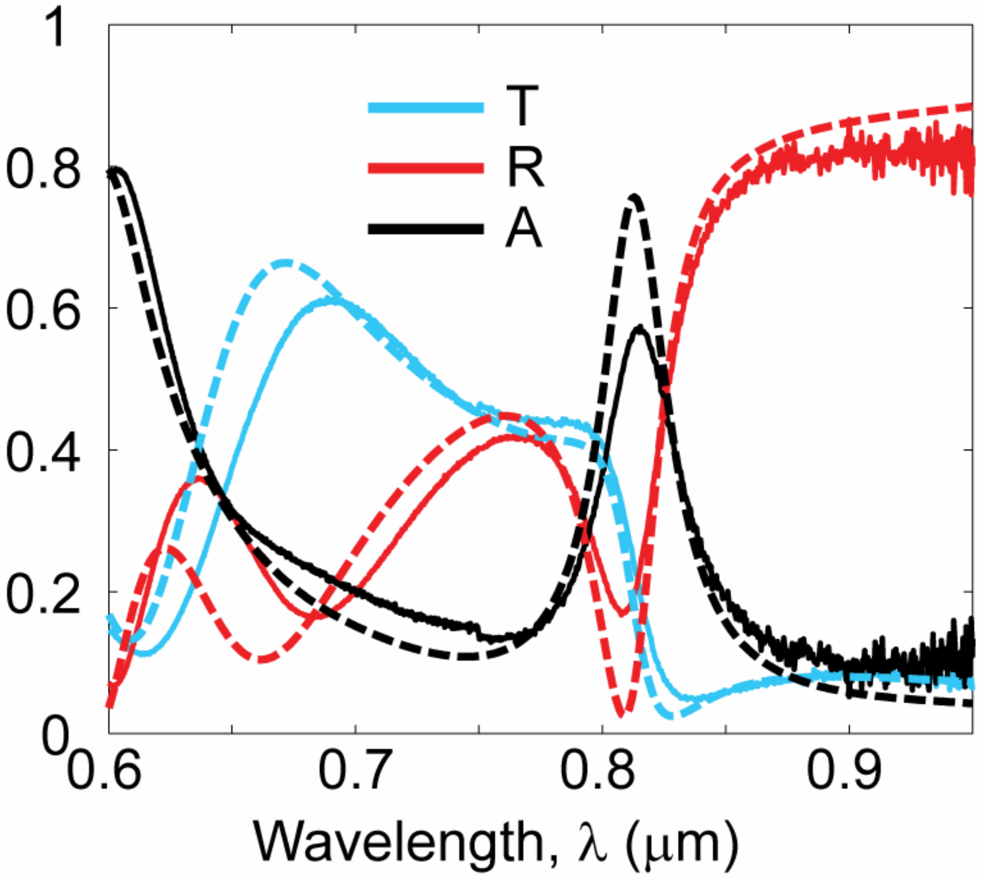
🟨 ITO

Spectra for Primary Polarization

- Magnetic resonance around λ = 800 nm
- Electric resonance around λ = 600 nm
- Finite Elements

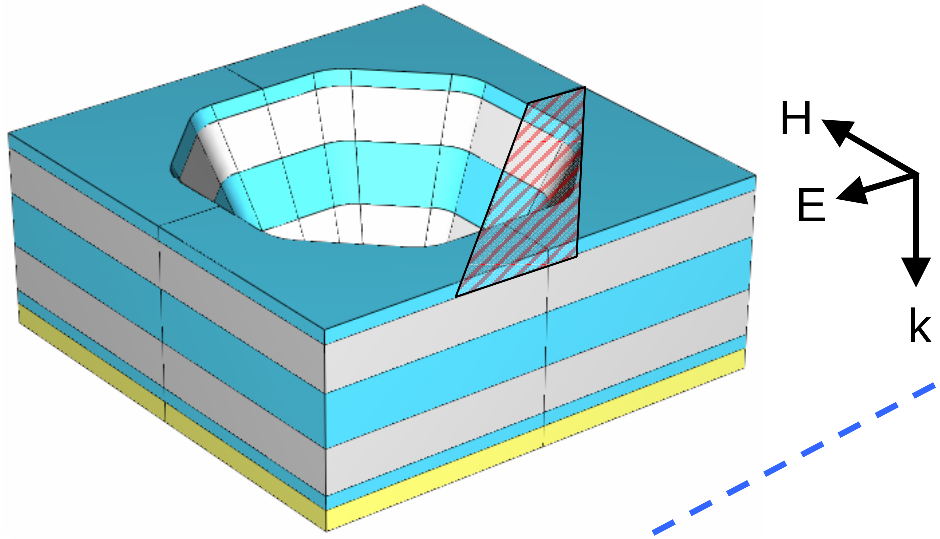
Solid line : Experimental

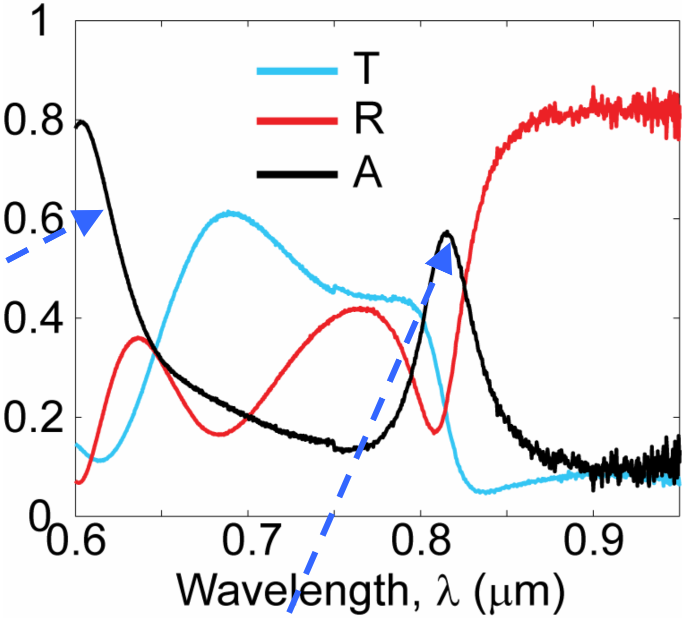
Dashed line: Simulated

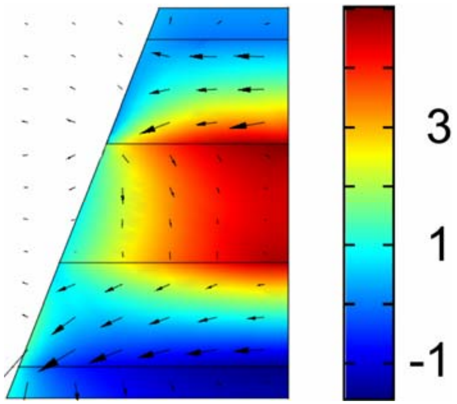


U. K. Chettiar, *et al*., Optics Letters **32**, 1671 (2007)

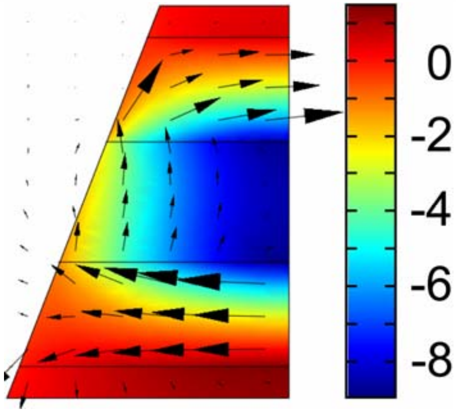
Field Maps for Primary Polarization





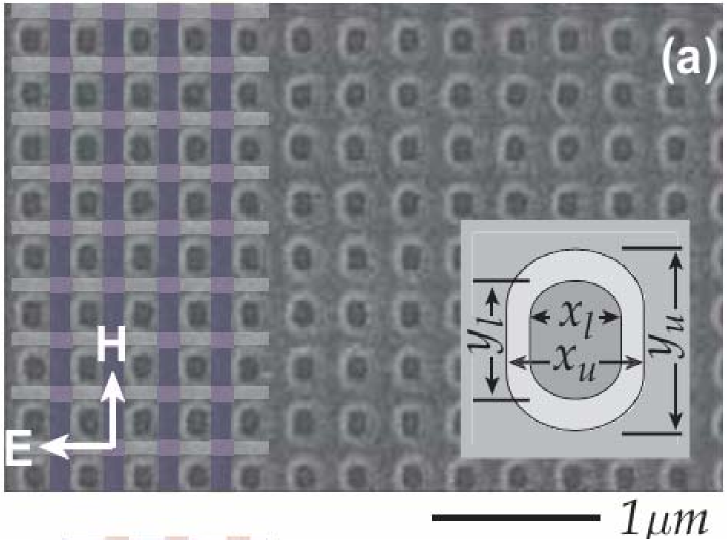


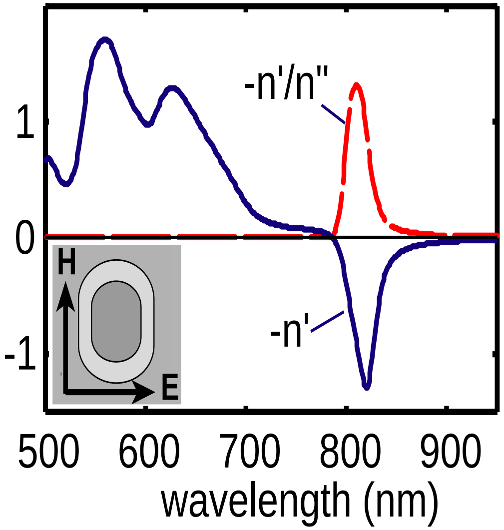
Electrical Resonance, λ = 625 nm

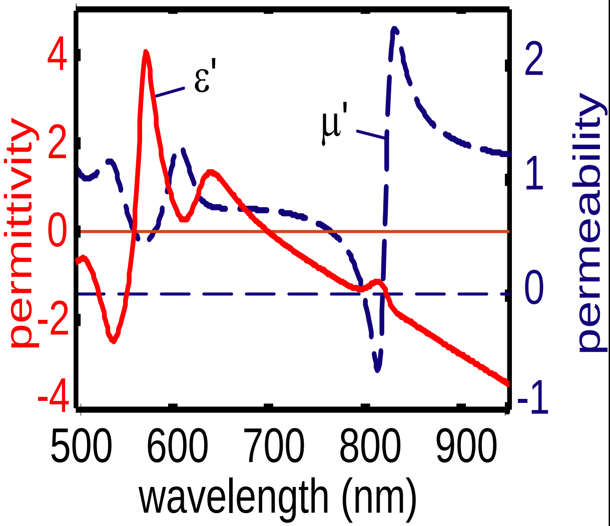


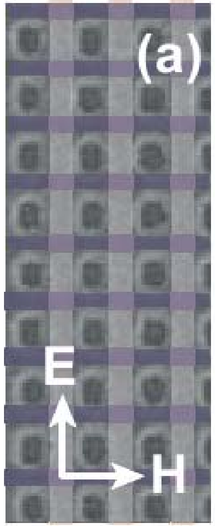
Magnetic Resonance, λ = 815 nm

Double Negative NIM (n'=-1.0, FOM=1.3, at 810 nm)
Single Negative NIM (n'=-0.9, FOM=0.7, at 770 nm)

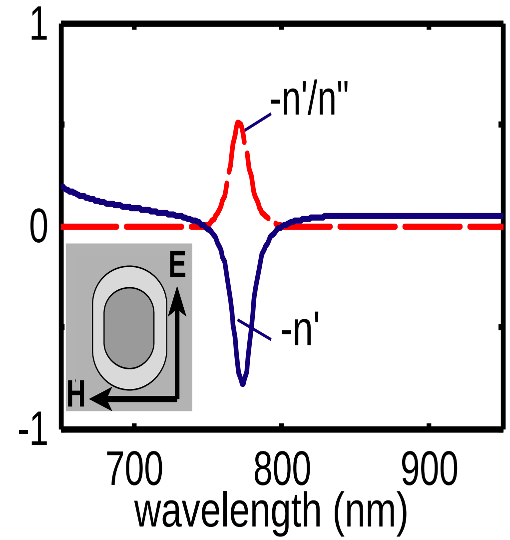


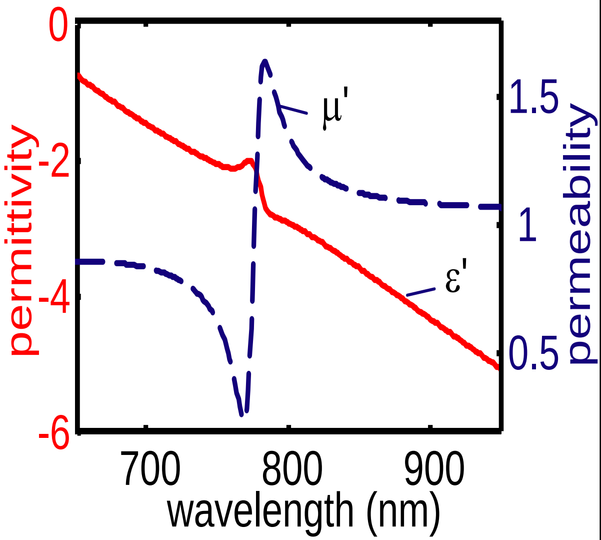






Chettiar et al
OL (2007)





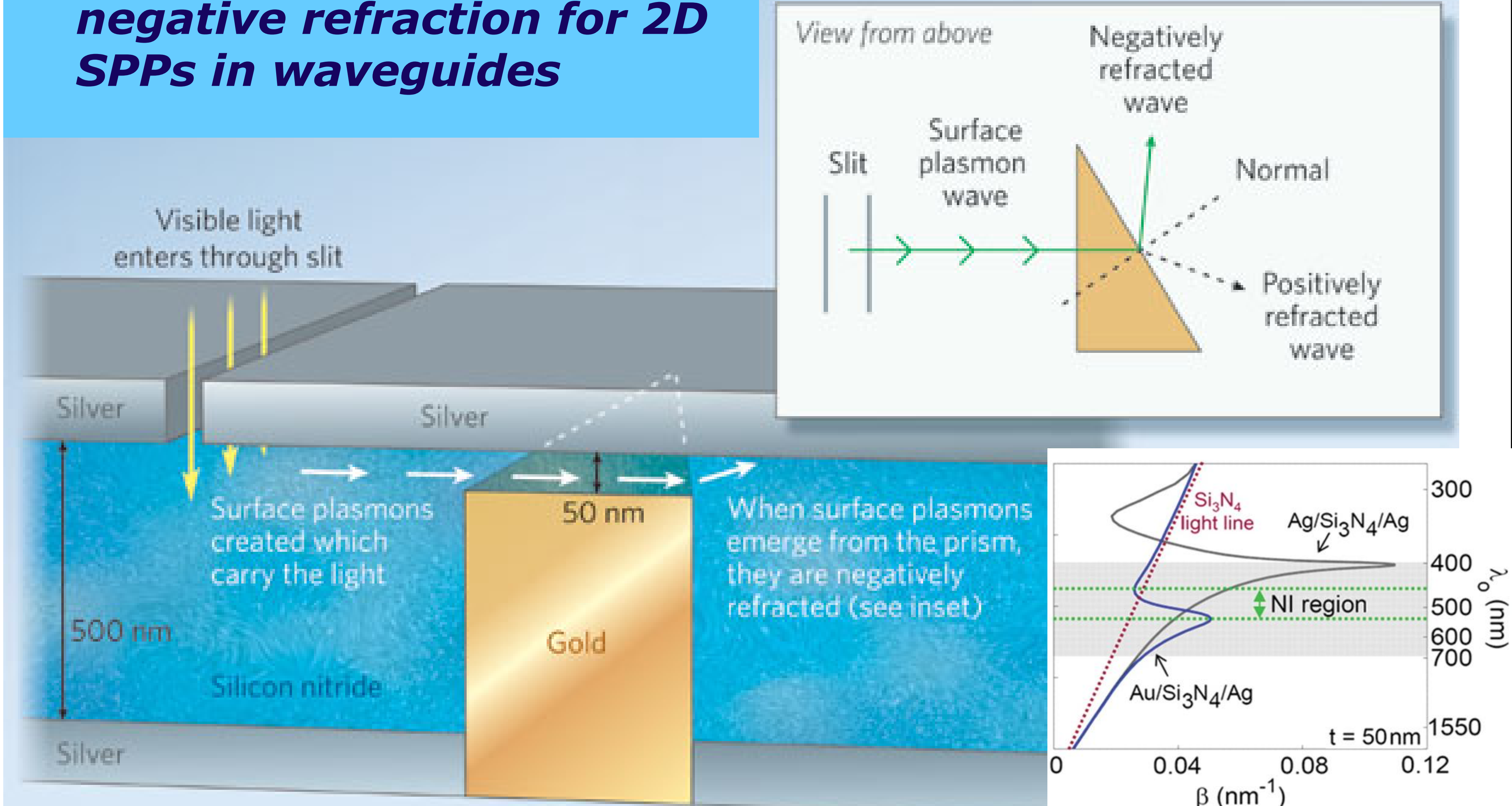
Summary on negative refractive index

- A Double Negative NIM (Negative index material) is demonstrated at a wavelength of ~810 nm
- The sample exhibits a figure of merit (-n′/n″) of 1.3 and a transmittance of 25% at 813 nm
- The same sample shows Single Negative NIM behavior for the orthogonal polarization at a wavelength of ~770 nm with a figure of merit of 0.7 and a transmittance of 10%

Negative Refraction for Waveguide Modes

negative refraction for 2D SPPs in waveguides

An mode index of ~ -5 is obtained at the green light.



Lezec, Dionne and Atwater, Science, 2007

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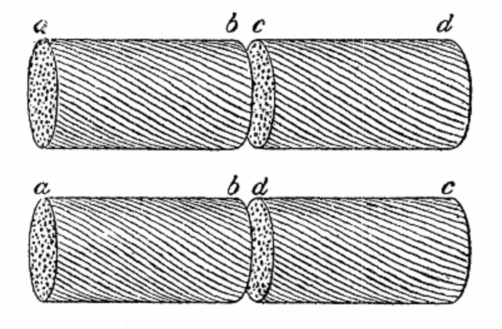
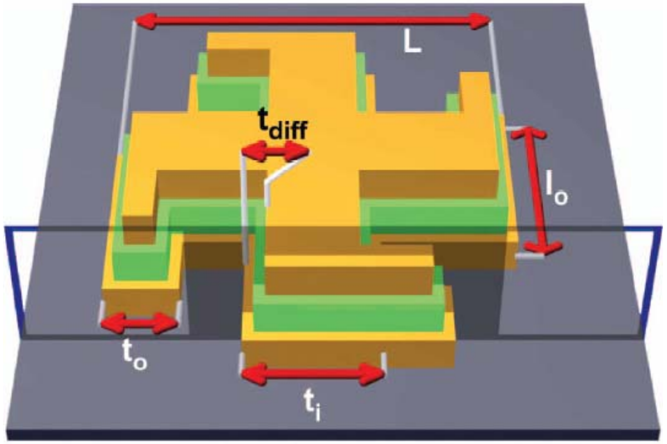
Chiral Optical Elements

Bose’s Artificial chiral molecules: Twisted jute elements

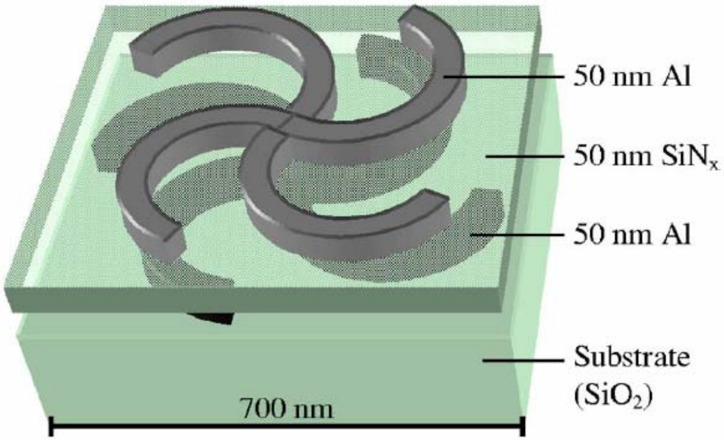


J. C. Bose, *Proceeding of Royal Soc. London*, 1898

Optical counterparts:



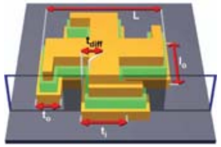
Decher, Klein, Wegener and Linden
Opt. Exp., 2007

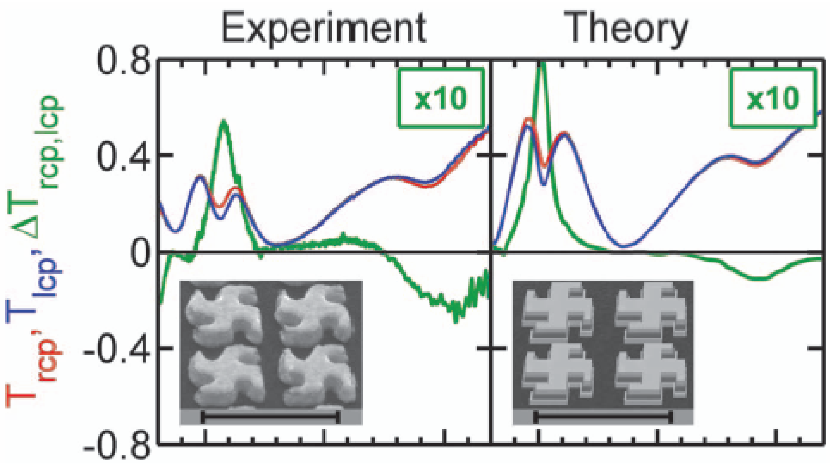


The Zheludev group, U. Southampton
Appl. Phys. Lett., 2007

Chiral Effects in Optical Metamaterials

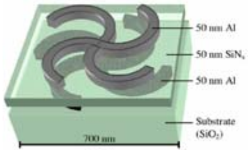
Circular dichroism:

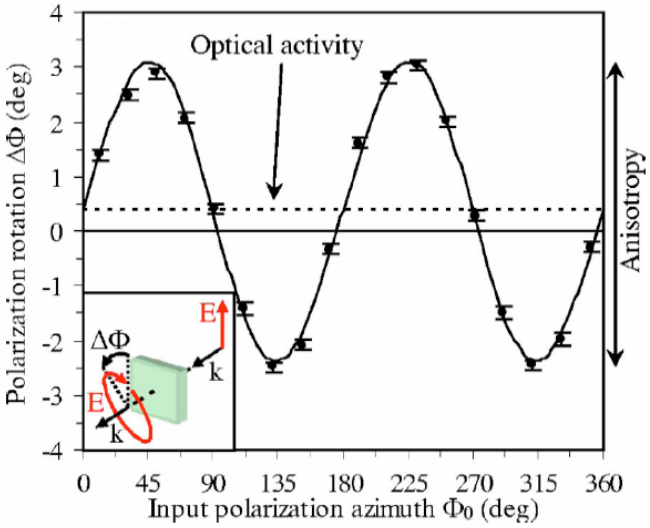




Decher, Klein, Wegener and Linden
Opt. Exp., 2007

Giant optical gyrotropy:





The Zheludev group, U. Southampton
Appl. Phys. Lett., 2007

Chirality can ease obtaining n<0:
Tretyakov, et al (2003), Pendry (Science 2004)

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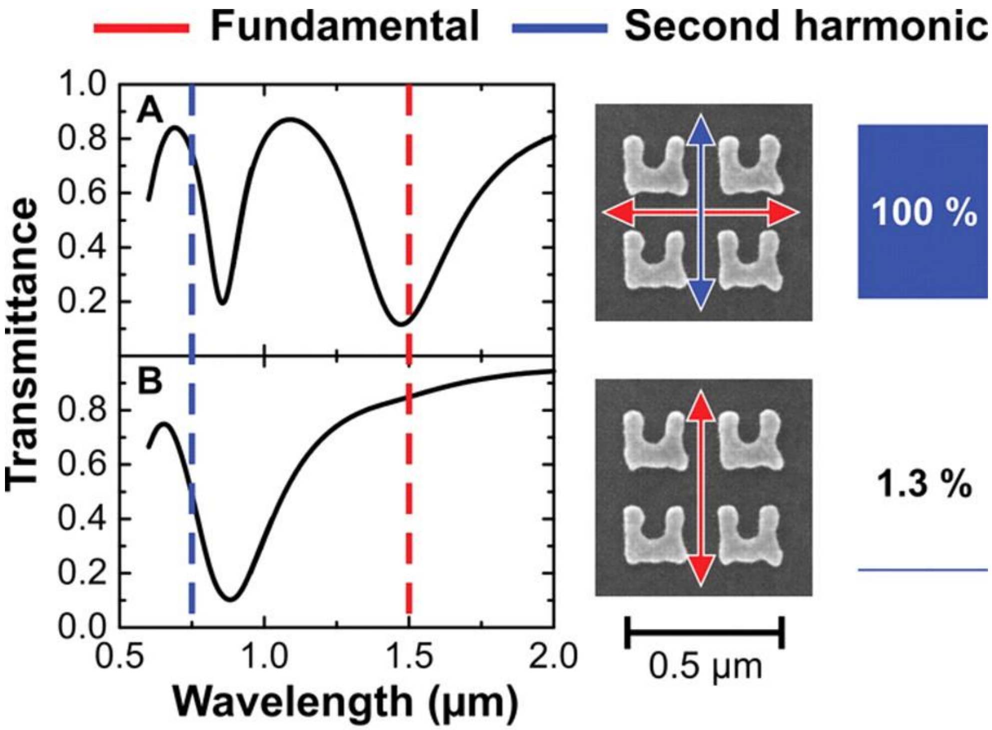
SHG and THG from Magnetic Metamaterial



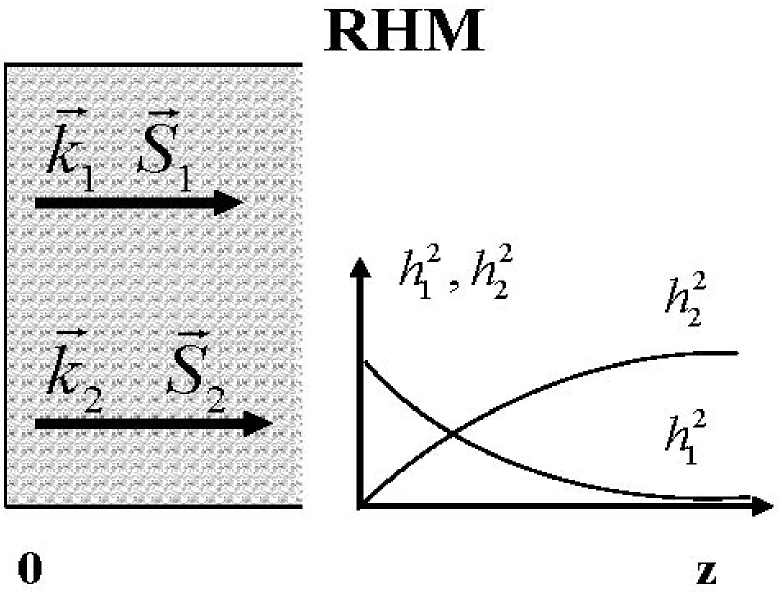
Excitation when magnetic resonance is excited (1st pol)

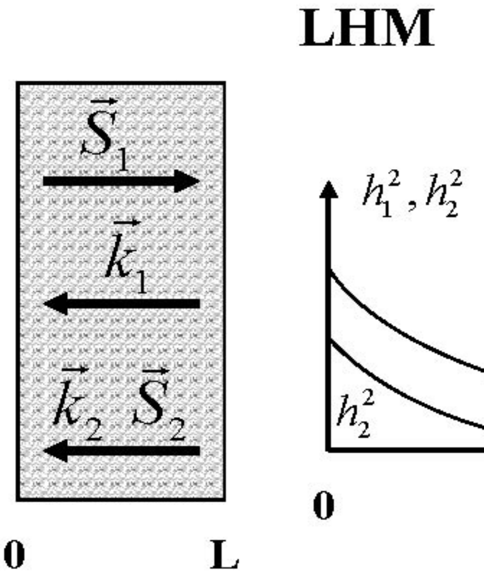
Excitation at 2nd pol. (no magnetic resonance)

<u>SHG:</u> Klein, Enkrich, Wegener, and Linden, Science, 2006
<u>SHG & THG:</u> Klein, Wegener, Feth and Linden, Opt. Express, 2007

NLO in NIMs: SHG

Backward Waves in NIMs:
Distributed feedback, cavity-like amplification, etc.





$n_1 < 0$ and $n_2 > 0$

Manley-Rowe Relations

$$\frac{dS_1}{dz} - \frac{dS_2}{dz} = 0,$$

Phase-matching: $\varepsilon_1 = -\varepsilon_2, k_2 = 2k_1$ ➡ $h_1^2(z) - h_2^2(z) = C$

SHG in NIMs: Nonlinear 100% Mirror

100% reflective SHG Mirror !

$$h_1^2(z) - h_2^2(z) = C$$

Finite Slab:

$$\sqrt{C}\kappa L = \arccos(\sqrt{C}/h_{10})$$

$$h_2(z) = \sqrt{C}\tan[\sqrt{C}\kappa(L-z)]$$

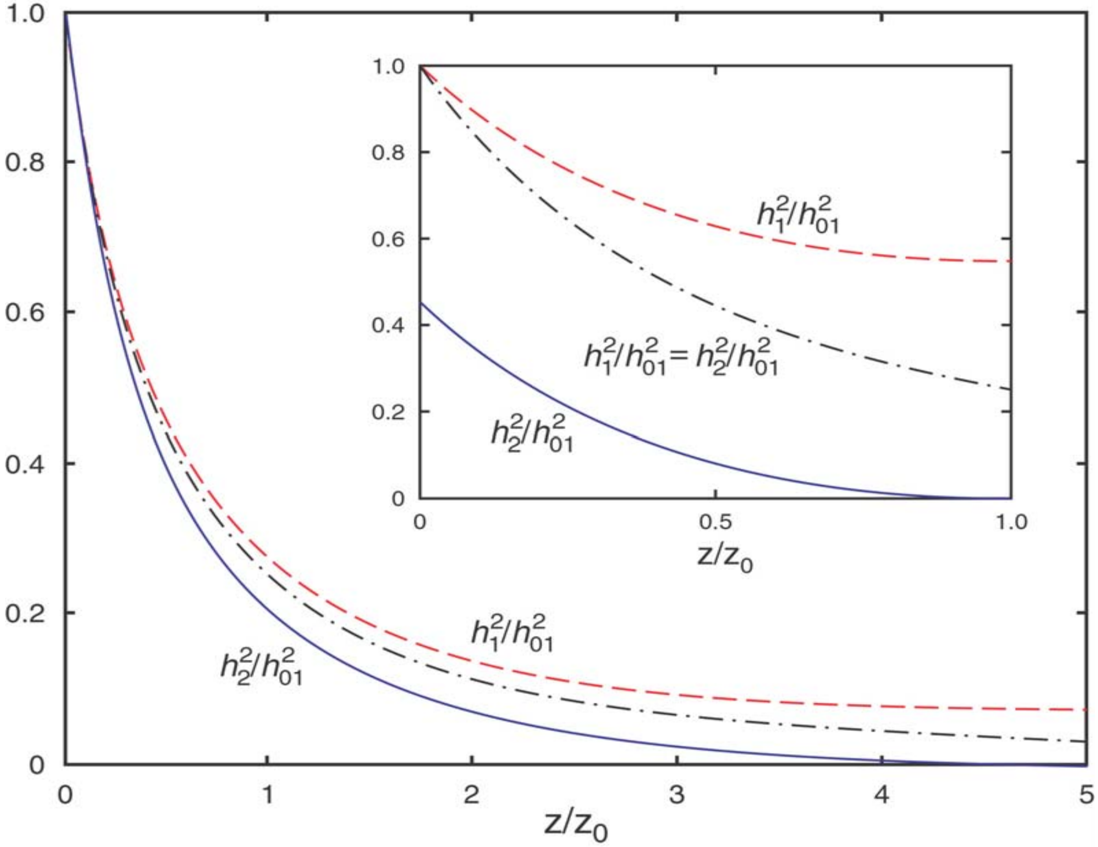
$$h_1(z) = \sqrt{C}/\cos[\sqrt{C}\kappa(L-z)]$$

Semi-Infinite Slab:

$$C = 0, h_2(z) = h_1(z)$$

$$h_2(z) = h_{10}/[1+(z/z_0)]$$

$$\kappa = 4\pi\chi^{(2)}\varepsilon_2\omega_2^2/k_2c^2 \quad z_0 = [\kappa h_{10}]^{-1}$$

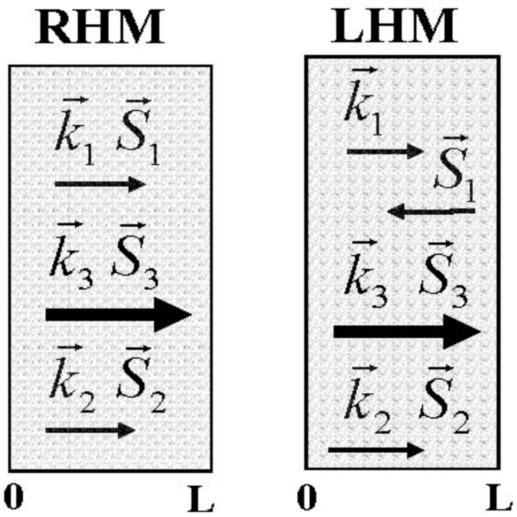


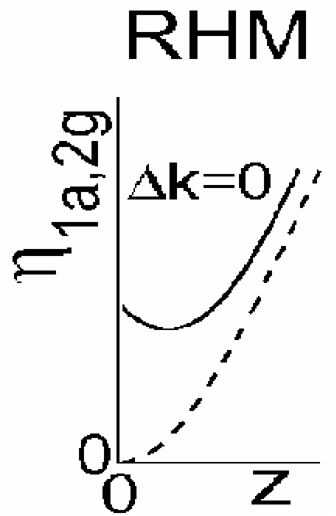
Other work on SHG:

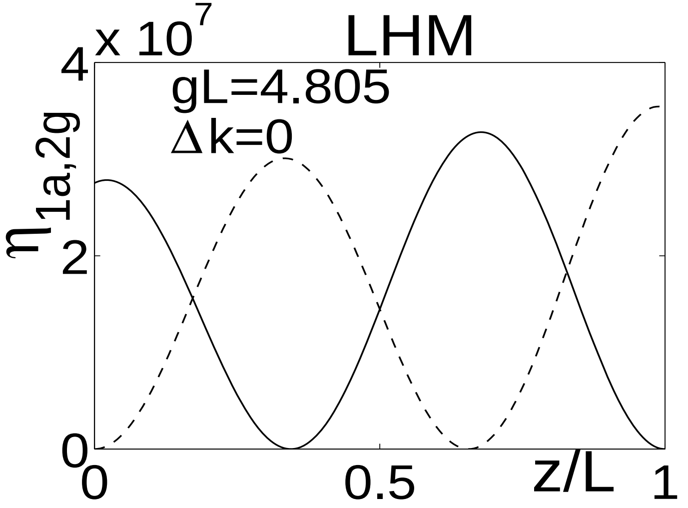
Kivshar et al; Zakhidov et al

Optical Parametric Amplification (OPA) in NIMs

$\omega_3 = \omega_1 + \omega_2$ ($n_1 < 0$, $n_2, n_3 > 0$) S_3 - Control Field (pump)







$$\eta_{1a} = \left|a_1(z)/a_{1L}\right|^2, \eta_{1g} = \left|a_1(z)/a_{20}\right|^2, \eta_{2g} = \left|a_2(z)/a_{1L}\right|^2$$

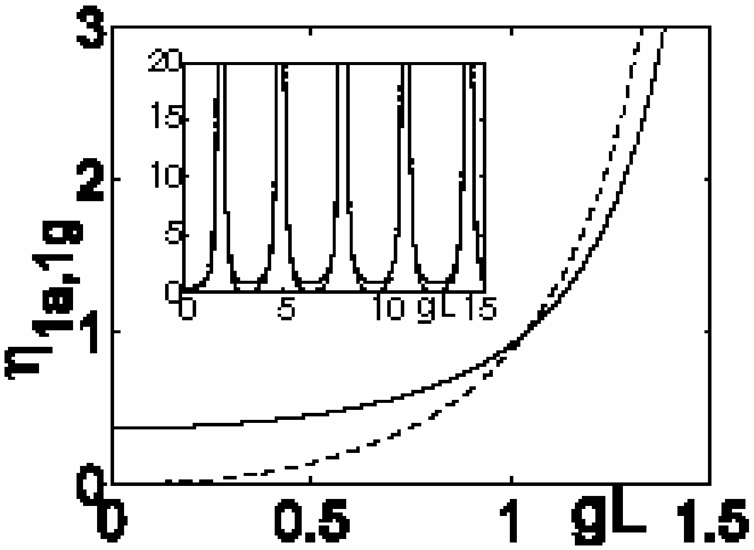
$$g = \left(\sqrt{\omega_1\omega_2}\sqrt[4]{\varepsilon_1\varepsilon_2/\mu_1\mu_2}\right)(8\pi/c)\chi^{(2)}h_3$$

Manley-Rowe Relations:

$$\frac{d}{dz}\left(\frac{S_1}{\hbar\omega_1} - \frac{S_2}{\hbar\omega_2}\right) = 0$$

Popov, VMS, Opt. Lett. (2006)
Appl. Phys. B (2006)
For SHG see also Agranovich et al and Kivshar et al

OPA in NIMs: Loss-Compensator and Cavity-Free Oscillator



Backward waves in NIMs -> Distributed feedback & cavity-like amplification and generation

Popov, VMS, OL (2006)

$$\Delta k = 0$$

$$g = \left(\sqrt{\omega_1 \omega_2}\sqrt[4]{\varepsilon_1 \varepsilon_2 / \mu_1 \mu_2}\right)(8\pi / c)\chi^{(2)} h_3 \qquad \eta_{1a} = \left|a_1(z)/a_{1L}\right|^2, \eta_{1g} = \left|a_1(z)/a_{20}\right|^2$$

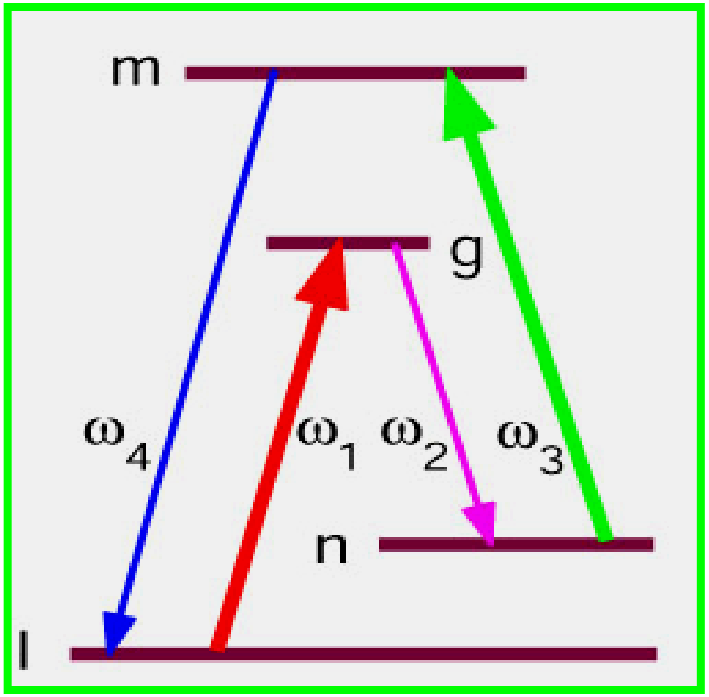
Resonances in output amplification and DFG

$\alpha_1 L = 1$, $\alpha_2 L = 1/2$

- **OPA-Compensated Losses**
- **Cavity-free (no mirrors) Parametric Oscillations**
- **Generation of Entangled Counter-propagating LH and RH photons**

OPA with 4WM

Four-level $\chi^{(3)}$ centers embedded in NIM



$\chi^{(3)}$ -OPA assisted by the Raman Gain:

ω_4 – signal; ω_1, ω_3 – control fields

$\omega_2 = \omega_1 + \omega_3 - \omega_4$ – idler

(Raman-enhanced; contributes back to OPA at ω_4)

- **$\chi^{(3)}$ -OPA: compensation of losses: transparency and amplification at ω_4**
- **Cavity-free generation of counter-propagating entangled right- and left-handed photons**
- **Control of local optical parameters through quantum interference**

See talk tomorrow by Popov et al on NLO in MMs

Popov, et al OL (2007)

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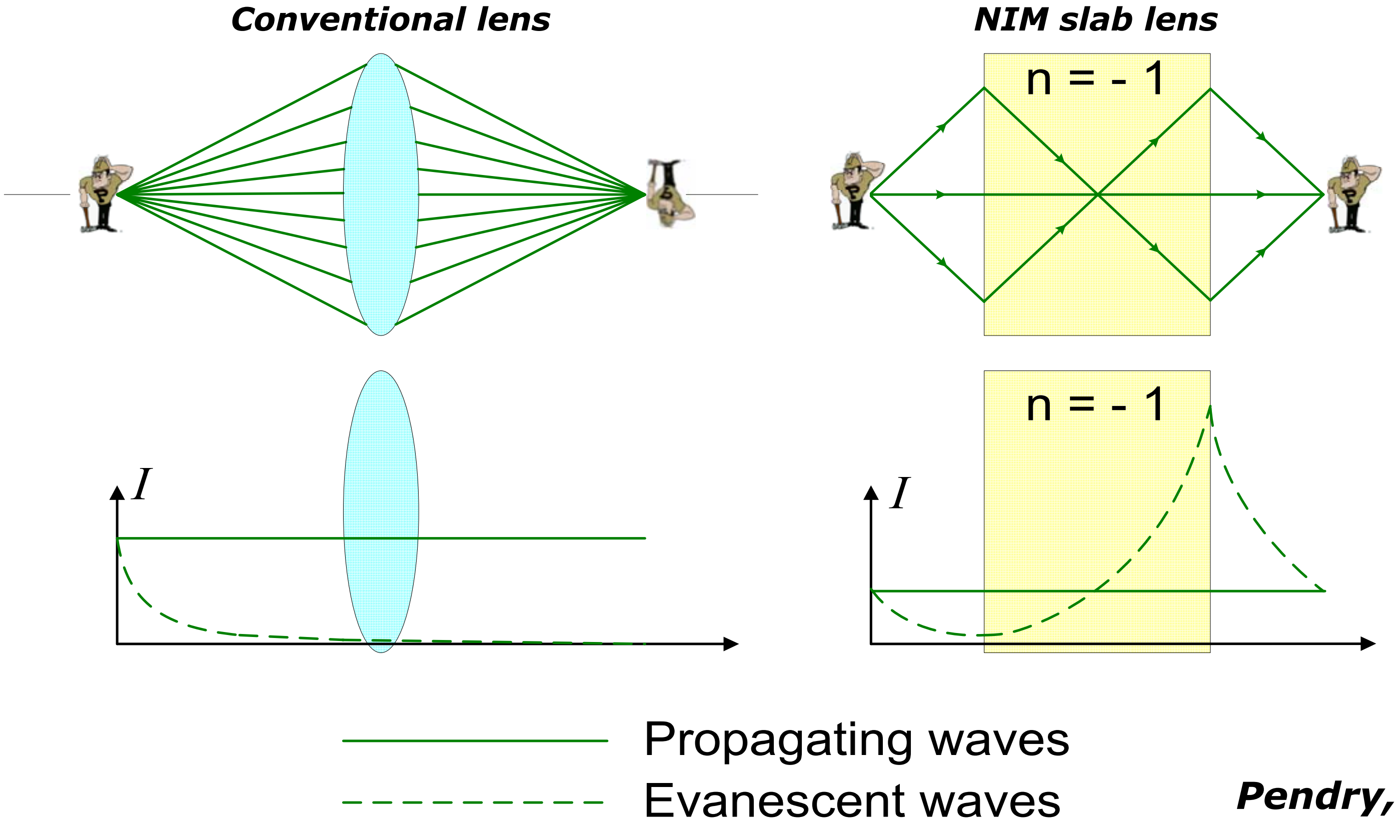
Super-resolution:
Amplification of Evanescent Waves Enables sub-λ Image!

Waves scattered by an object have all the Fourier components $k_z = \sqrt{k_0^2 - k_x^2 - k_y^2}$

The propagating waves are limited to: $k_t = \sqrt{k_x^2 + k_y^2} < k_0$

To resolve features Δ, we must have $\lambda_t = 2\pi / k_t < \Delta, \;\; \Delta < \lambda \Rightarrow \;\; k_t = \sqrt{k_x^2 + k_y^2} > k_0, \;\; k_z^2 < 0$

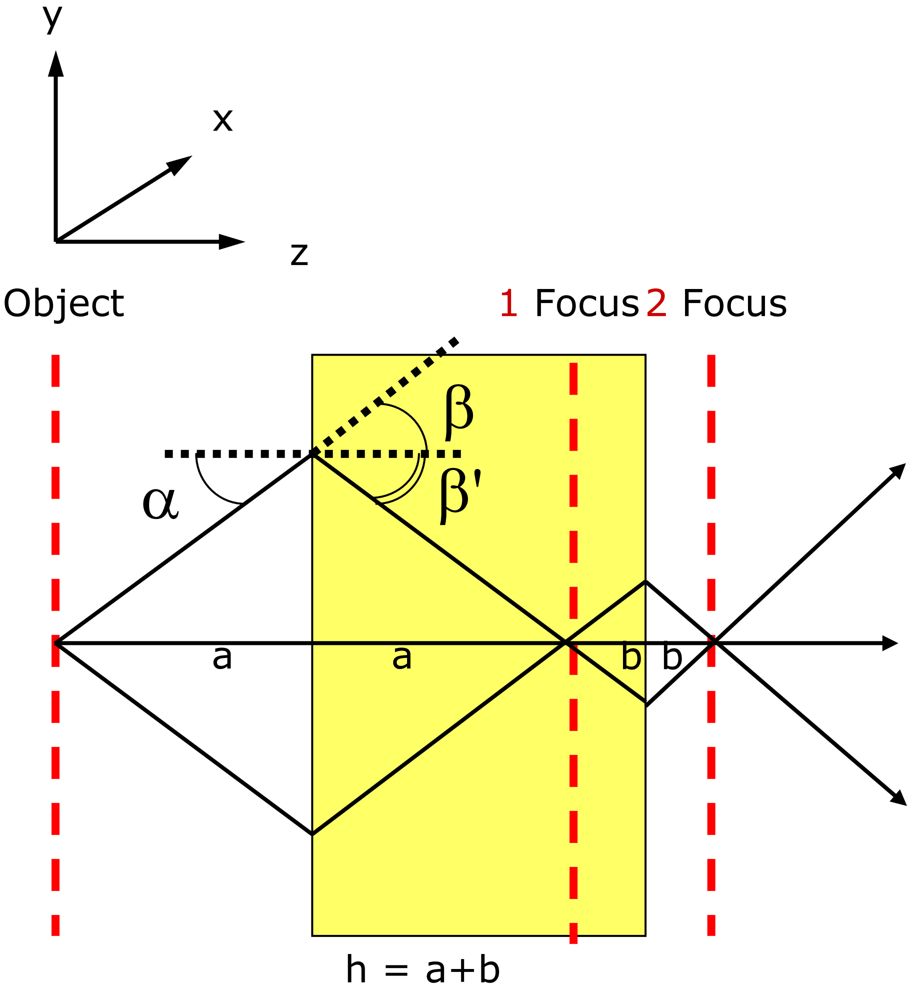
The evanescent waves are “re-grown” in a NIM slab and fully recovered at the image plane


Conventional lens

NIM slab lens

Pendry, PRL, 2000

Perfect Lens



$n = -1$ (ε = -1; μ = -1)

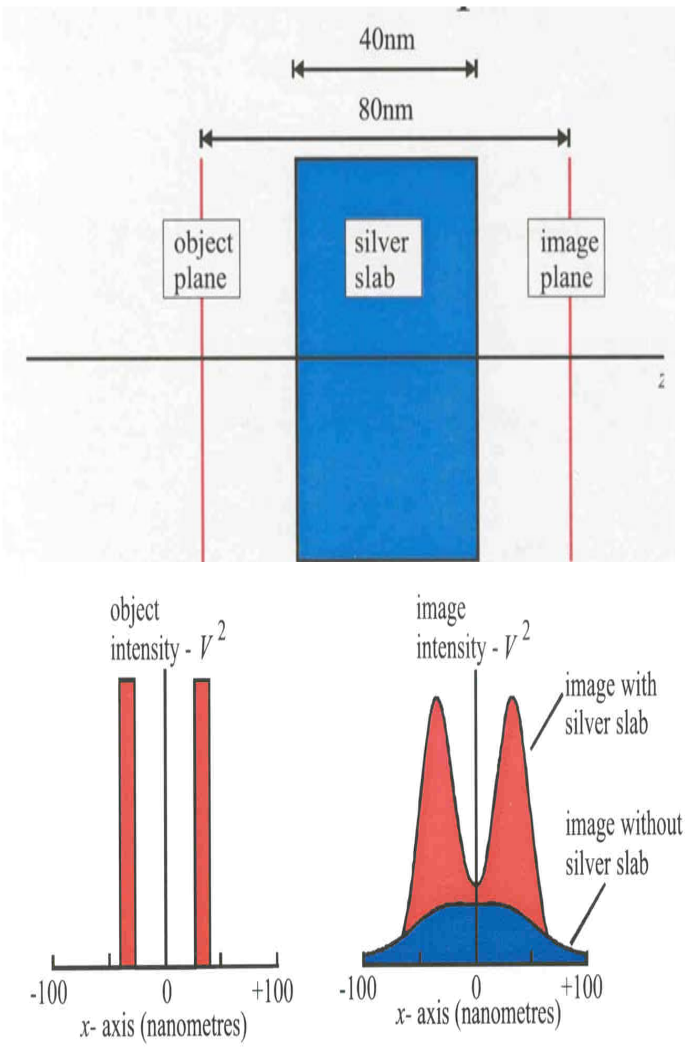
$$\sin(\alpha) = n\sin(\beta') = -\sin(\beta') = \sin(\beta)$$

$$E(y,z) = \sum_q A_q \exp\left(iqy + i\sqrt{(nk)^2 - q^2}\; z \right)$$

$$Phaseshift =$$

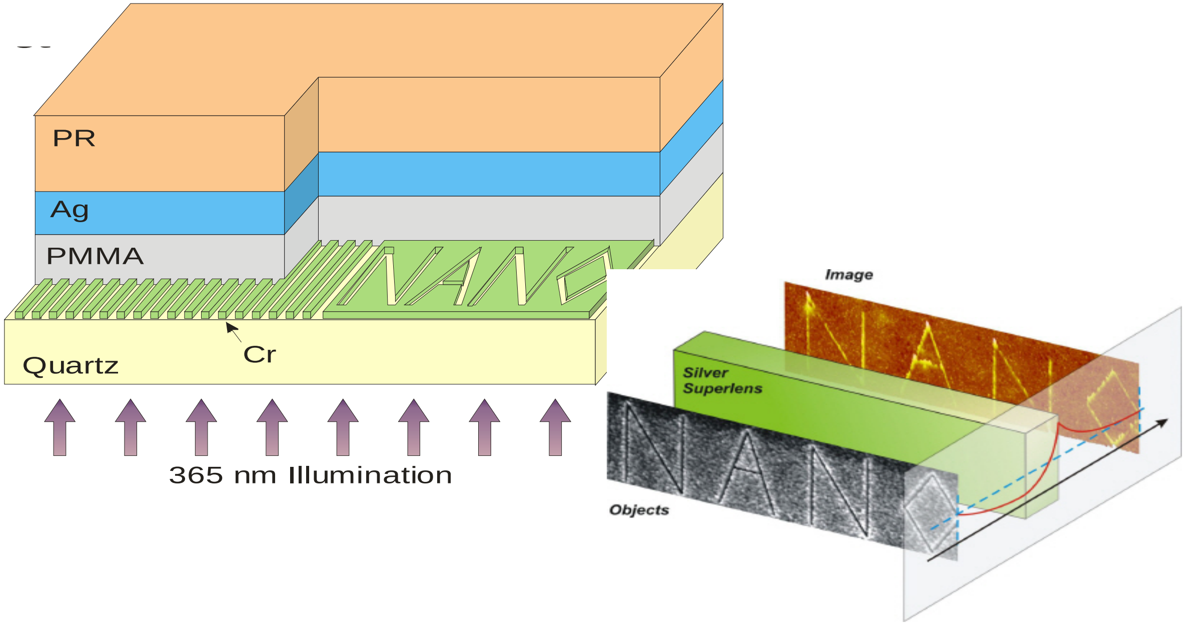
$$\left(iqy + i\sqrt{k^2 - q^2}\; z\right) + \left(-iqy - i\sqrt{(-k)^2 - q^2}\; z\right) = 0$$

The Poor Man's (Near-Field) Superlens ($\varepsilon < 0$, $\mu = 1$)



Original implementation by Pendry: use a plasmonic material (silver film) to image 10 nm features with hw = 3.48 eV;

$$\boldsymbol{\varepsilon = 5.7 - 9^2/\omega^2 + 0.4i} \quad (= -\varepsilon_h)$$



Near-field super-lens (NFSL)

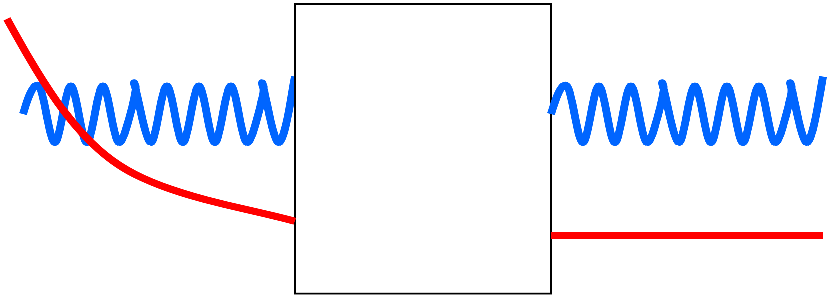
super-resolution with superlens: Zhang et al. (2005); Blaikie, et al (2005)

Mid-IR: Shvets et al. (2006)

Superlens High and Low

Ordinary Lens:

evanescent field lost



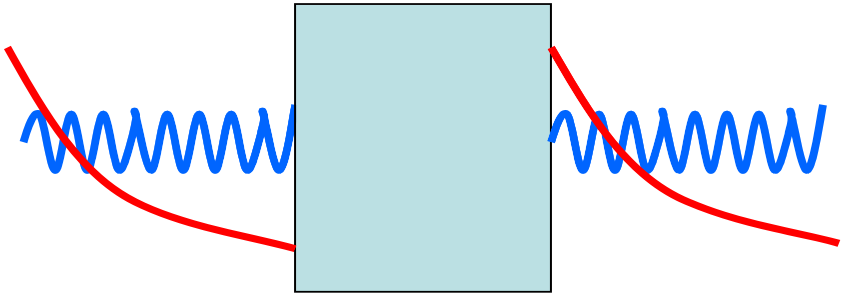
Super Lens:

evanescent field enhanced

but decays away from the lens

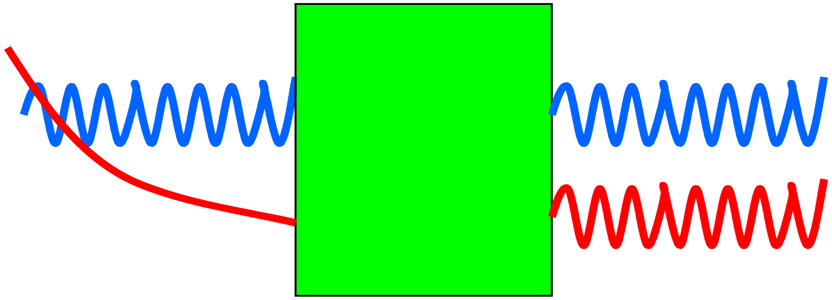
* LIMITED TO NEAR FIELD

* EXPONENTIALLY SENSITIVE TO DISORDER, LOSSES,...



Hyper Lens:

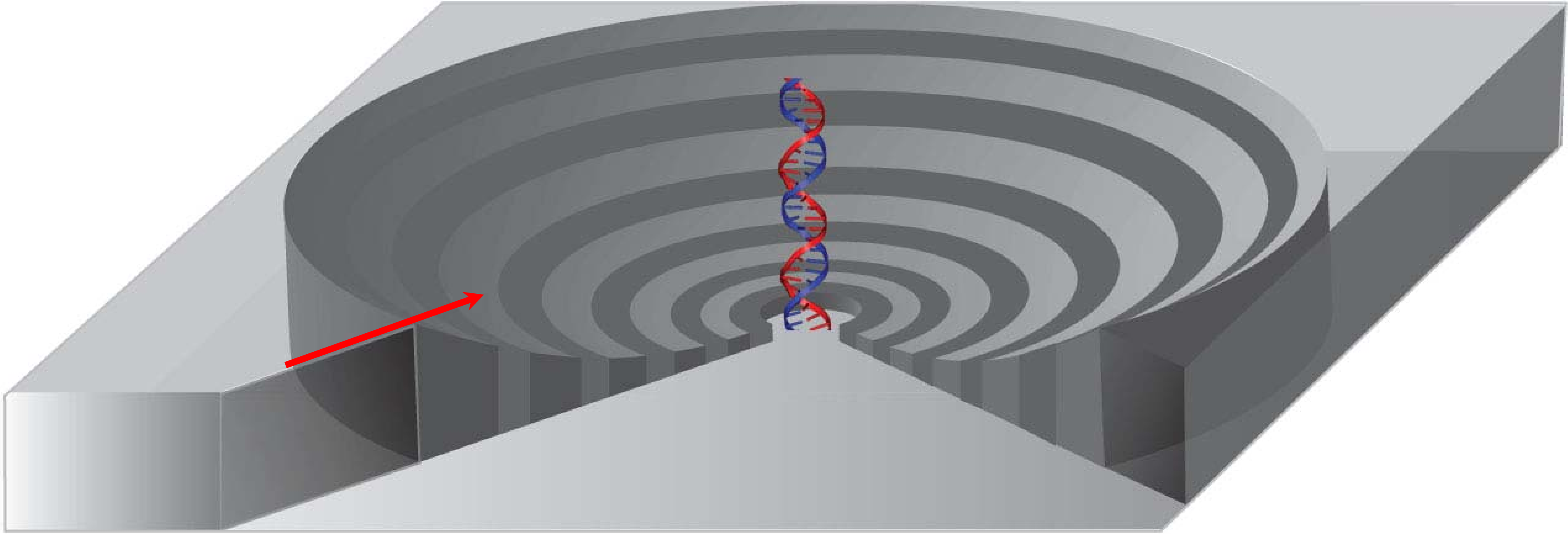
evanescent field converted to propagating waves (that do not mix with the others)



Hyperlens:

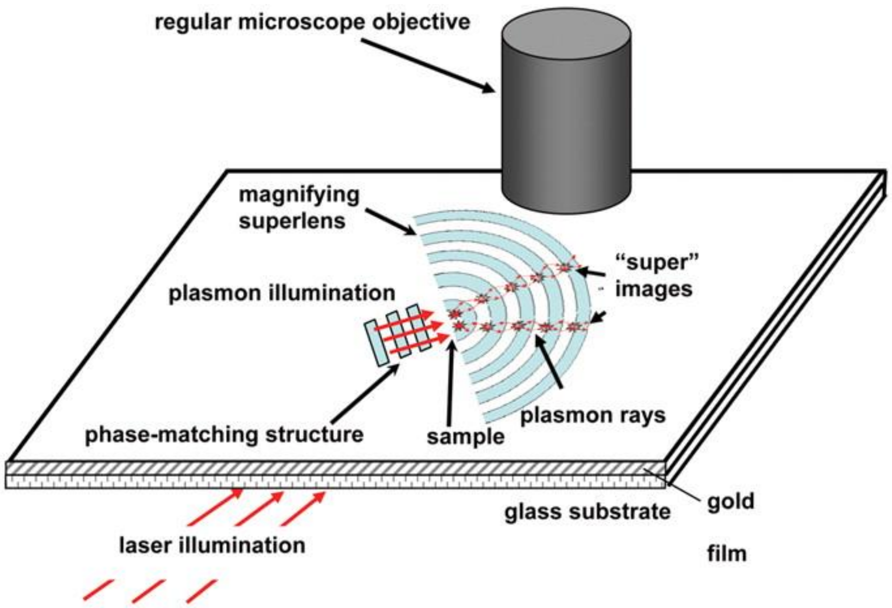
Converting evanescent components to propagating waves

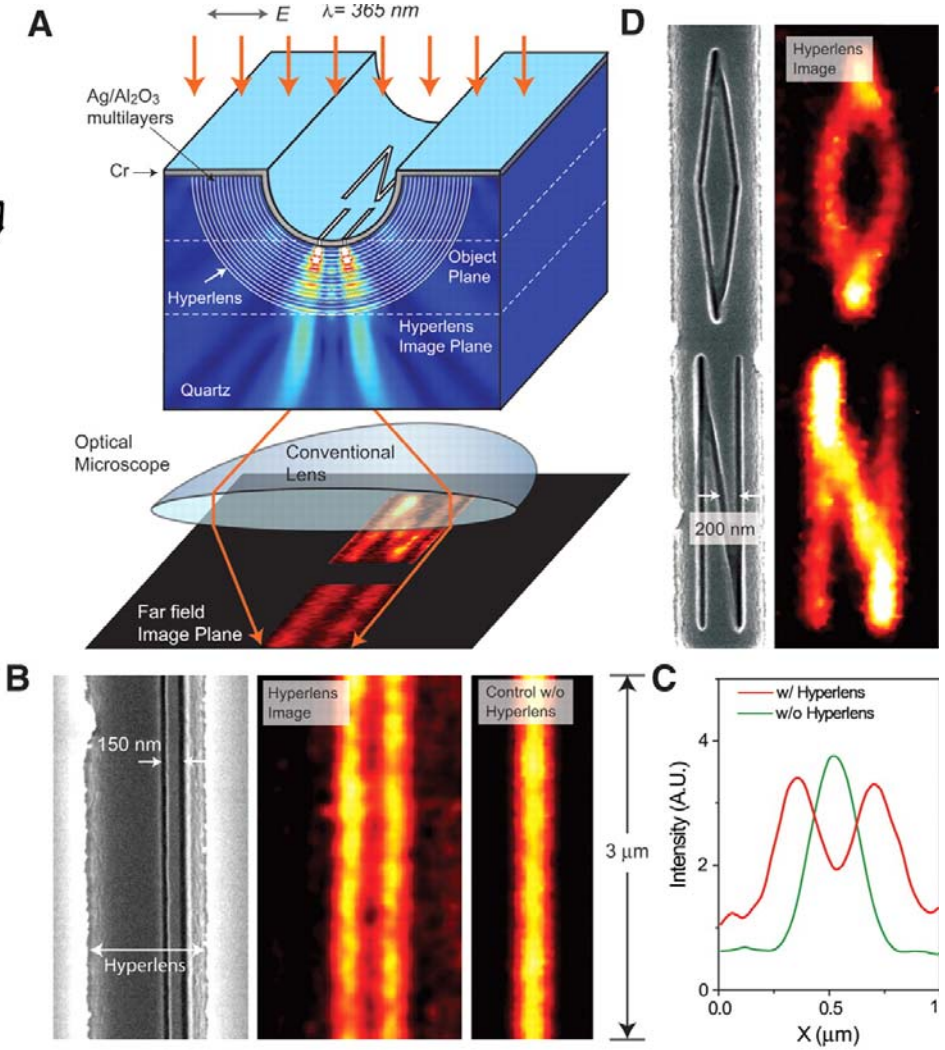
(Narimanov eta al; Engheta et al)



Far-field sub-λ imaging

Optical Hyperlens





Theory:

Jacob, Narimanov, OL, 2006

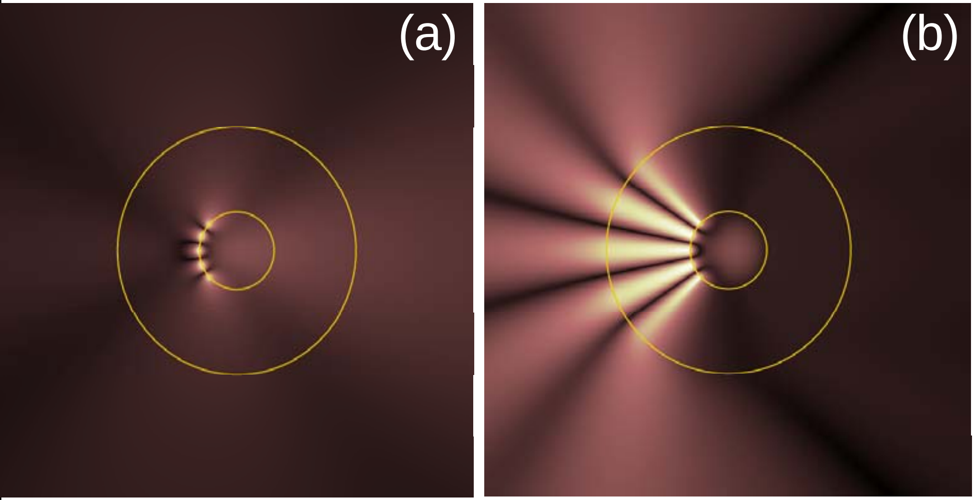
Salandrino, Engehta, PRB, 2006

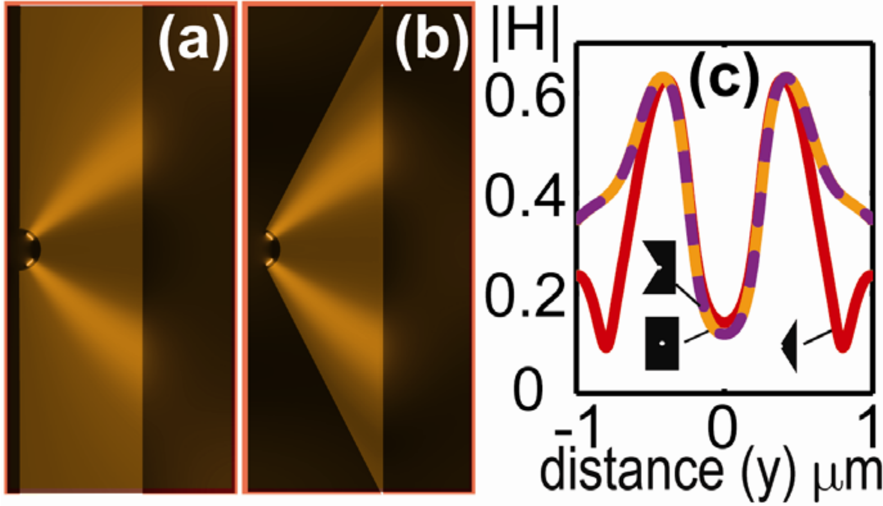
Experiments:

Z. Liu et al., Science, 2007

Smolyaninov et al., Science, 2007

Advanced Optical Hyperlens





Impedance-matched hyperlens

Kildishev, Narimanov
(Opt. Lett., 2007)

Flat hyperlenses:
½- & ‘¼-body lenses

Kildishev, Shalaev
(Opt. Lett., 2008)

Engineering Space for Light with Metamaterials

Part 1: Electrical and Magnetic Metamaterials

Part 2: Negative-Index Metamaterials, NLO, and super/hyper-lens

<u>Part 3: Cloaking and Transformation Optics</u>