Basics of single negative and double negative metamaterials

Ekaterina Shamonina

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DFG

SAOT
erlangen
graduate school in
advanced optical technologies

Contents

- Definition of single negative and double negative media
- Properties and resulting applications
- Common ε-negative and μ-negative media
- How they work

- Example: Near field imaging with silver superlens

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- Near field imaging with magnetic metamaterials
  (Anna Radkovskaya's lecture)

What are metamaterials?

μετά = beyond (Greek)

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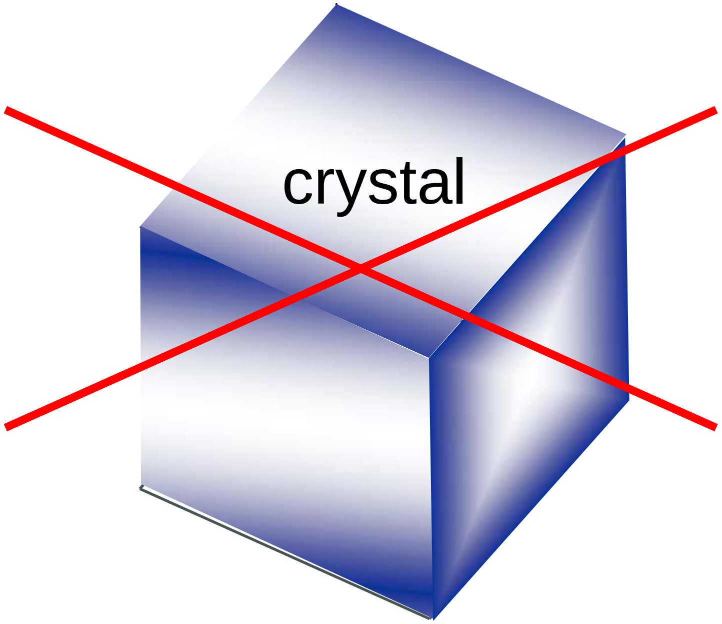
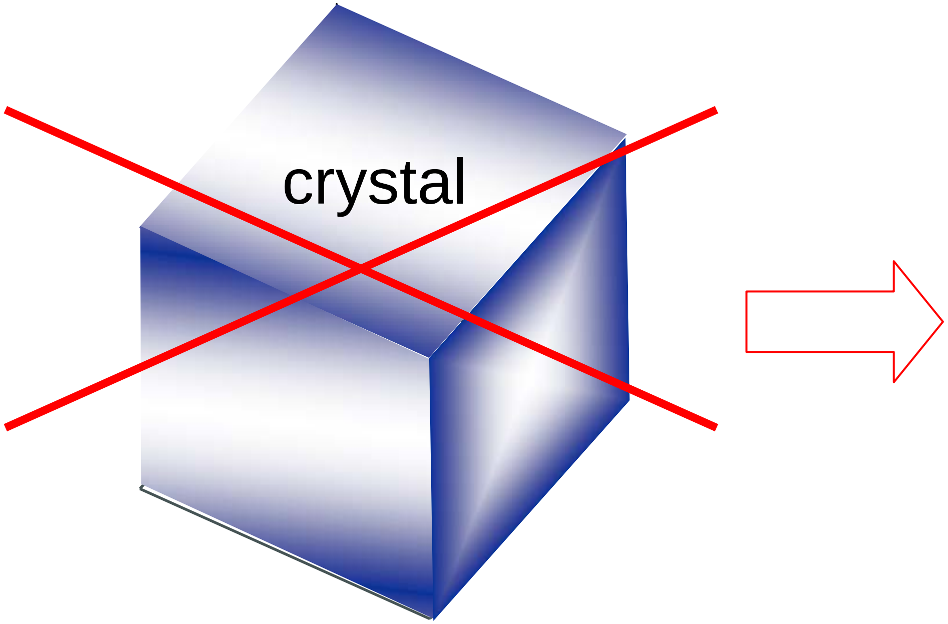
Metamaterials are not natural materials

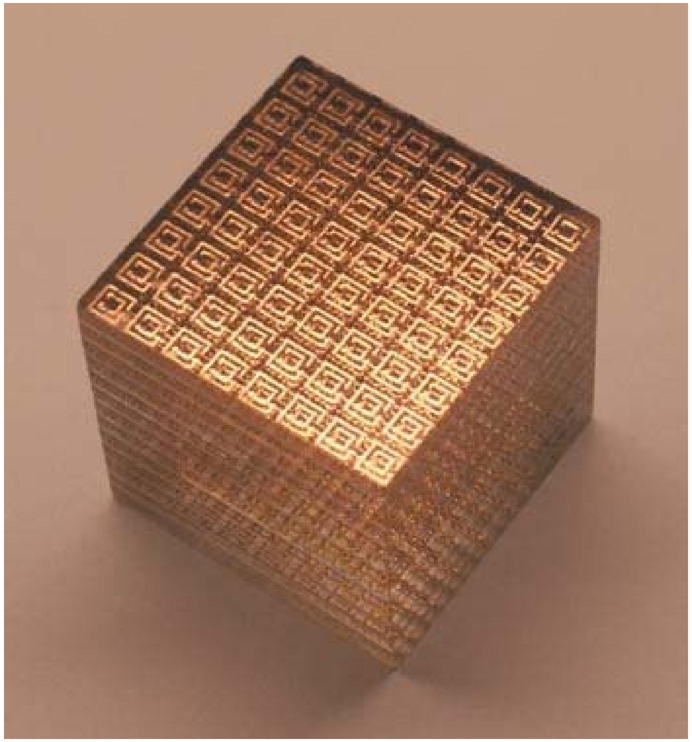


What are metamaterials?

μετά = beyond (Greek)

Metamaterials are engineered composites



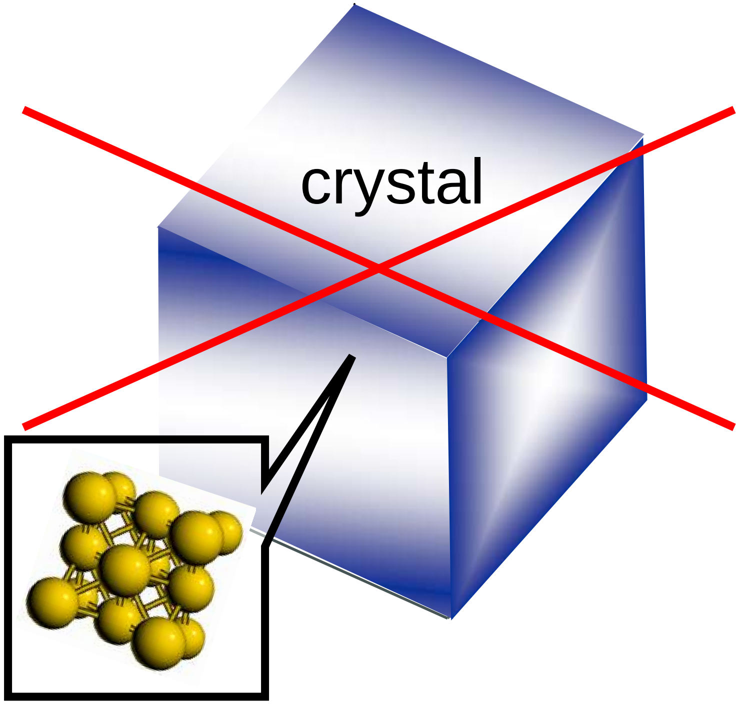


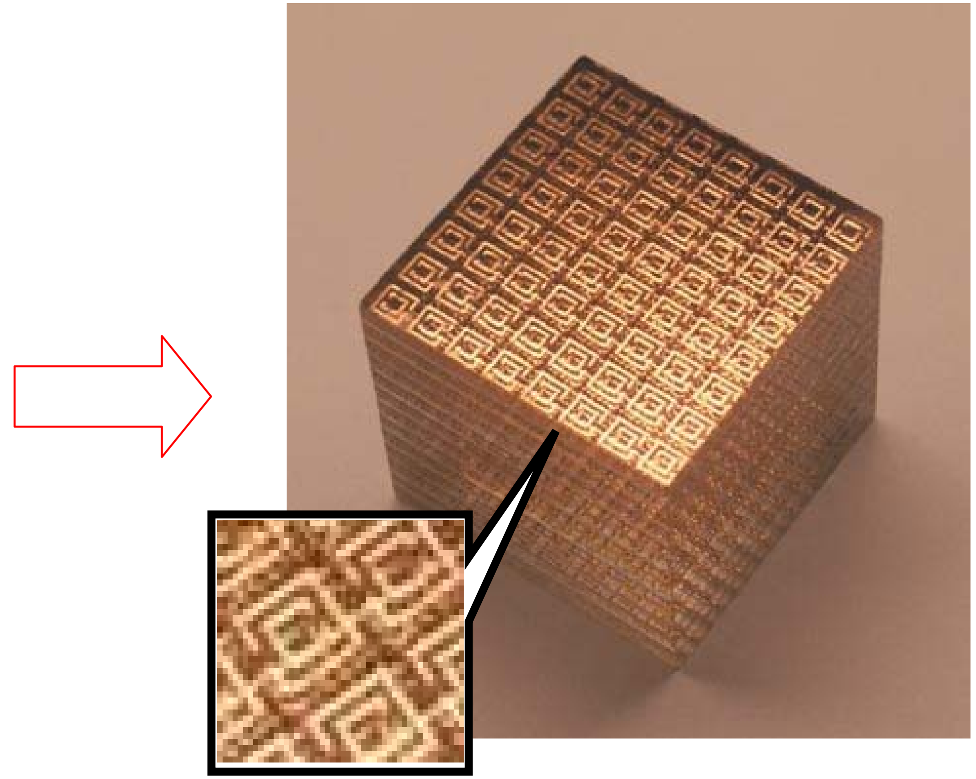
http://physicsweb.org/articles/world/16/5/3/1#pwpia2_05-03

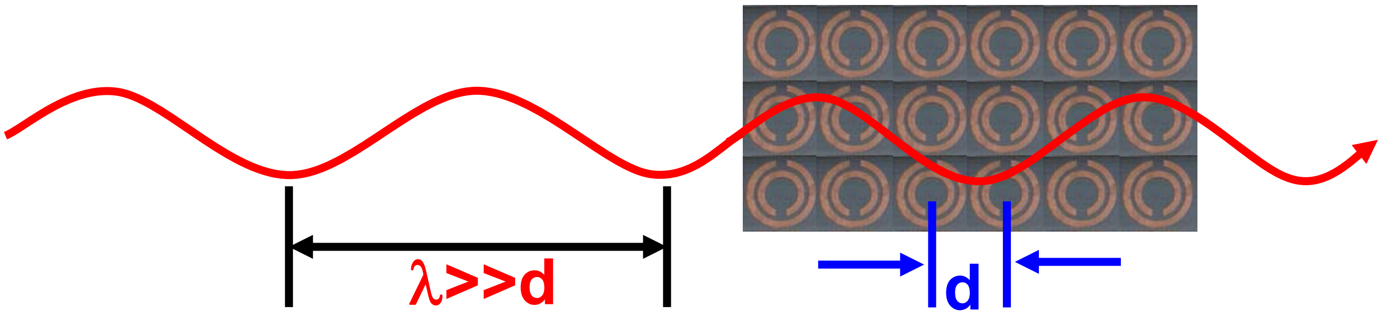
What are metamaterials?

μετά = beyond (Greek)

Metamaterials are engineered composites that exhibit superior properties not found in nature and not observed in the constituent materials.



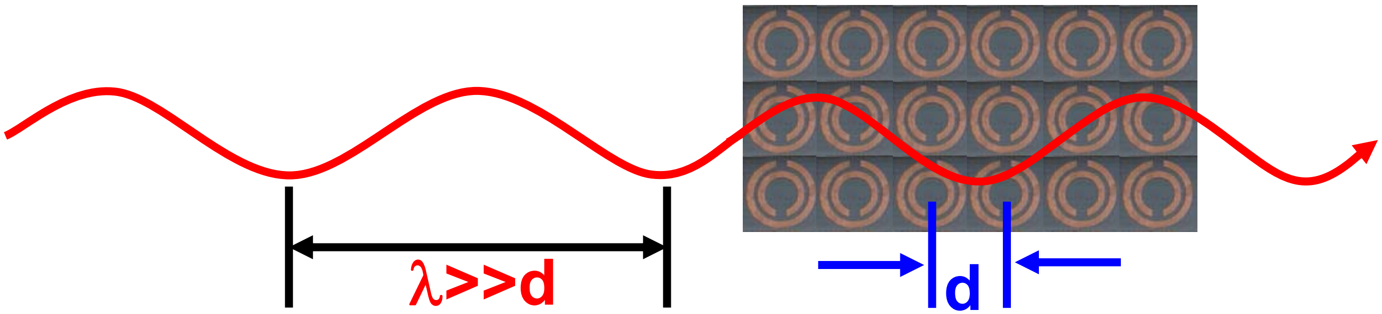




What is a metamaterial?

Metamaterial is an artificial material in which electromagnetic properties **(ε,μ)** can be **controlled.**

It is made up of periodic arrays of metallic **resonant** elements. Both the size of the element and the unit cell are **small** relative to the wavelength.



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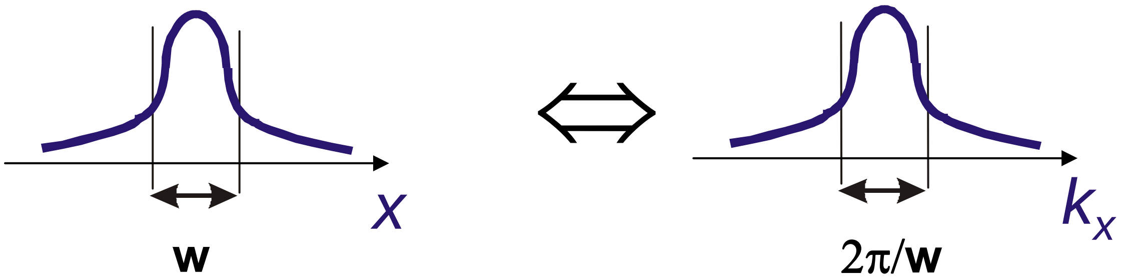
Why is it important?

Because it makes possible the **manipulation** of fields and waves at a **subwavelength** scale.

Near field: evanescent waves

An object of width w can be represented in terms of Fourier components up to $k_x = \frac{2\pi}{w}$



NEAR FIELD IMAGING REQUIREMENT:

Transfer Function $T(k_x)=1$ for all Fourier components!

Near field: evanescent waves

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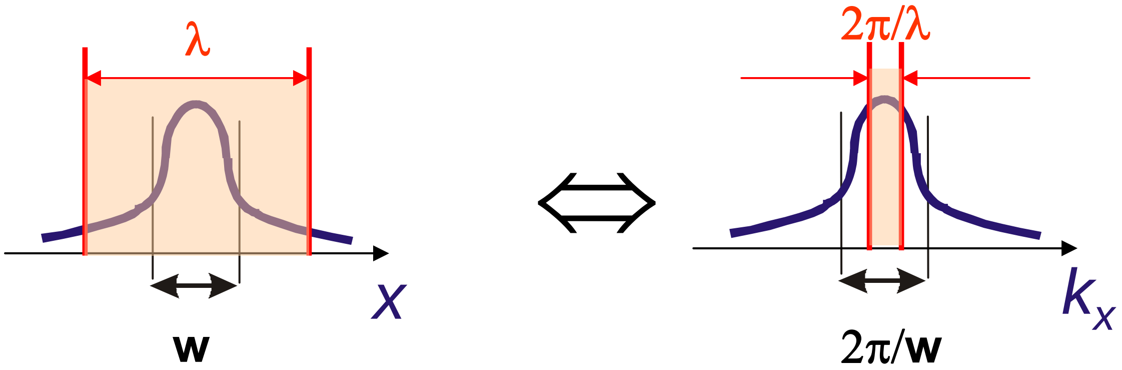

If $w < \lambda$ $k_x > k = \frac{2\pi}{\lambda}$ wave is evanescent:

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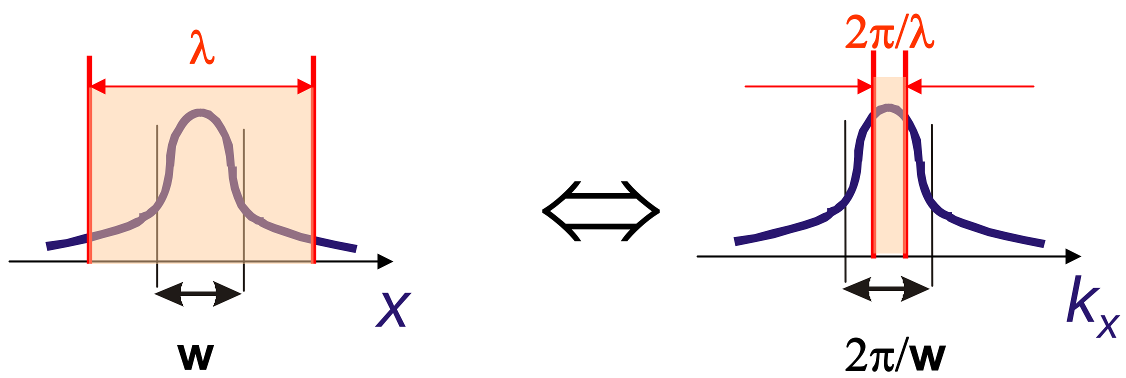
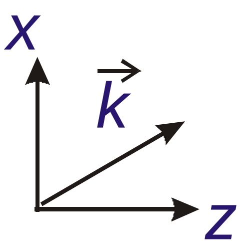


If $w < \lambda$ $\quad k_x > k = \frac{2\pi}{\lambda}$ wave is evanescent:

Wave with $\vec{k} = (k_x, k_z)$.

Wave $\exp[-j\vec{k}\cdot\vec{r}] = \exp\left[-j(k_z z + k_x x)\right]$

$\left|\vec{k}\right| = \sqrt{k_z^2 + k_x^2}$ so that $k_z = \sqrt{k^2 - k_x^2} = \sqrt{\omega^2 \mu\varepsilon - k_x^2}$



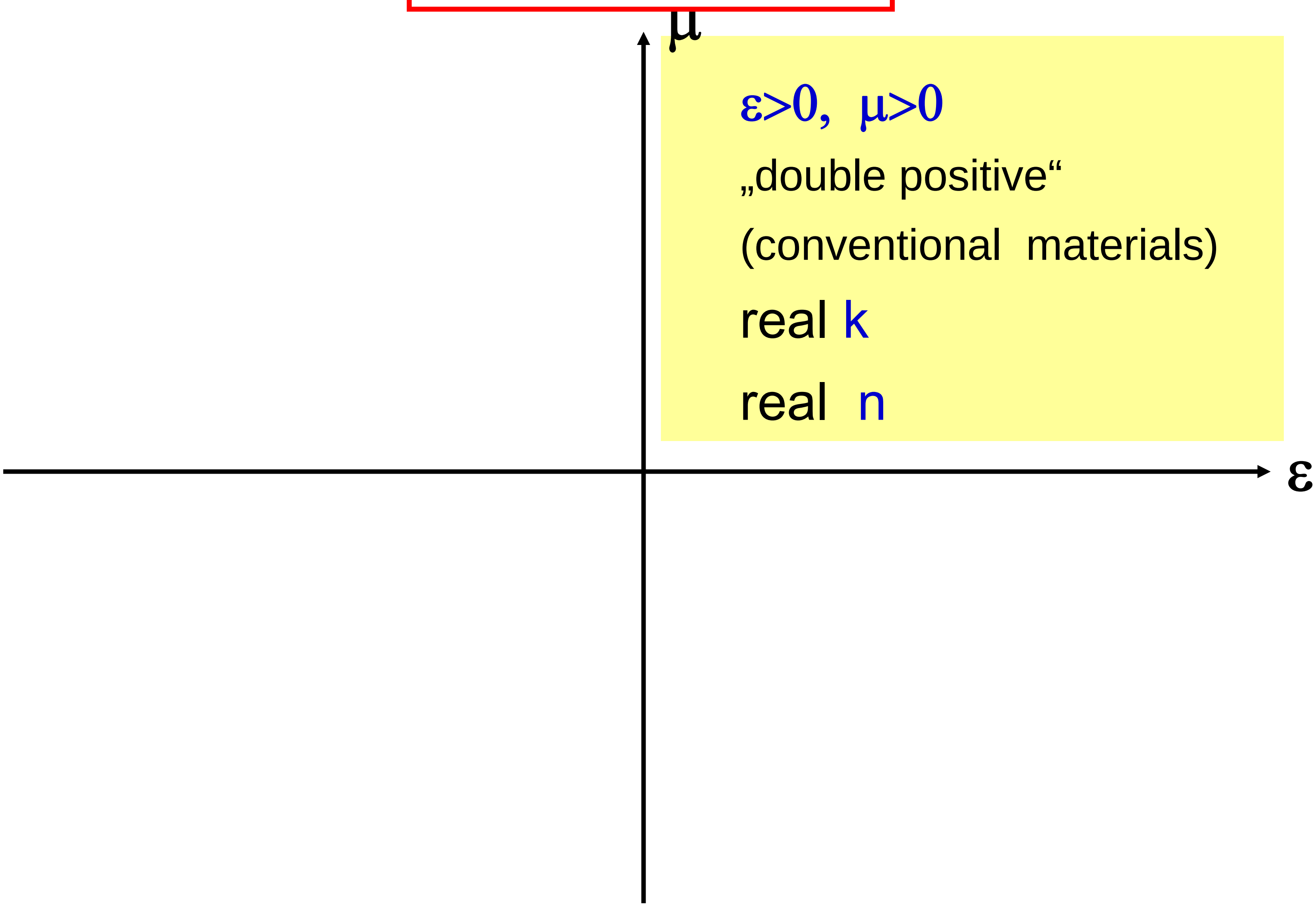
If $k_x > k = \frac{2\pi}{\lambda} = \frac{\omega}{v} = \omega\sqrt{\mu\varepsilon}$ then k_z is imaginary and the wave is evanescent.

NEAR FIELD IMAGING REQUIREMENT:

Transfer Function *$T(k_x)=1$* for all Fourier components!

Definition of single negative and double negative media

$$k = \pm\frac{\omega}{c}\sqrt{\varepsilon\mu}, \qquad n = \pm\sqrt{\varepsilon\mu}$$



Definition of single negative and double negative media

$$k = \pm\frac{\omega}{c}\sqrt{\varepsilon\mu}, \qquad n = \pm\sqrt{\varepsilon\mu}$$

μ

ε<0, μ>0

„single negative“

(plasmas, rod MM)

complex k

complex n

ε>0, μ>0

„double positive“

(conventional materials)

real k

real n

ε

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(ferrites, ring MM)

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Definition of single negative and double negative media

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μ

$\varepsilon<0,\ \mu>0$ „single negative“ (plasmas, rod MM) complex k complex n	$\varepsilon>0,\ \mu>0$ „double positive“ (conventional materials) real k real n
$\varepsilon<0,\ \mu<0$ „double negative“ (ring-rod MM) real k real n	$\varepsilon>0,\ \mu<0$ „single negative“ (ferrites, ring MM) complex k complex n

ε

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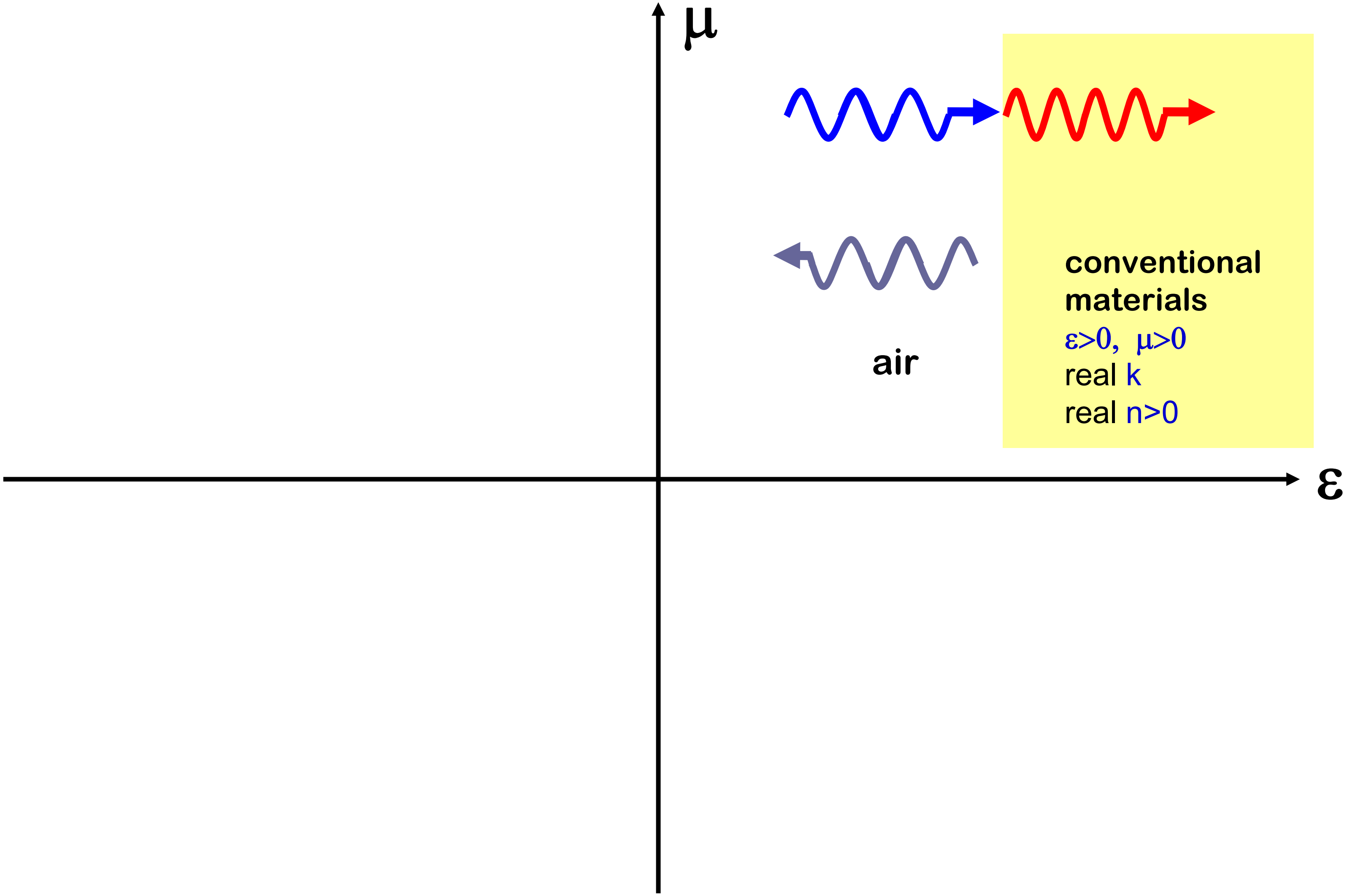

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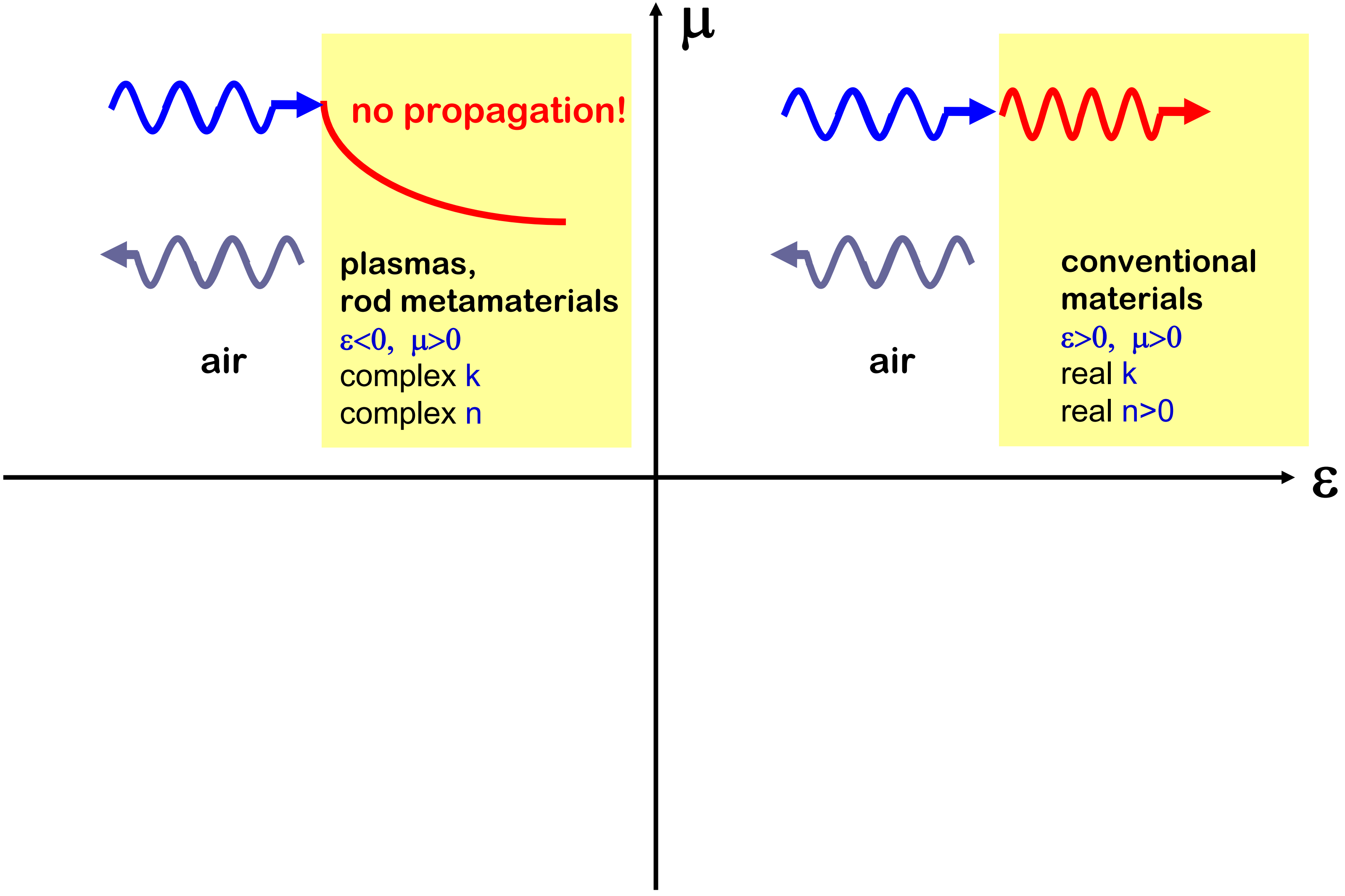

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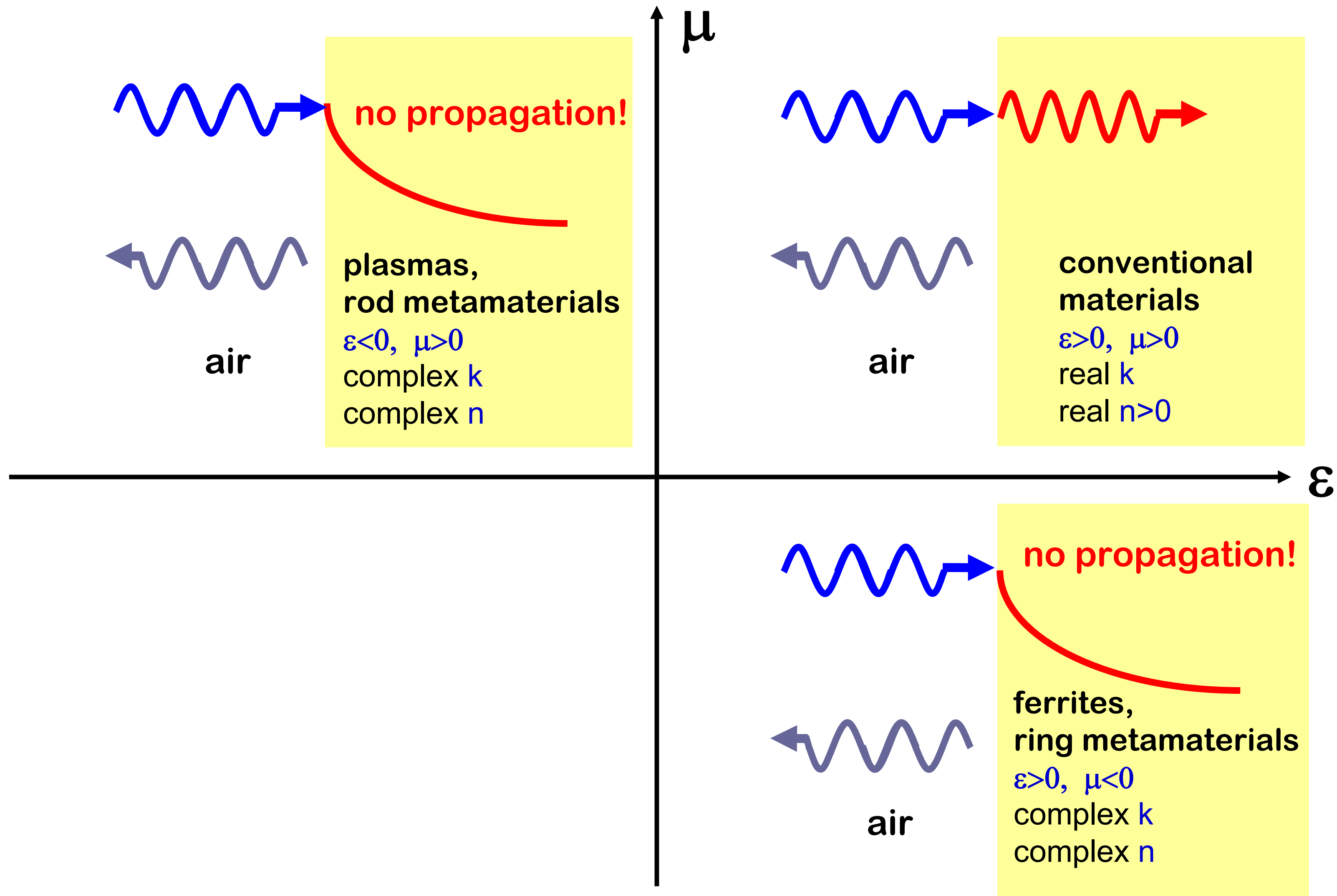

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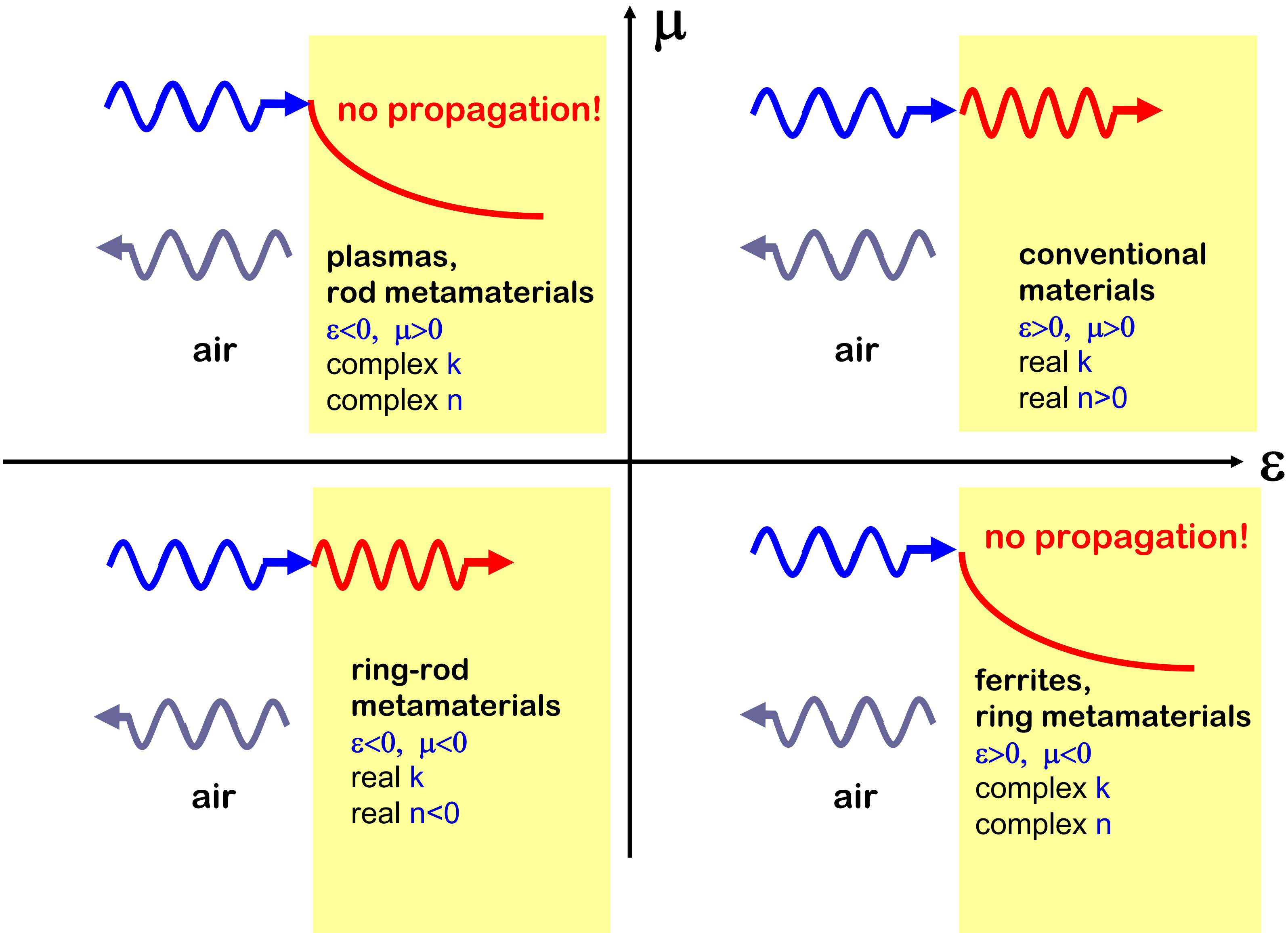

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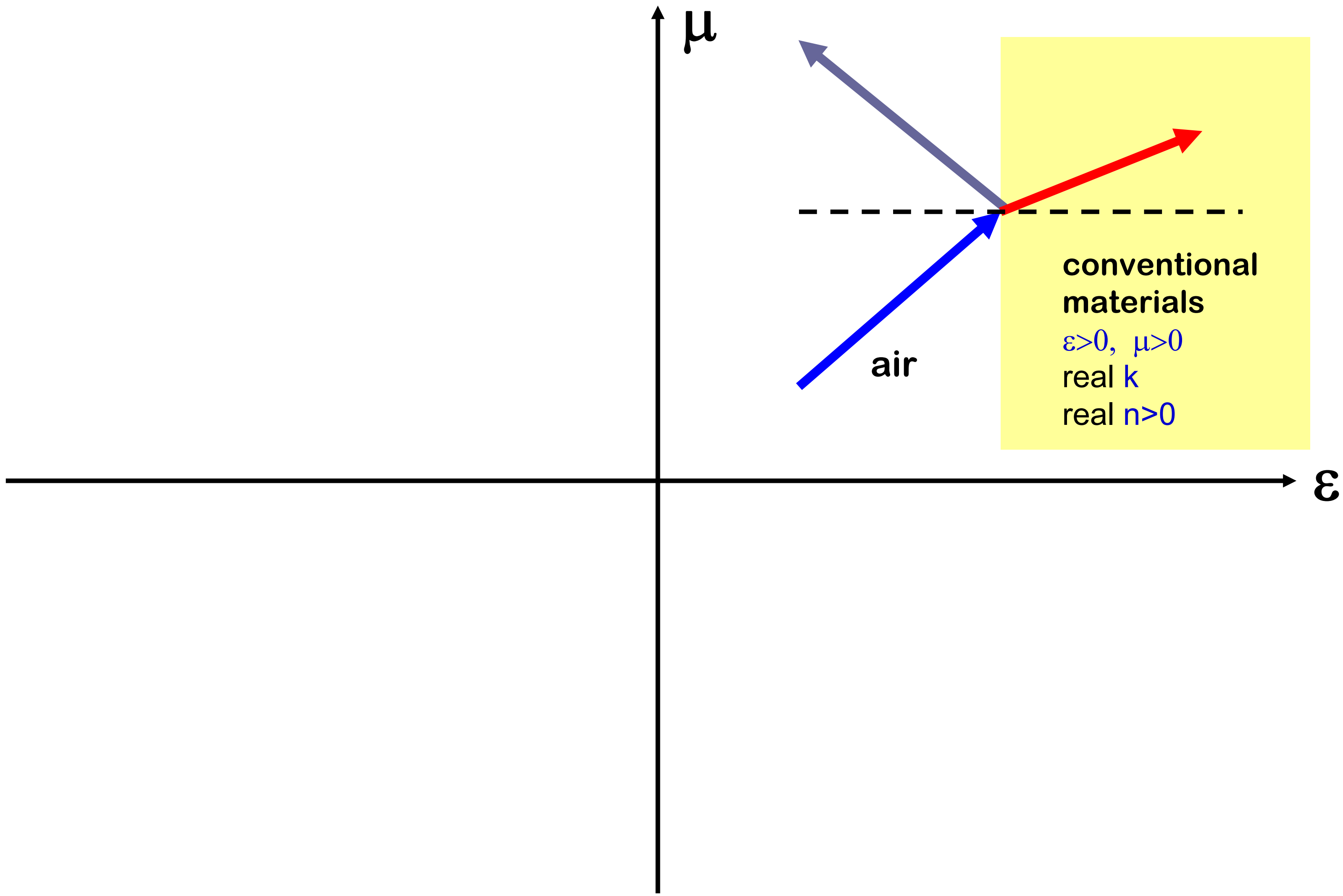

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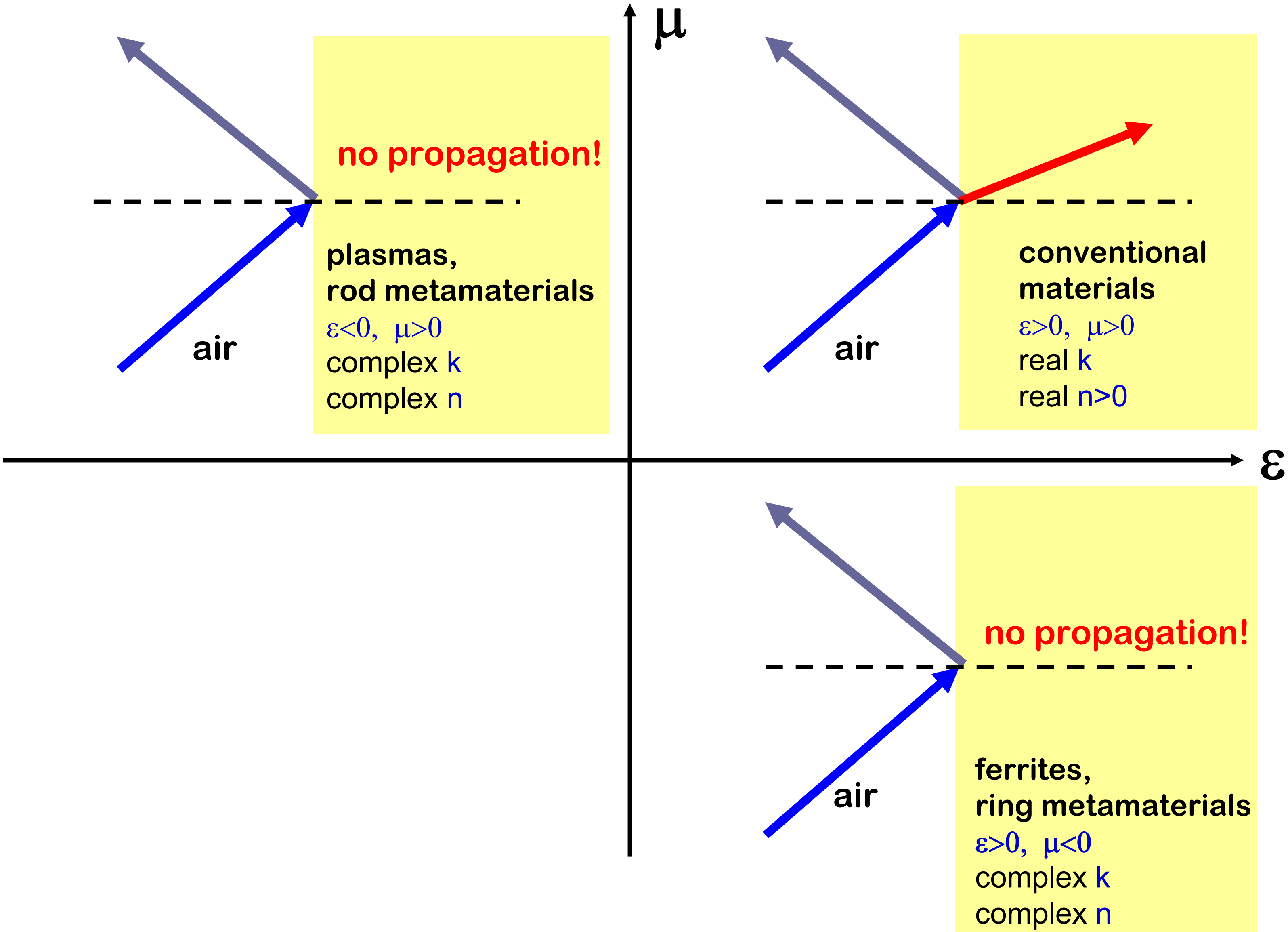

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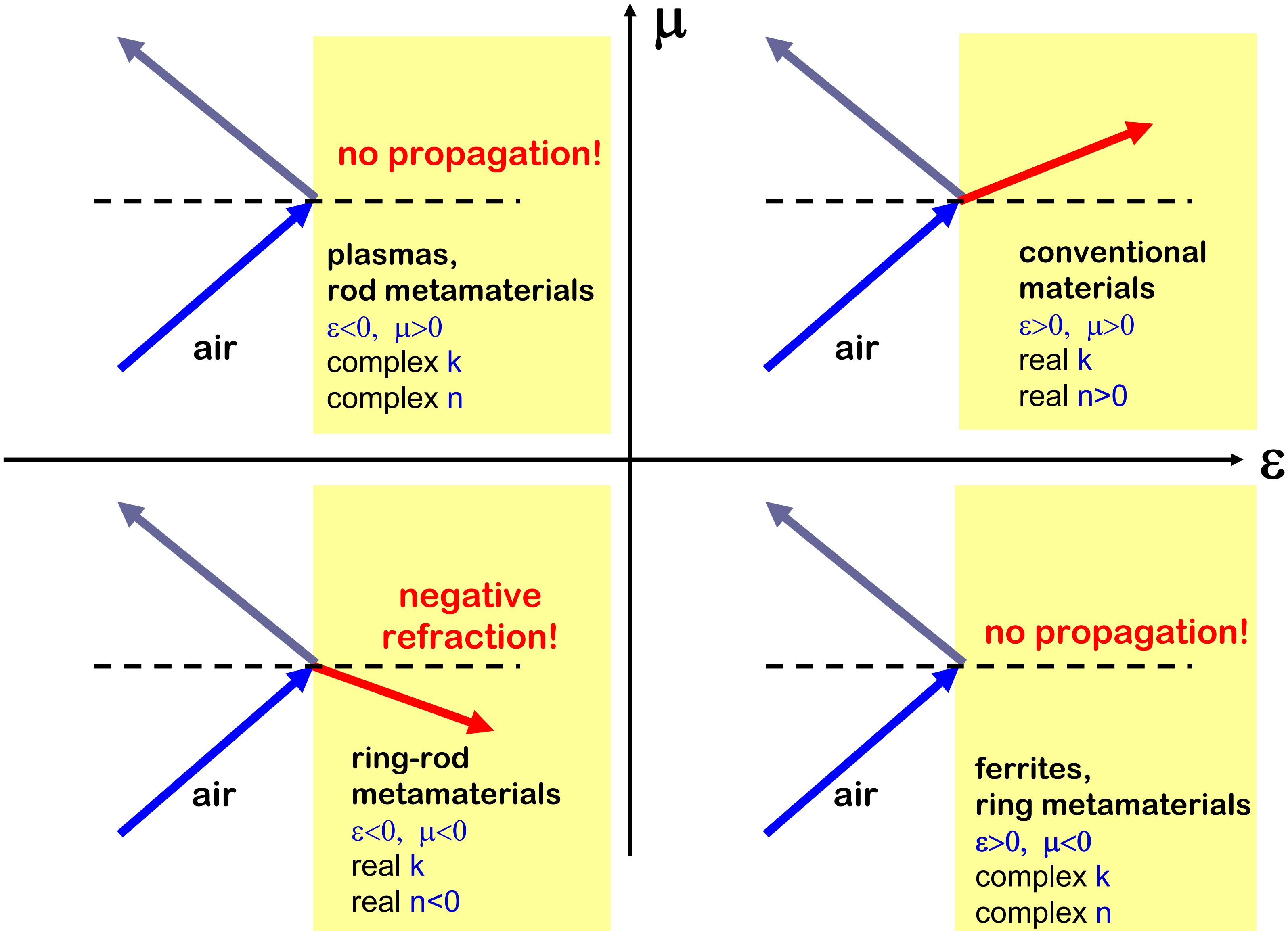
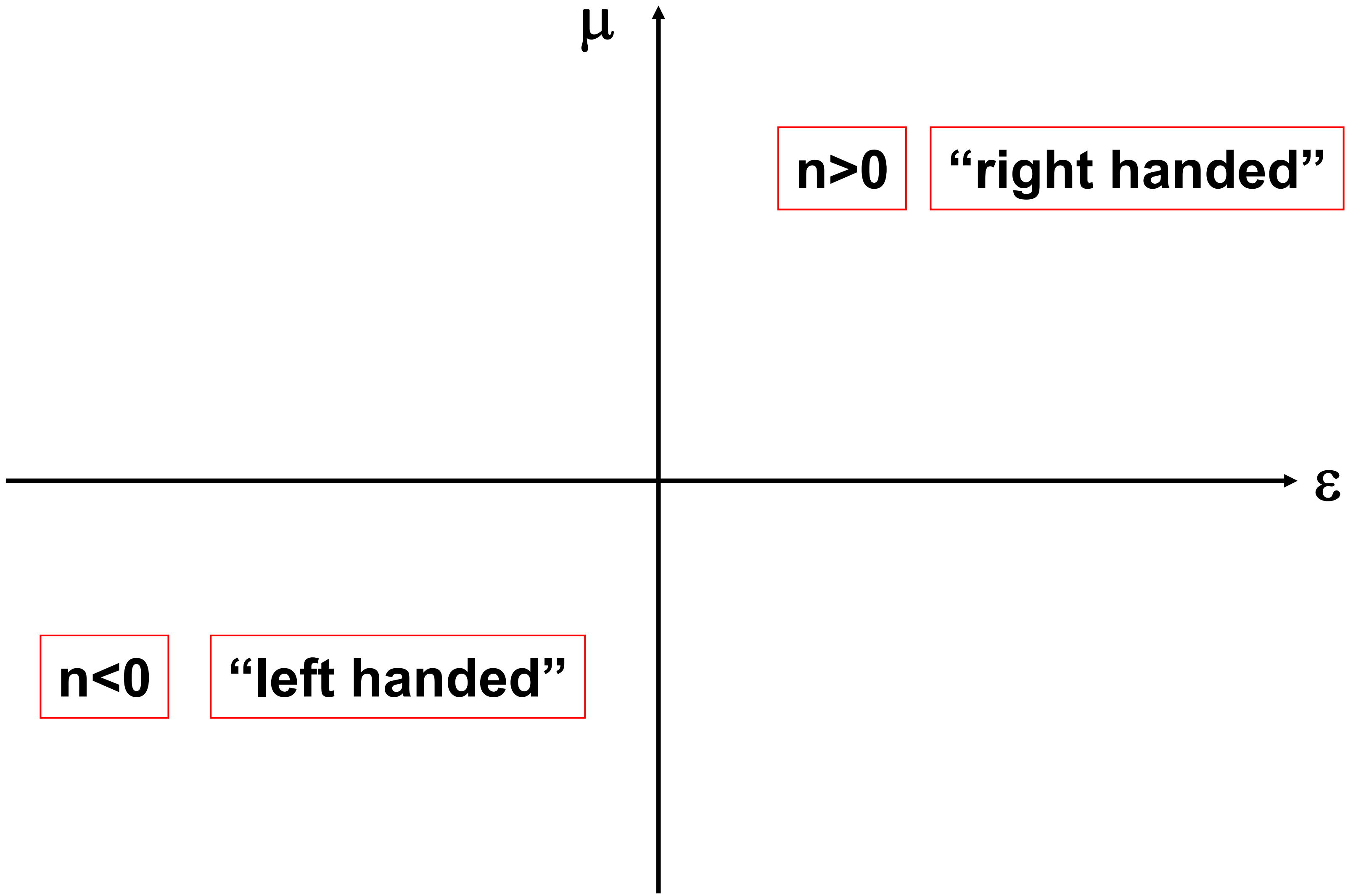


Double negative media

Various names, the same physics

- Double Negative Medium DNM
- Veselago Medium
- Negative Refractive Index Medium NRIM
- Negative Index Medium NIM
- Left-Handed Medium LHM
- Backward Wave Medium BWM

Double negative media: why “left-handed”?



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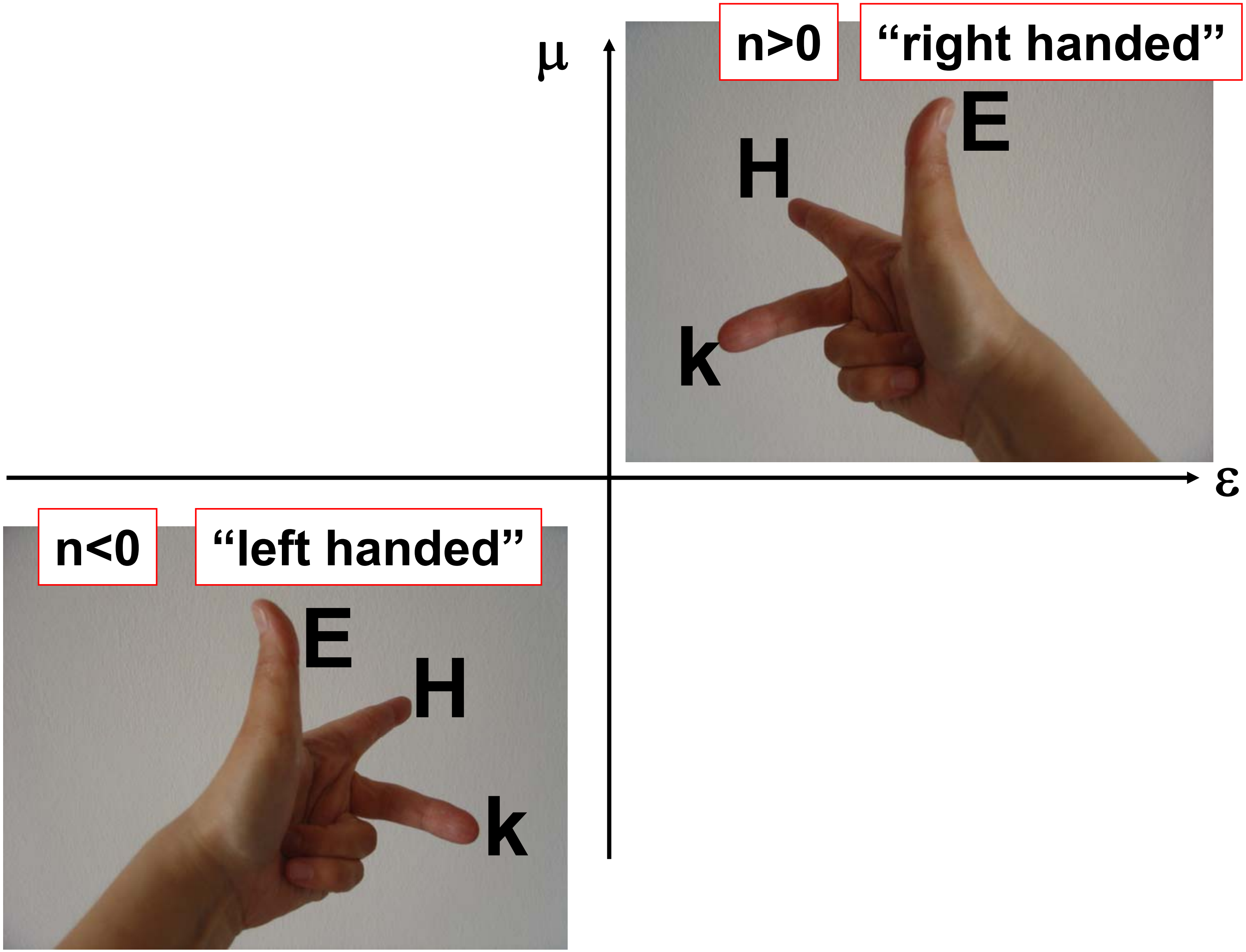
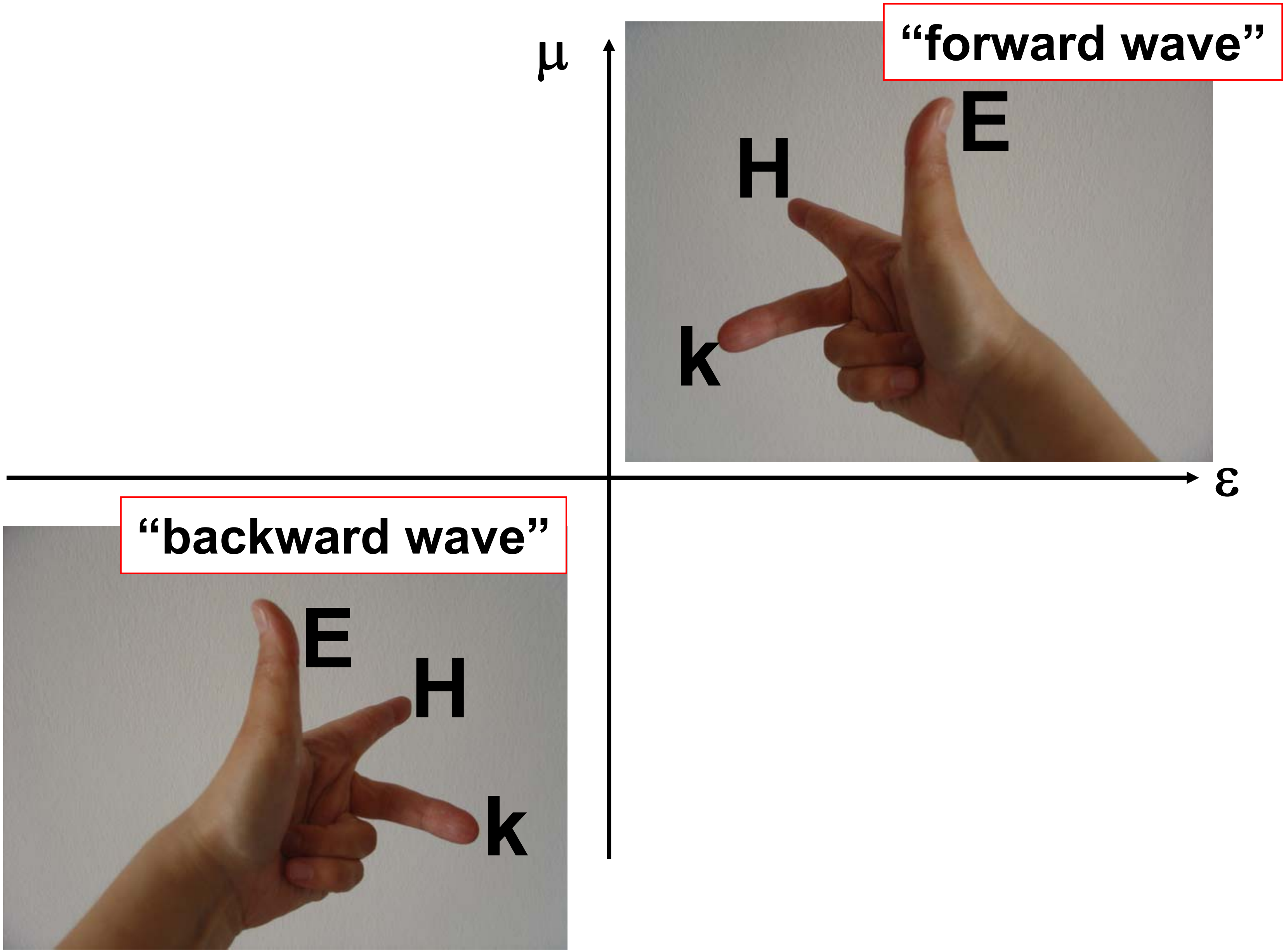


Double negative media: why “backward wave media”?



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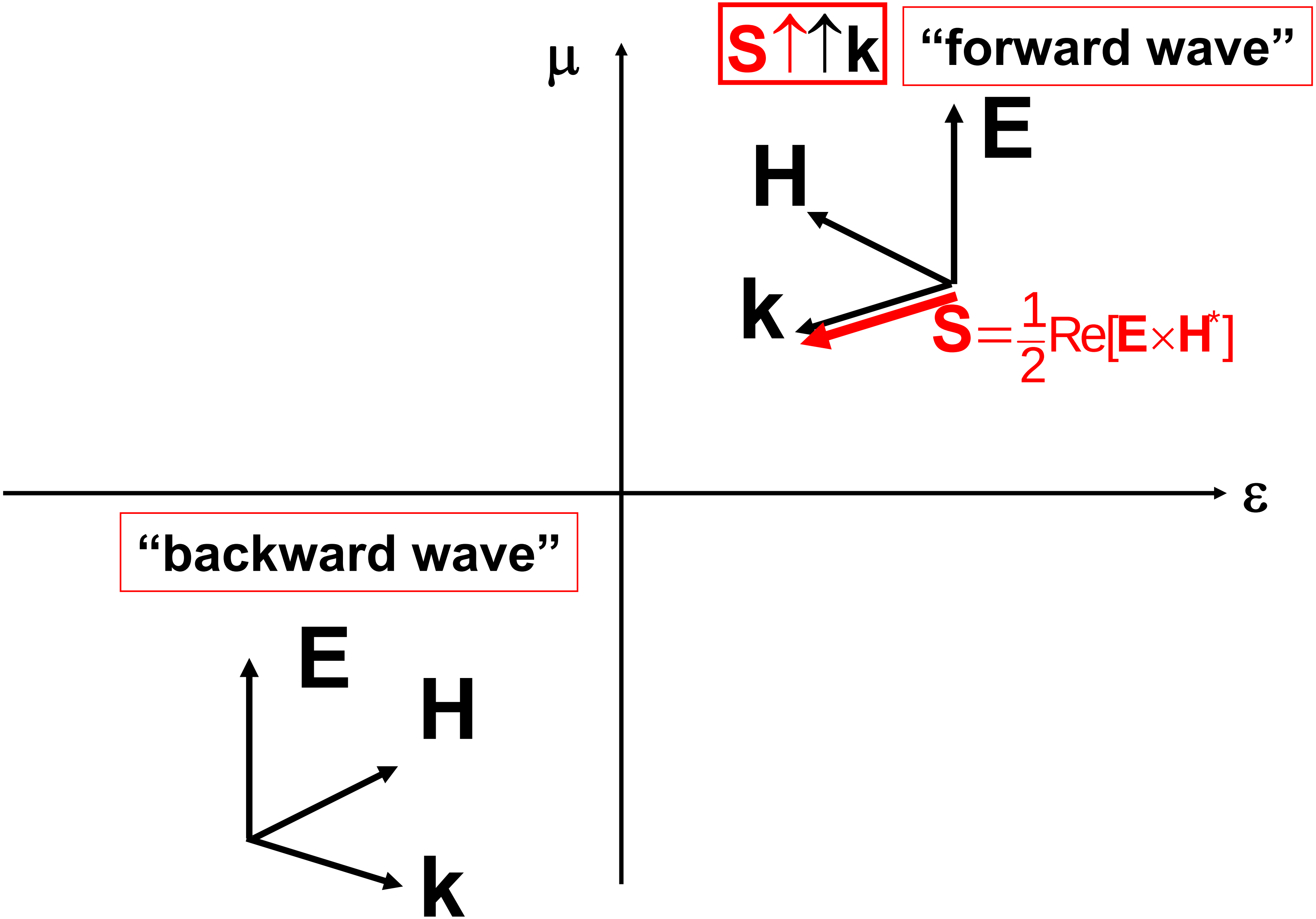

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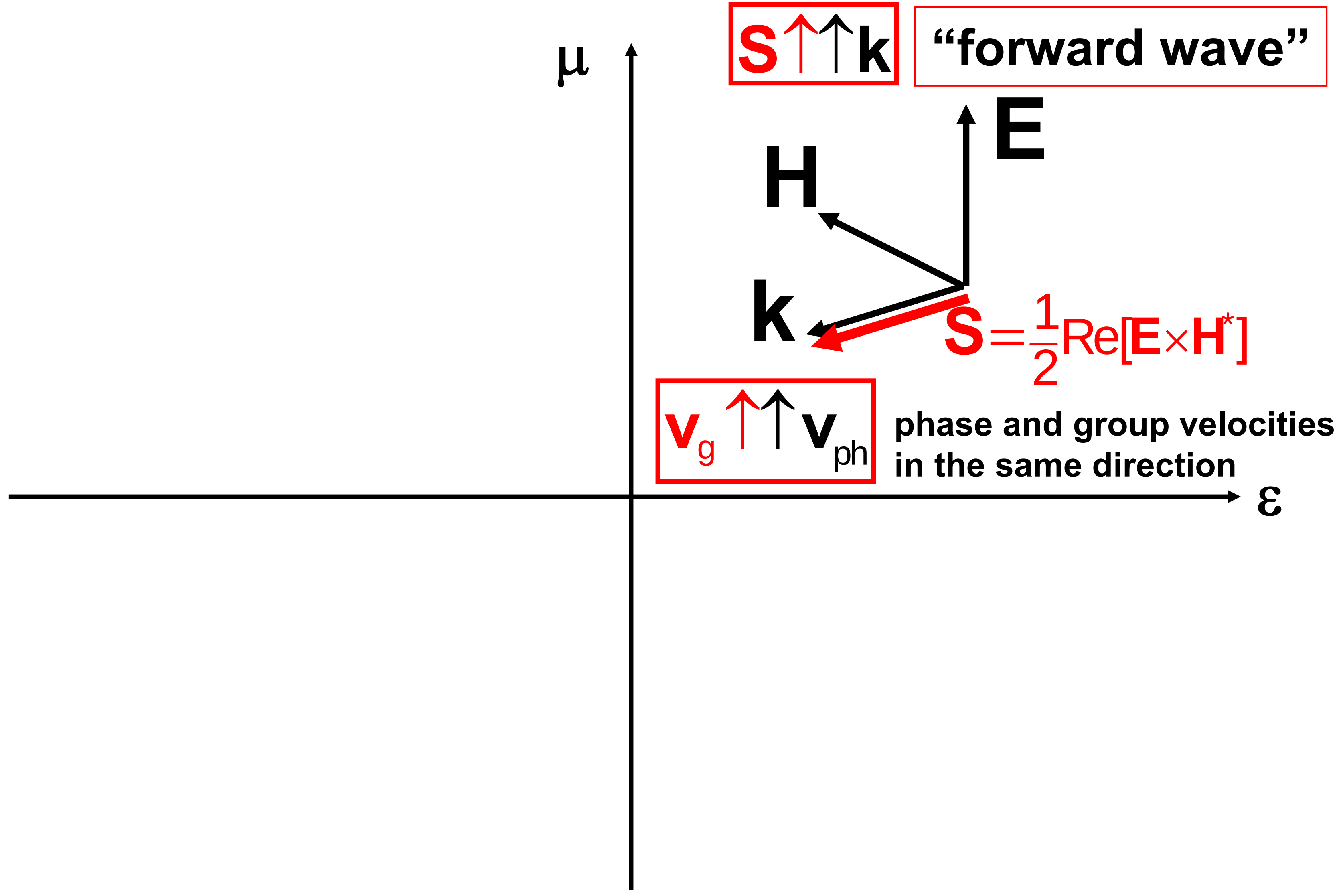

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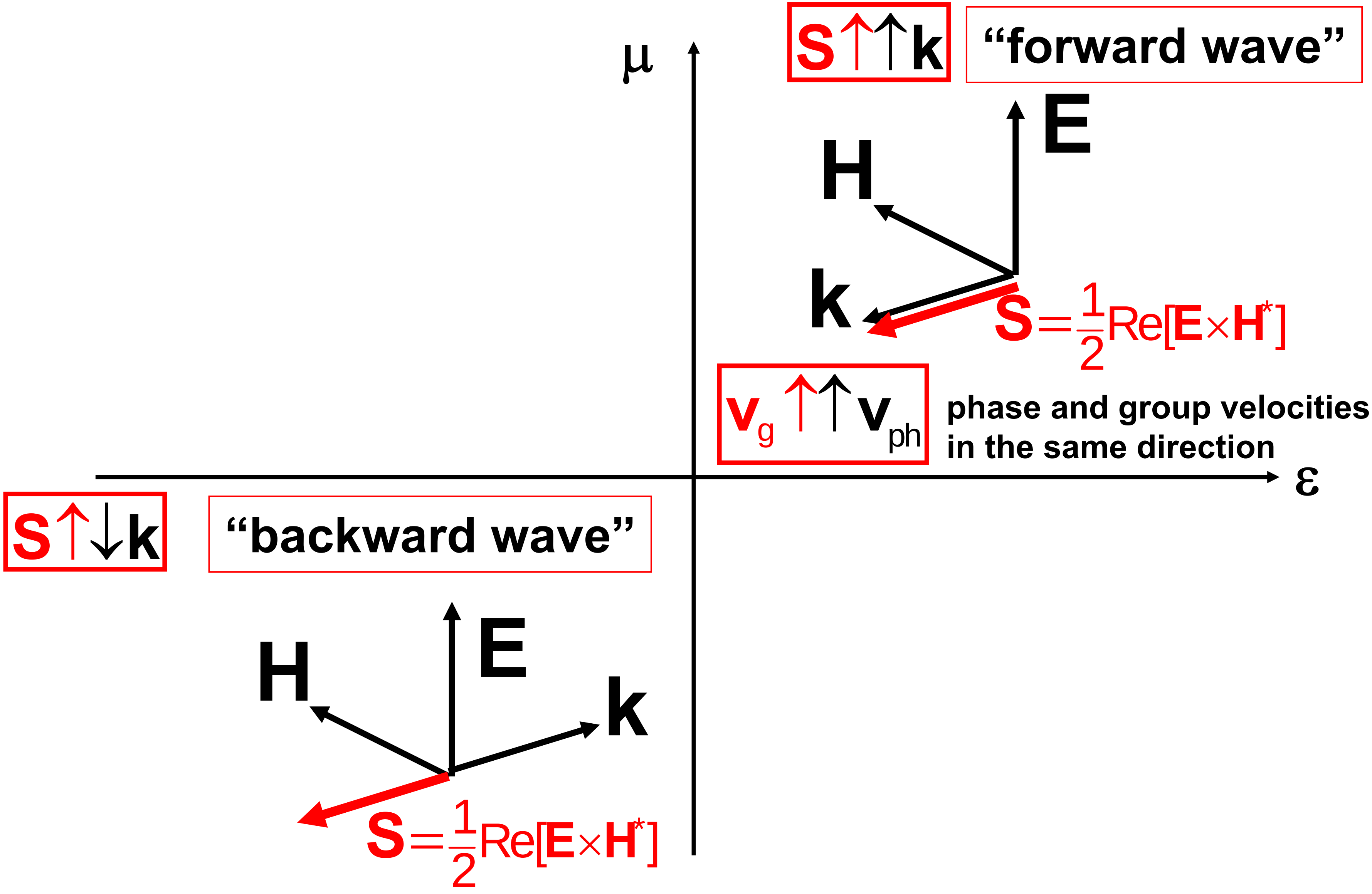

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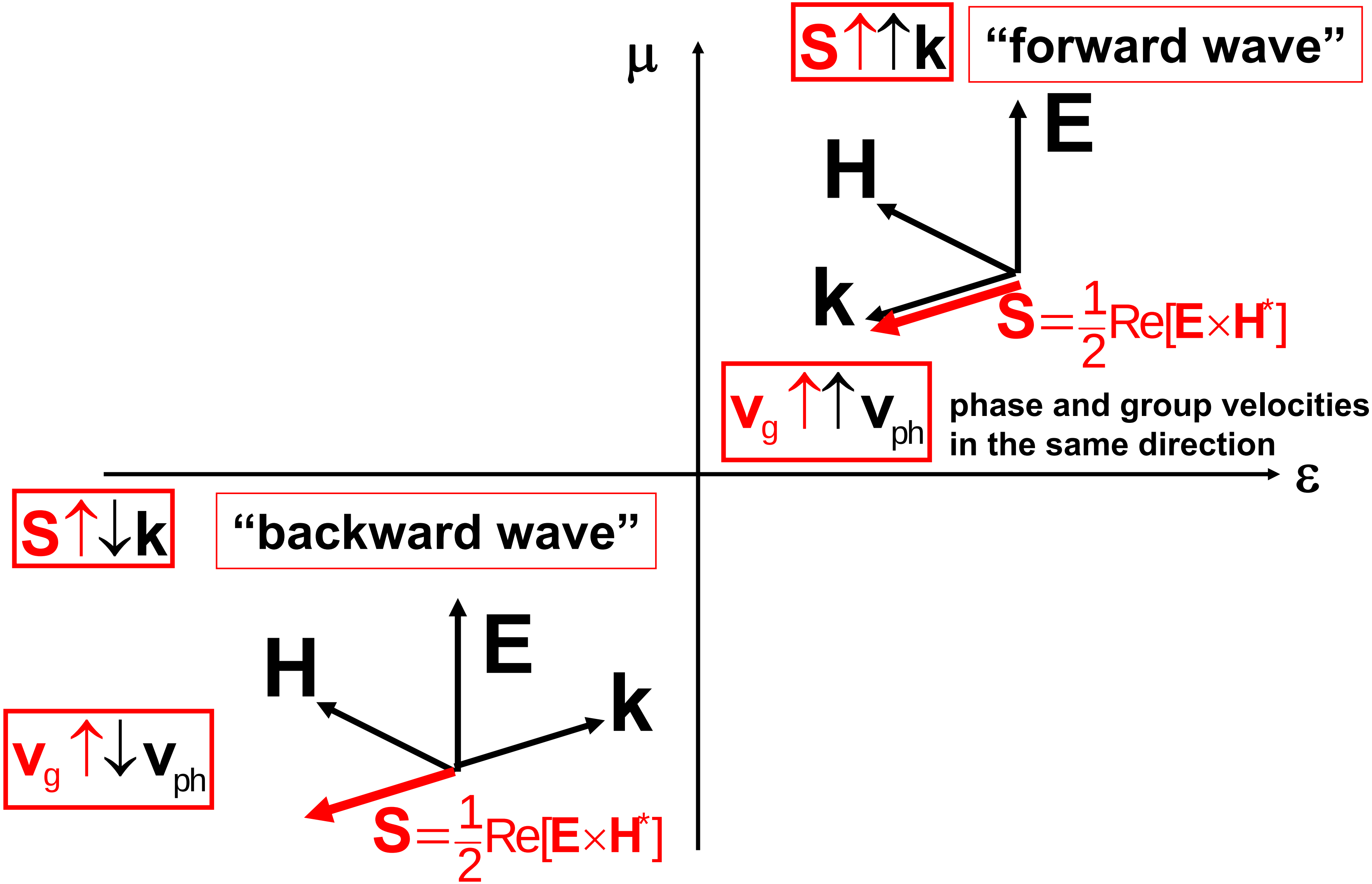
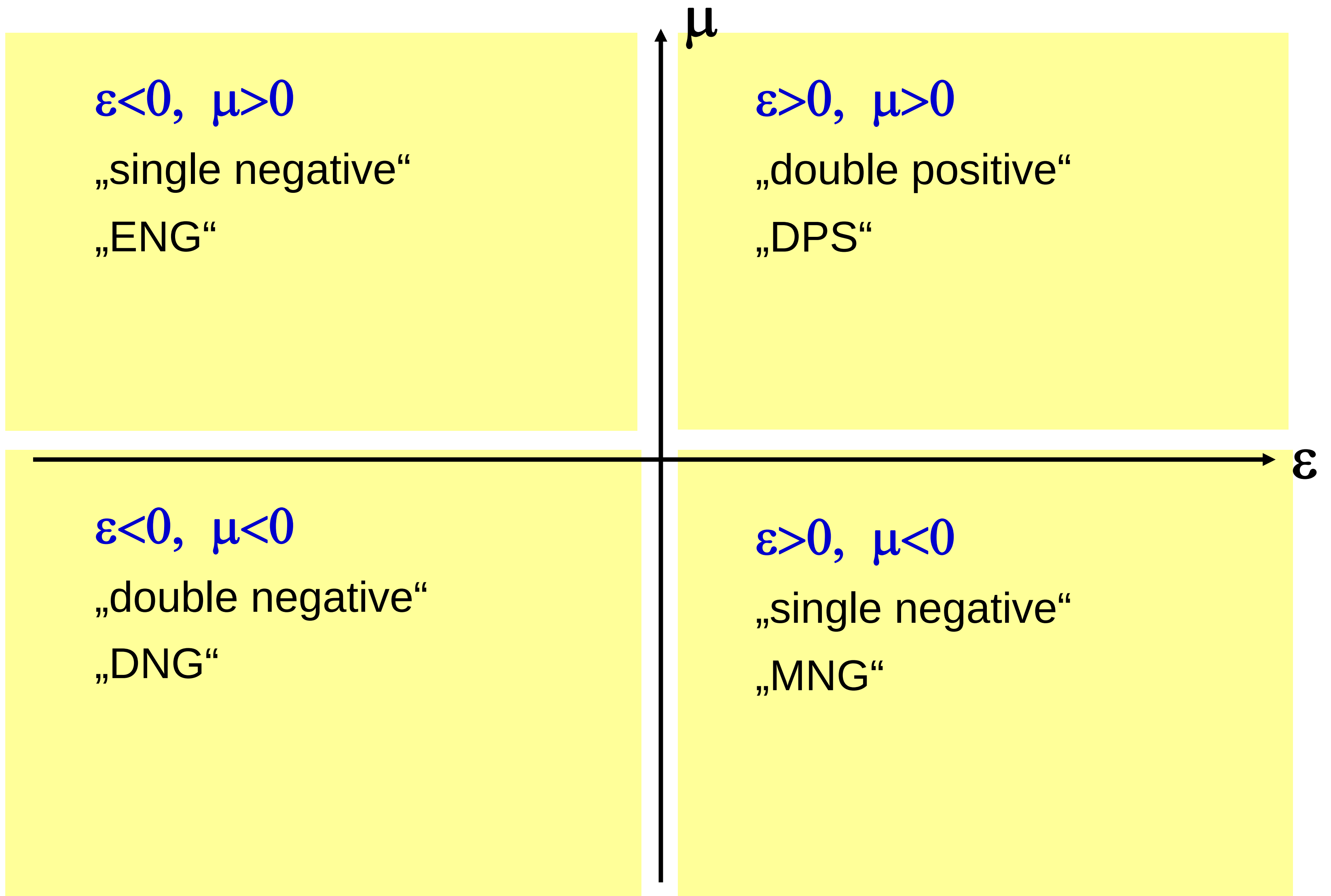


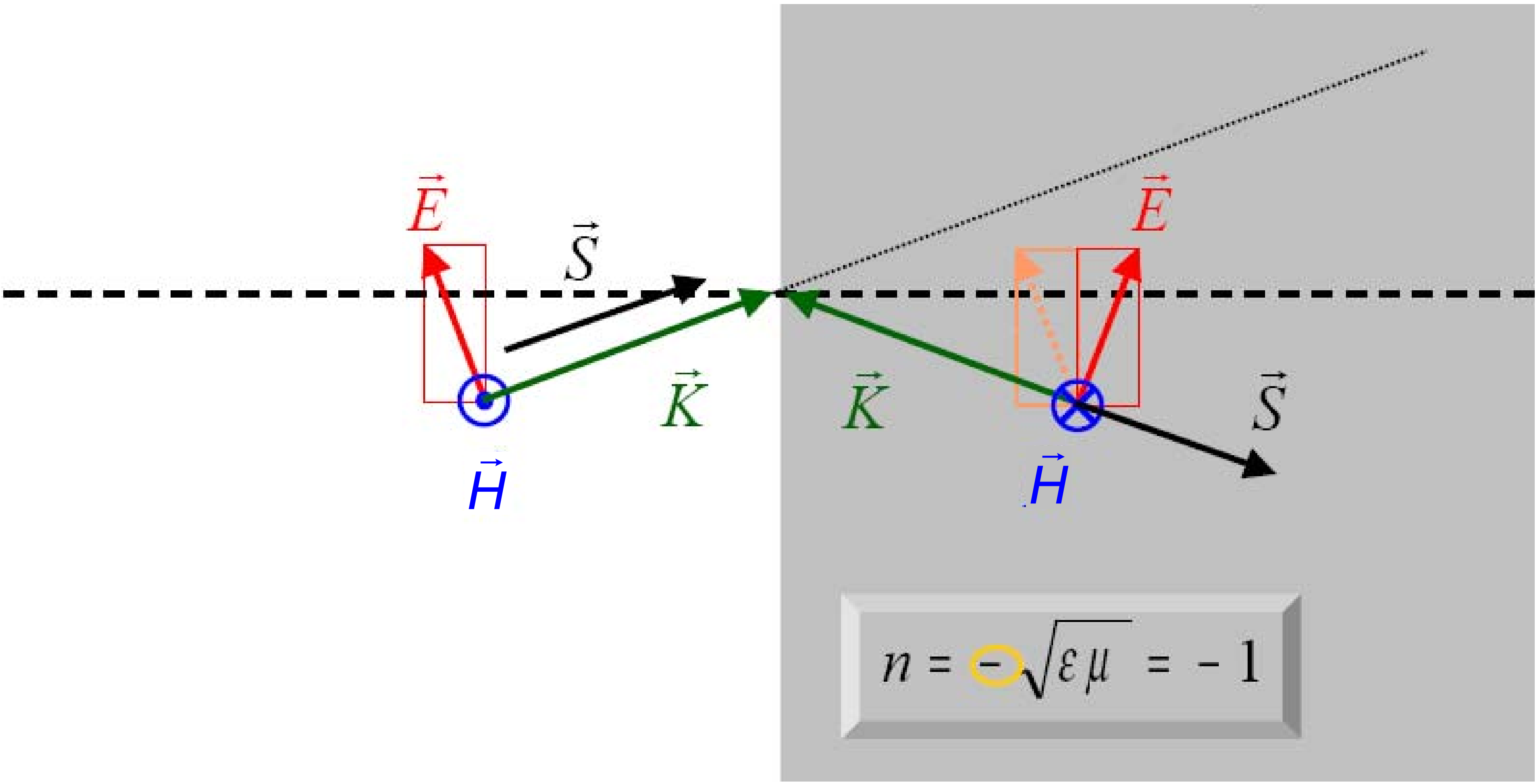
opposite phase and group velocities

More on terminology for single/double negative media



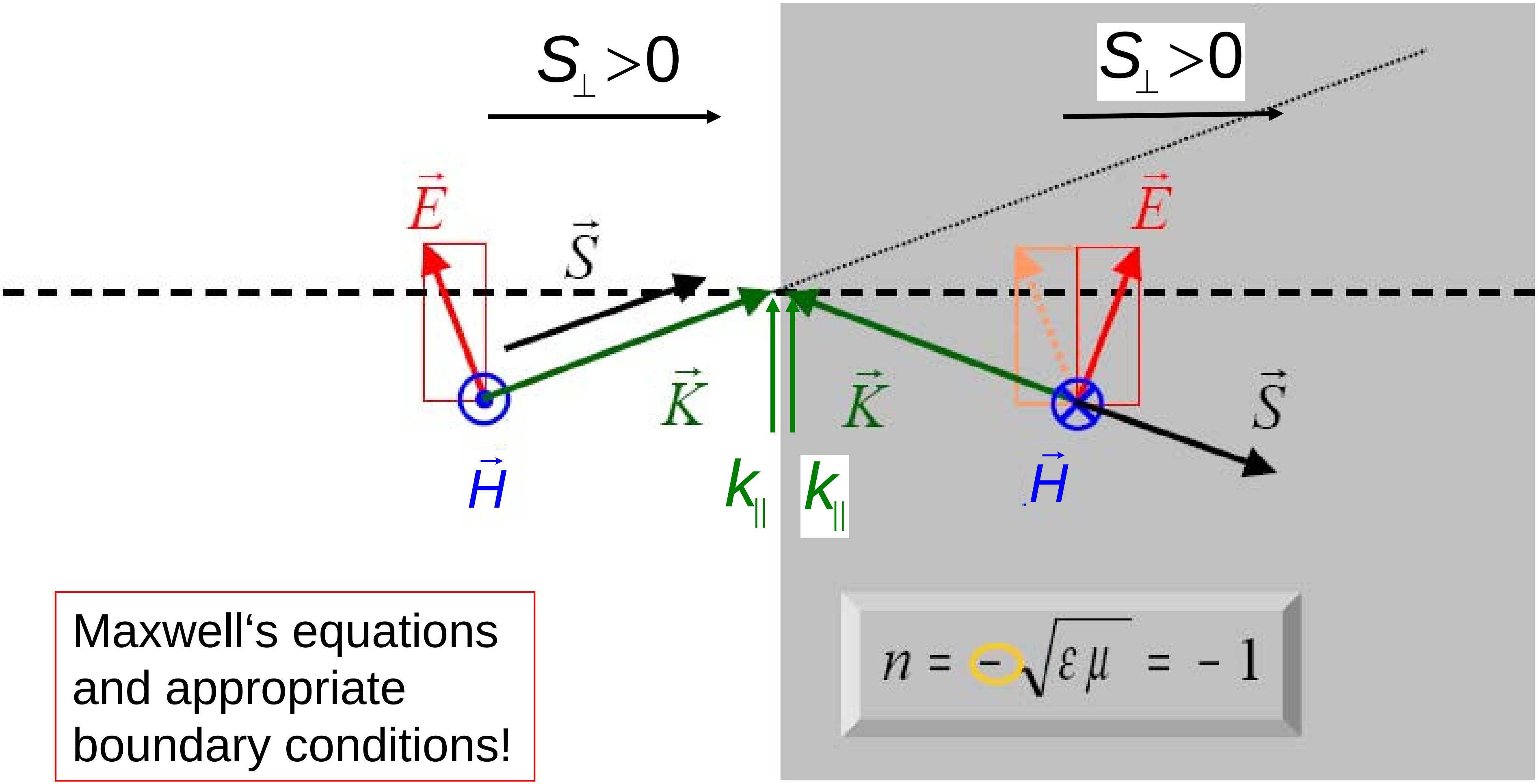
Negative refraction

Maxwell's equations and appropriate boundary conditions!



Negative refraction

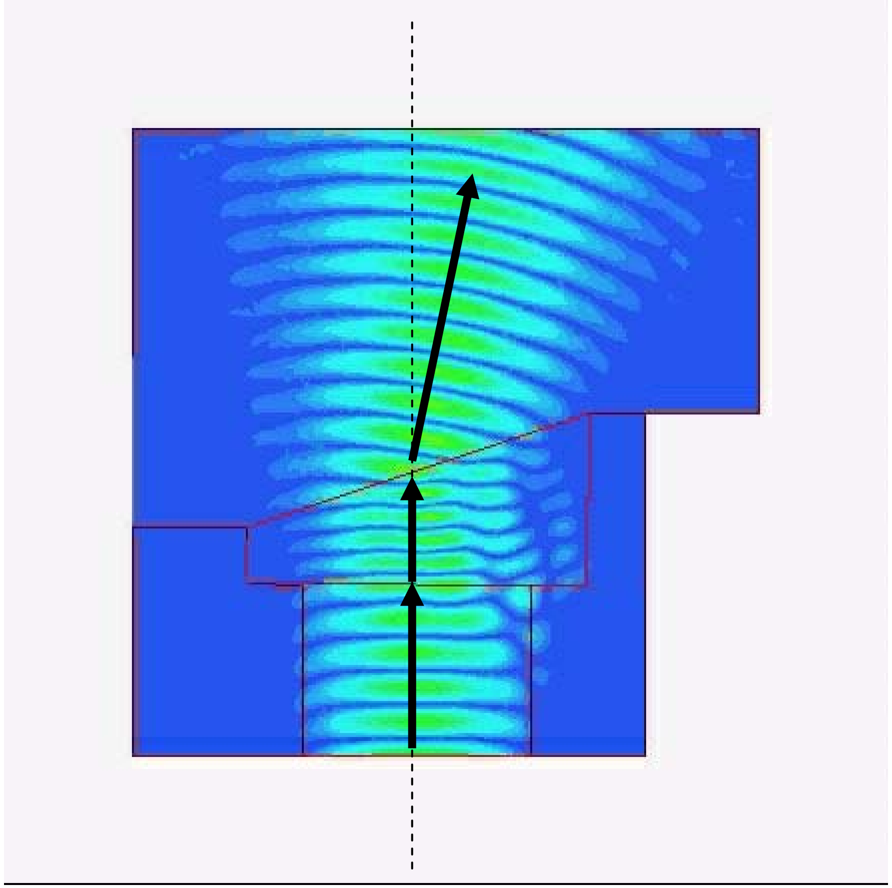
+ **Boundary condition for the wave vector** or



Maxwell‘s equations and appropriate boundary conditions!

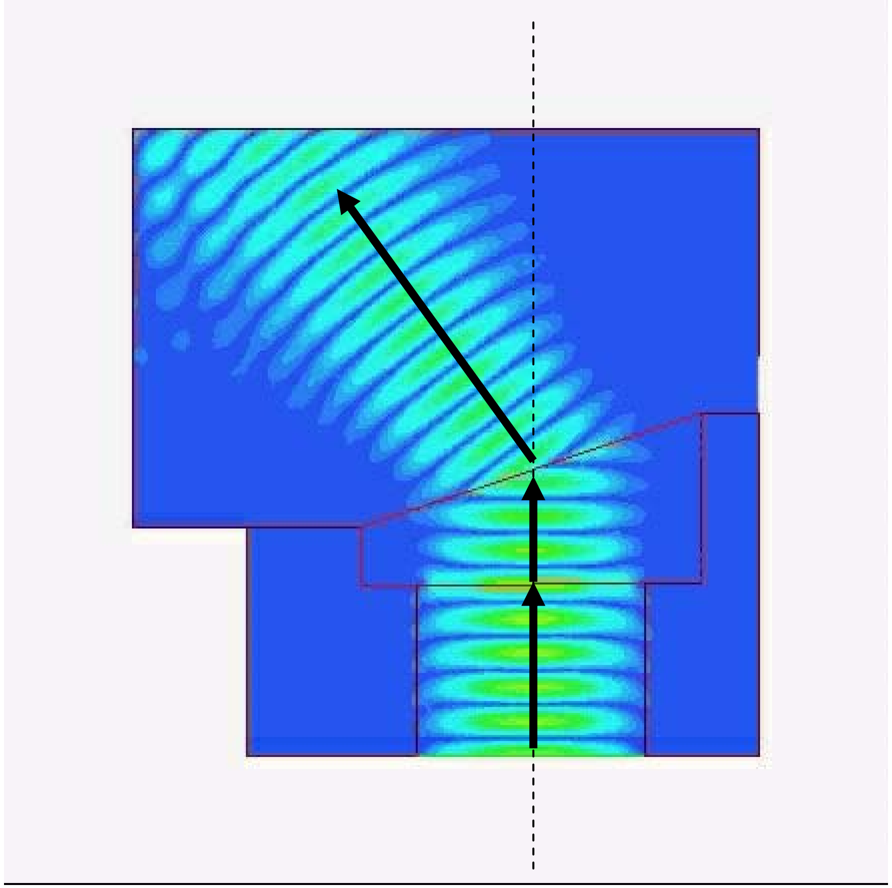
Positive refraction vs negative refraction

S↑↑k "forward wave"



wedge ε=2.2, μ=1

S↑↓k "backward wave"



wedge ε=-1, μ=-1

Pavel Kolinko and David R. Smith 7 April 2003 / Vol. 11, No. 7 / OPTICS EXPRESS 640

Historic remark…

AN INTRODUCTION

TO THE

THEORY OF OPTICS

BY

ARTHUR SCHUSTER,

PH.D. (HEIDELBERG), SC.D. (CANTAB.), F.R.S.

PROFESSOR OF PHYSICS AT THE UNIVERSITY OF MANCHESTER.

LONDON

EDWARD ARNOLD

41 & 43, MADDOX STREET, BOND STREET, W.

1904

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1904 **ARTHUR SCHUSTER, An Introduction to the Theory of Optics, 1904**

direction to the wave velocity. If there is a convection of energy forward, the waves must therefore move backwards. In all optical media where the direction of the dispersion is reversed, there is a very powerful absorption, so that only thicknesses of the absorbing medium can be used which are smaller than a wave-length of light. Under these circumstances it is doubtful how far the above results have any application. But Professor Lamb† has devised mechanical ar-

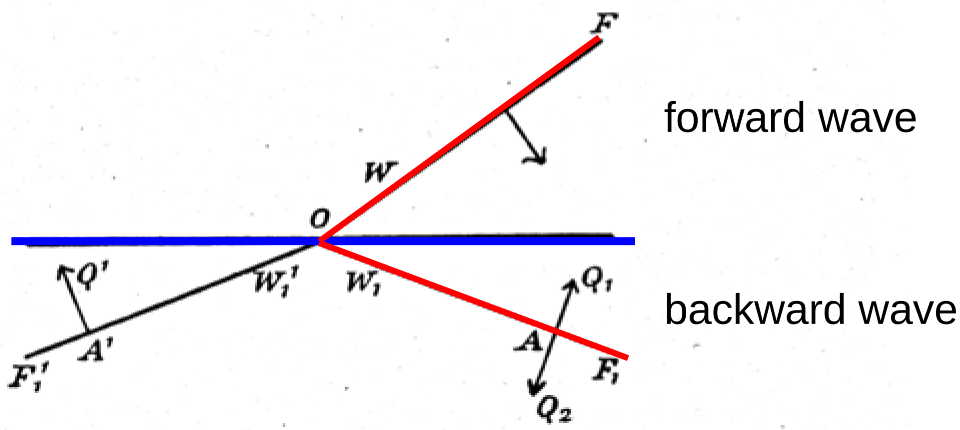


Fig. 179.

rangements in which without absorption there is a negative wave velocity. One curious result follows: the deviation of the wave on entering such a medium is greater than the angle of incidence, so that the wave normal is bent over to the other side of the normal as indicated in Fig. 179. This is seen at once by considering that the traces on the

Historic remark…

Backward waves, negative refraction

1904 Lamb, Schuster

1944 Mandelstam

1968 Veselago: $\varepsilon<0$ **and** $\mu<0 \rightarrow n<0$

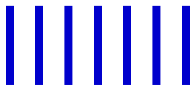
Historic remark…

ε<0

silver ($\omega<\omega_p$)

1961 **Rotman**: rods

1996 **Pendry**: rods



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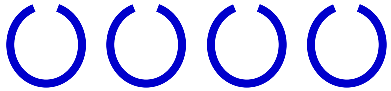
μ<0

1956 **Thompson**: ferrites

1981 **Hardy:** split rings

1999 **Pendry:** split rings



Historic remark…

ε<0

silver ($\omega<\omega_p$)

1961 Rotman: rods

1996 Pendry: rods

Backward waves, negative refraction

1904 Lamb, Schuster

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1968 Veselago: **ε<0 and μ <0 → n<0**

μ<0

1956 Thompson: ferrites

1981 Hardy: split rings

1999 Pendry: split rings

2000 Smith et al.: **ε<0 and μ <0 → n<0**

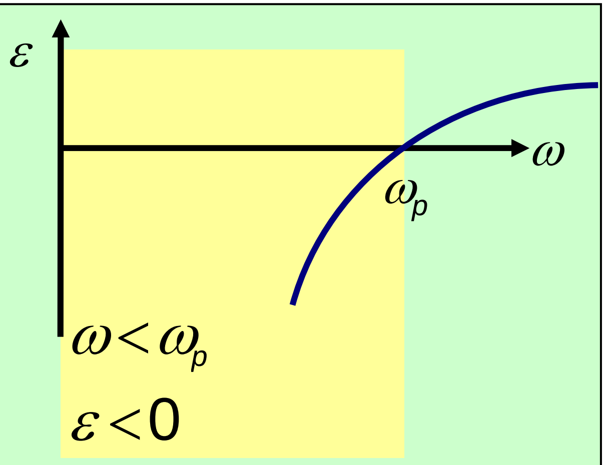
2001 Shelby et al.: first experiment

Artificial medium with ε<0: realisation?

Drude response

bulk metal $$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2}$$

plasma frequency $$\omega_p = \frac{Ne^2}{\varepsilon_0 m}$$



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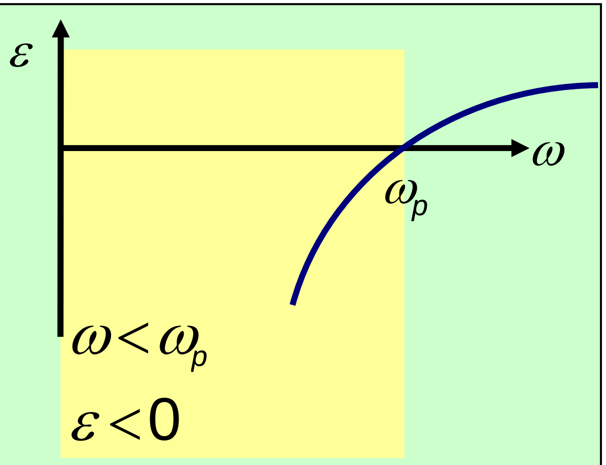
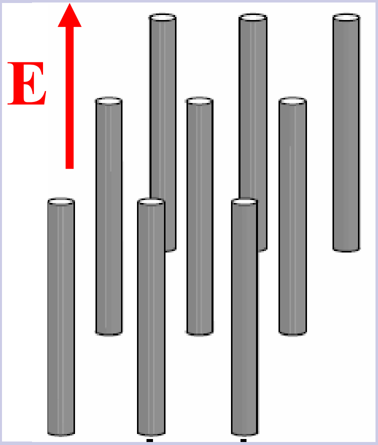
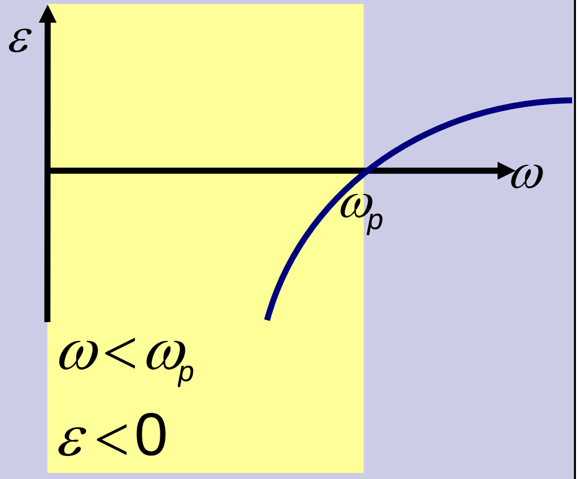


„wire medium“



Drude-like response

$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2}$



Brown 1950's, Rotman 1960's, Pendry 1996

Artificial medium with ε<0: realisation?

Drude response

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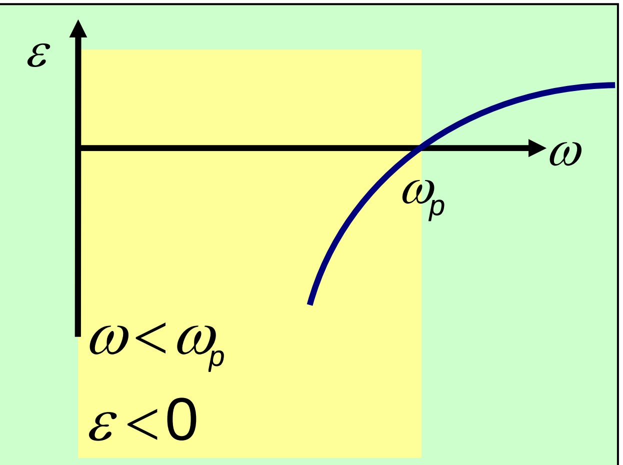

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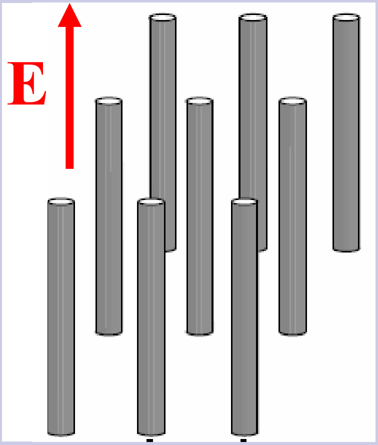
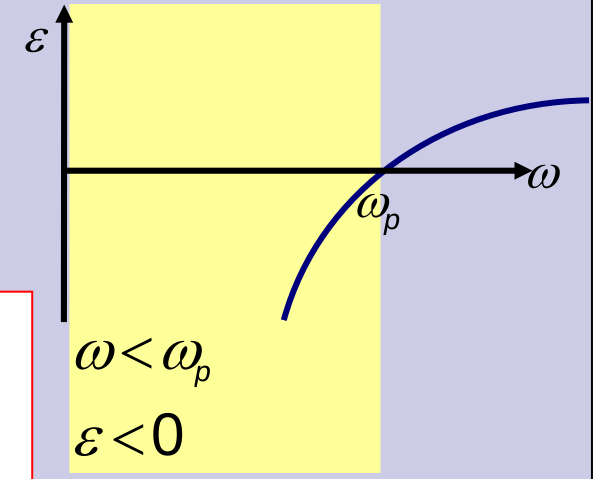


Drude-like response

$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2}$

plasma frequency $\omega_p = \frac{2\pi c^2}{\varepsilon_0 \ln(a/r)}$

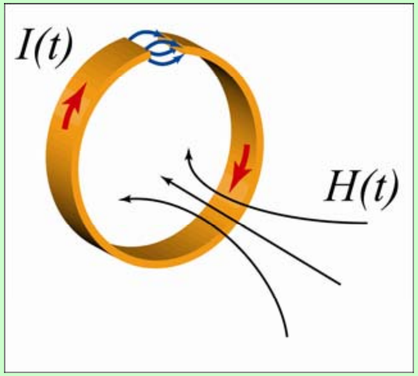
tunable, depends on the geometry!



Brown 1950‘s, Rotman 1960‘s, Pendry 1996

Artificial medium with μ<0: realisation?

single split ring: LC circuit



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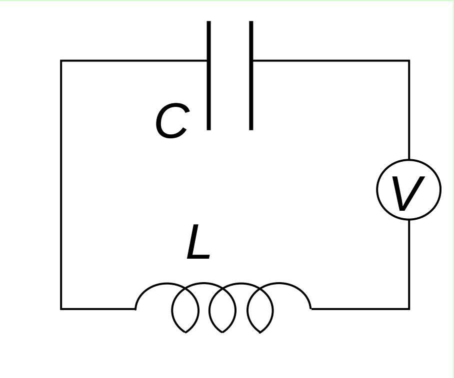

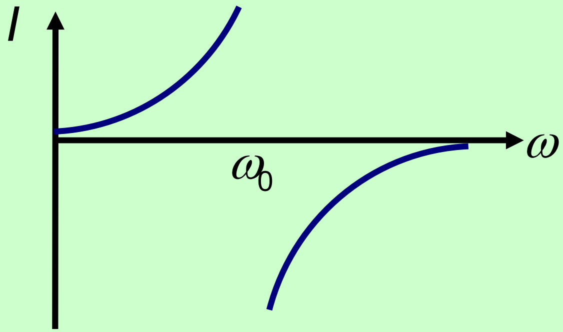

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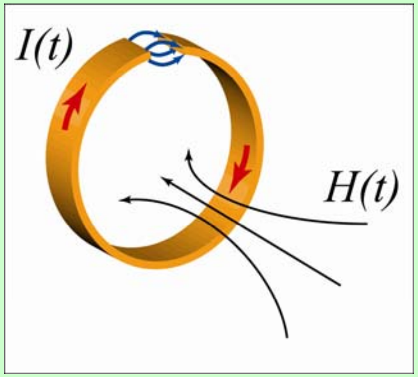
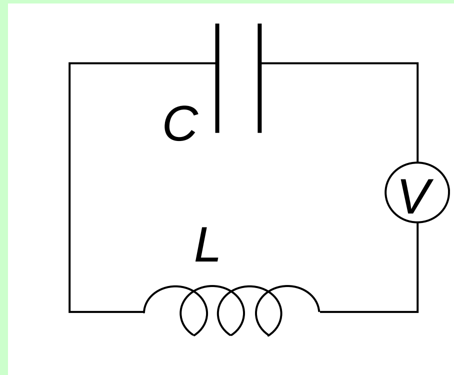
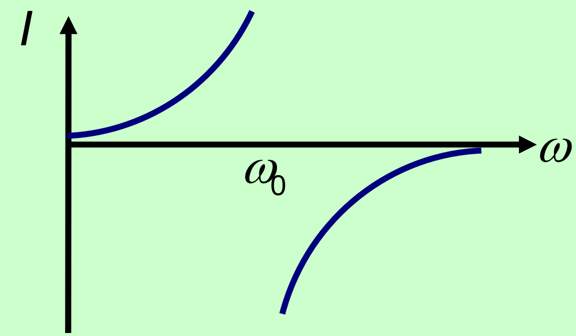






impedance

$$Z = j(\omega L - \frac{1}{\omega C}) = j\omega L\left(1 - \frac{\omega_0^2}{\omega^2}\right)$$

resonant frequency

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

voltage

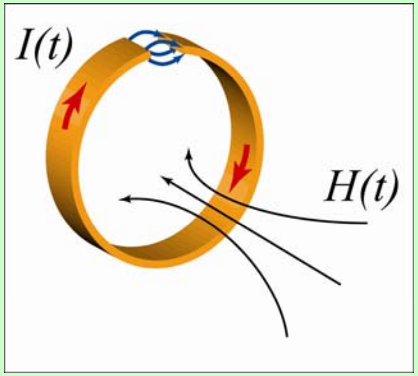
$$V = -\frac{\partial \Phi}{\partial t} = j\omega\mu_0 H\pi r^2$$

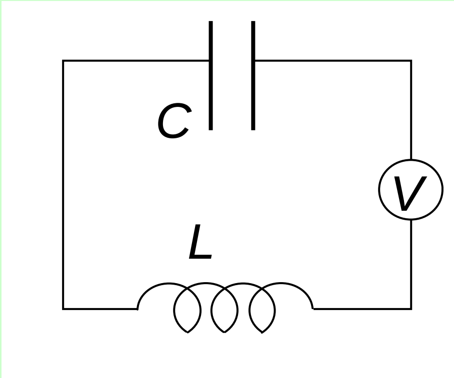
$$I = \frac{V}{Z} = \frac{V}{j(\omega L - 1/\omega C)} = \frac{j\omega\mu_0 H\pi r^2}{j\omega L}\frac{\omega^2}{\omega^2 - \omega_0^2}$$

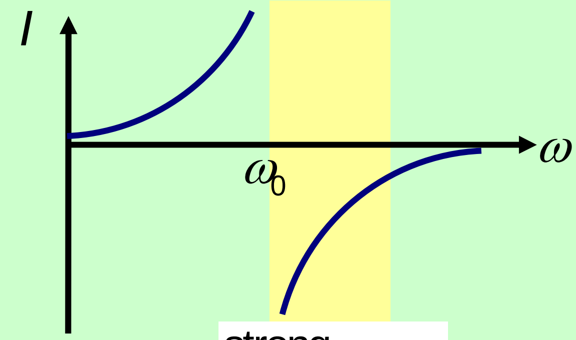
Pendry 1999

Artificial medium with μ<0: realisation?

single split ring: LC circuit







strong diamagnetic response

impedance

$$Z = j(\omega L - \frac{1}{\omega C}) = j\omega L\left(1 - \frac{\omega_0^2}{\omega^2}\right)$$

resonant frequency

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

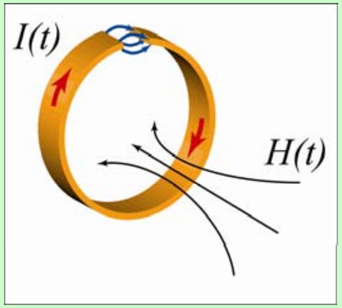
voltage

$$V = -\frac{\partial \Phi}{\partial t} = j\omega\mu_0 H\pi r^2$$

$$I = \frac{V}{Z} = \frac{V}{j(\omega L - 1/\omega C)} = \frac{j\omega\mu_0 H\pi r^2}{j\omega L}\frac{\omega^2}{\omega^2 - \omega_0^2}$$

Pendry 1999

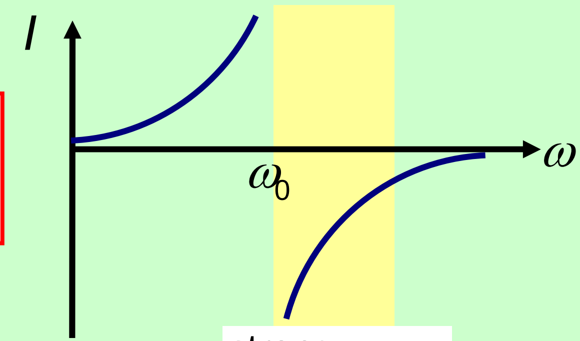
Artificial medium with μ<0: realisation?



single split ring: LC circuit

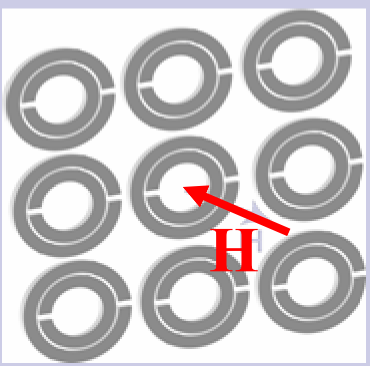
$$I = \frac{V}{Z} = \frac{V}{j(\omega L - 1/\omega C)} = \frac{j\omega H \pi r^2}{j\omega L} \frac{\omega^2}{\omega^2 - \omega_0^2}$$

resonant frequency $\omega_0 = \frac{1}{\sqrt{LC}}$



strong diamagnetic response

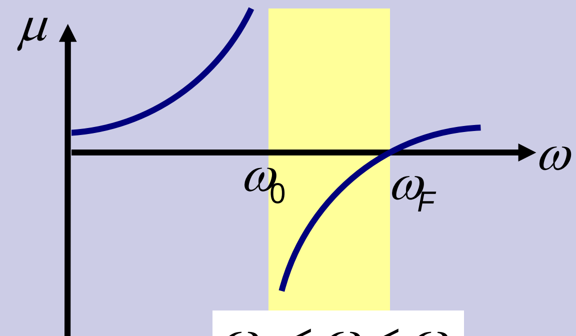
„split ring medium“



$$\mu = 1 - F \frac{\omega^2}{\omega^2 - \omega_0^2}$$

frequencies ω_0, ω_F

depend on the geometry!

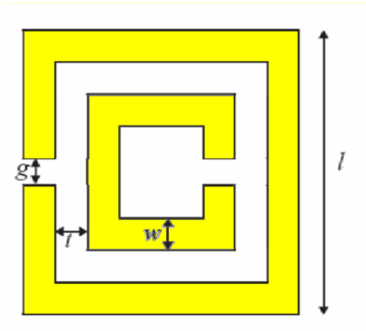


$\omega_0 < \omega < \omega_F$

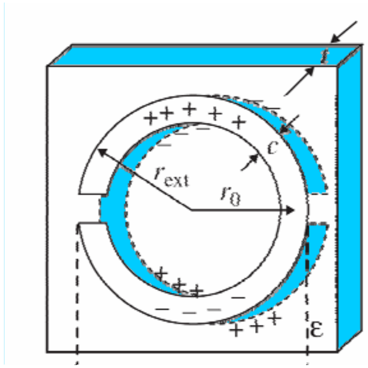
$\mu < 0$

Pendry et al.1999

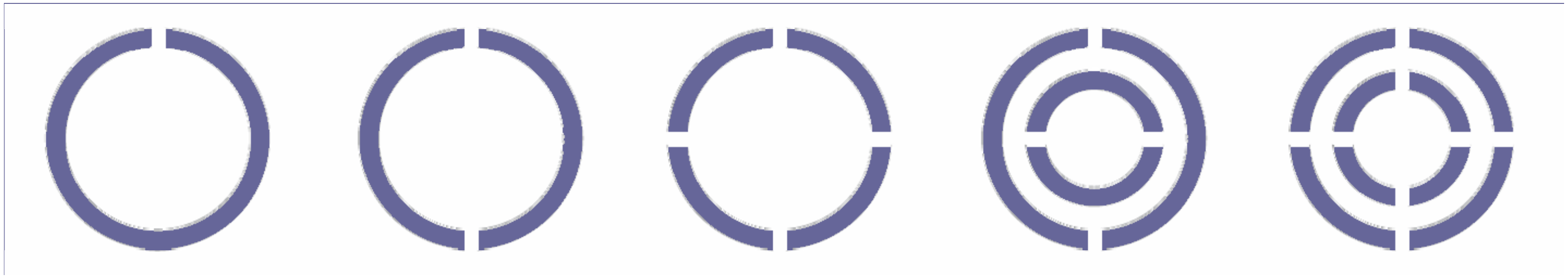
Exploring magnetic „atoms“: Split Ring Resonators



Kafesaki et al. 2005

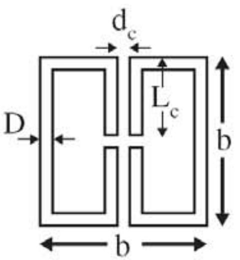


Marques et al. 2003



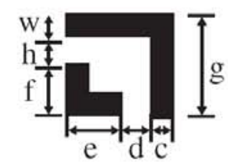
Aydin et al. 2005

Exploring magnetic „atoms“: the family grows…

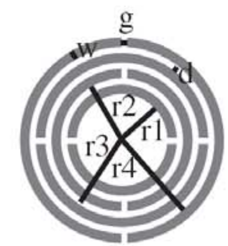


O‘Brien & Pendry 2005

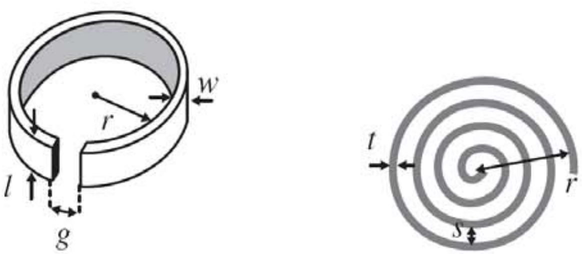
Guo et al. 2005



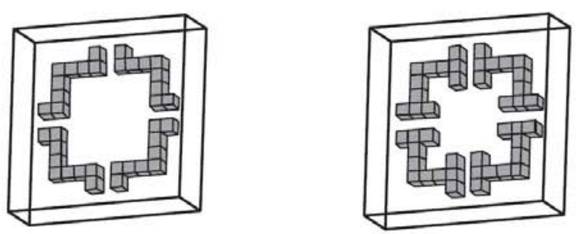
Hsu et al. 2004



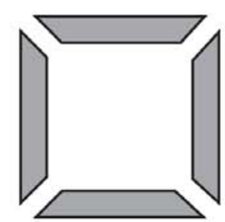
Bulu et al. 2005



Radkovskaya et al. 2007

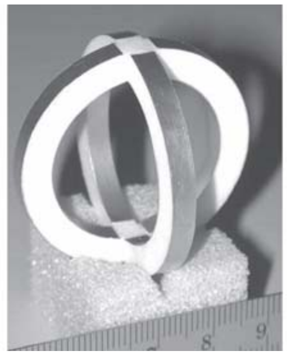


Kafesaki et al. 2005

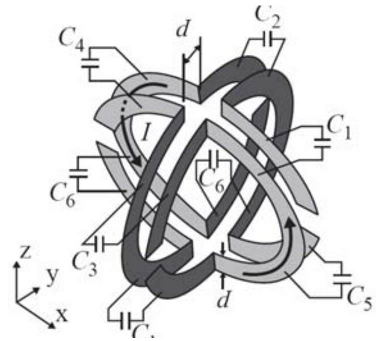


Kafesaki et al. 2005

Isotropic magnetic „atoms“

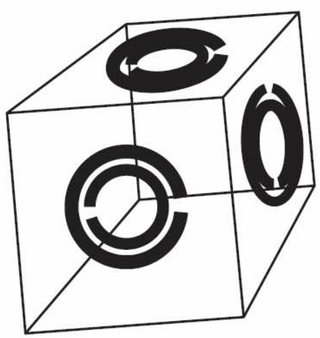


Gay-Balmaz, Martin 2002

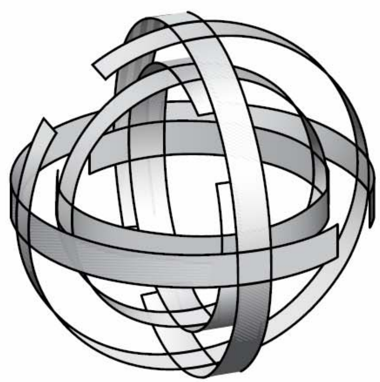


Chen et al. 2006

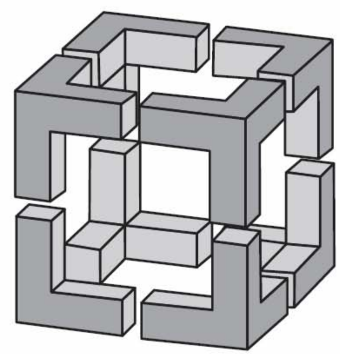
in 2D



Baena 2005



Gay-Balmaz, Martin 2002

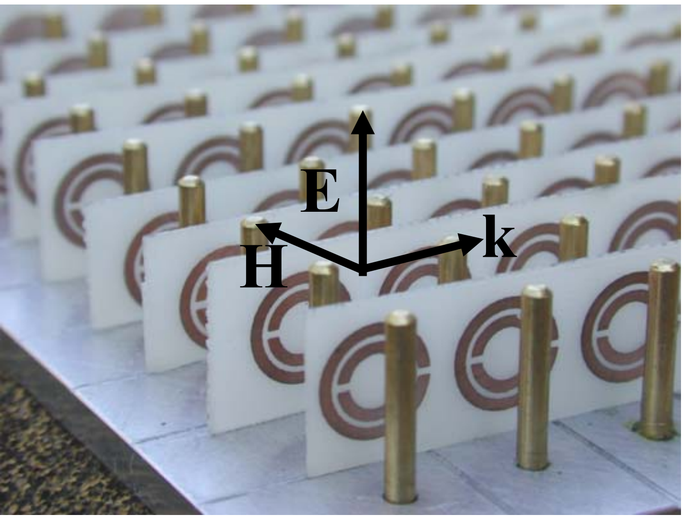


Padilla 2005

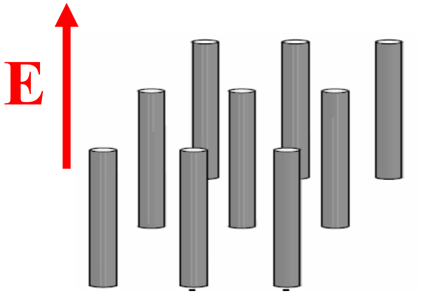
in 3D

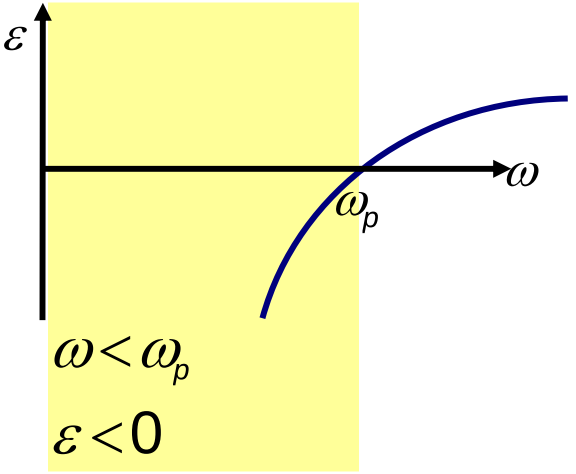
Double negative media: realisations

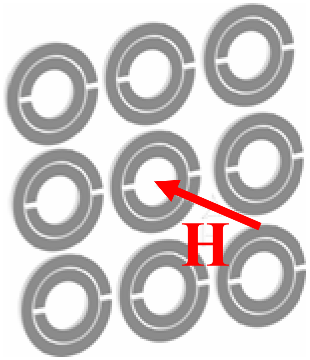
Combination of SRRs (μ<0) & wires (ε<0)

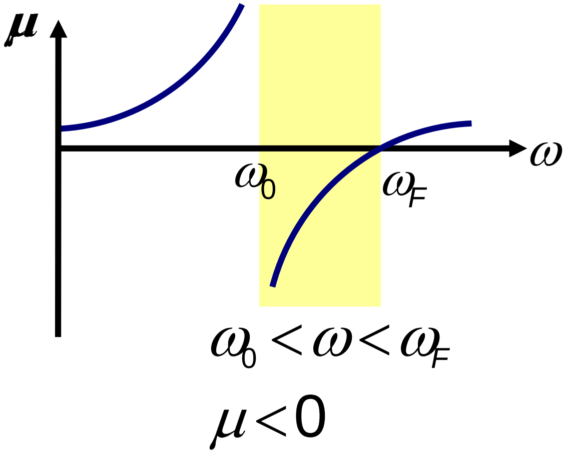


Smith et al. 2000









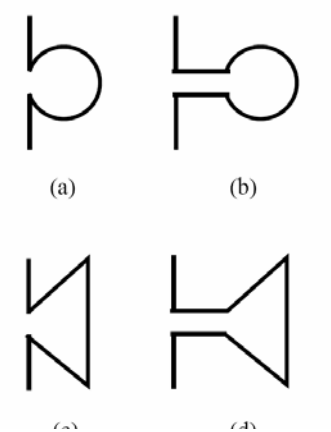
Double negative media: realisations

SRR+rod

Smith et al. 2000

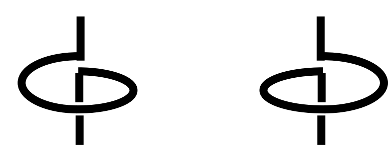
Shelby et al. 2001

Omega-particles



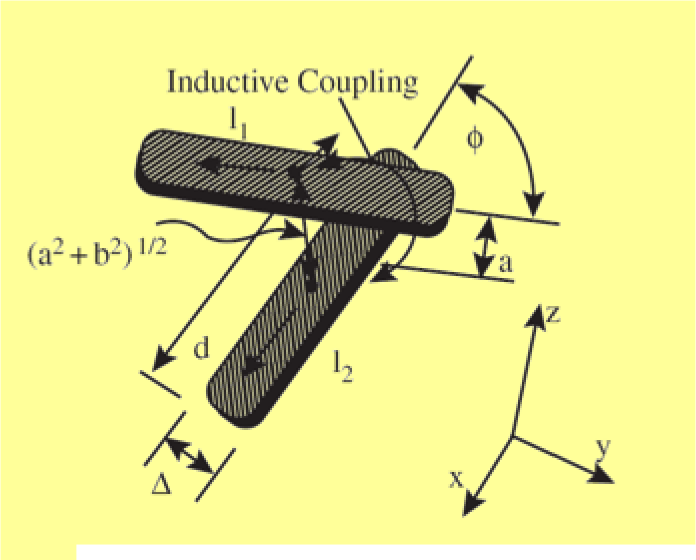
Saadoun, Engheta 1992, 1994

chiral particles

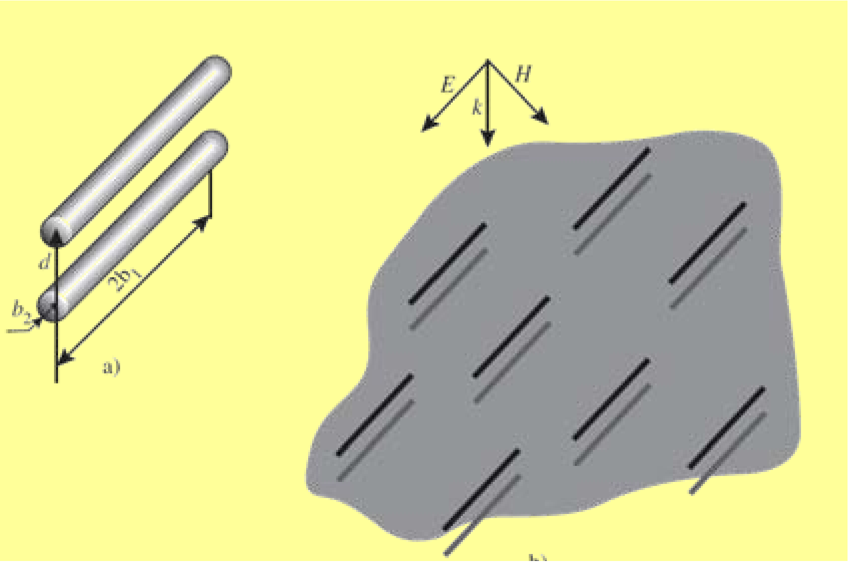


Tretyakov 1996

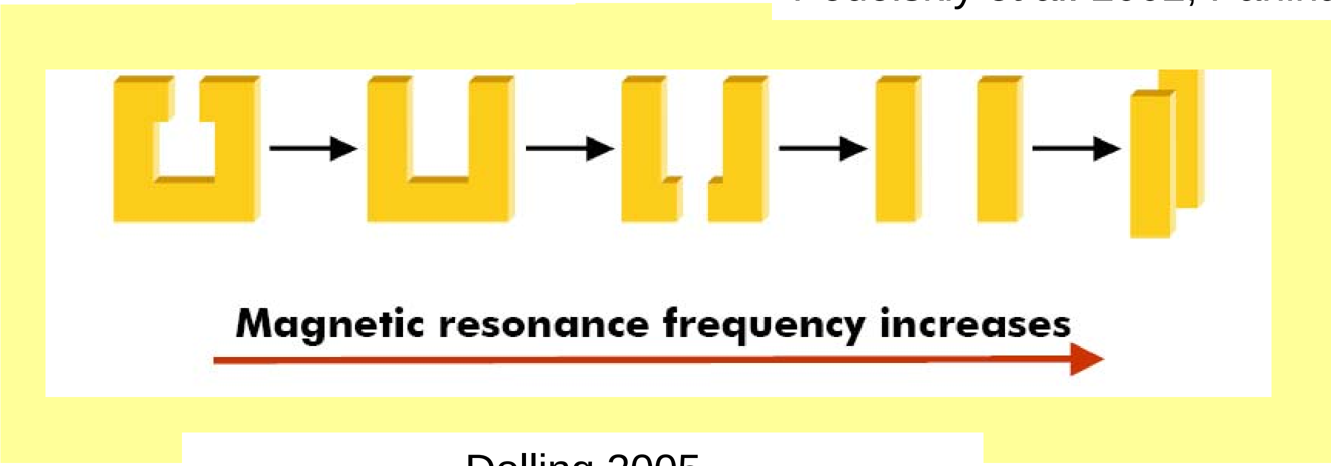
From SRR to wire pairs …



Svirko et al. 2001

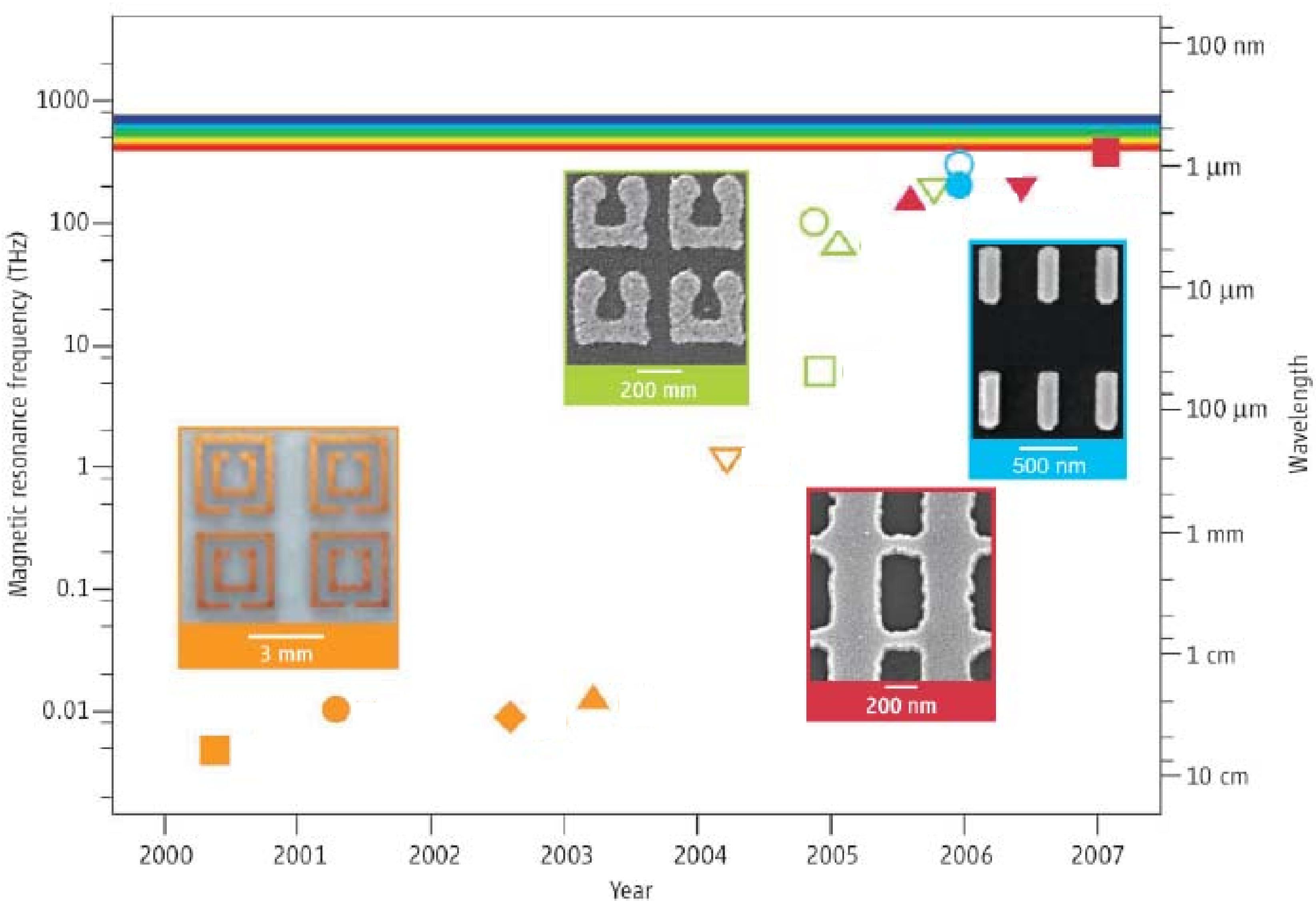


Podolskiy et al. 2002, Panina et al. 2002



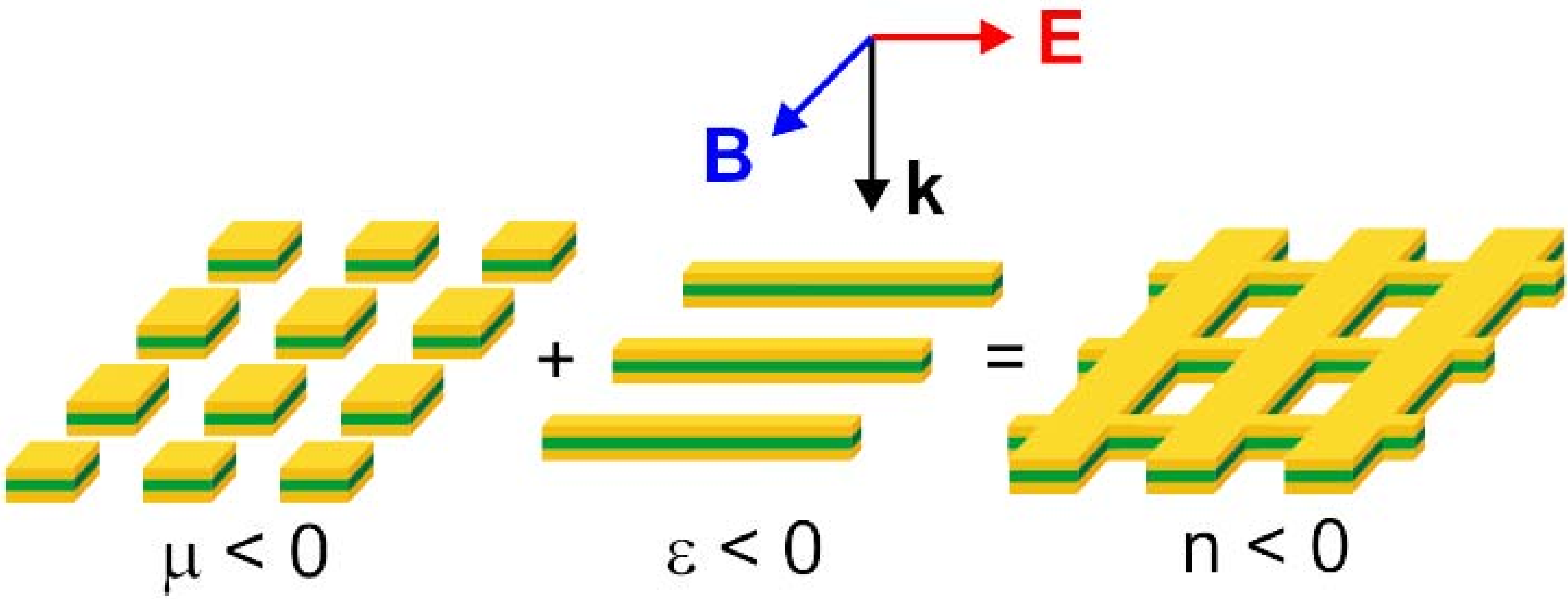
Dolling 2005

From microwave to optical frequencies ...



source: Wegener, Linden, von Freymann, lecture course 2007, Karlsruhe

Double negative metamaterials: realisation



Why Metamaterials?

Physics

Extension of electromagnetism

“inverse” electromagnetic phenomena

- inverse Snell’s law (negative refraction of rays)
- inverse Doppler shift, Cherenkov radiation, Goos-Haenchen shift
- “growing” evanescent waves

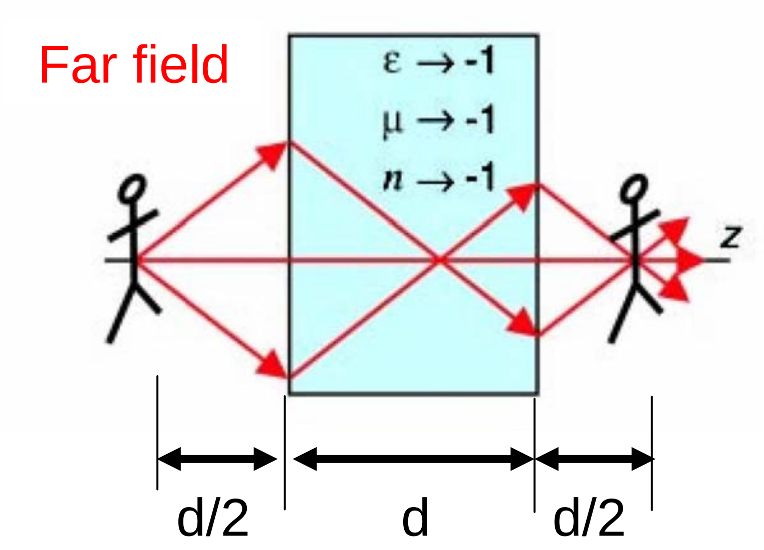
Applications

- “Perfect lens”, subwavelength imaging in photonics
- Invisibility and cloaking
- “Nano-circuits”, miniaturisied waveguide components
- Medical imaging

Superlens

2000 Pendry:

metamaterial plate with n<0
acts as a perfect lens

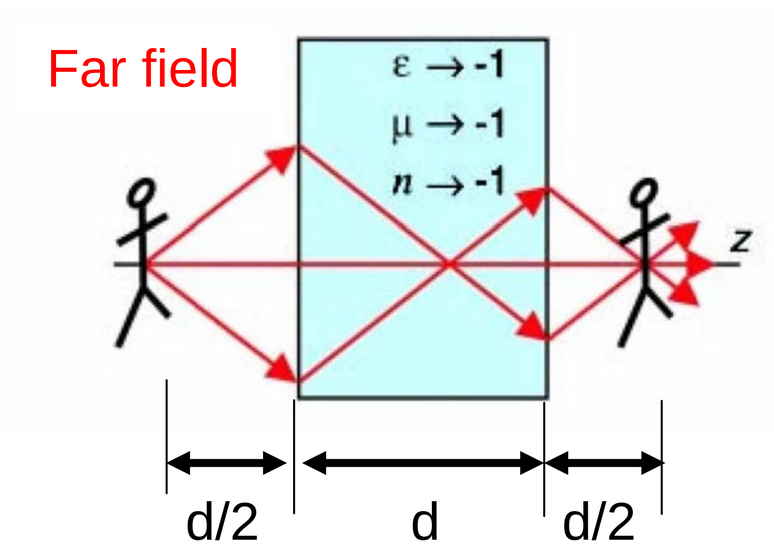


Superlens

2000 Pendry:

metamaterial plate with n<0
acts as a perfect lens

also for a sub-λ-object?



Superlens

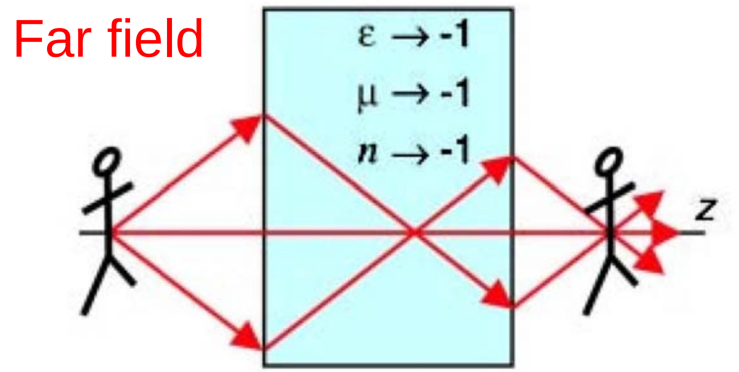
2000 Pendry:

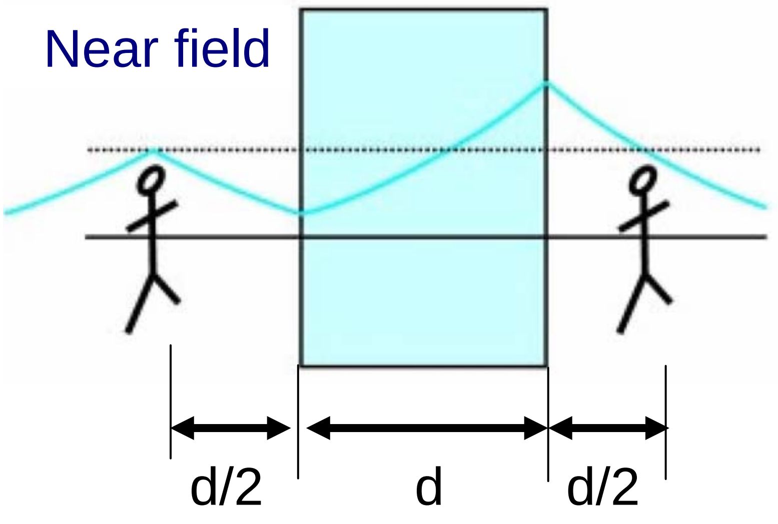
metamaterial plate with n<0
acts as a perfect lens

also for a sub-λ-object?

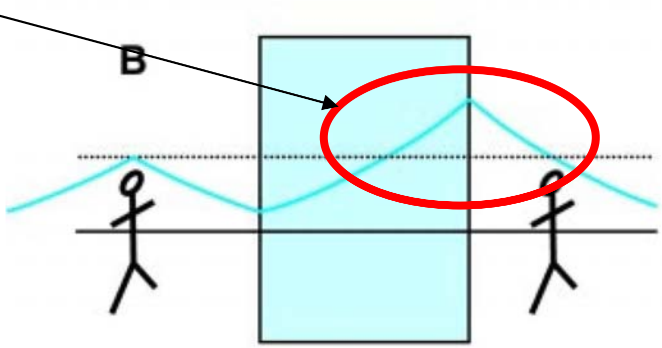
<u>Explanation: Near field</u>
n>0 exponential decay
n<0 exponential growth

<u>Mechanism: surface resonant modes</u>
couple to the evanescent part of the object spectrum and lead to the reconstruction of the object in the image plane

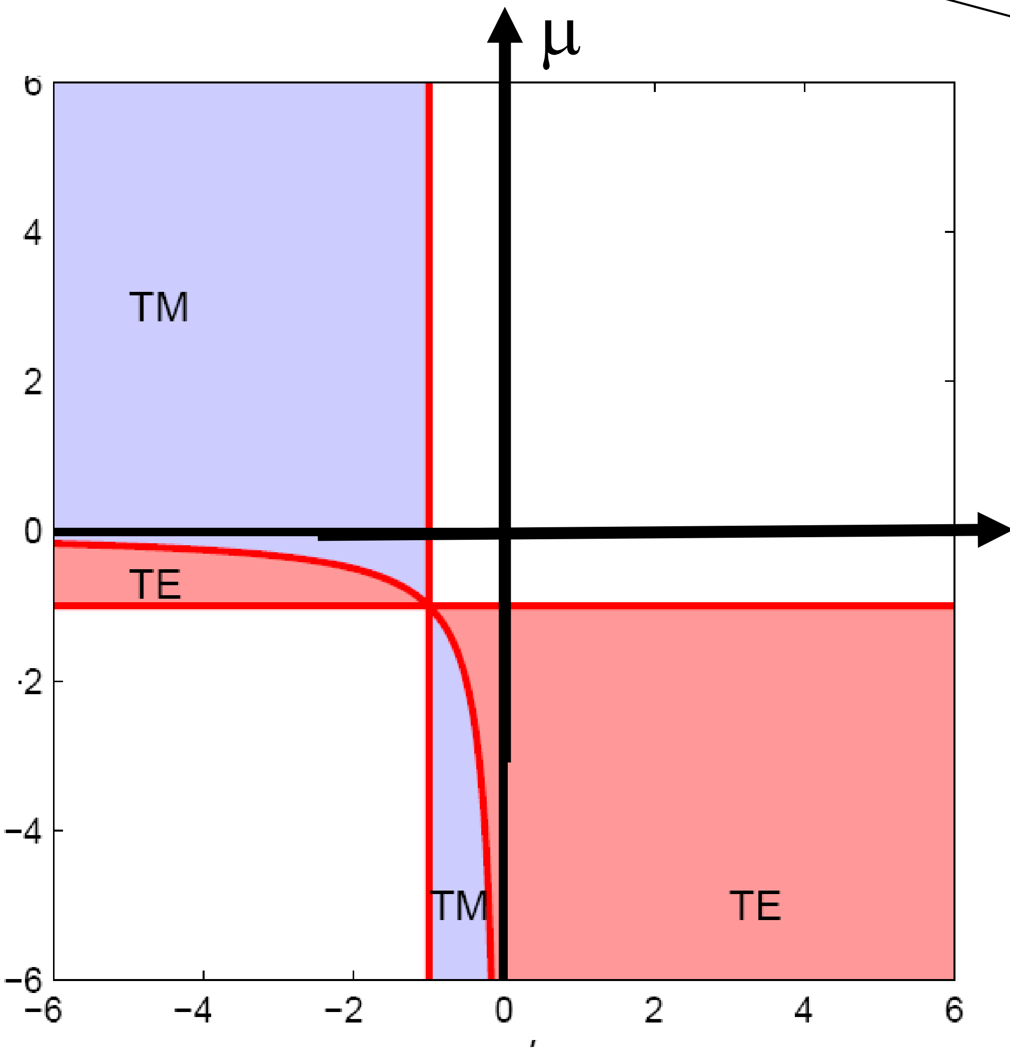




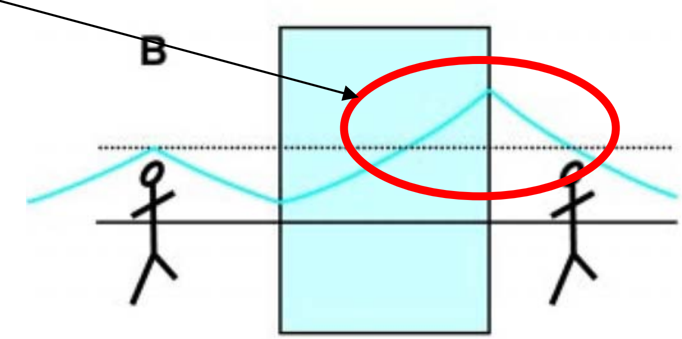
Surface modes in metamaterials?



Surface modes in metamaterials?



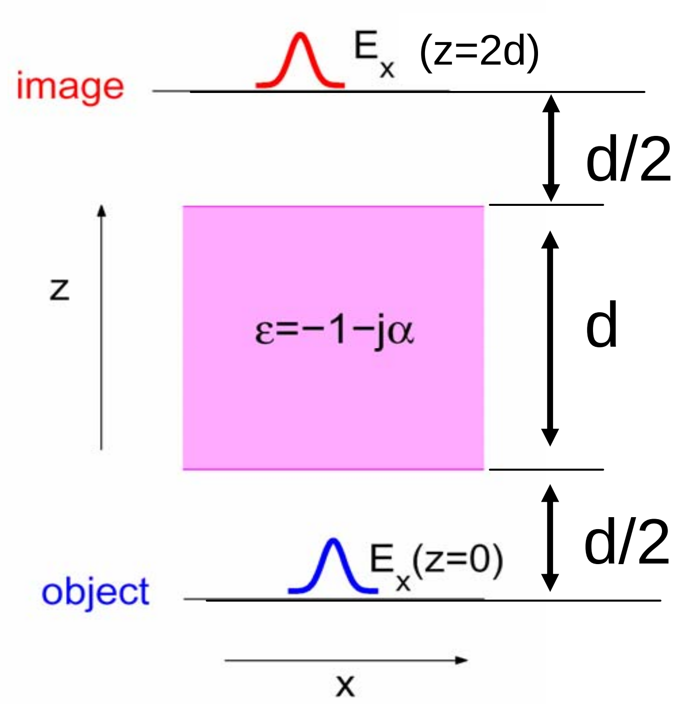
Domains of existence of surface modes

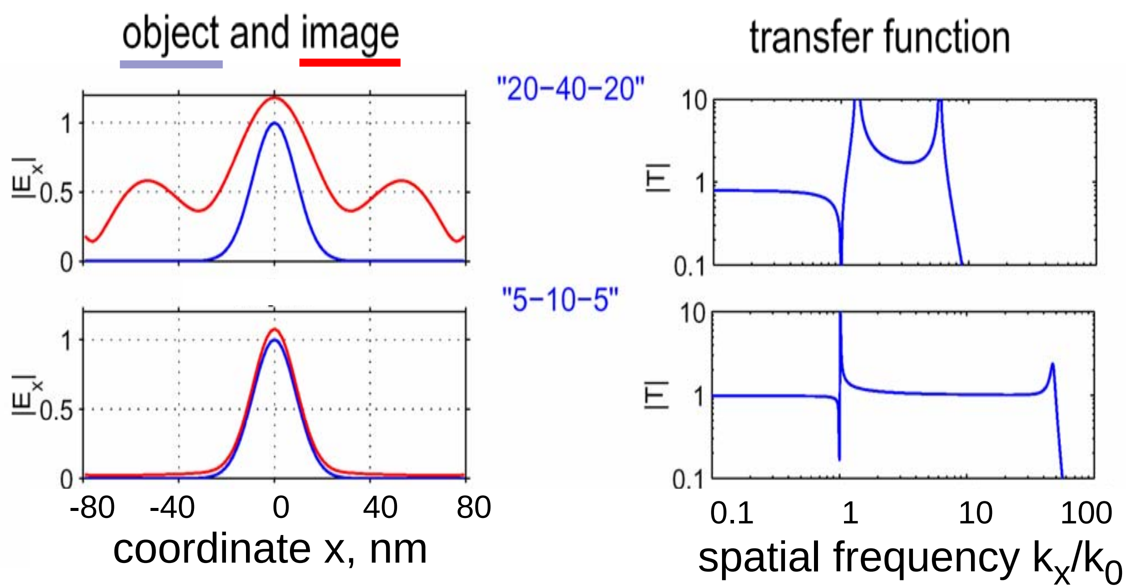


TM: „transverse magnetic“
TE: „transverse electric“

Silver slab as a superlens: surface plasmon-polaritons

- Coupled modes of surface plasmon-polariton resonances
- Two spatial resonances; flat transfer function in-between



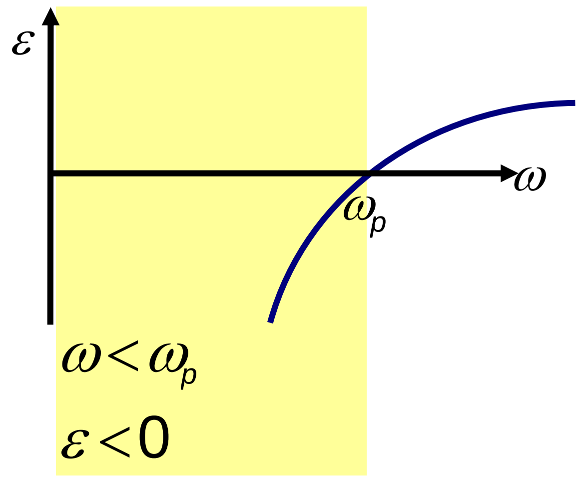


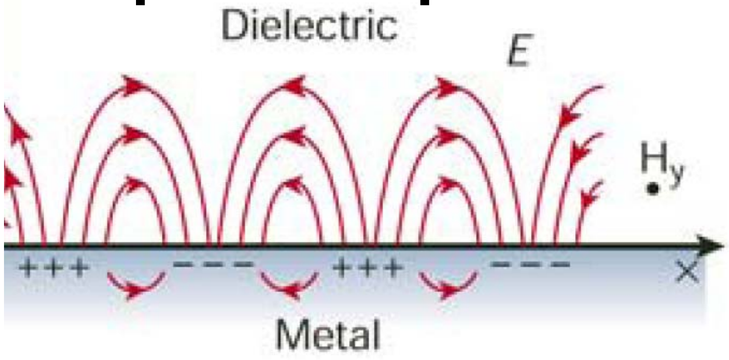
the thinner the slab, the flatter the transfer function

λ=360nm

Shamonina et al., Electr.Lett. (2001)

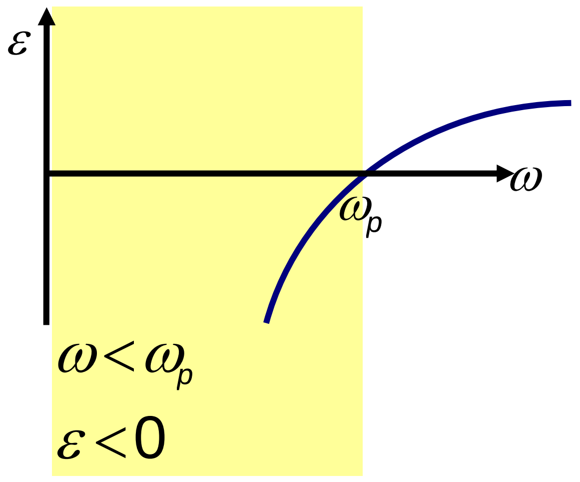
Silver slab as a superlens: surface plasmon-polaritons

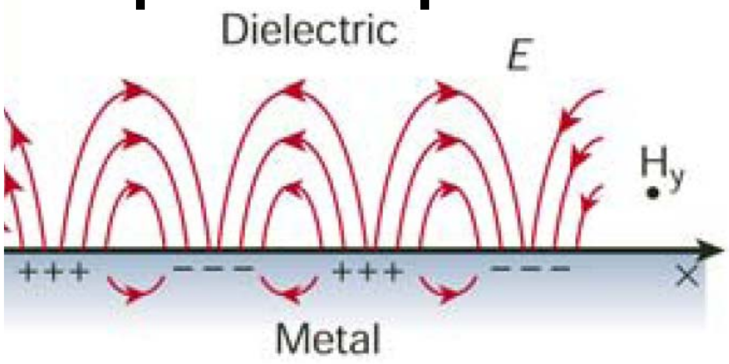




Surface electromagnetic eigenmode of the medium

Silver slab as a superlens: surface plasmon-polaritons

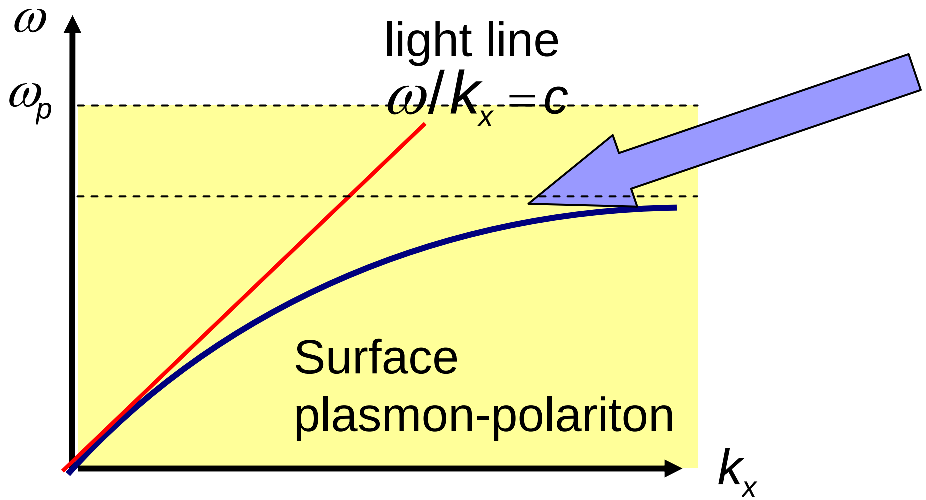




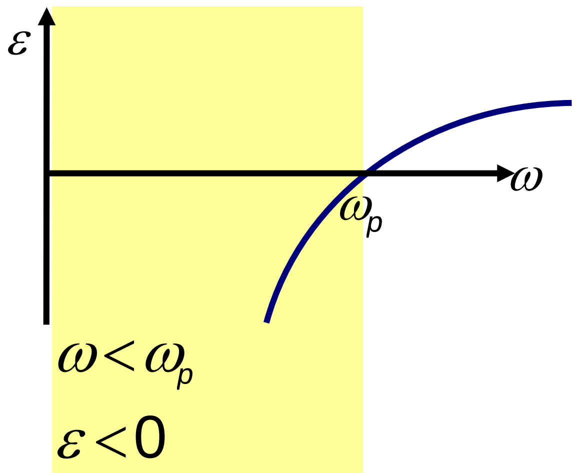
Surface electromagnetic eigenmode of the medium

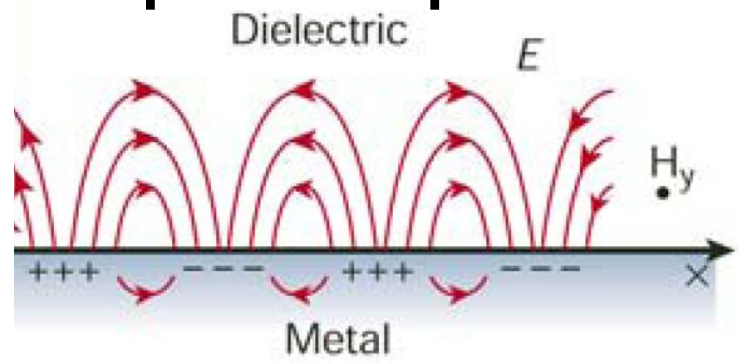
slow waves of short wavelength!

cannot interact with propagating waves!

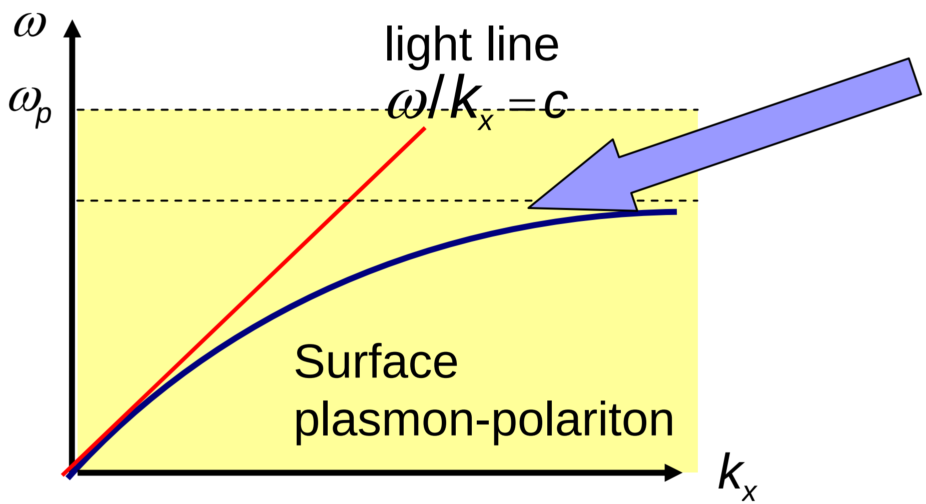


Silver slab as a superlens: surface plasmon-polaritons





Surface electromagnetic eigenmode of the medium

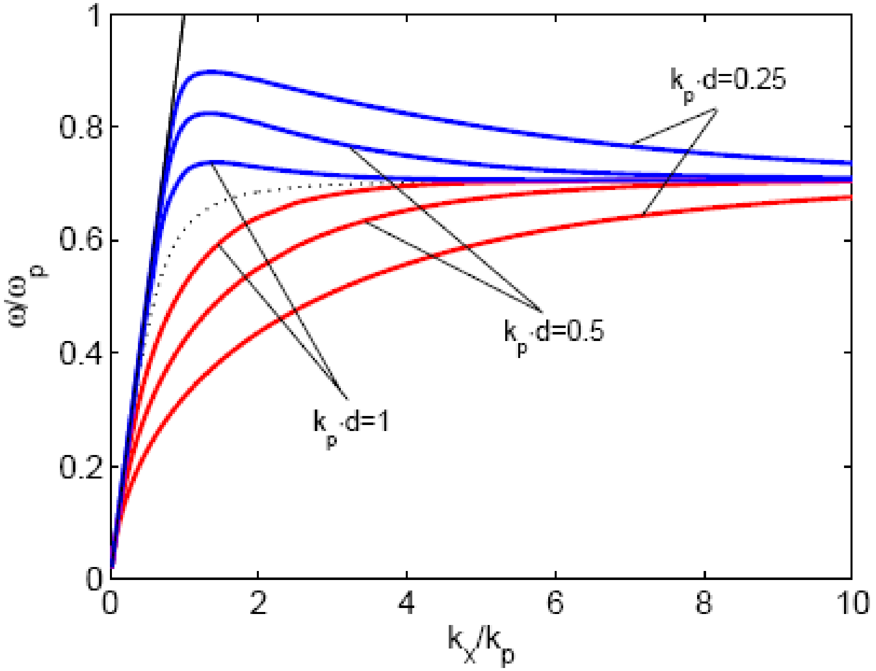


slow waves of short wavelength!

cannot interact with propagating waves!

do interact with the evanescent, near field components of the Fourier spectrum of an object!

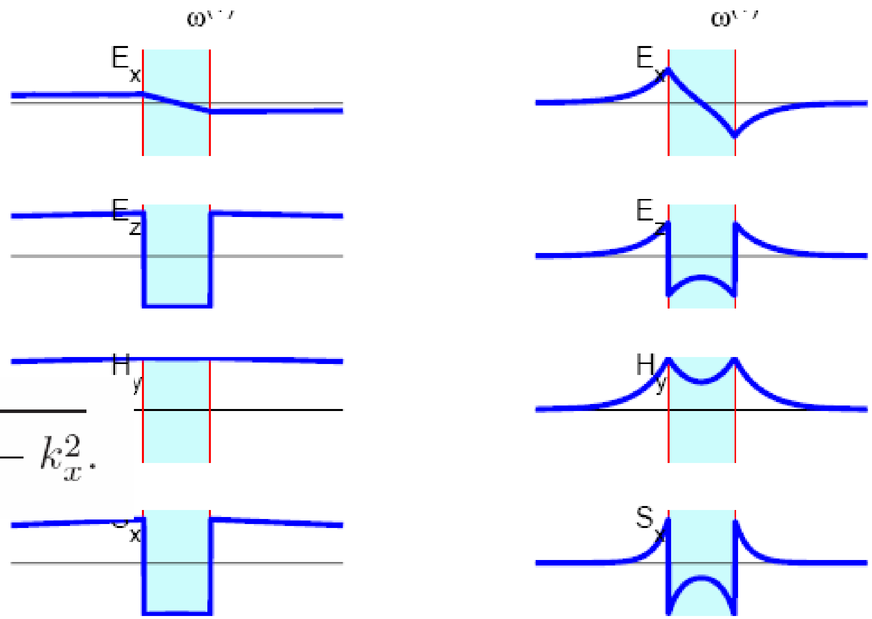
SLAB: TWO SURFACES



$$\zeta_{\mathrm{e}} = -\tanh\frac{\kappa_2 d}{2}$$

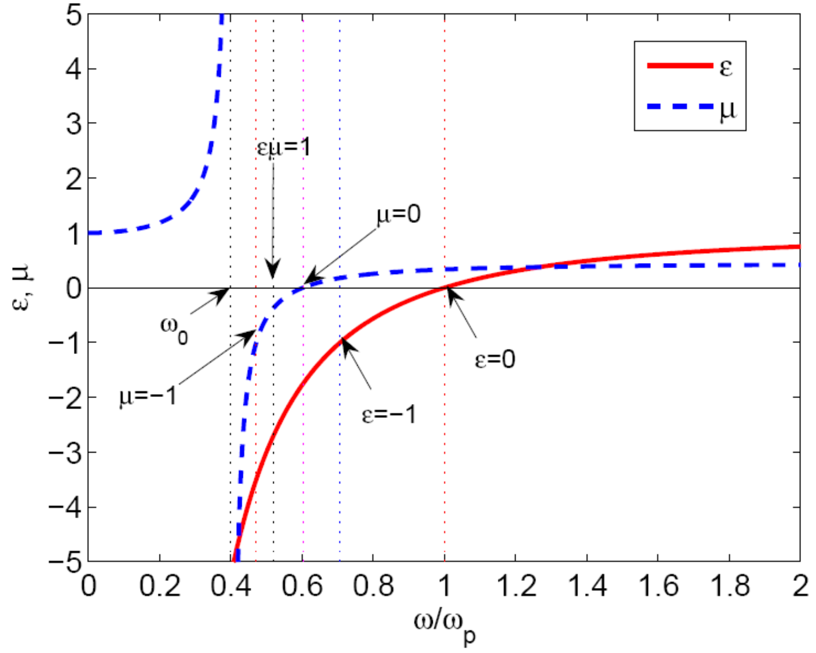
$$\zeta_{\mathrm{e}} = -\coth\frac{\kappa_2 d}{2}.$$

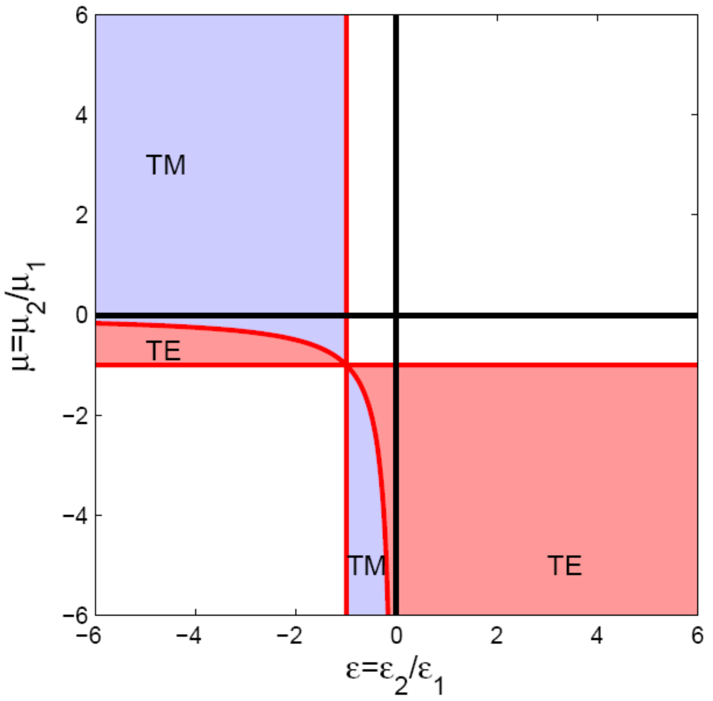
$$k_{z1} = -j\kappa_1, \qquad k_{z2} = -j\kappa_2.$$



$$k_{z1} = \sqrt{\varepsilon_{\mathrm{r1}}\mu_{\mathrm{r1}}k_0^2 - k_x^2}, \qquad k_{z2} = \sqrt{\varepsilon_{\mathrm{r2}}\mu_{\mathrm{r2}}k_0^2 - k_x^2}.$$

ARBITRARY VALUES OF μ,ε

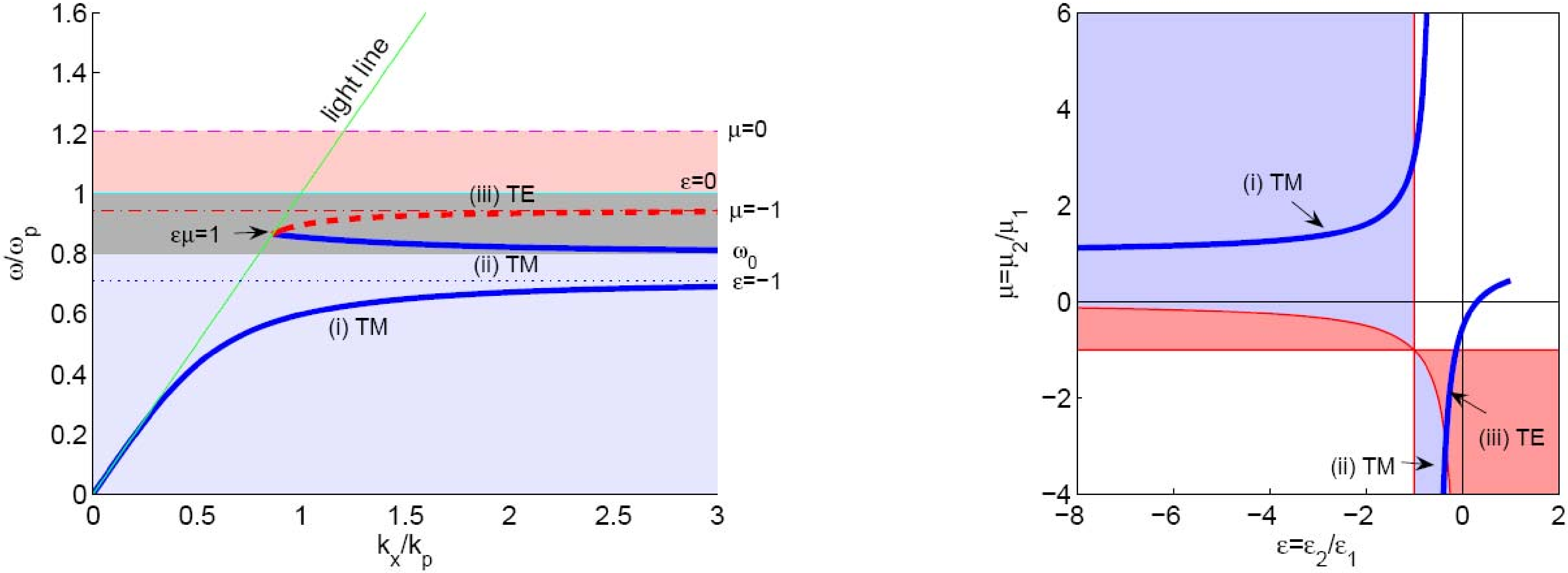




$$\varepsilon_{r2} = 1 - \frac{\omega_p^2}{\omega^2}$$

$$\mu_{r2} = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2}.$$

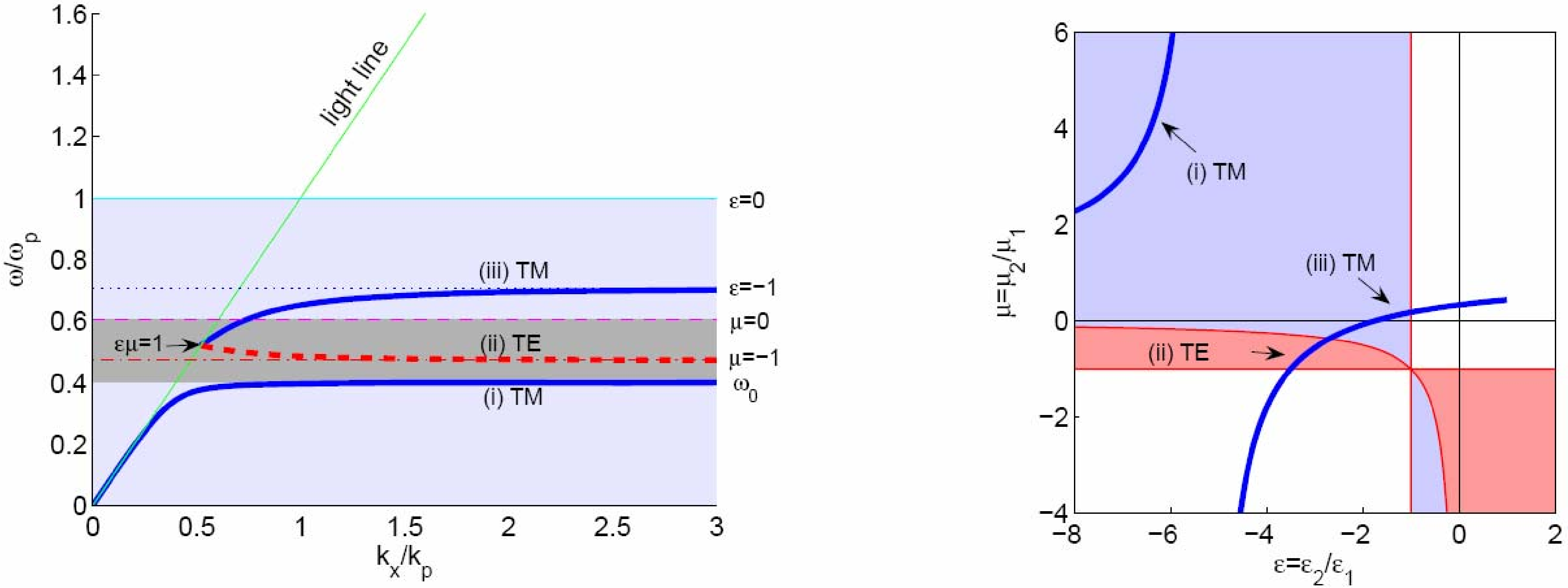
ARBITRARY VALUES OF μ,ε



SPP dispersion for single interface. $F = 0.56$, $\omega_0 = 0.8\omega_{\mathrm{p}}$.(a) $\omega - k_x$ diagram. (b) $\mu - \varepsilon$ diagram.

$$\varepsilon_{\mathrm{r}2} = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2} \qquad \mu_{\mathrm{r}2} = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2}.$$

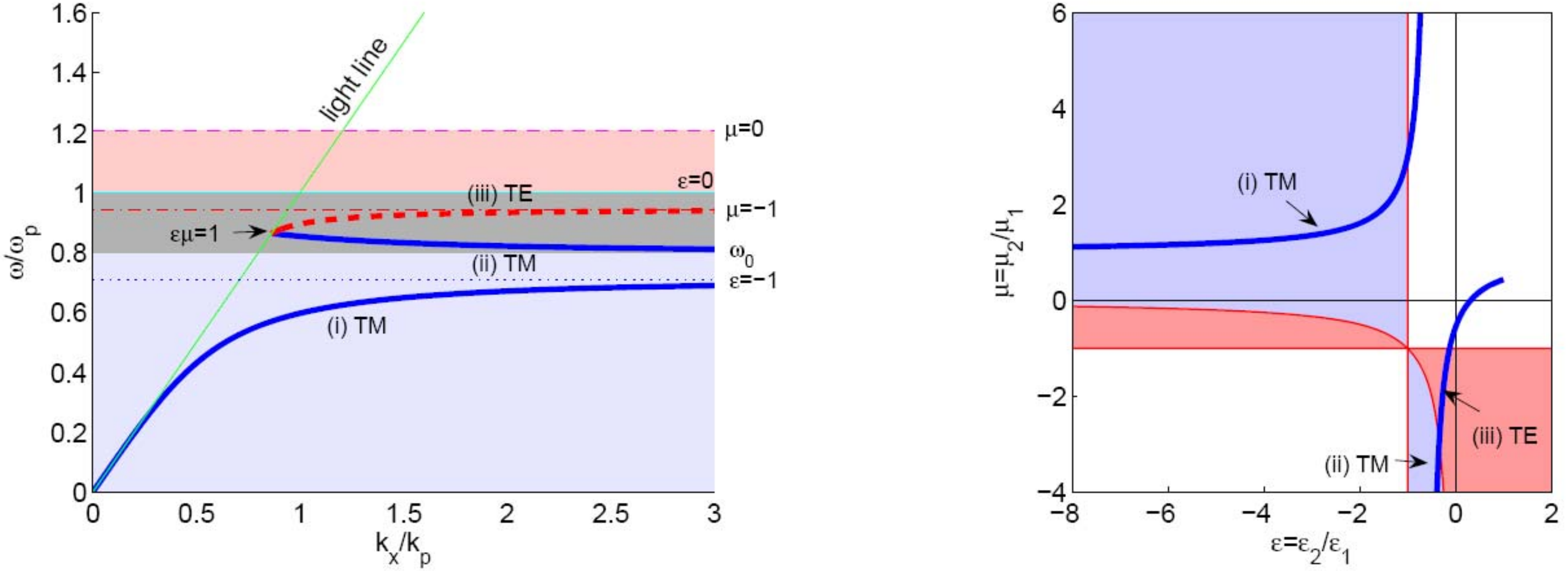
ARBITRARY VALUES OF μ,ε



: SPP dispersion for single interface. $F = 0.56$, $\omega_0 = 0.6\omega_{\rm p}$.(a) $\omega - k_x$ diagram. (b) $\mu - \varepsilon$ diagram.

$$\varepsilon_{\rm r2} = 1 - \frac{\omega_{\rm p}^2}{\omega^2} \qquad \mu_{\rm r2} = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2}.$$

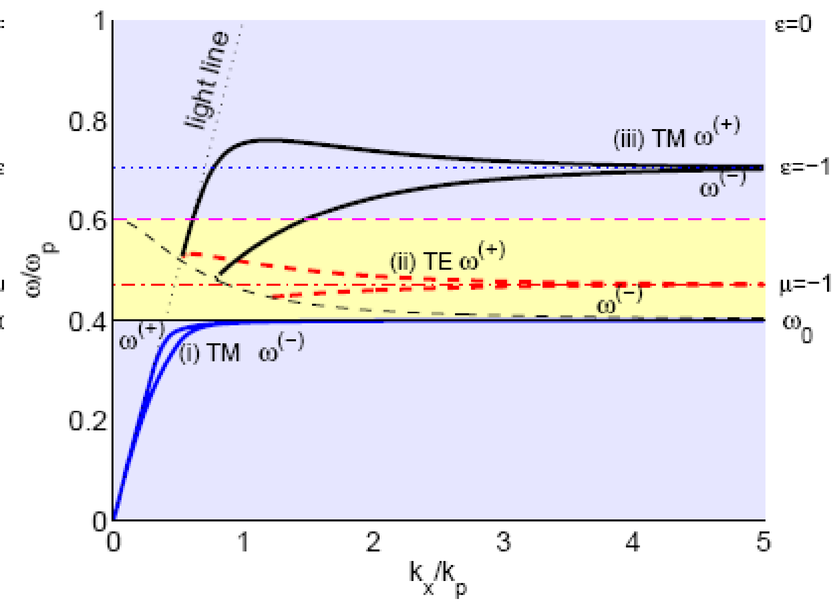
ARBITRARY VALUES OF μ,ε

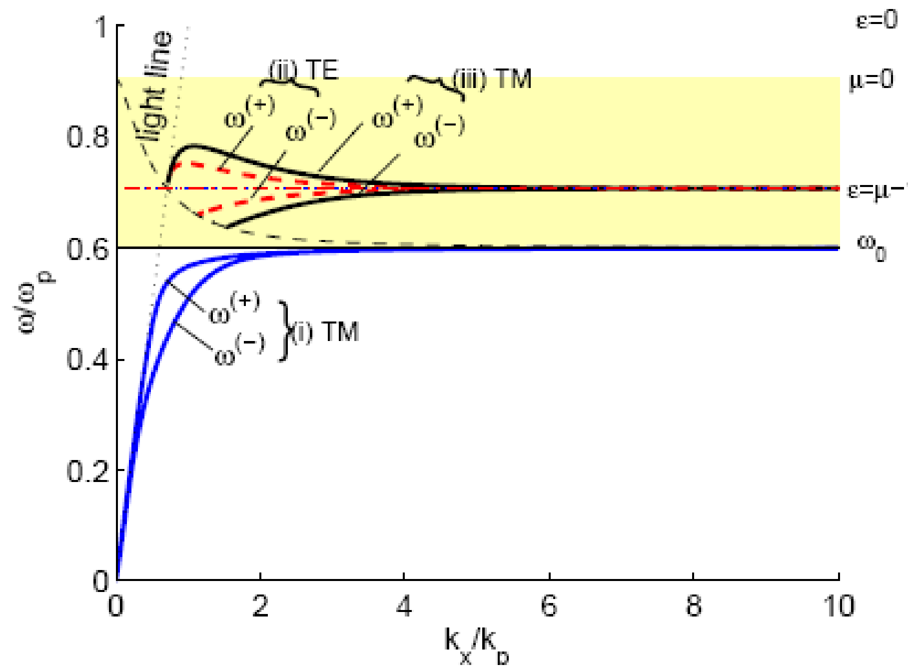


SPP dispersion for single interface. $F = 0.56$, $\omega_0 = 0.8\omega_\mathrm{p}$.(a) $\omega - k_x$ diagram. (b) $\mu - \varepsilon$ diagram.

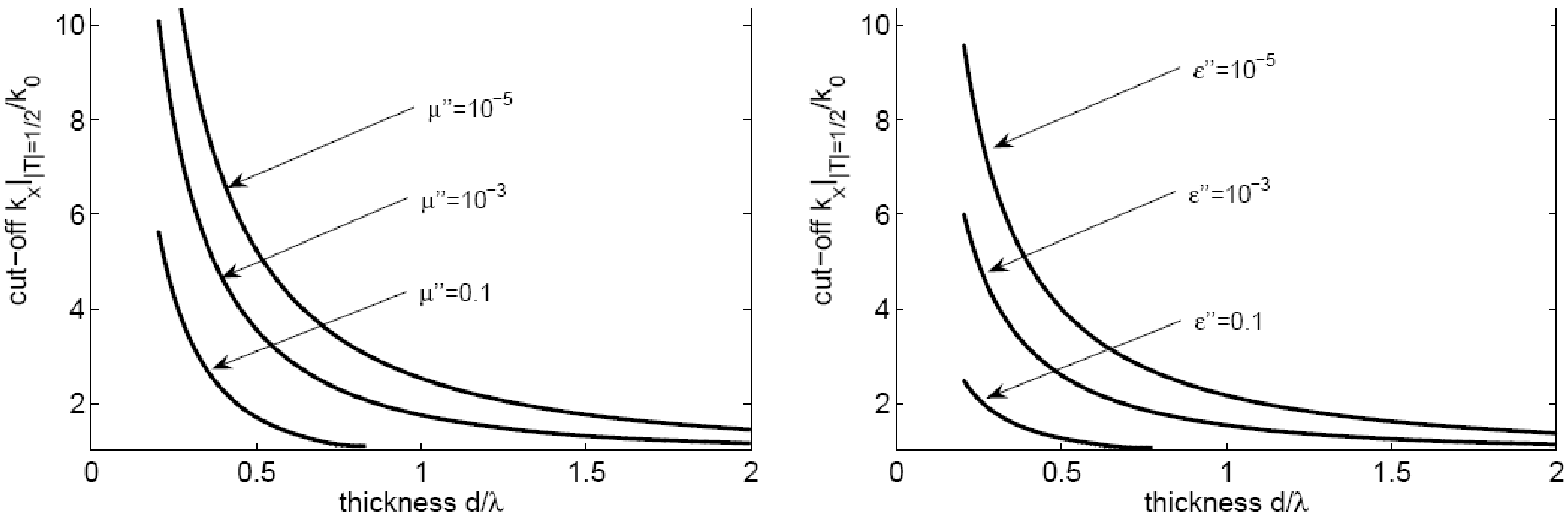
$$\varepsilon_{\mathrm{r}2} = 1 - \frac{\omega_\mathrm{p}^2}{\omega^2} \qquad \mu_{\mathrm{r}2} = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2}.$$

SLAB, ARBITRARY VALUES OF μ,ε





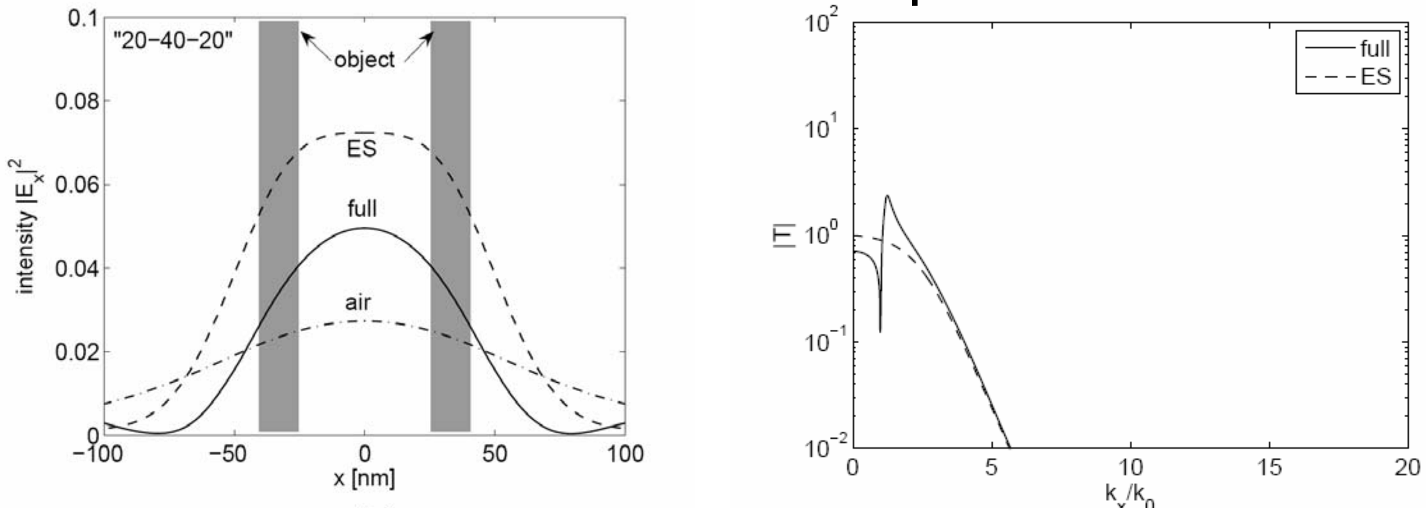
$\varepsilon \simeq -1,\ \mu \simeq -1$: Near-perfect? Near-sighted!



In order to achieve a cut-off at 10 k_0 (for resolution λ/10)
a slab of d=0.1 λ tolerates a loss of 0.002,
a slab of d=0.67 λ tolerates a loss of not more than 10^{-19}!

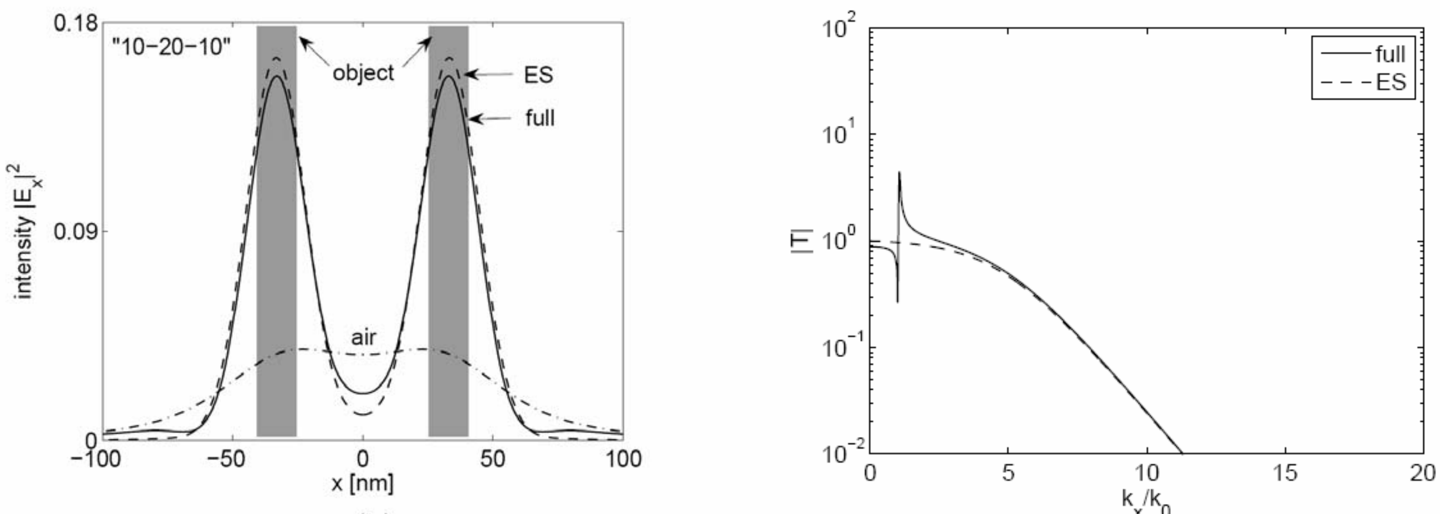
Podolskiy and Narimanov (2005)
Smith *et al.* (2003), French *et al.* (2006).

Silver lens: Near-perfect?



(a)

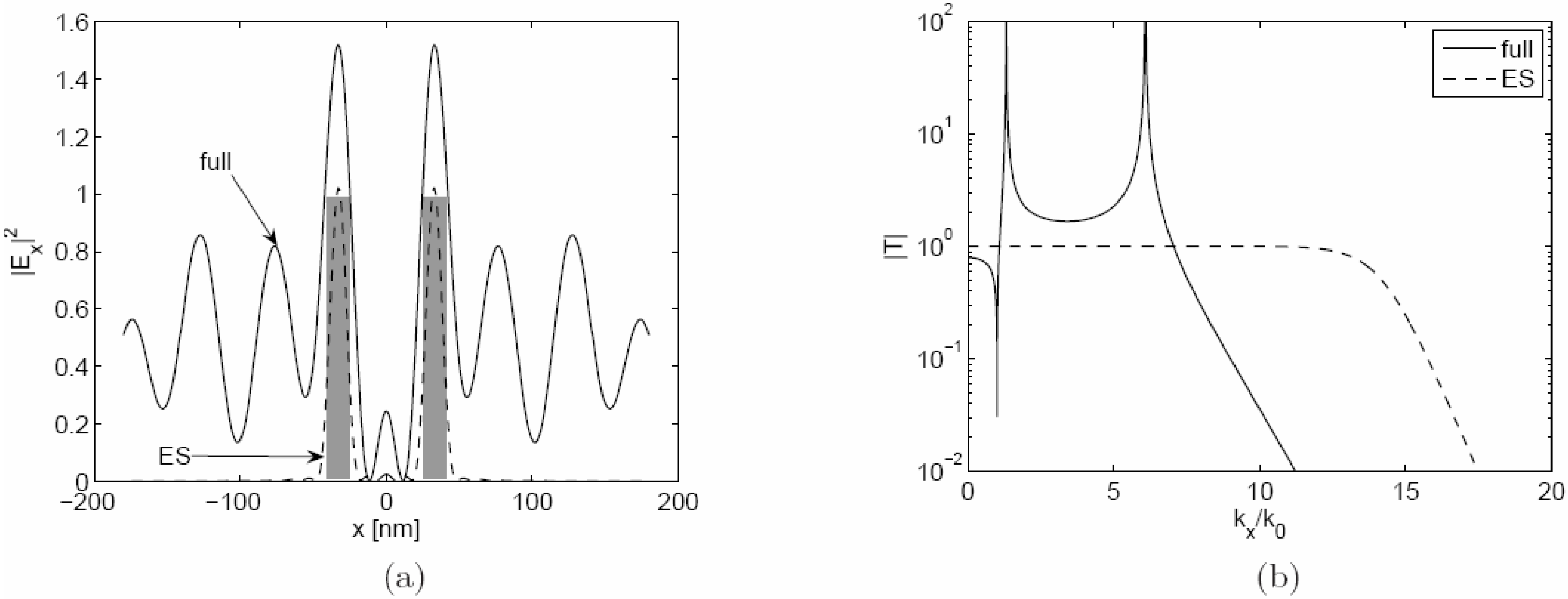
d=40 nm
thick!



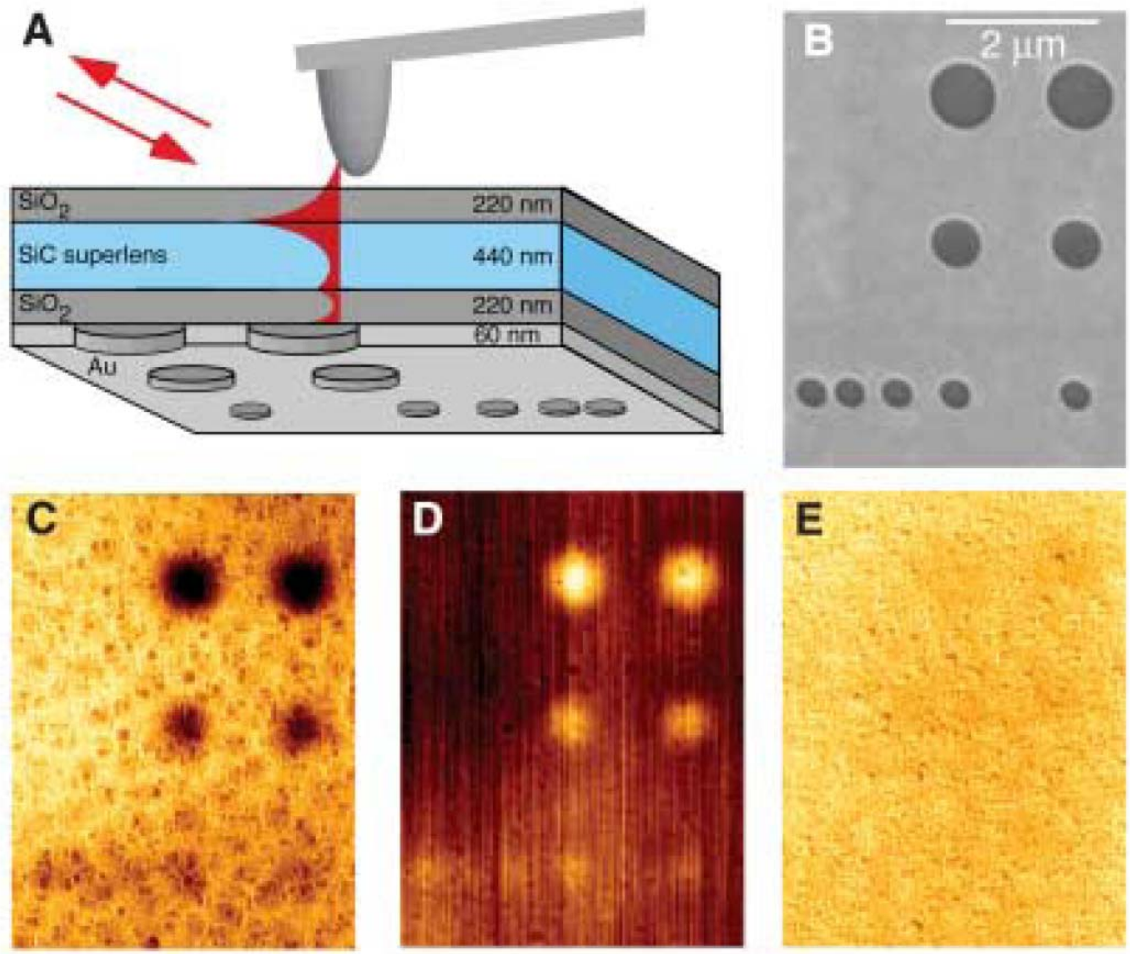
(b)

d=20 nm

Silver lens: perfect without losses? No!



Experiment: SiC Superlens for IR



Near-Field Microscopy Through a SiC Superlens

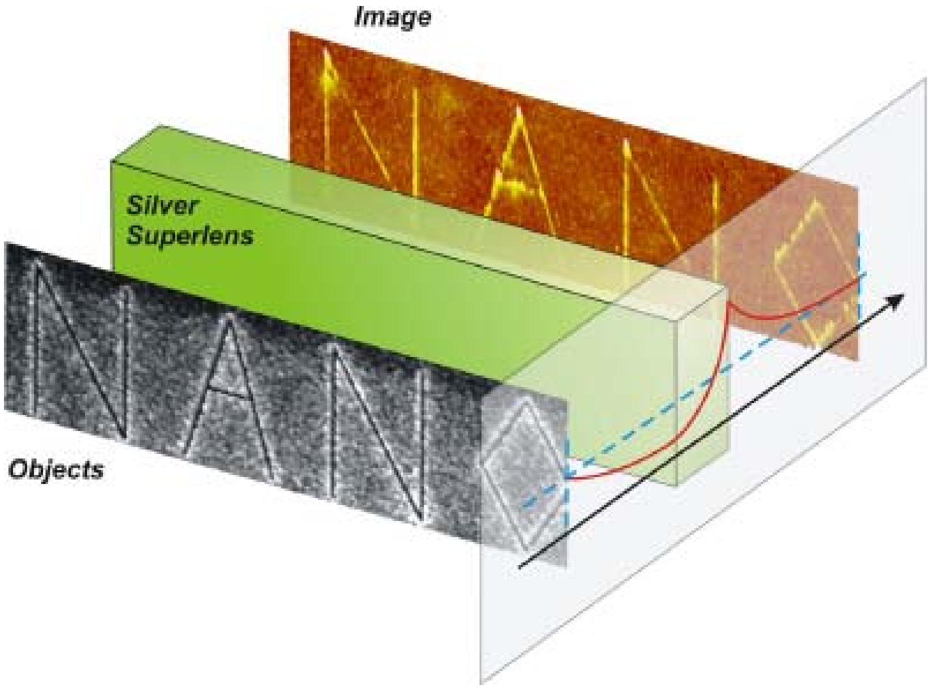
Thomas Taubner,[1*] Dmitriy Korobkin,[2] Yaroslav Urzhumov,[2] Gennady Shvets,[2] Rainer Hillenbrand[1]†

- Resolution $\lambda/20$ (λ=10.85μm)
- Optical Signal Processing

Fig. 1. Near-field microscopy through a 880-nm-thick superlens structure: (**A**) Experimental setup. (**B**) Scanning electron micrograph (mirrored) of the object plane, showing holes in a 60-nm-thick Au film. (**C**) Infrared amplitude in the image plane at λ = 10.85 μm where superlensing is expected. (**D**) Infrared phase contrast (λ = 11.03 μm). (**E**) Control image showing infrared amplitude at λ = 9.25 μm (no superlensing).

T. Taubner et al., SCIENCE 313, 2006

Experiment: Silver Superlens for UV



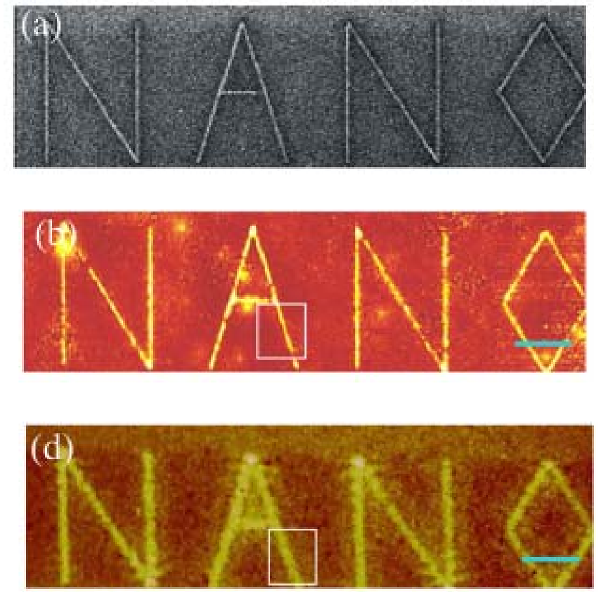
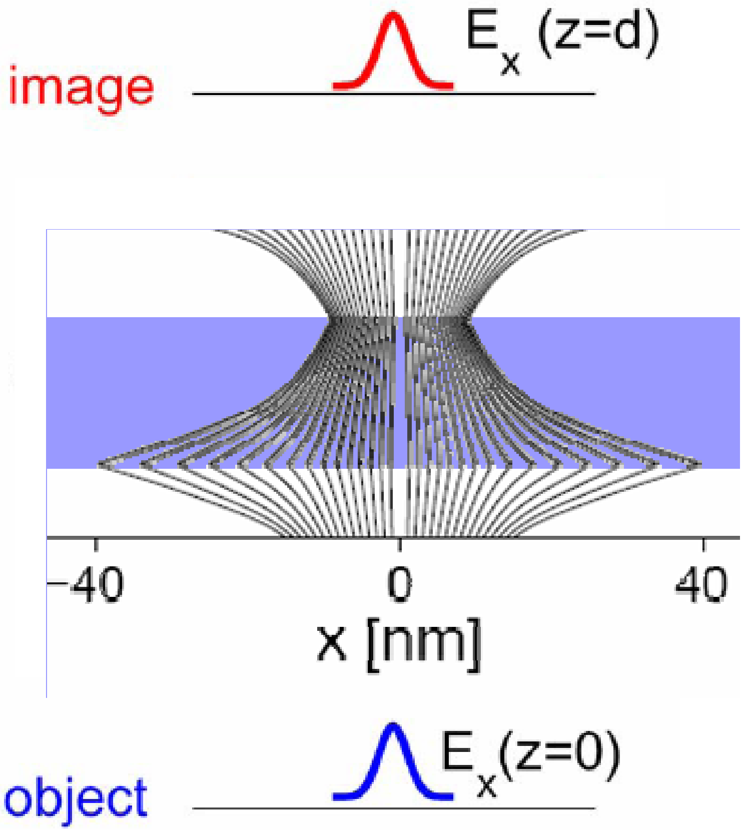


Fig.3: The image of a 2D arbitrary object "NANO". (a) FIB(Focused Ion Beam) image of the object "NANO" after fabrication on Cr film. (b) Superlensing image (scale bar 2um) and (c) its cross-section profile. (d) Control imaging result of the same object(scale bar 2um) and (e) its average line cross-section.

N Fang et al., Science 308, 2005

Silver slab: Poynting vector optics



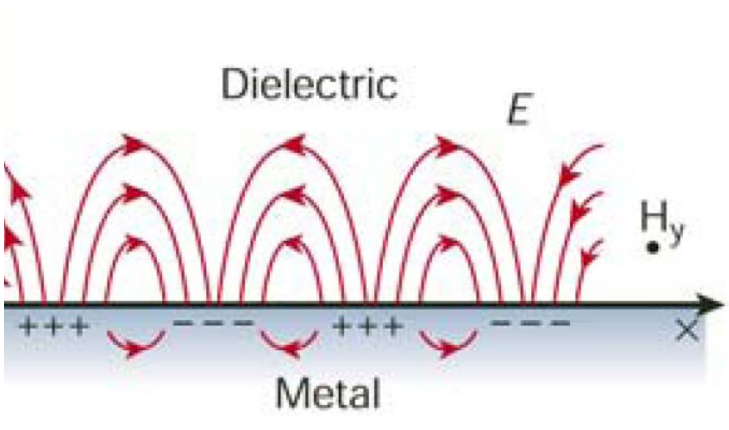
NEGATIVE REFRACTION?!
(only ε is negative!)

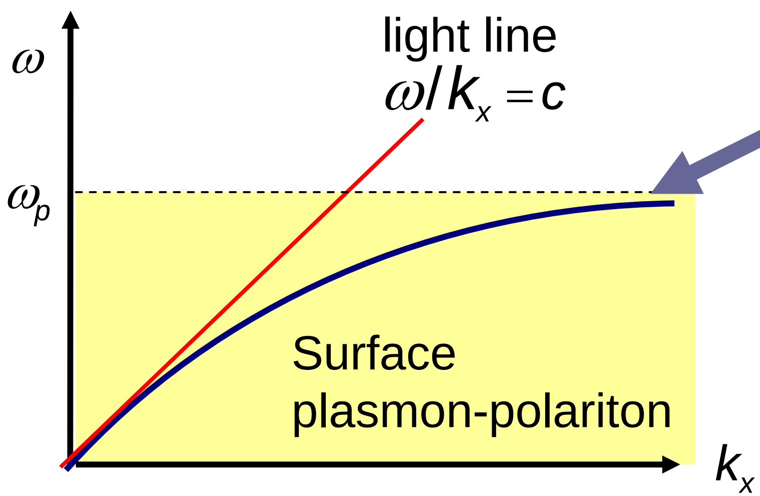
ε=-1-jα, α=10^{-4}

Shamonina et al., Electron. Lett. (2001)

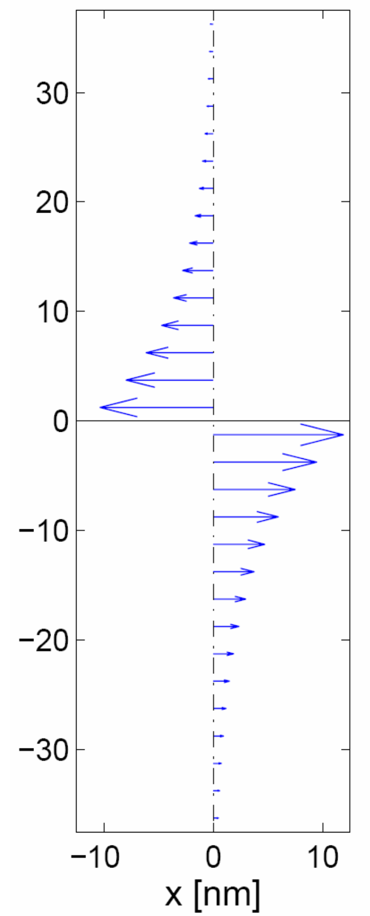
Shamonina et al., PIERS 2002

NEGATIVE REFRACTION?! (only ε is negative!)





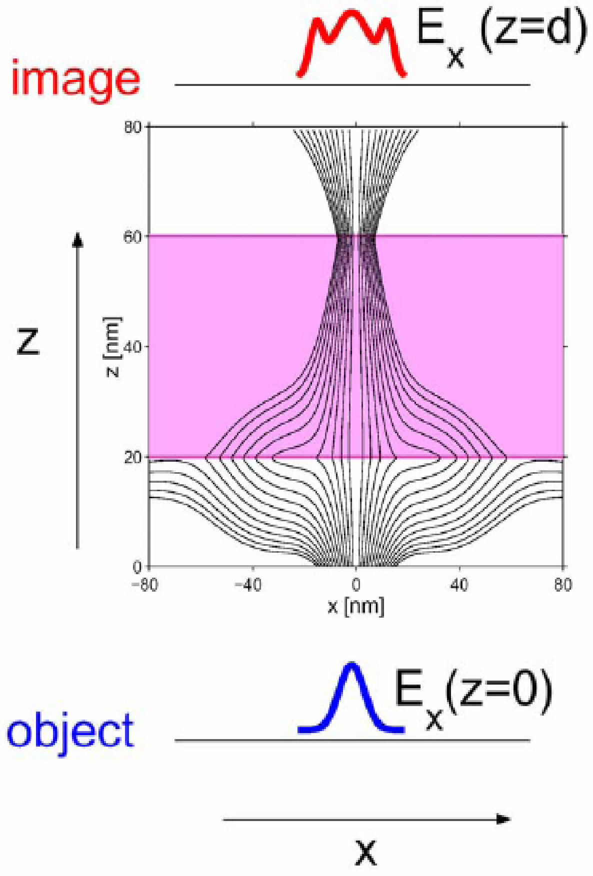
Group velocity near zero!

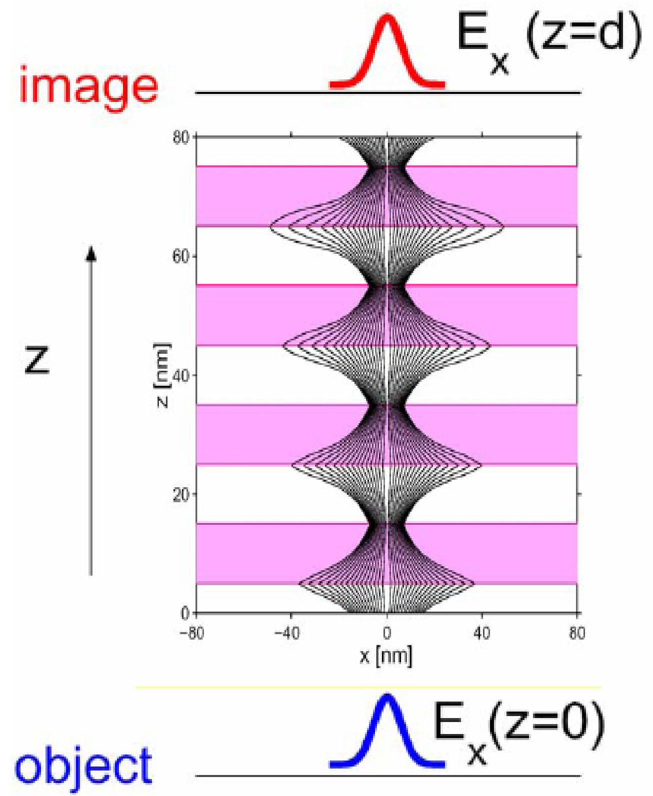


Poynting vector

Multilayered superlens

60nm slab too thick for λ=360nm!





Microscopic picture: „Poynting vector optics"

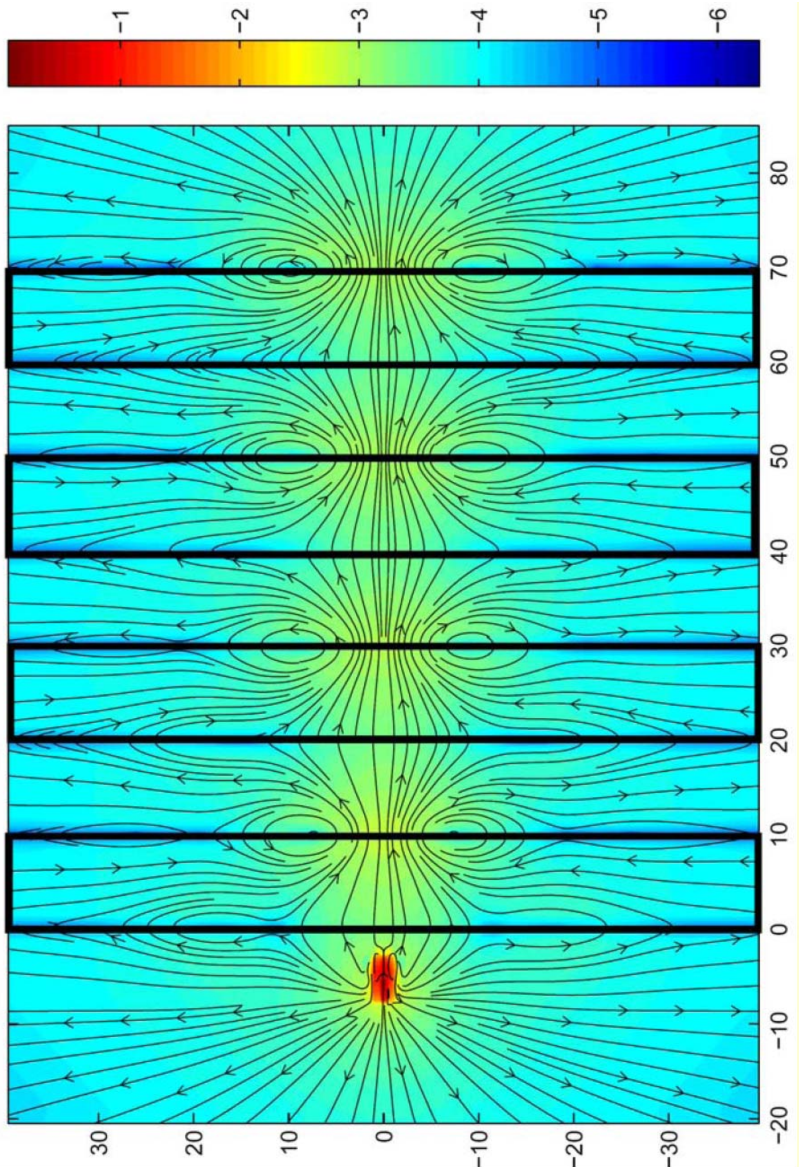
λ=360nm, $\varepsilon=-1-j\alpha$, $\alpha=0.1$

$\varepsilon=-1-j\alpha$, $\alpha=10^{-4}$

Shamonina et al., Electron. Lett. (2001)

Shamonina et al., PIERS 2002

Multilayered superlens



Microscopic picture:
„Poynting vector
optics”

Numerical simulation
(CST Microwave Studio)

E.Tatartschuk (Erlangen)

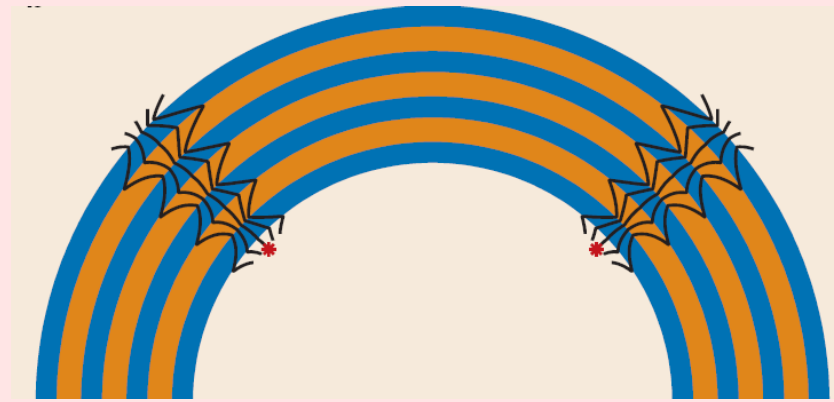
Magnifying multilayered superlens

Microscopic picture: „Poynting vector optics“

flat „near-sighted“ lens

!

cylindrical „far-sighted“ lens

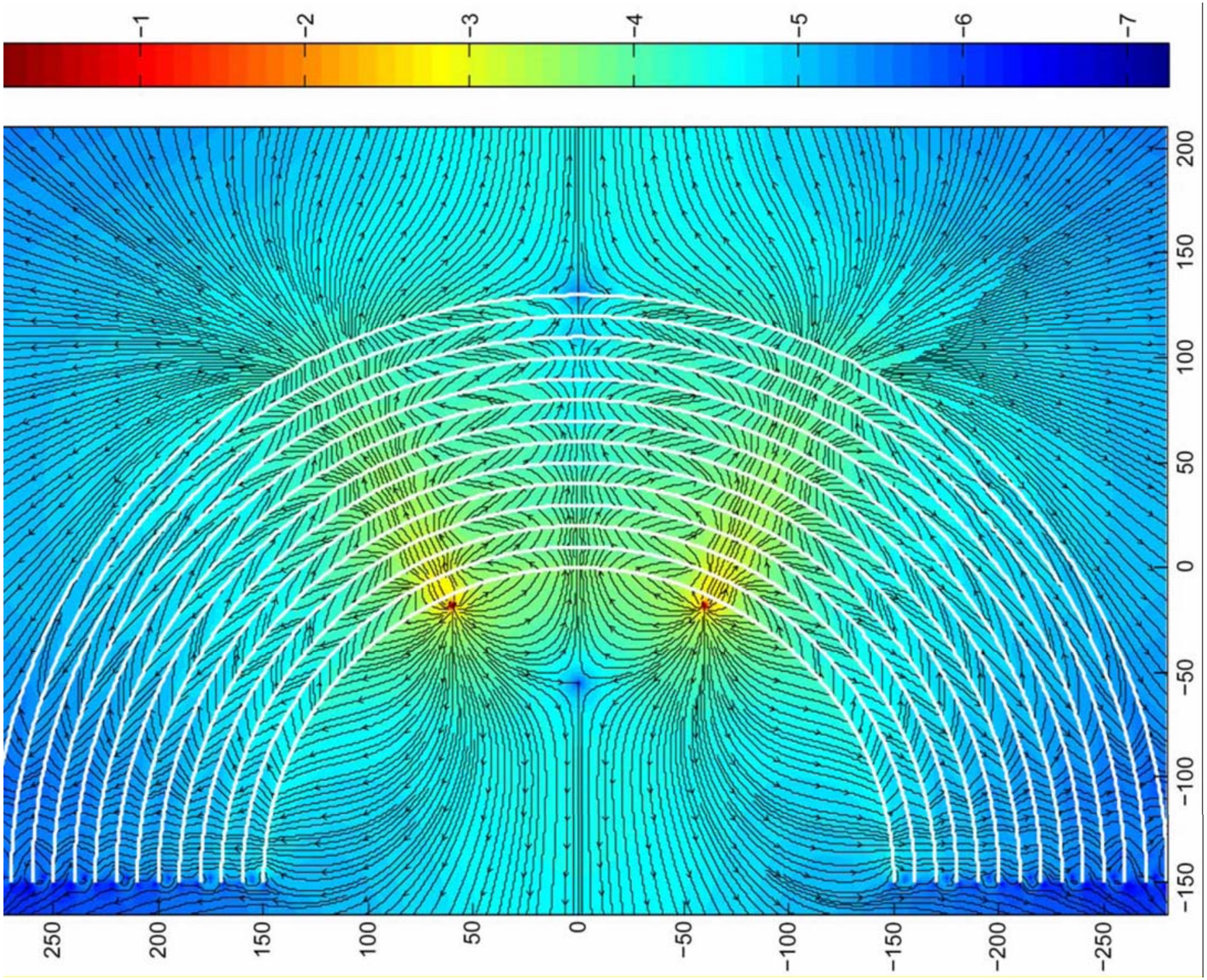


The image is not magnified

The image is magnified and can be captured with an optical microscope

Theory: Jacob et al. Opt. Expr. (2006), Salandrino and Engheta, Phys. Rev. B (2006)
Experiment: Liu et al. Science (2007), Smolyaninov et al., Science (2007)

Magnifying multilayered superlens: simulation



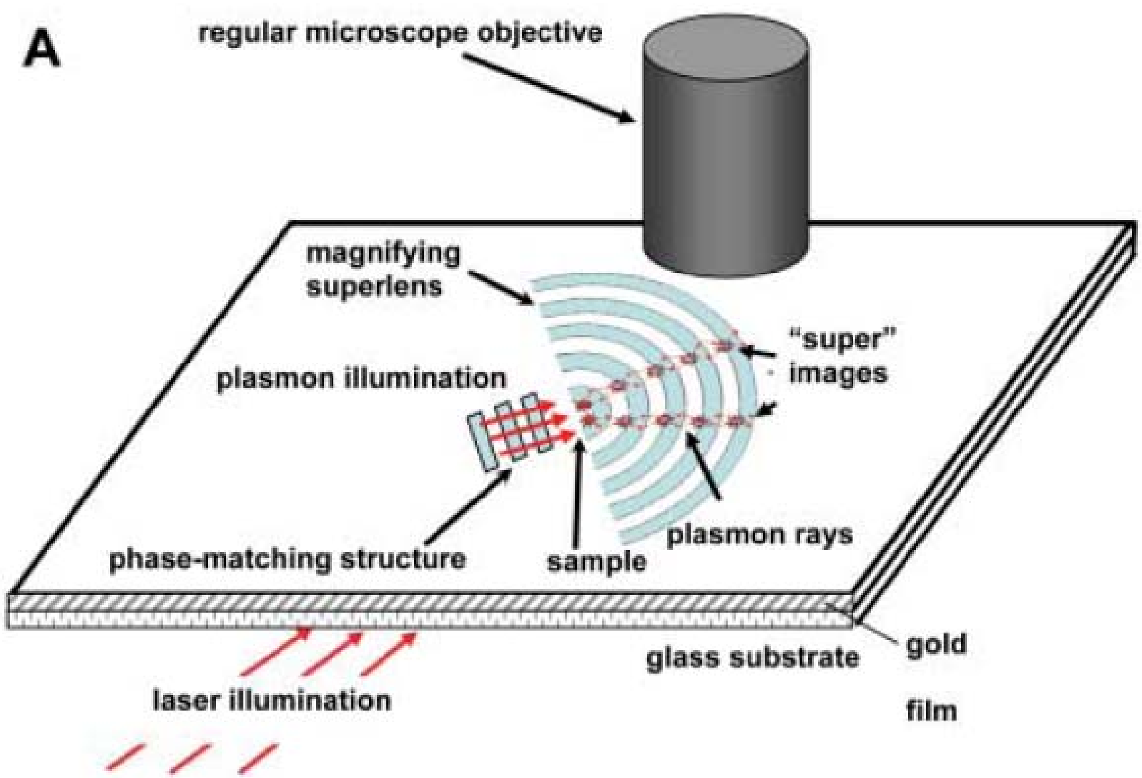
Microscopic picture:
„Poynting vector optics"

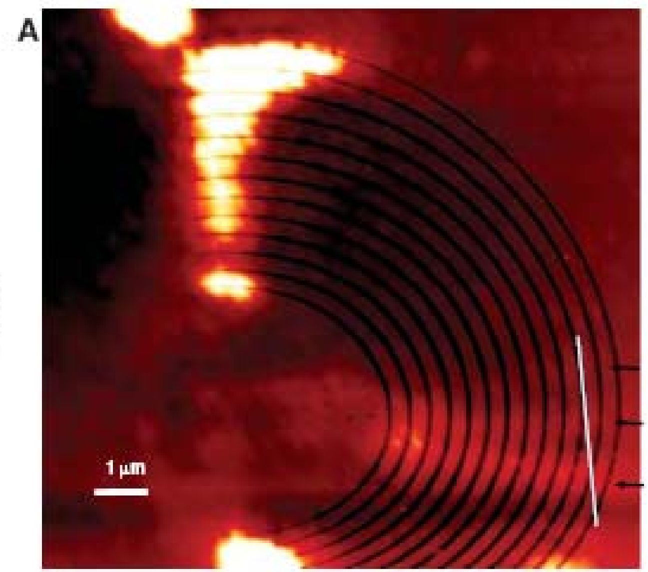
Numerical simulation (CST Microwave Studio): E.Tatartschuk (Erlangen)

Cylindrical multilayered superlens: experiment

Magnifying Superlens in the Visible Frequency Range

Igor I. Smolyaninov,* Yu-Ju Hung, Christopher C. Davis



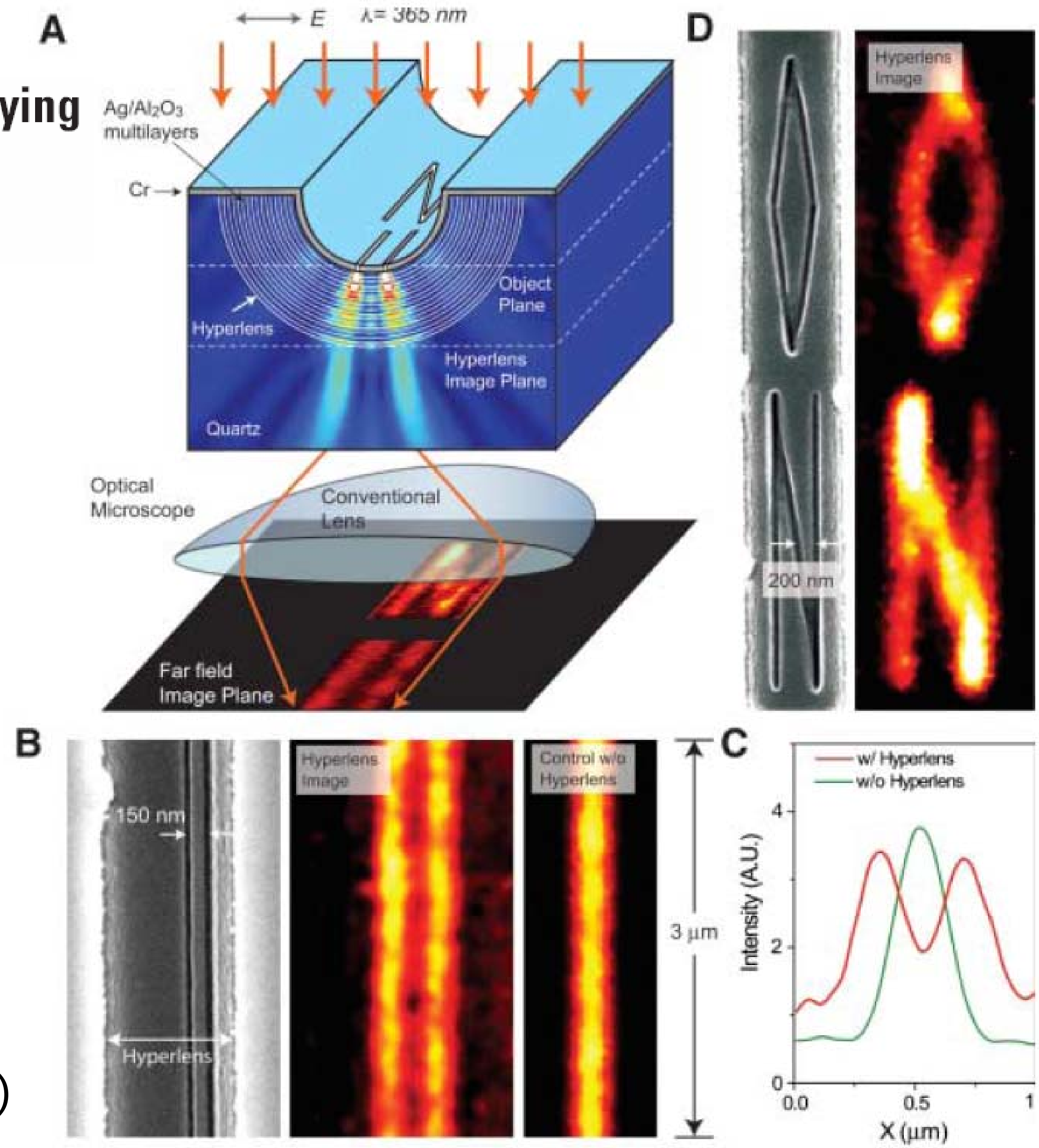


I.I. Smolyaninov et al., Science 315 (2007)

Cylindrical multilayered superlens: experiment

Far-Field Optical Hyperlens Magnifying Sub-Diffraction-Limited Objects

Zhaowei Liu,* Hyesog Lee,* Yi Xiong, Cheng Sun, Xiang Zhang†



Z. Liu et al., Science 315 (2007)

Metamaterials

Physics

Extension of electromagnetism

"inverse" electromagnetic phenomena

- inverse Snell's law (negative refraction of rays)
- inverse Doppler shift, Cherenkov radiation, Goos-Haenchen shift
- "growing" evanescent waves

Applications

- "Perfect lens", subwavelength imaging in photonics
- Invisibility and cloaking
- "Nano-circuits", miniaturisied waveguide components
- Medical imaging

Basics of single negative and double negative metamaterials

Summary

- Definition of single negative and double negative media
- Properties and resulting applications

- Common ε-negative and μ-negative media
- How they work

- Example: Near field imaging with silver superlens

Summary

- Definition of single negative and double negative media
- Properties and resulting applications

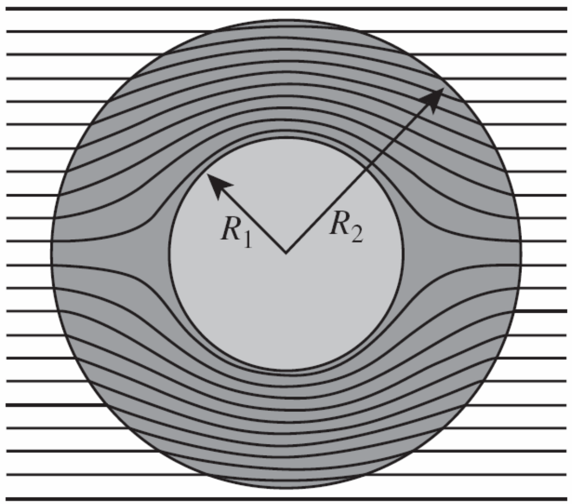
- Common ε-negative and μ-negative media
- How they work

- Example: Near field imaging with silver superlens

↓

- Near field imaging with magnetic metamaterials
(Anna Radkovskaya's lecture)

Invisibility and cloaking



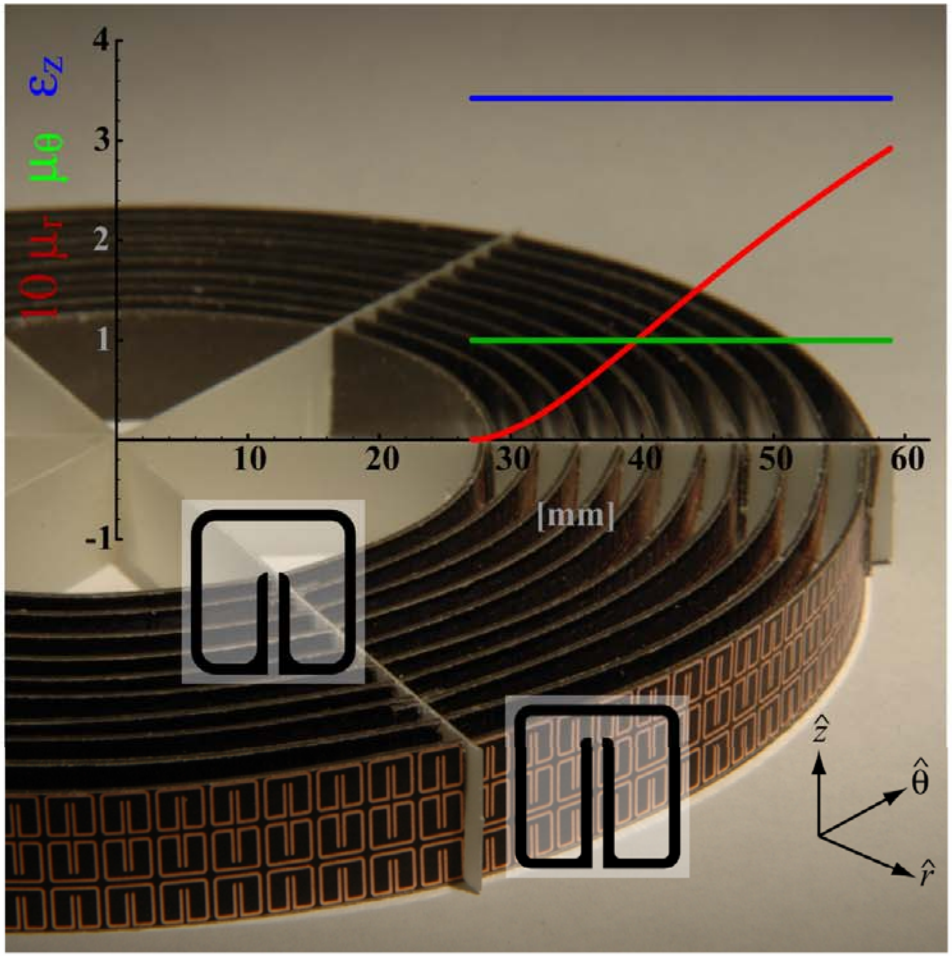
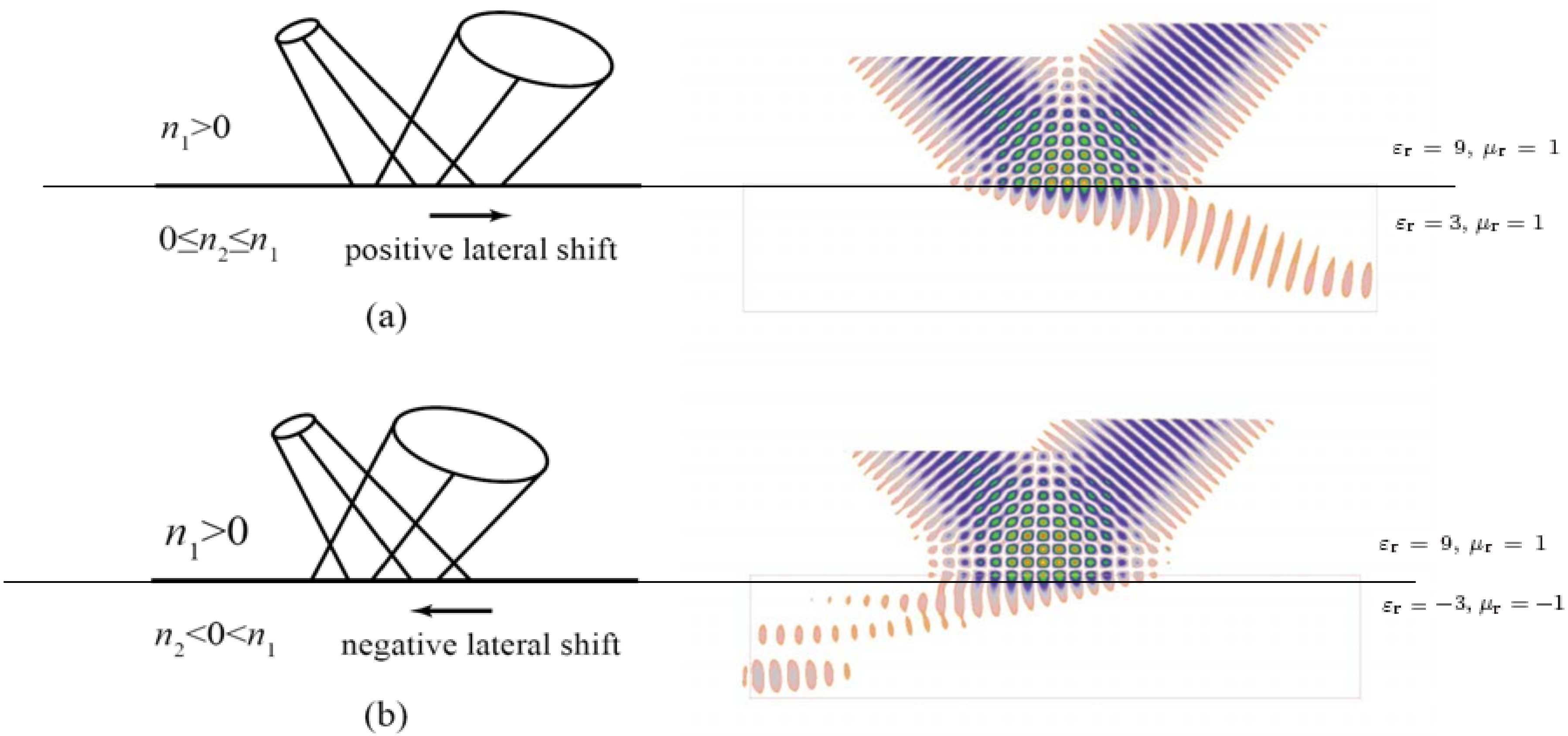


Fig. 9.24 2D microwave cloaking structure with a plot of the material parameters implemented. μ_r (red line) is multiplied by a factor of 10 for clarity. μ_θ(green line) $= 1$, $\varepsilon_z = 3.423$. The SRRs of cylinder 1 (inner) and cylinder 10 (outer) are shown in expanded schematic form. From Schurig *et al.* (2006).

Positive and negative Goos-Haenchen Shift



Ziolkowski 2003