‘Negative’ World of Metamaterials
or
How Ambiguity of Square Root Reversed Electromagnetics

“Negativan” svijet metamaterijala
ili
kako je dvoznačnost kvadratnog korijena okrenula elektromagnetizam naglavačke

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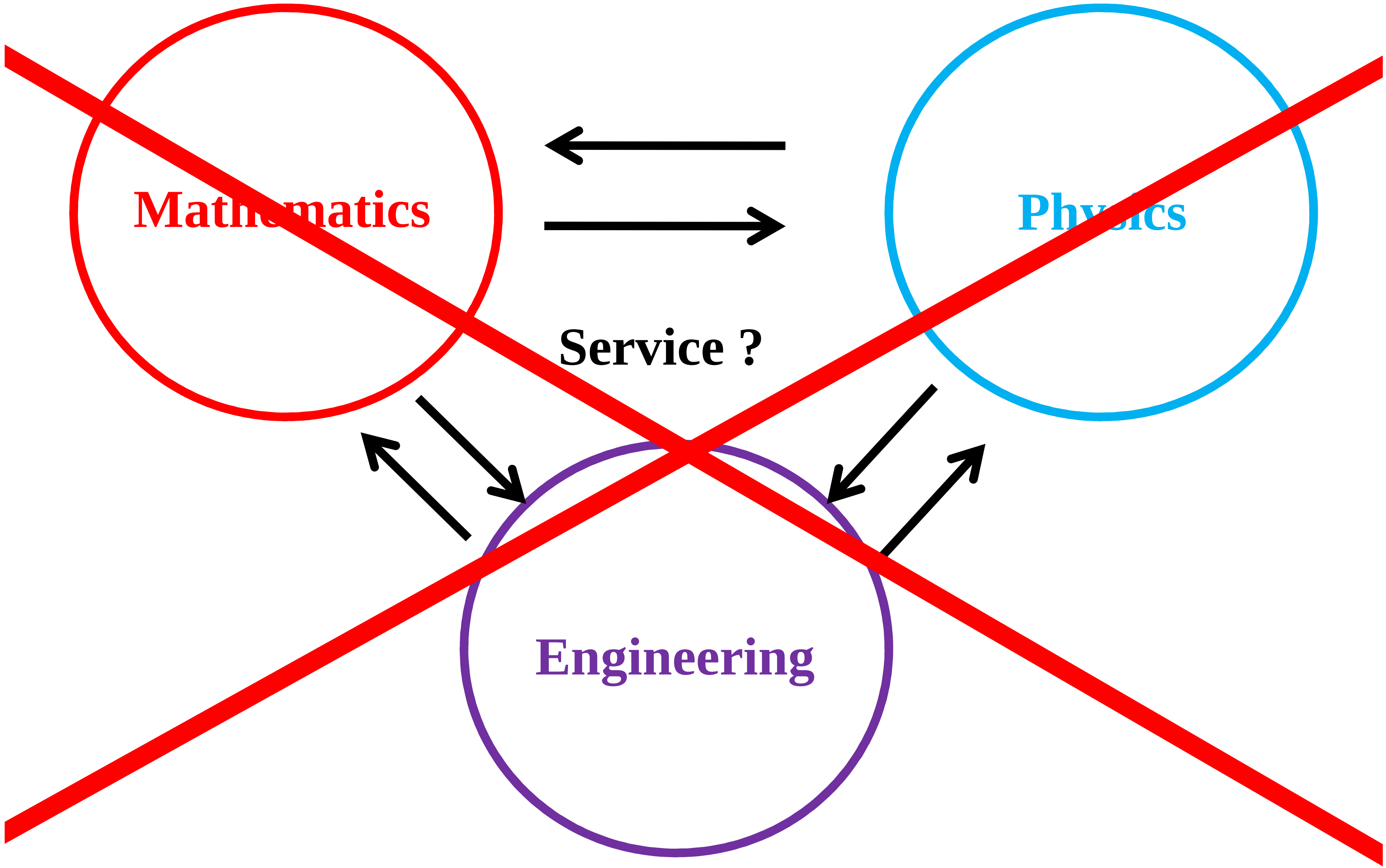
Outline

- Mathematics versus Physics and Engineering
- Electromagnetics of Classical ("Positive") Materials
- Are "Negative" Materials Possible?
- New Physical Phenomena - Fundamental research
- Potential Engineering Applications – Applied Research
- Conclusions

Mathematics versus Physics and Engineering


Mathematics
Physics
Service ?
Engineering

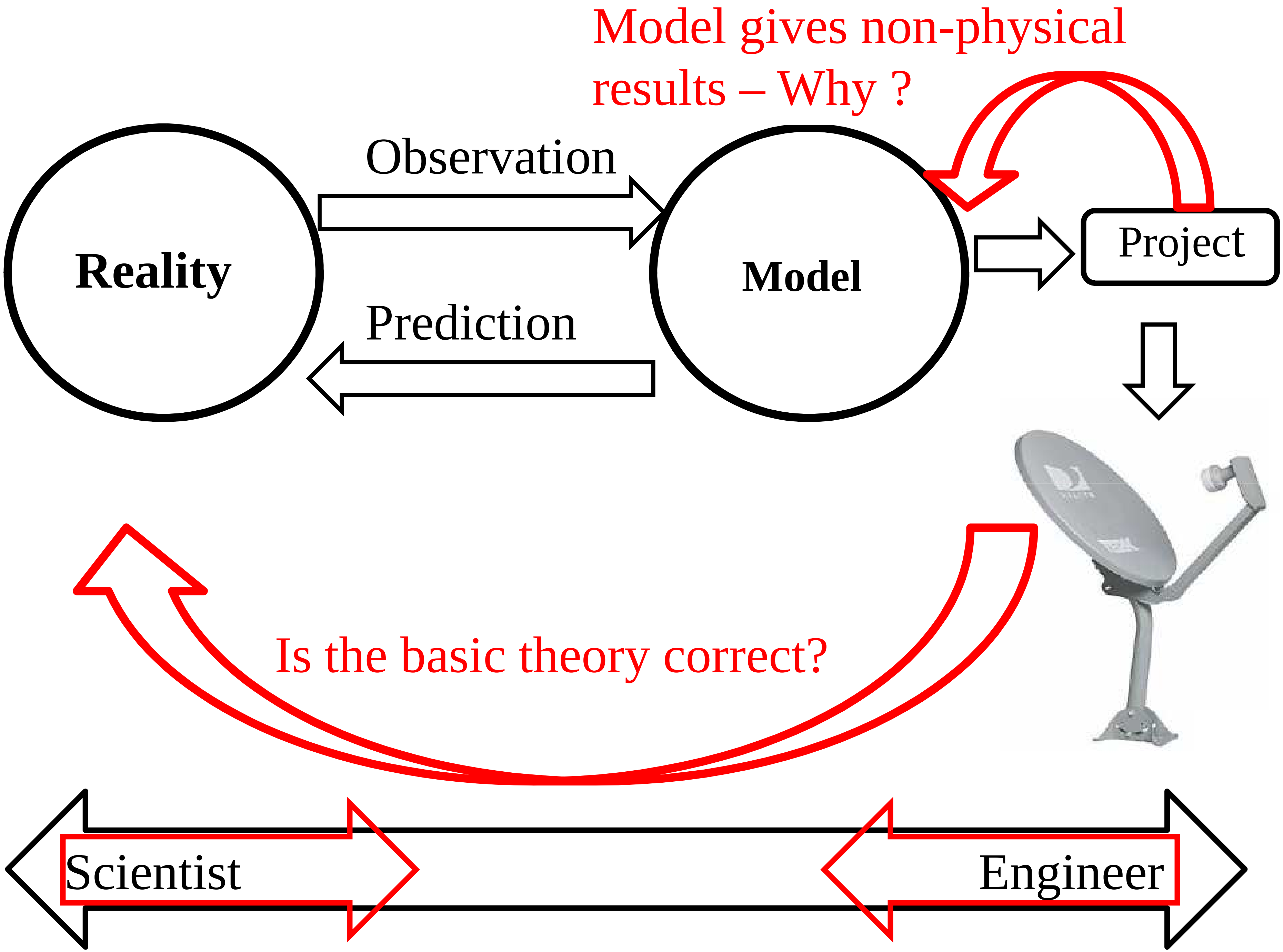
What is the difference among engineers , physicists and mathematicians ?

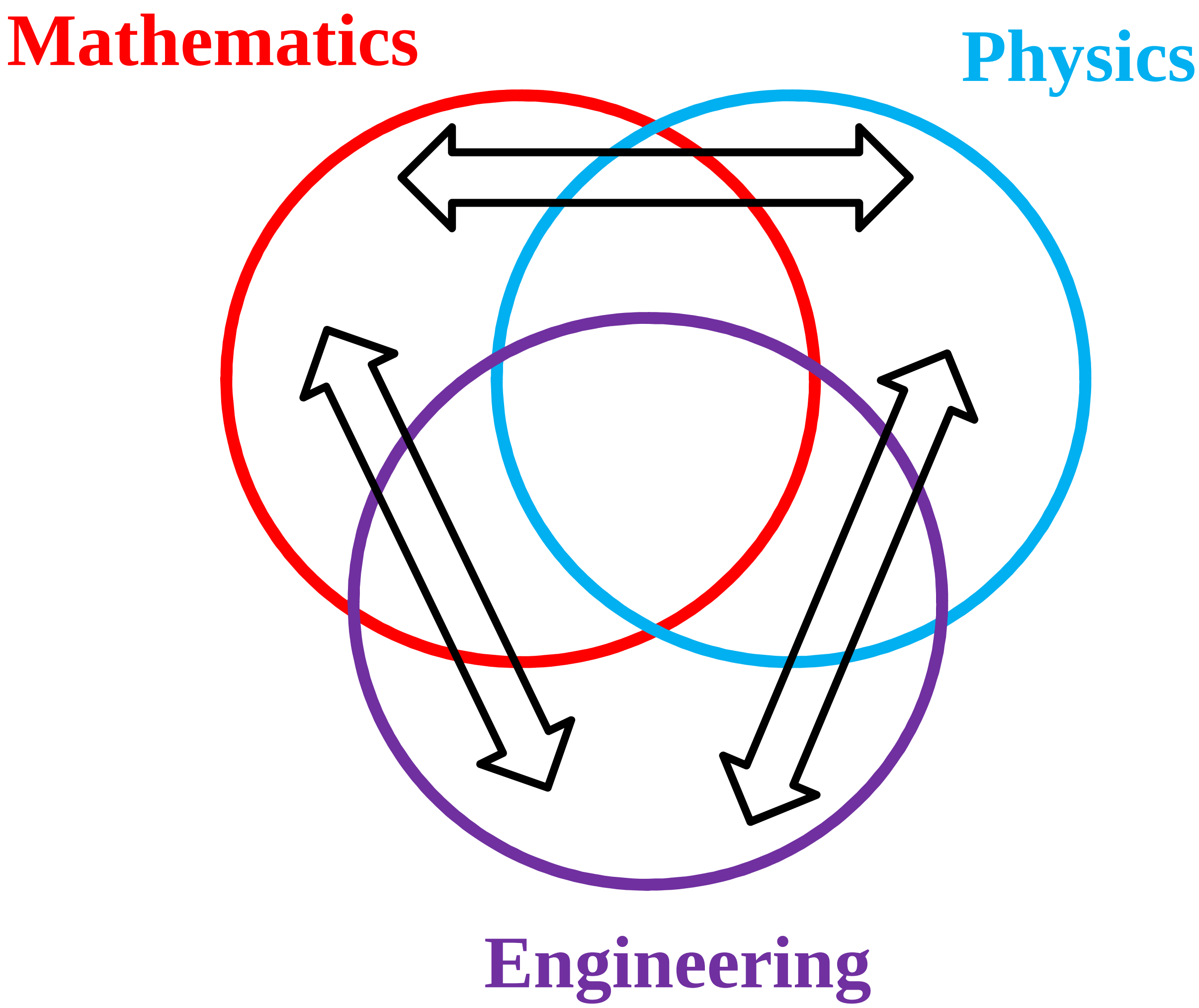
Theodor von Karman

(1881-1963)

Scientists look at things that are and ask "why";

Engineers dream of things that never were and ask "why not"

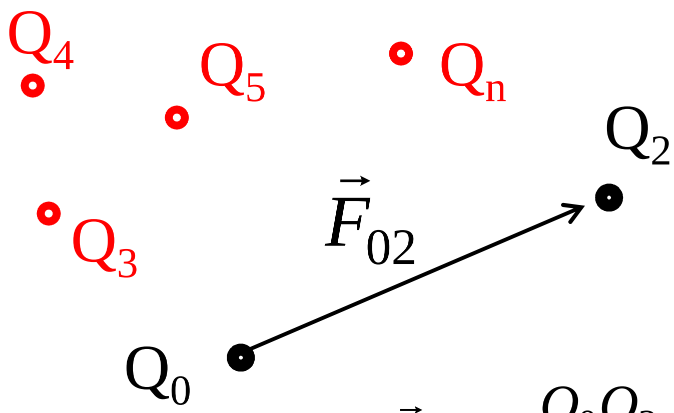

Model gives non-physical results – Why ?
Observation
Reality
Model
Project
Prediction
Is the basic theory correct?
Scientist
Engineer


Mathematics
Physics
Engineering

Electromagnetics of Classical (“Positive”) Materials

The Story of Electricity

- **Ancient Greece – Why does amber attract papyrus ?**
- **Charles Augustin de Coulomb (1736-1806) and concept of Electric field**



$$\vec{F} = K\frac{Q_0 Q_2}{R_{02}^2}\vec{a}_{12}$$

$$\vec{F} = K\frac{Q_0 Q_2}{R_{02}^2}\vec{a}_{12} + K\frac{Q_0 Q_3}{R_{03}^2}\vec{a}_{13} + \ldots K\frac{Q_0 Q_n}{R_{0n}^2}\vec{a}_{1n}$$

$$\vec{E} = \lim_{Q_0 \to 0}\frac{\vec{F}}{Q_0}$$

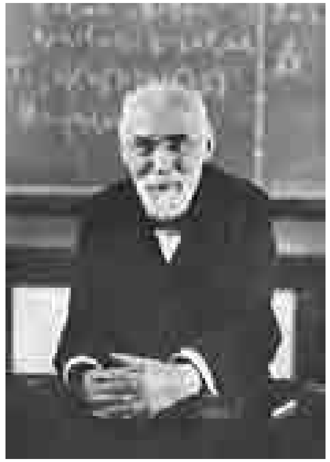
$$\vec{F} = Q_0\left[K\left(\frac{Q_2}{R_{02}^2}\vec{a}_{12} + \frac{Q_3}{R_{03}^2}\vec{a}_{13}\ldots\frac{Q_n}{R_{0n}^2}\vec{a}_{1n}\right)\right] = Q_0\vec{E}$$

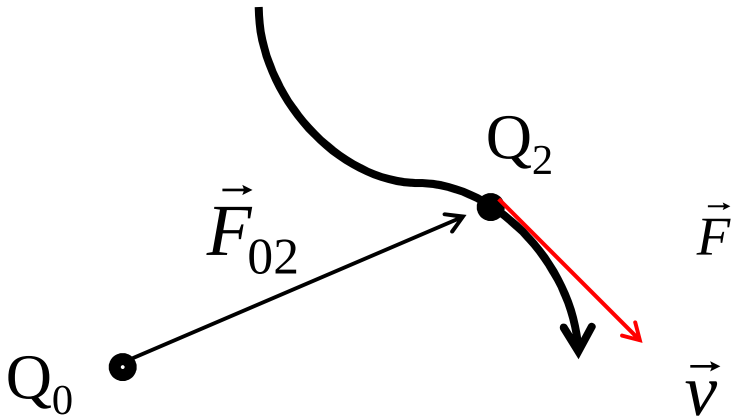
The Story of Magnetism

- **Ancient Greece – a strange rock from island of Magnesia**

Hendrik Antoon Lorentz

$$\vec{F} = Q_0\vec{E} + f(\vec{v}, Q_0, R_{02})$$
$$= Q_0\left(\vec{E} + \vec{v}\times\vec{B}\right) \quad \vec{E} \perp \vec{B}.$$

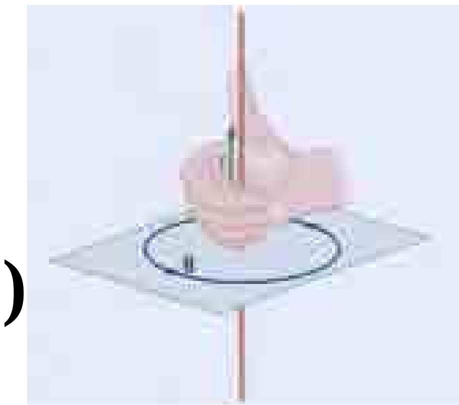




$$\vec{F} \neq Q\vec{E}$$

Concept of B field

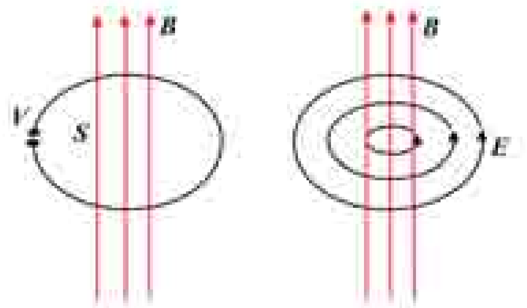
Andre Marie Ampere (1775-1836)



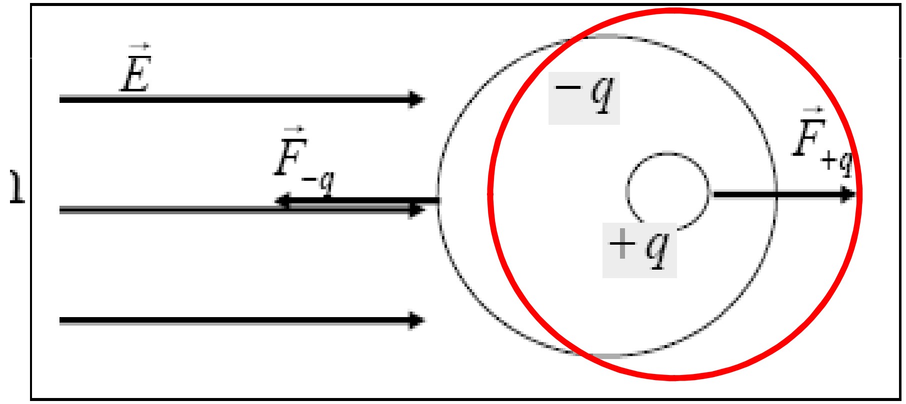
Wedding of Electricity and Magnetism – Electromagnetism (Electromagnetics)

- Michael Farady (1791-1867)

$$V = -\frac{\partial \vec{B}}{\partial t}$$



Are the E and B Vectors Enough?



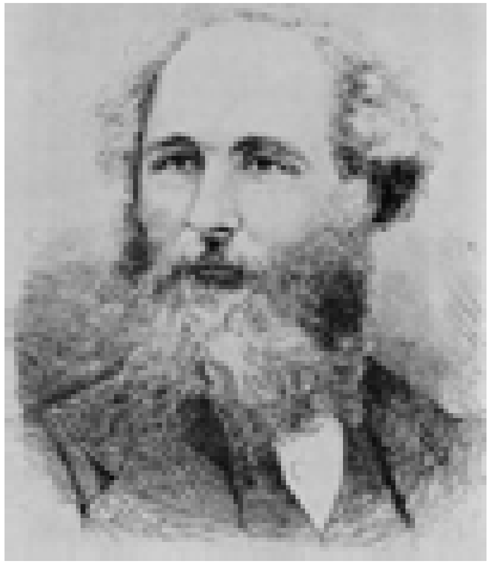
Yes in principle, but what about the influence of matter?

…atomic dimensions are on order of 10^{-11} m!

$\vec{D} = \varepsilon \cdot \vec{E}$ Electric flux density

$\vec{H} = \frac{1}{\mu} \cdot \vec{B}$ Magnetic field

James Clerk Maxwell (1831-1879)

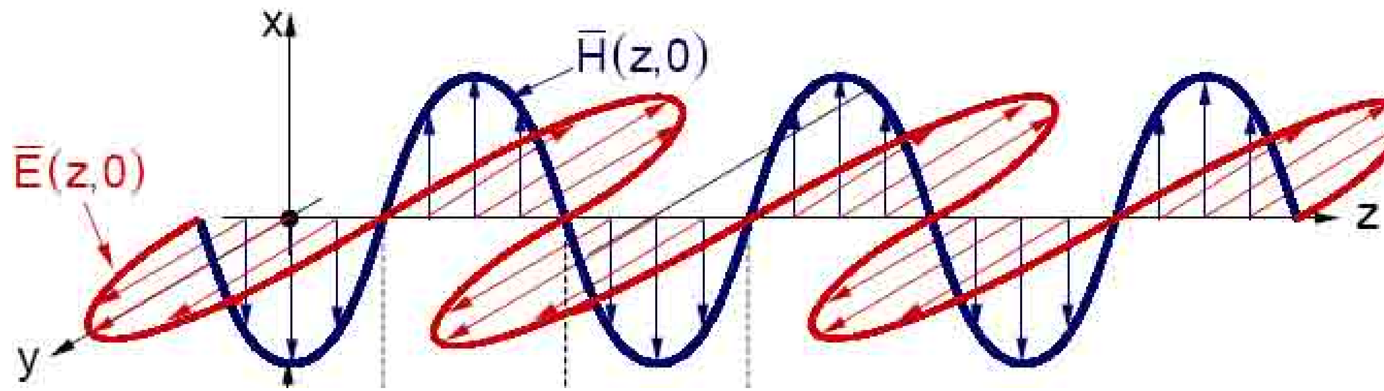


$$\nabla \times \vec{H} = \vec{J} + \varepsilon \frac{\partial \vec{E}}{\partial t}$$

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t}$$

Solution of these equations is a wave!

What is EM Harmonic Wave ?

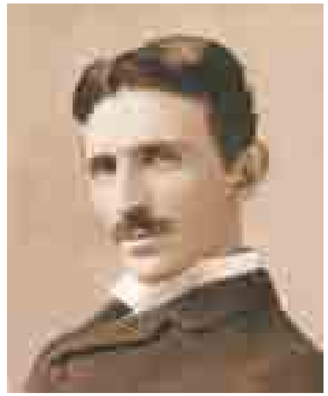


$$e(x,t) = A\cos(\omega t - k \cdot z) = \mathrm{Re}\left\{ A e^{j\omega t} e^{j\vec{k}\,\vec{z}} \right\}$$

Wave vector $\vec{k} = \dfrac{2\pi}{\lambda}\vec{a}_0$

From Theory towards Applications…

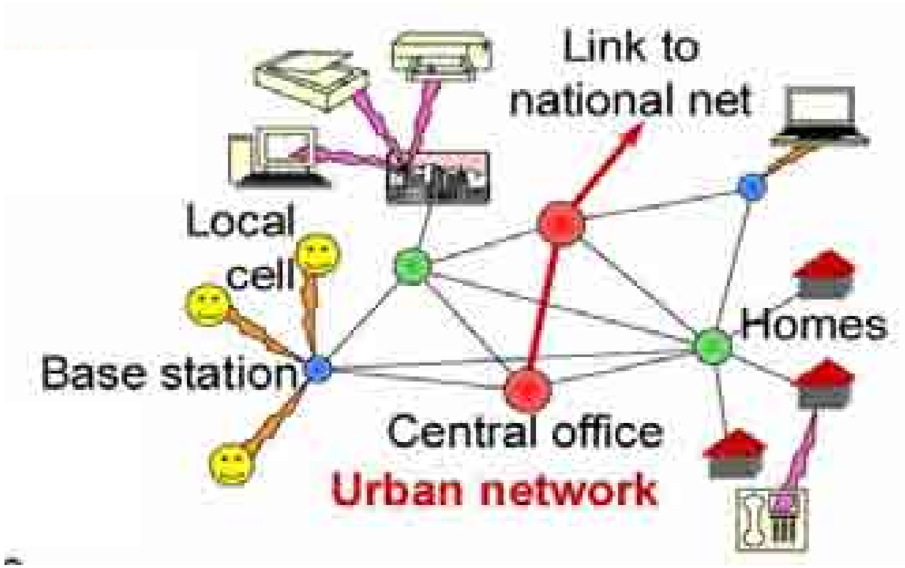
- **Heinrich Rudolf Hertz** (1857-1894)

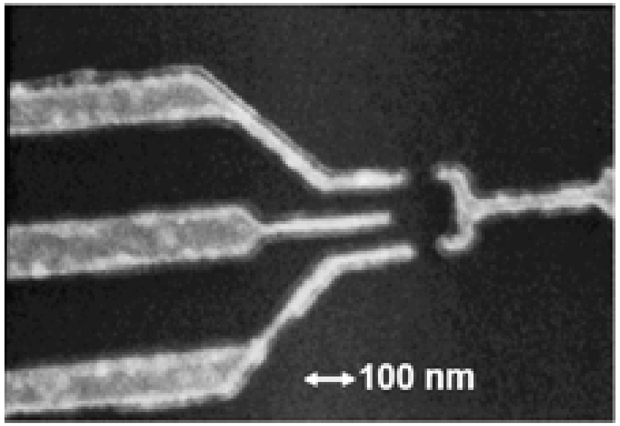


- **Nikola Tesla (**1856-1943)

- **Guglielmo Marconi (**1874-1937)

…. and here we are !





$$\vec{E}, \vec{H}, \quad \varepsilon, \mu.$$

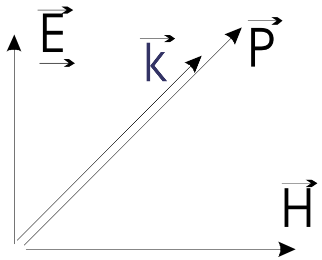
Are “Negative” Materials Possible?

(Are some solutions of Maxwell equations meaningless?)

What would happen if μ and ε were negative numbers? (Veselago, 1968)

- A plane wave solution of Maxwell equations:

Forward wave



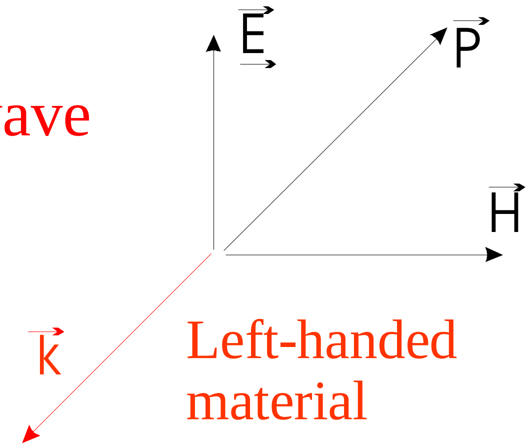
Right-handed material

$$\vec{E} = Ae^{-j\vec{k}\vec{r}}$$

$$\vec{k} = \vec{u}_0\,\omega\sqrt{\mu\varepsilon}$$

$$\vec{P} = \vec{E}\times\vec{H}$$

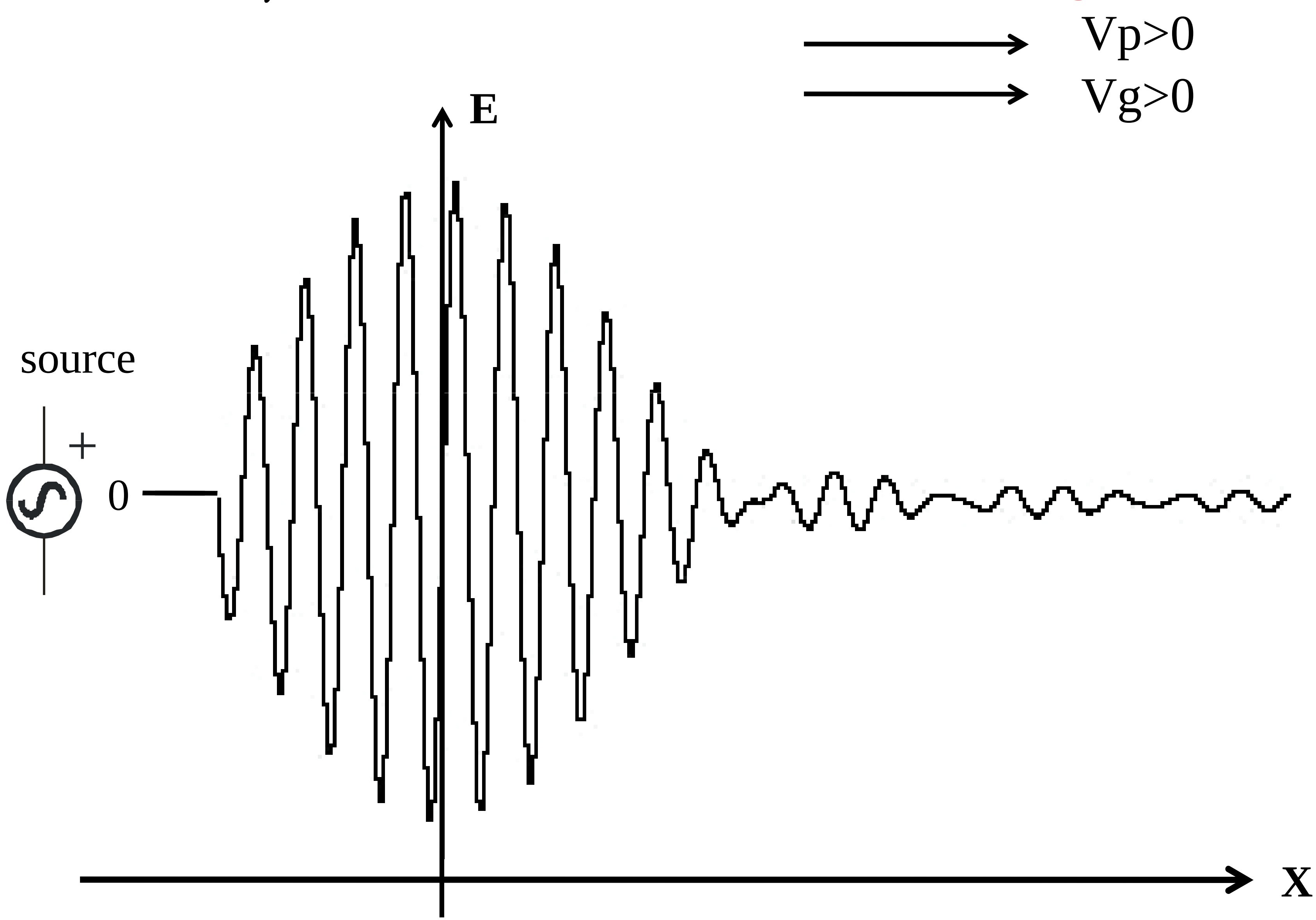
Backward wave



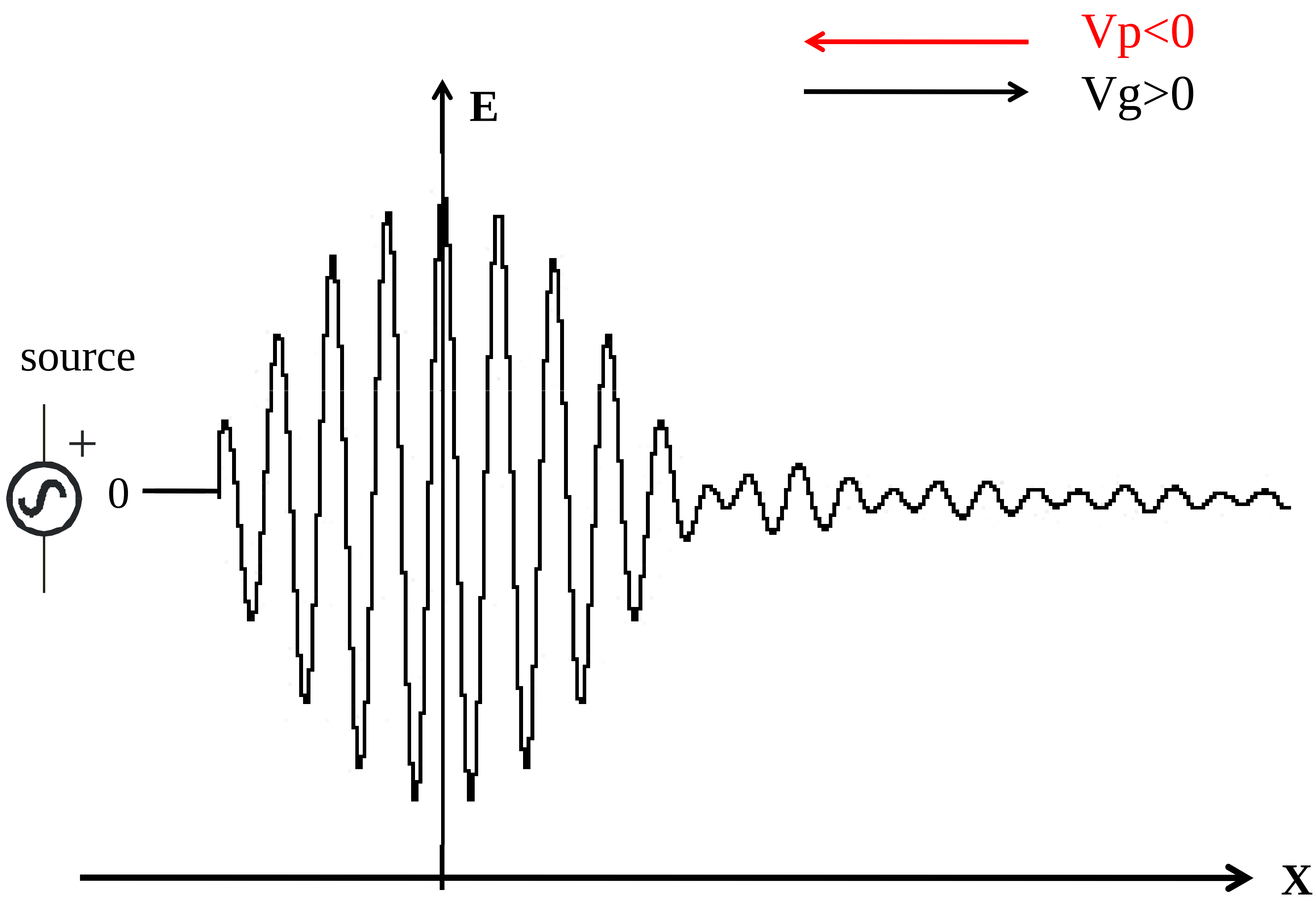
Sign ambiguity

Left-handed material

One-dimensional Wave Propagation in Material with $\mu > 0$ and $\varepsilon > 0$ (forward wave propagation)



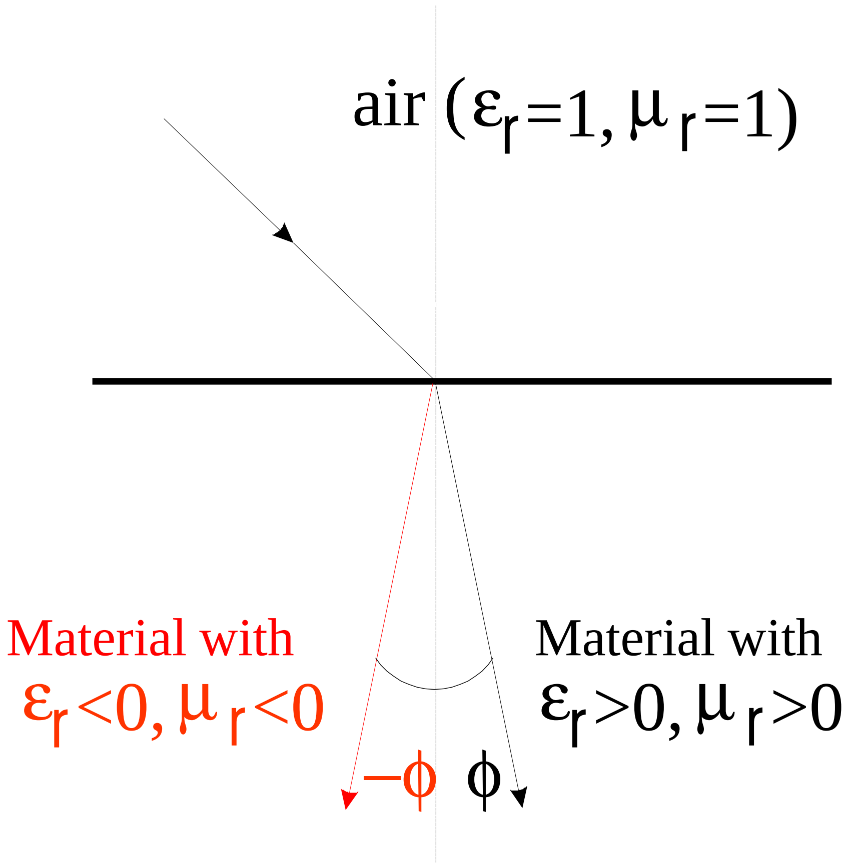
One-dimensional Wave Propagation in Material with $\mu<0$ and $\varepsilon<0$ (backward wave propagation)

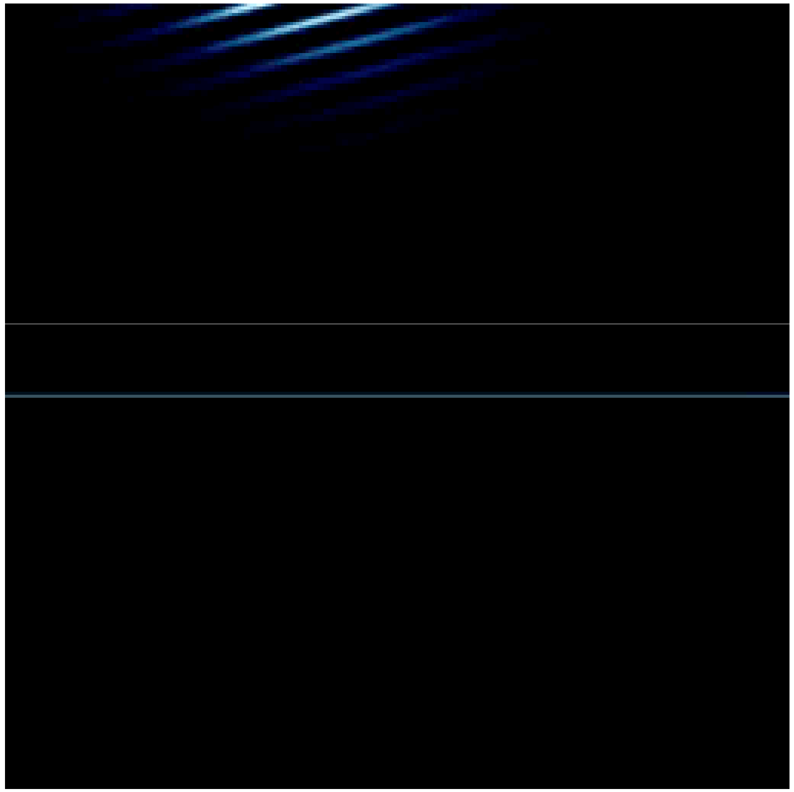


- ***P*** is **opposite** to ***k*** !

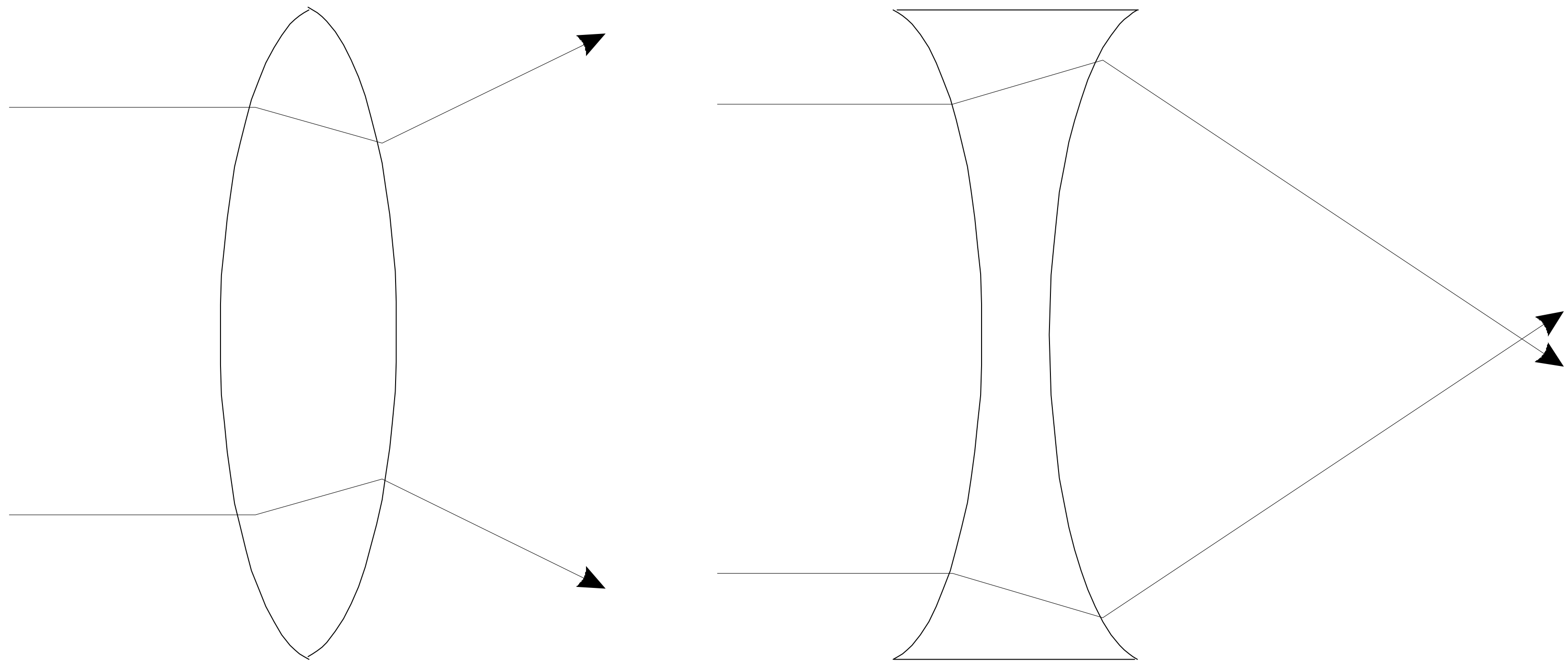
- This causes ‘reversion’ of many basic electromagnetic phenomena such as Snell law, Doppler effect e.t.c.

‘Reversion’ of Snell Law



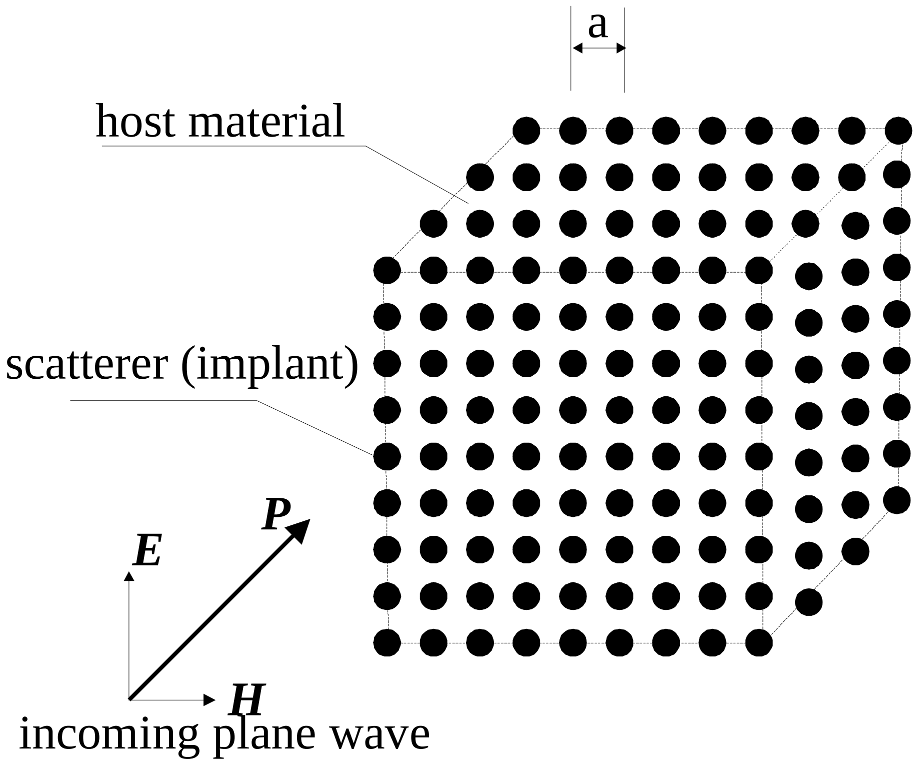


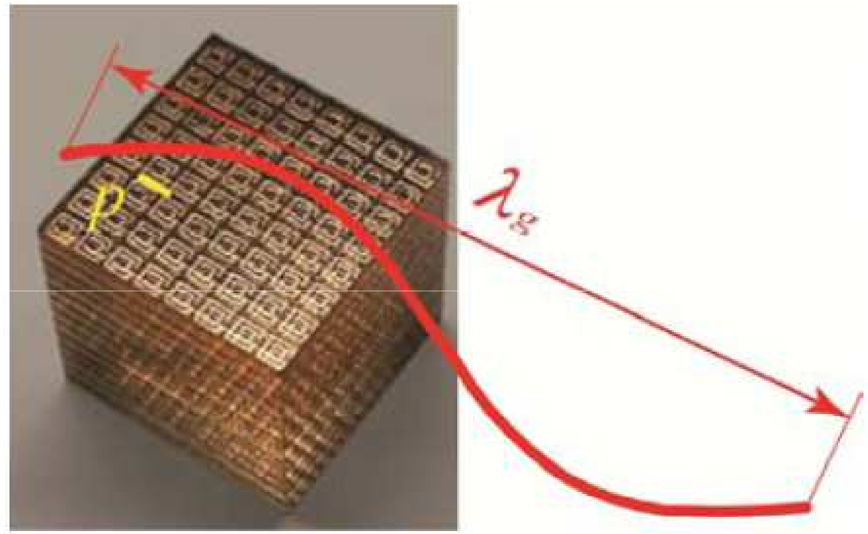
Concave and Convex Lenses using material with μ <0 and ε <0



The Concept of Metamaterial

μετα = meta = beyond (Greek)

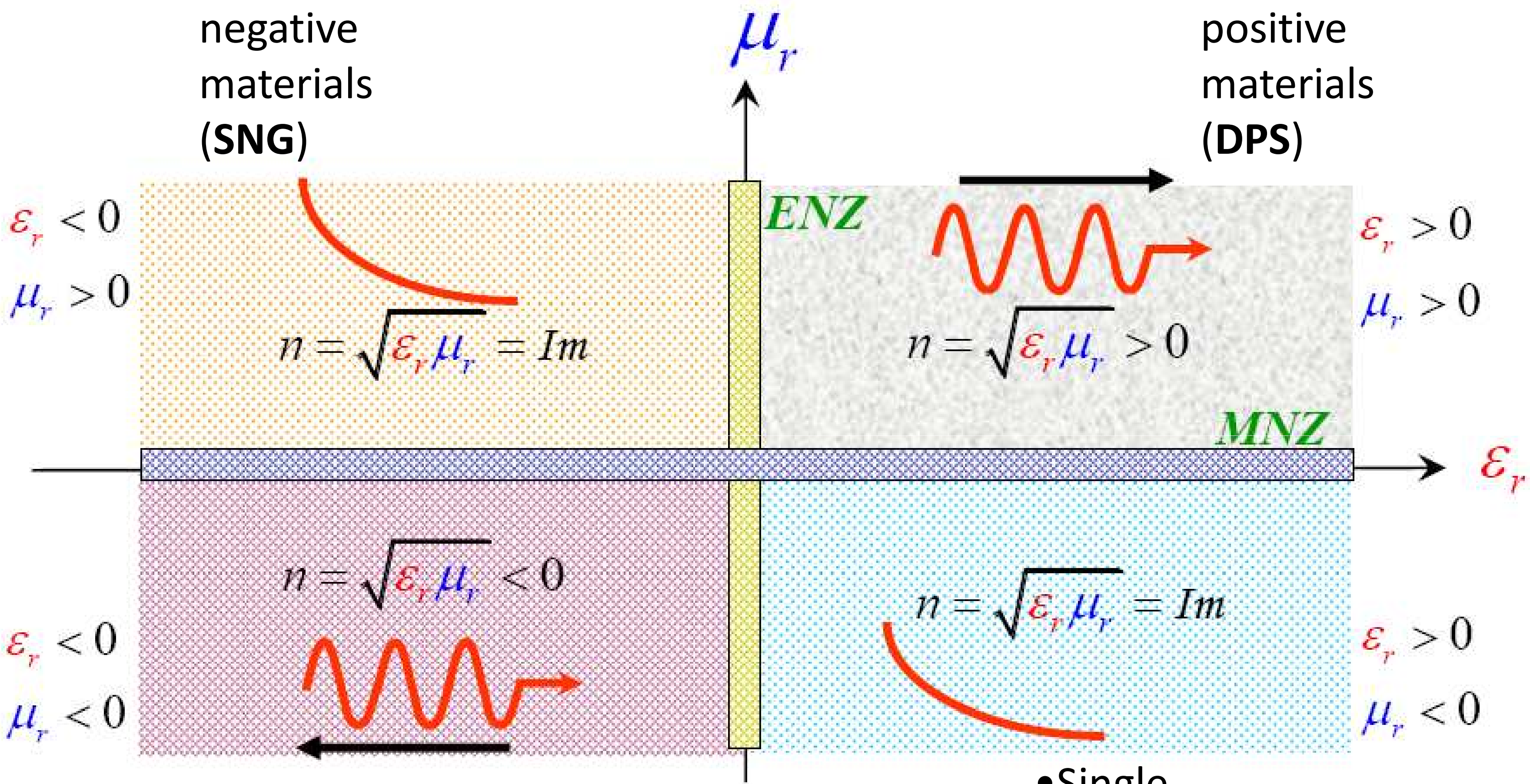




- $a \ll \lambda$, the structure behaves as a homogenous material with some new μ and $\varepsilon \Rightarrow$ metamaterial

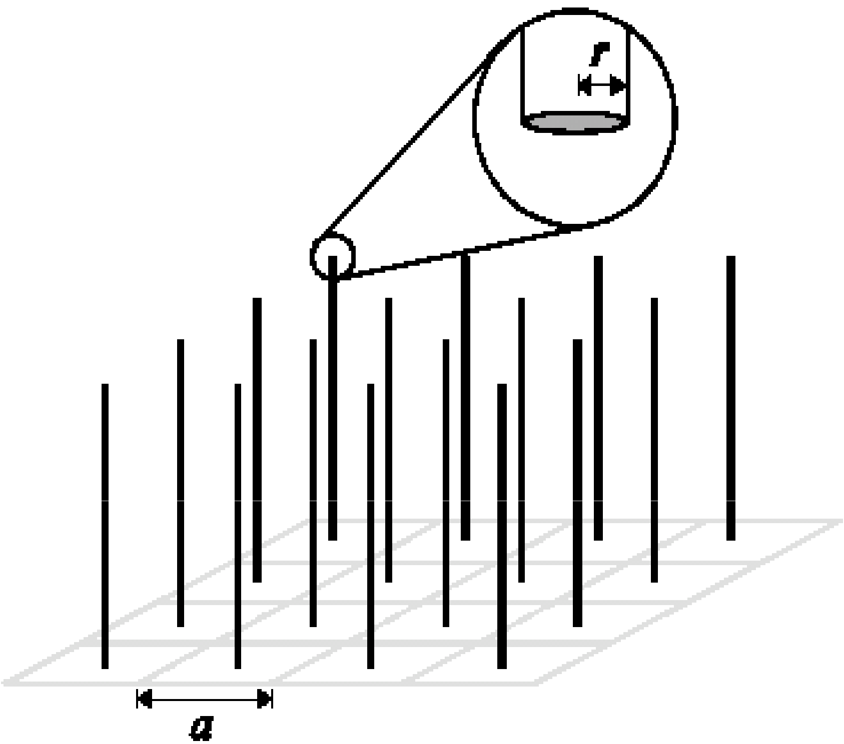
Classification of Metamaterials

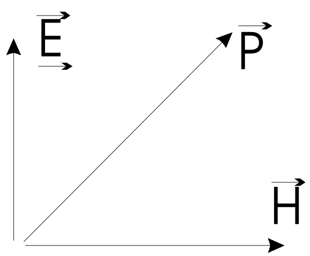
- Single-negative materials (**SNG**)
- Double-positive materials (**DPS**)



- Double-negative materials (**DNG**)
- Single-negative materials (**SNG**)

Thin-wire Plasma-like Structure with $\varepsilon < 0$
(Rotman 1962, Pendry 1998)

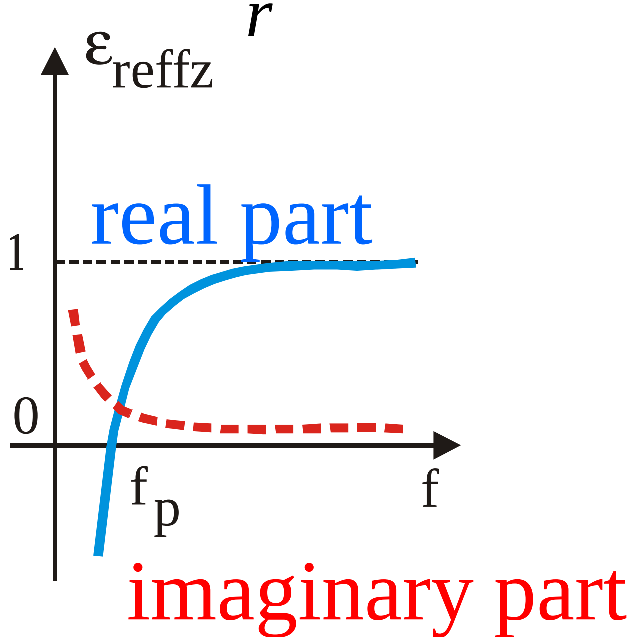




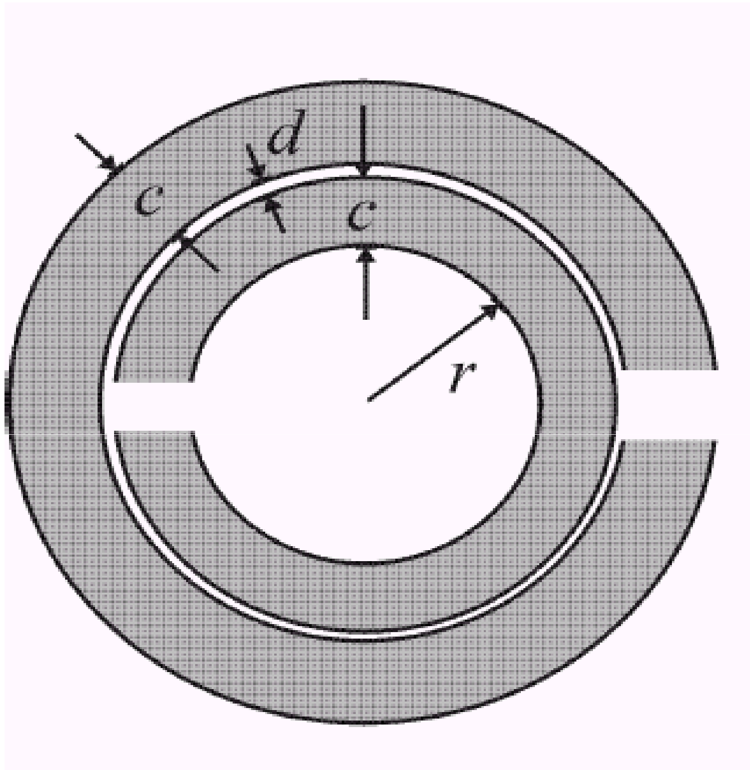
$$\varepsilon_r = 1 - \left(\frac{\omega_p}{\omega}\right)^2$$

$$a << \lambda$$

$$\frac{a}{r} >> 1$$

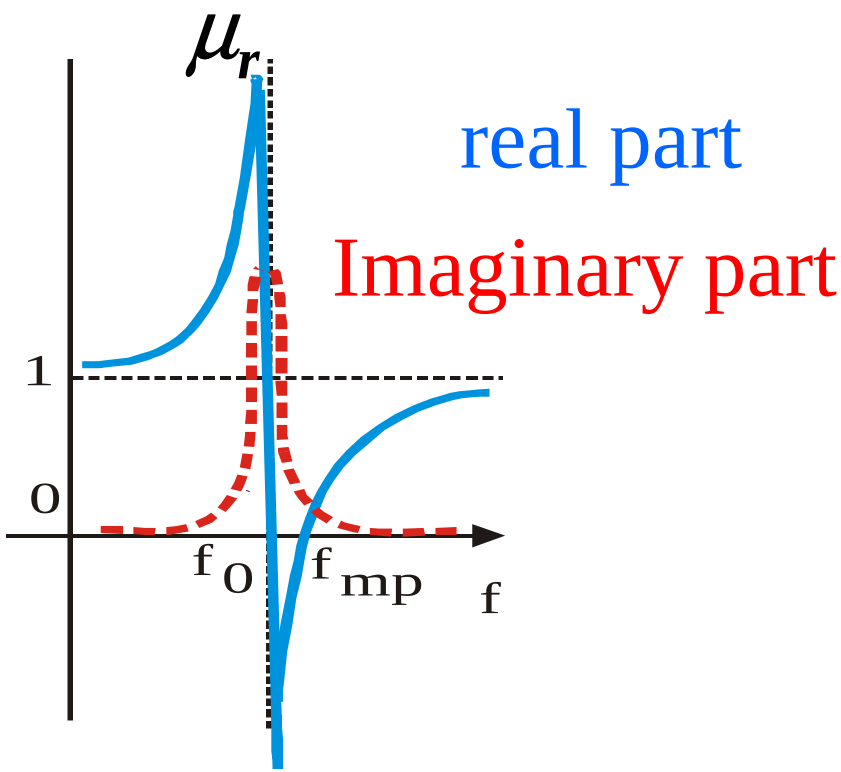


The 'Split-ring Resonator' Structure with $\mu<0$ (Pendry 1999)

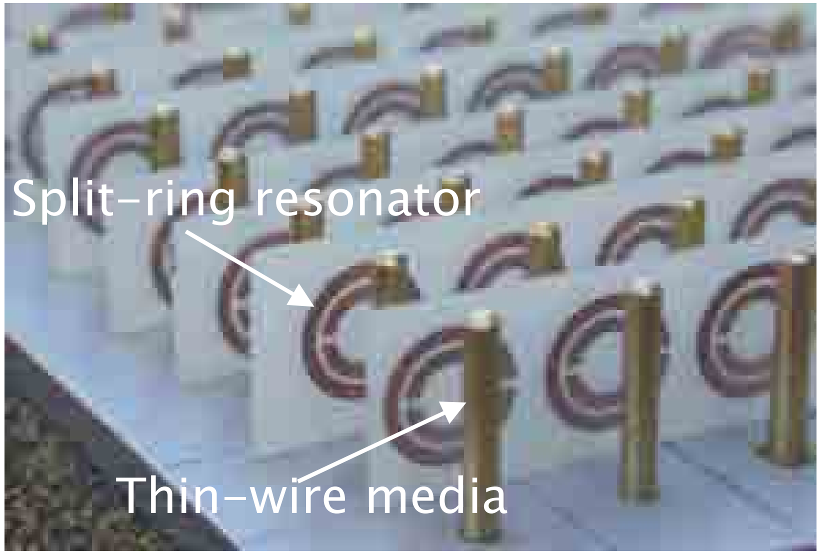


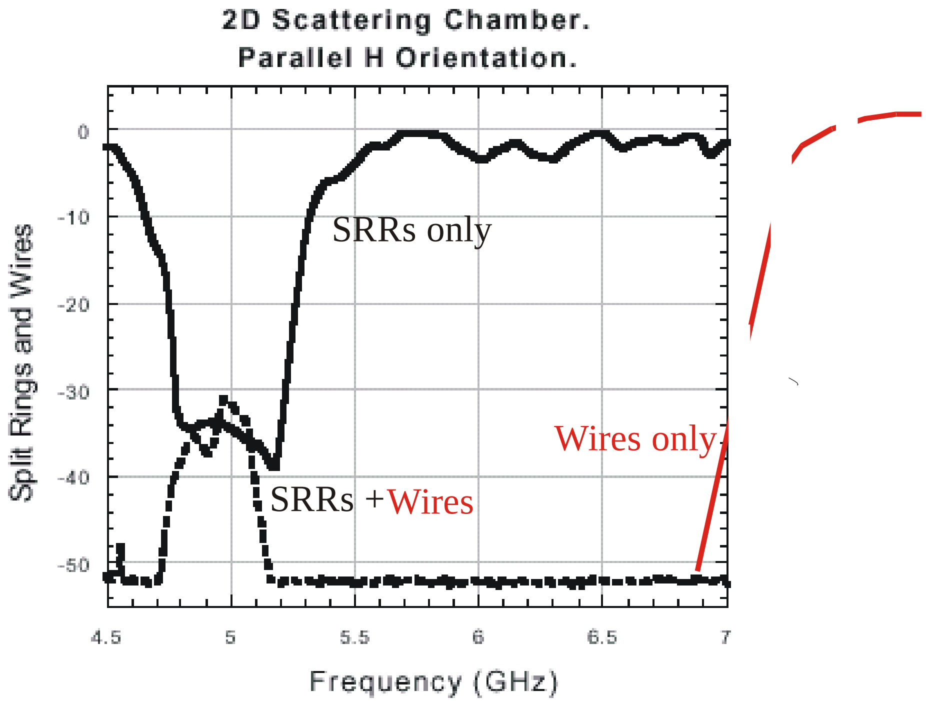
$r << \lambda$

$a << \lambda$



The first reported Backward-wave Material (Smith et al. 2000)

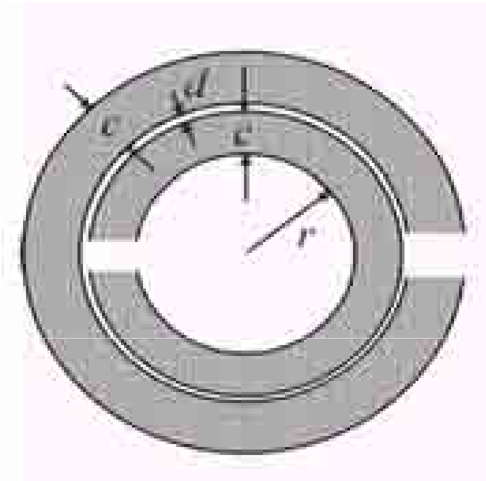


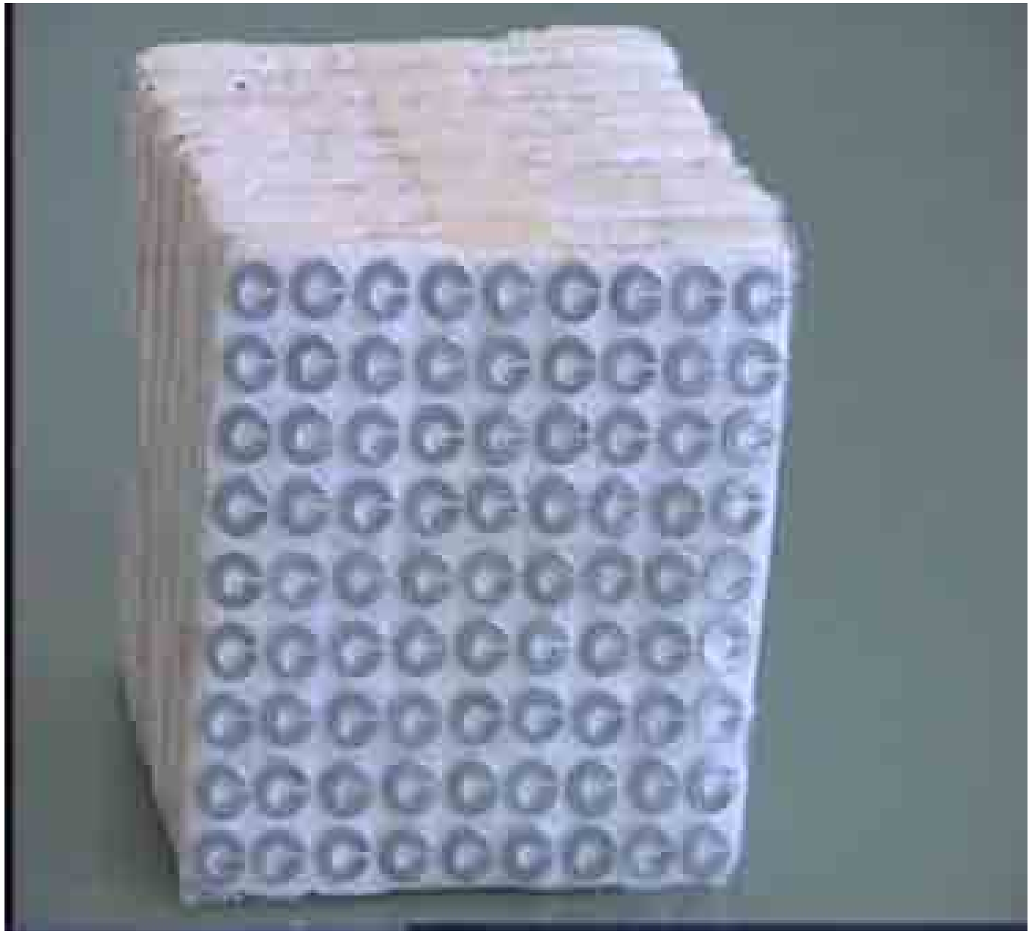


$$k = \omega\sqrt{\mu\varepsilon}$$

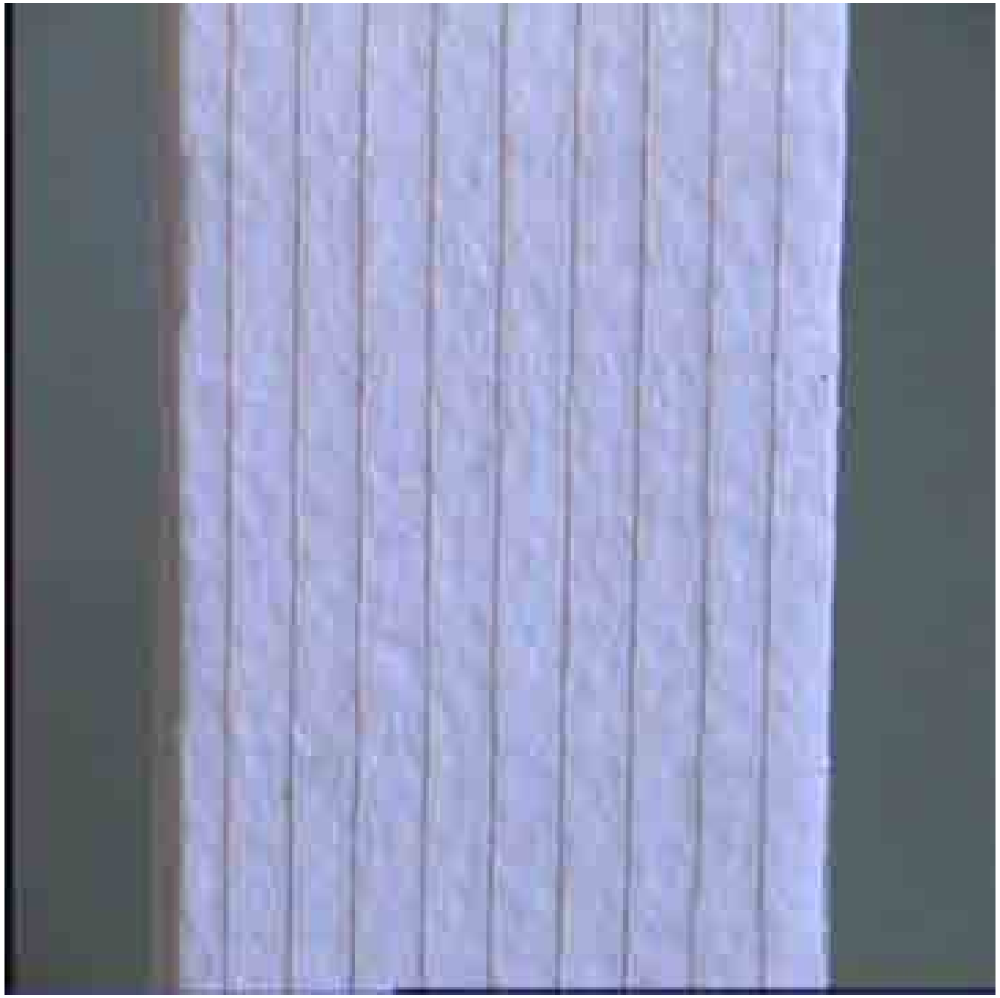
SRR's and wires : μ<0 ε<0, k becomes positive real number $\Rightarrow$ backward-wave propagation

Capacitivelly loaded loops and thin-wire structure (Hrabar, Barbaric; 2000 –1/3)

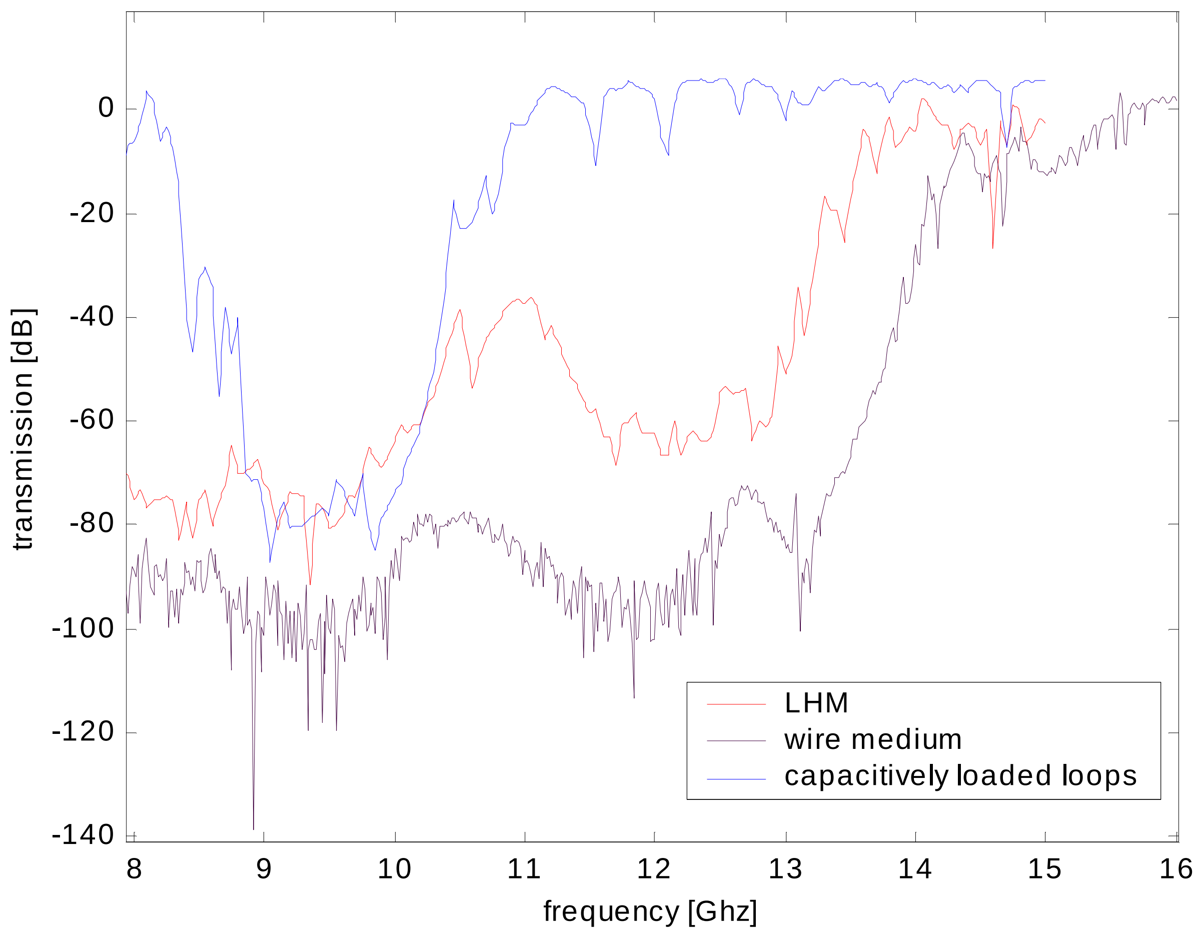




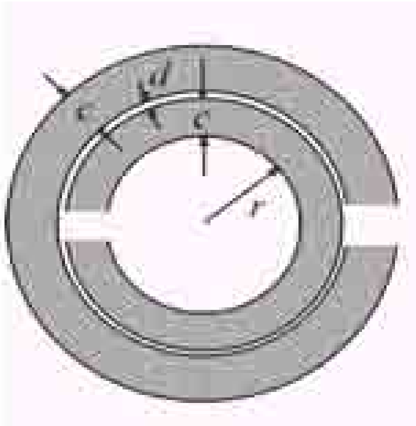
Capacitivelly loaded loops and thin-wire structure (Hrabar, Barbaric 2000; –2/3)



Capacitivelly loaded loops and thin-wire structure (Hrabar, Barbaric 2000; –3/3)



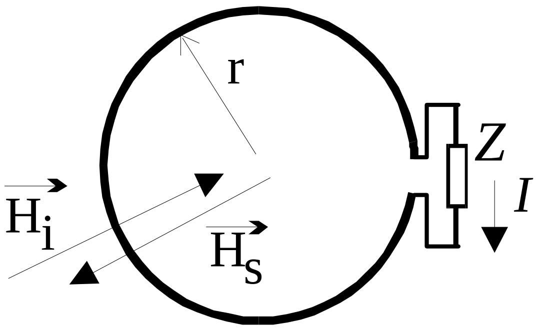
The SRR behaves as capacitivelly loaded loop (Hrabar, Bartolic, Eres; 2002)

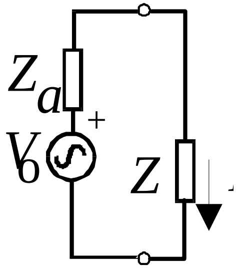


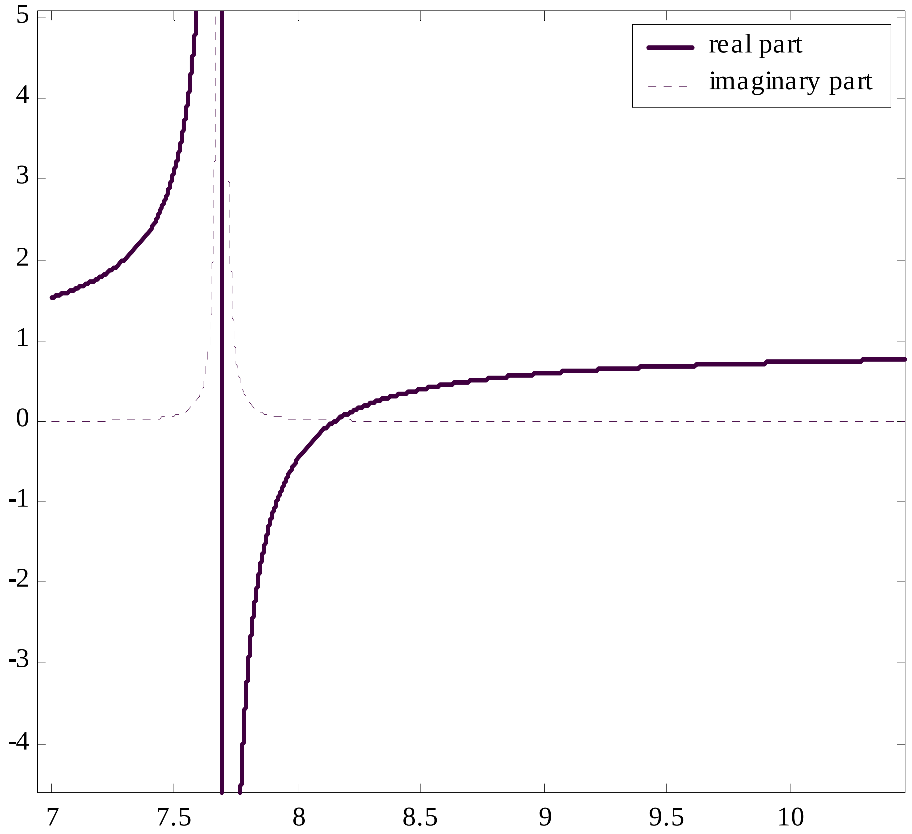
$$H = H_i + H_s$$

$$H = H_i\left(1 - j\frac{K\omega\mu_{0S}}{R + j\omega L - j/\omega C}\right) \quad .$$

Calculated effective permeability







Frequency [GHz]

Schelkunoff, Friis –’Antennas, Theory and Practice’, 1952

by decreasing the permeability and increasing the dielectric constant. This is particularly undesirable since the effects of the changes in μ and ε on the index of refraction are opposite. What we need is a way of *increasing* the permeability rather than decreasing it.

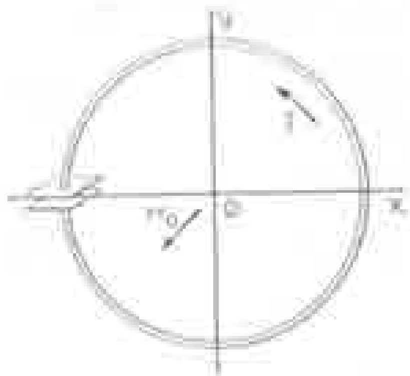


FIG. 19.10 A loop loaded with capacitance.

19.10 Methods for increasing the permeability of artificial dielectrics

Consider a loop with a capacitor (Fig. 19.10). Let the impressed magnetic intensity H_0 be in the positive z direction. The counterclockwise induced current is

$$I = \frac{-j\omega\mu_0 H_0 S}{j\omega L_s + (1/j\omega C)} = \frac{\omega^2 \mu_0 C S H_0}{1 - \omega^2 LC}, \qquad (52)$$

where L is the inductance of the loop and C the capacitance in series with it. The moment of the magnetic doublet equivalent to the loop is

$$p_m = \mu_0 I S. \qquad (53)$$

FIG. 19.11 A loop approaching resonance.

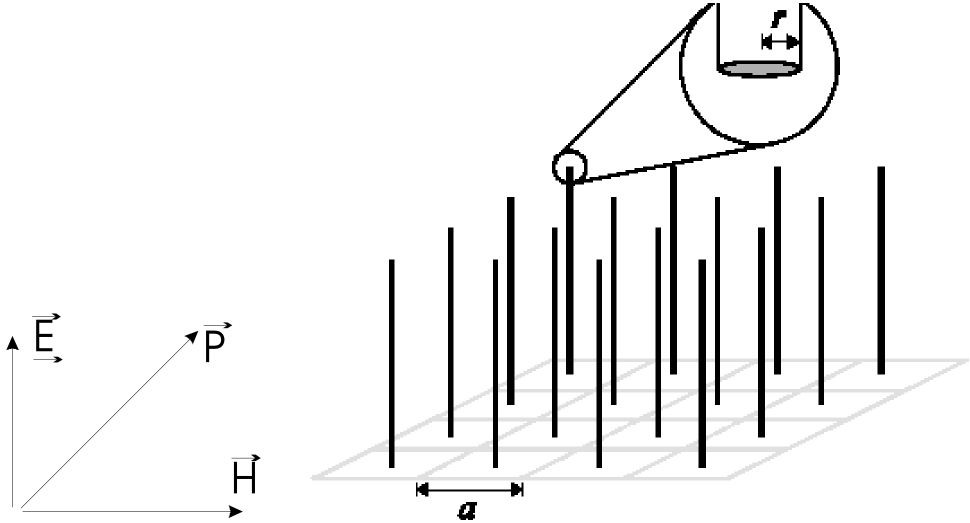
Hence, the magnetic polarizability is

$$\chi_m^0 = \frac{\omega^2 \mu_0^2 C S^2}{1 - \omega^2 LC} = \frac{\omega^2 \mu_0 \varepsilon_0 (C/\varepsilon_0) S^2}{1 - \omega^2 \mu_0 \varepsilon_0 (LC/\mu_0 \varepsilon_0)}\, \mu_0. \qquad (54)$$

The ratios C/ε_0 and L/μ_0 depend only on the geometry of the metal object; $\omega^2 \mu_0 \varepsilon_0 = 4\pi^2/\lambda^2$ where λ is the wavelength in free space corresponding to the given frequency.

The capacitance may be supplied by the loop itself (Fig. 19.11) if

Wire Medium as Transmission Line (Hrabar 2003,2006)



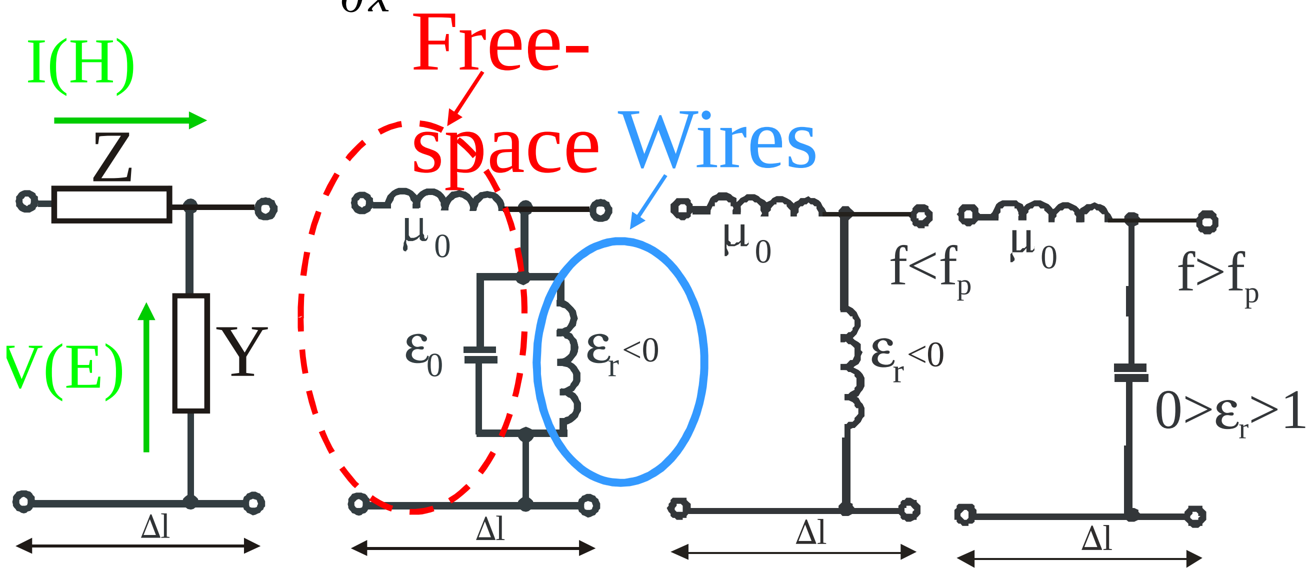
$$\varepsilon_r = 1 - \left(\frac{\omega_p}{\omega}\right)^2$$

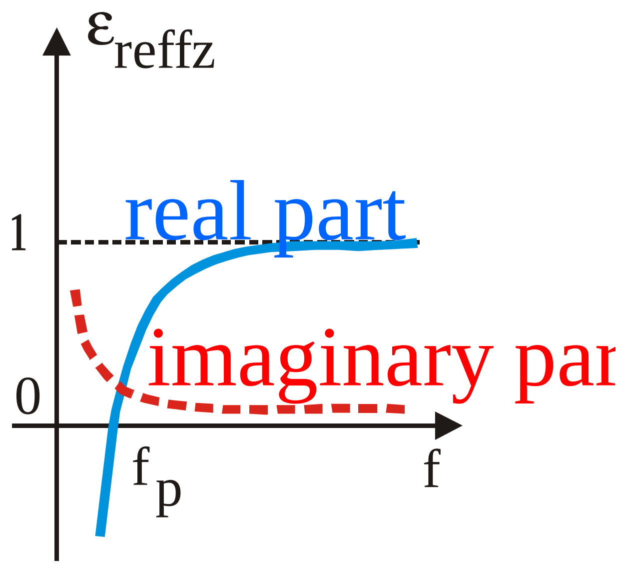
$$a << \lambda$$

$$\frac{a}{r} >> 1$$

$$\nabla^2 E = -\omega^2 \mu\varepsilon E = \left(j\omega\sqrt{\mu}\right)\left(j\omega\sqrt{\varepsilon}\right)E$$

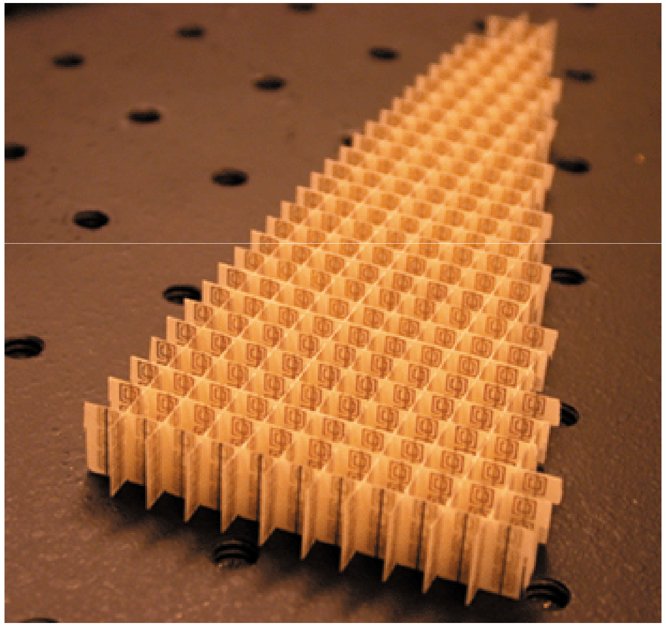
$$\frac{\partial^2 V}{\partial x^2} = -ZY\ V = \left(j\omega X_{series}\right)\left(j\omega Y_{shunt}\right)V$$



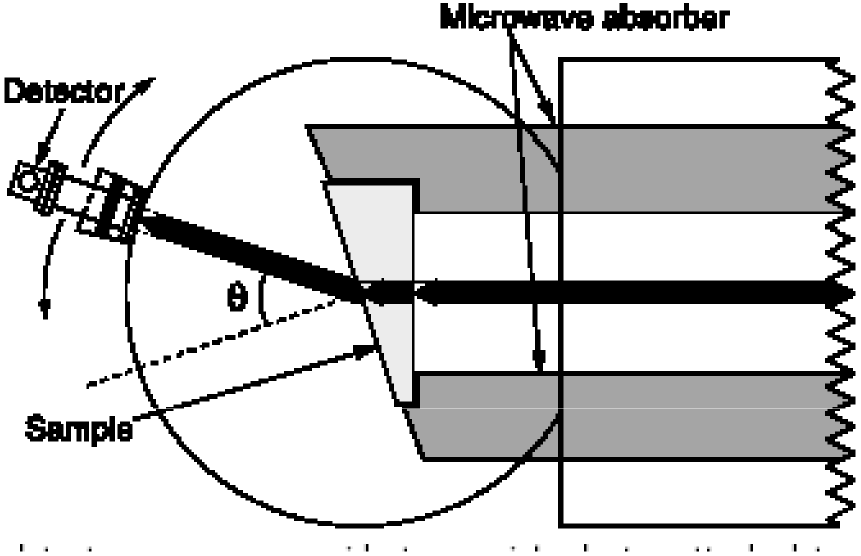


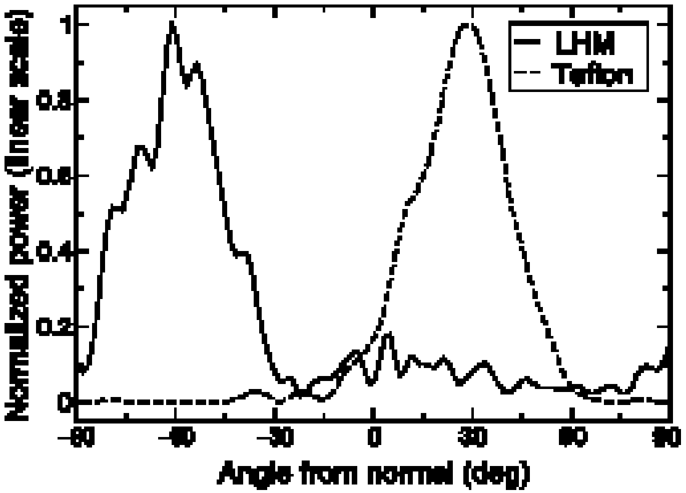
New Physical Phenomena - Fundamental research

Experimental Verification of Negative Refraction (Shelby et al. 2001)

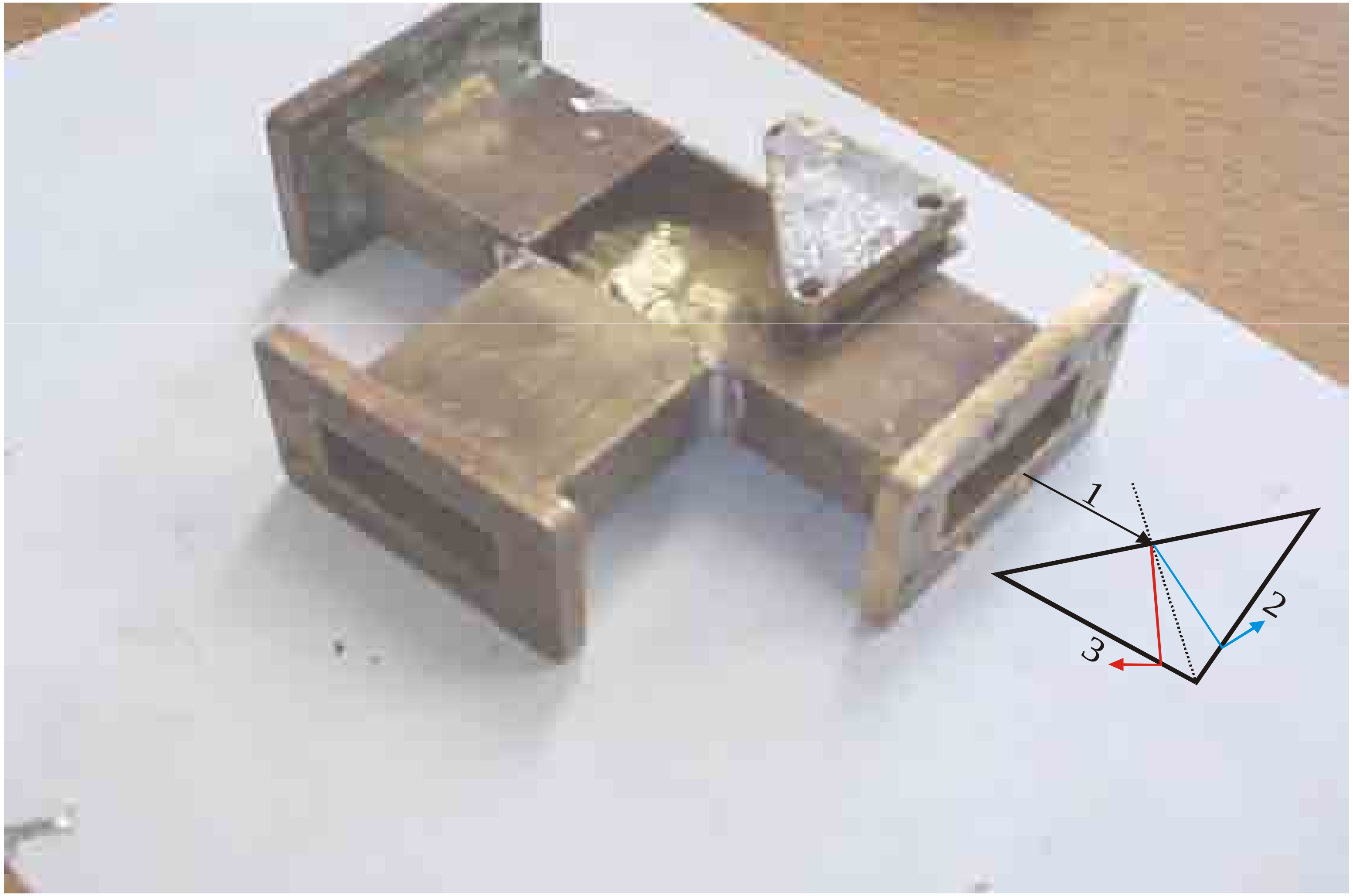


Experimental Verification of Negative Refraction (Shelby et al. 2001)

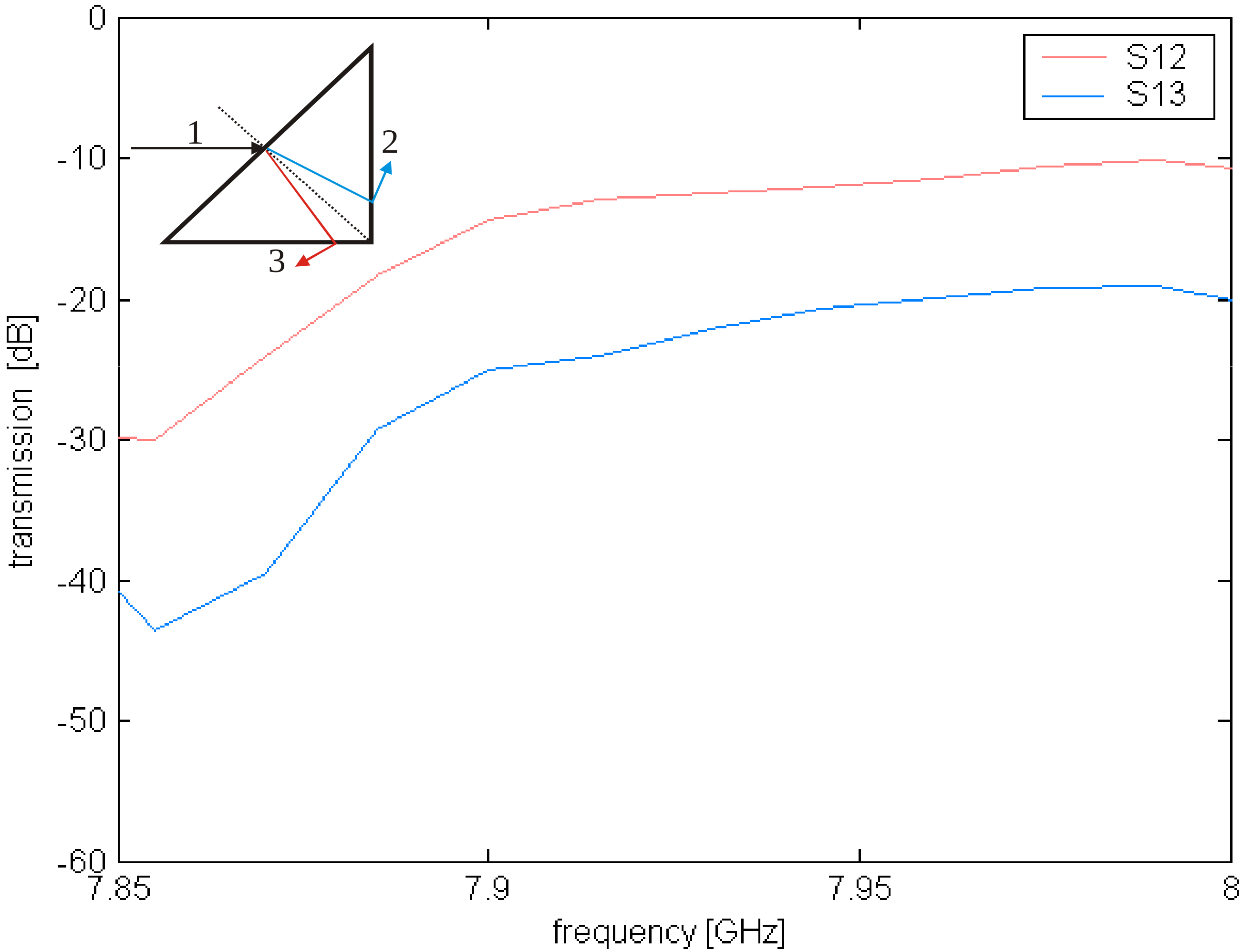




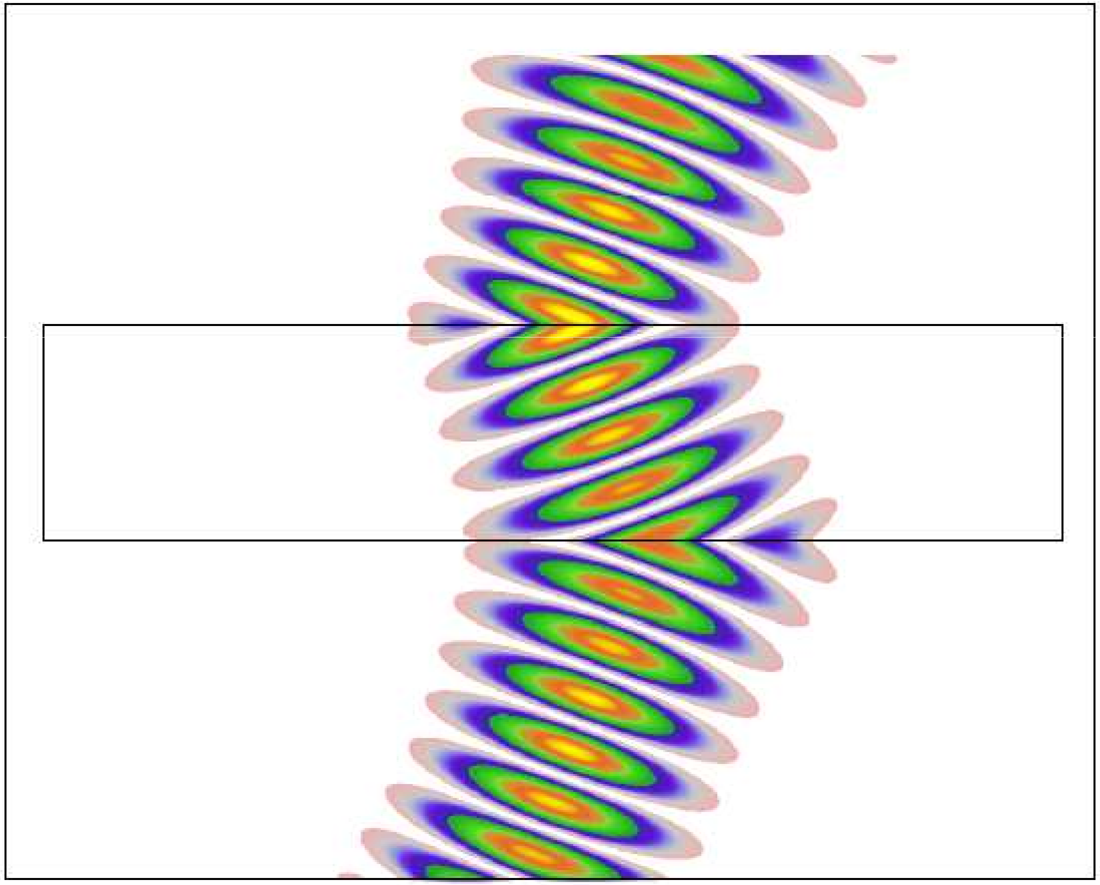
Experimental Verification of Negative Refraction (Hrabar, Bartolic; 2003-1/2)



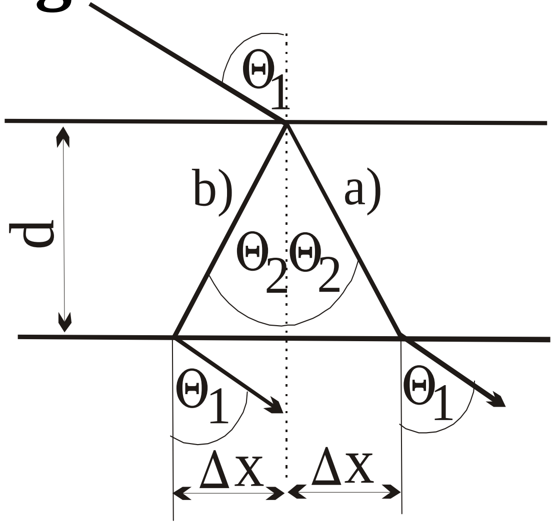
Experimental Verification of Negative Refraction (Hrabar, Bartolic; 2003-2/2)

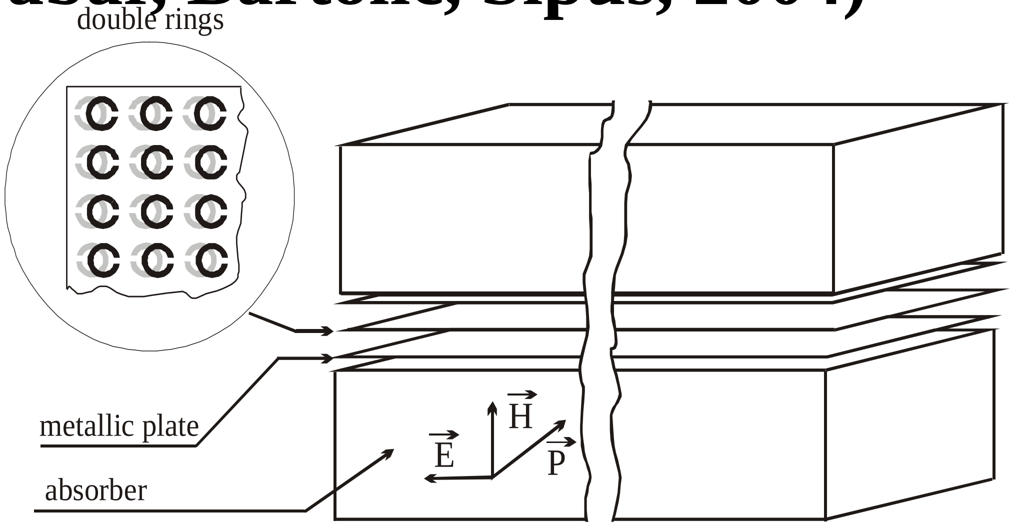


Simulation of Negative Refraction at Plan-parallel Slab with n=-1 (Ziolkowski; 2003)

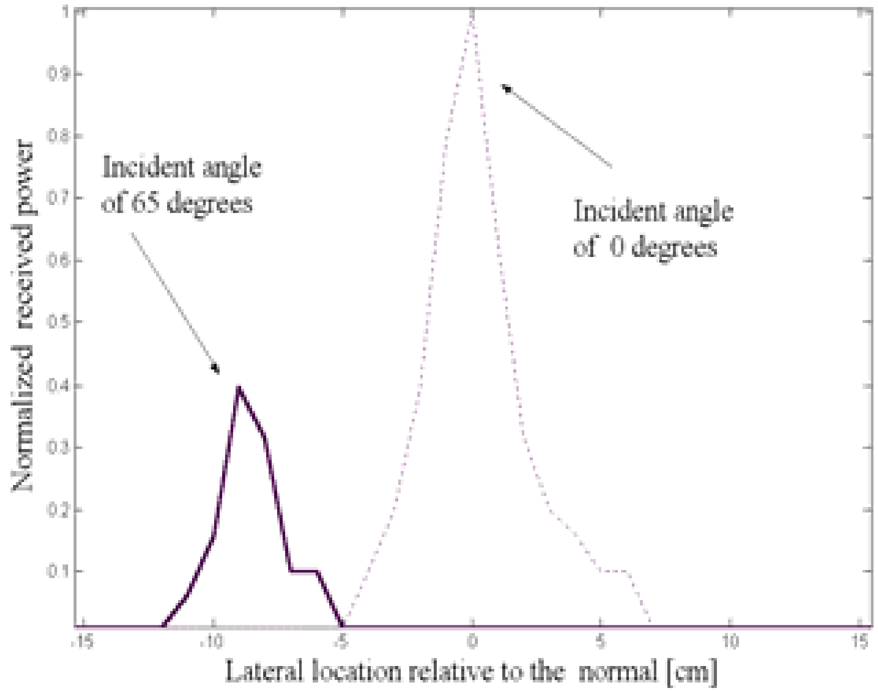


Verification of BW propagation by measurement of Negative Refraction (Hrabar, Bartolic, Sipus, 2004)

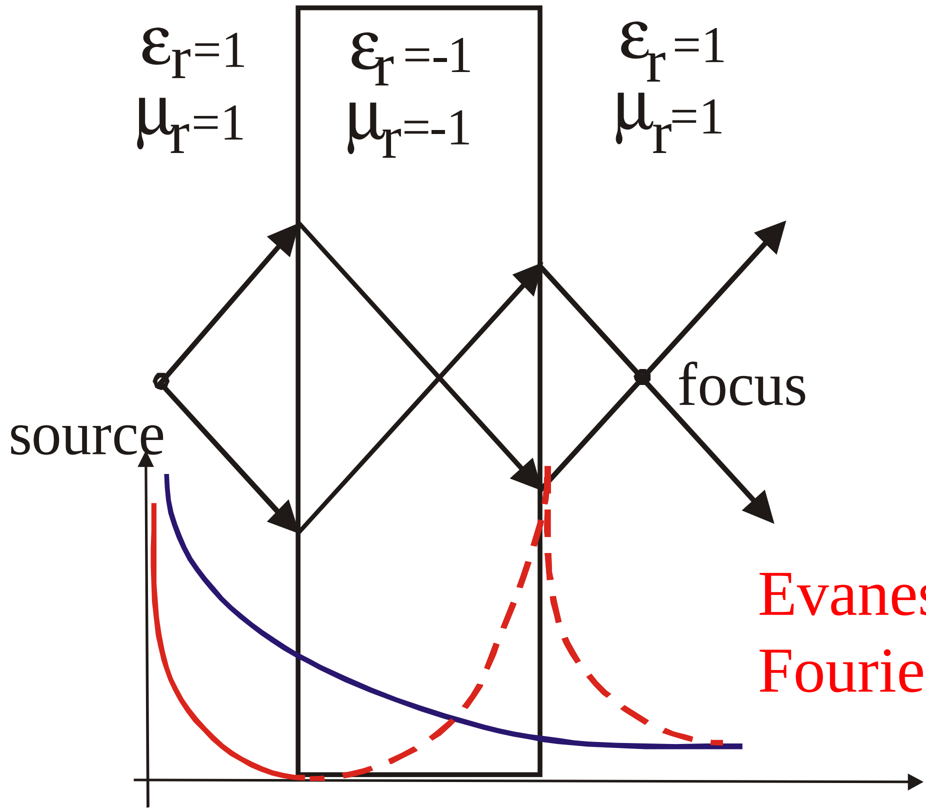




a) A case of ‘forward-wave’ slab (ε>0,μ>0)
b) A case of ‘backward-wave’ slab (ε<0,μ<0)



Super Lens' with no Resolution Limit (Pendry, 2000)



Propagating part of Fourier spectrum

Evanescent part of Fourier spectrum

$$E(x,y,z,t) = \sum_{k_x,k_y} A(k_x,k_y)e^{i(k_z z + k_y y + k_x x - \omega t)}$$

$$k_z = \sqrt{\frac{\omega^2}{c^2} - \left(k_x^2 + k_y^2\right)}$$

$$k_x^2 + k_y^2 > \frac{\omega^2}{c^2}$$

$$k_z' = -\sqrt{\frac{\omega^2}{c^2} - \left(k_x^2 + k_y^2\right)}$$

Experimental verification (Grbic et al. 2004 –1/2)

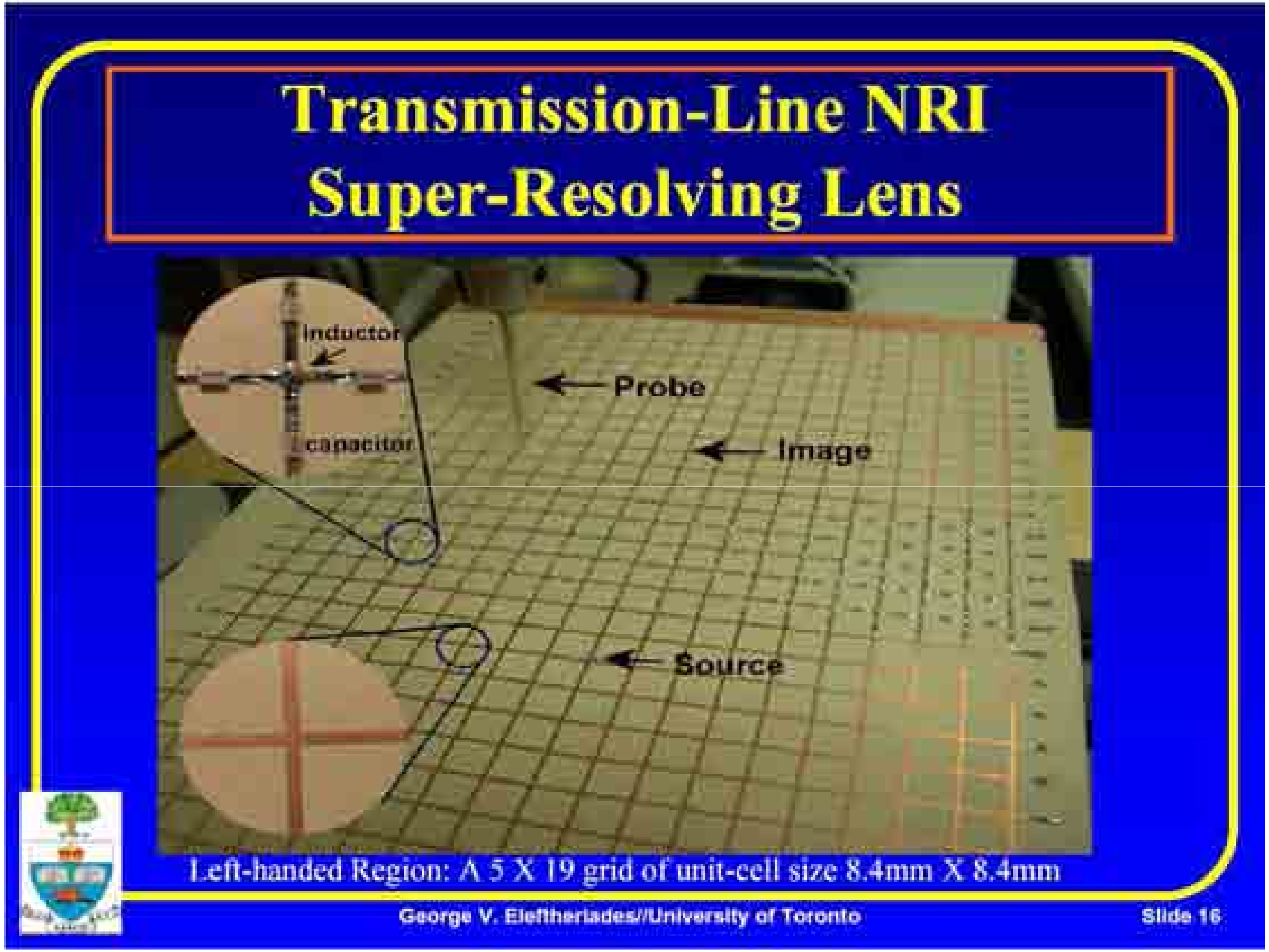


Figure taken from G. Eleftheriades (University of Toronto) presentation slides

Experimental verification (Grbic et al. 2004 – 2/2)

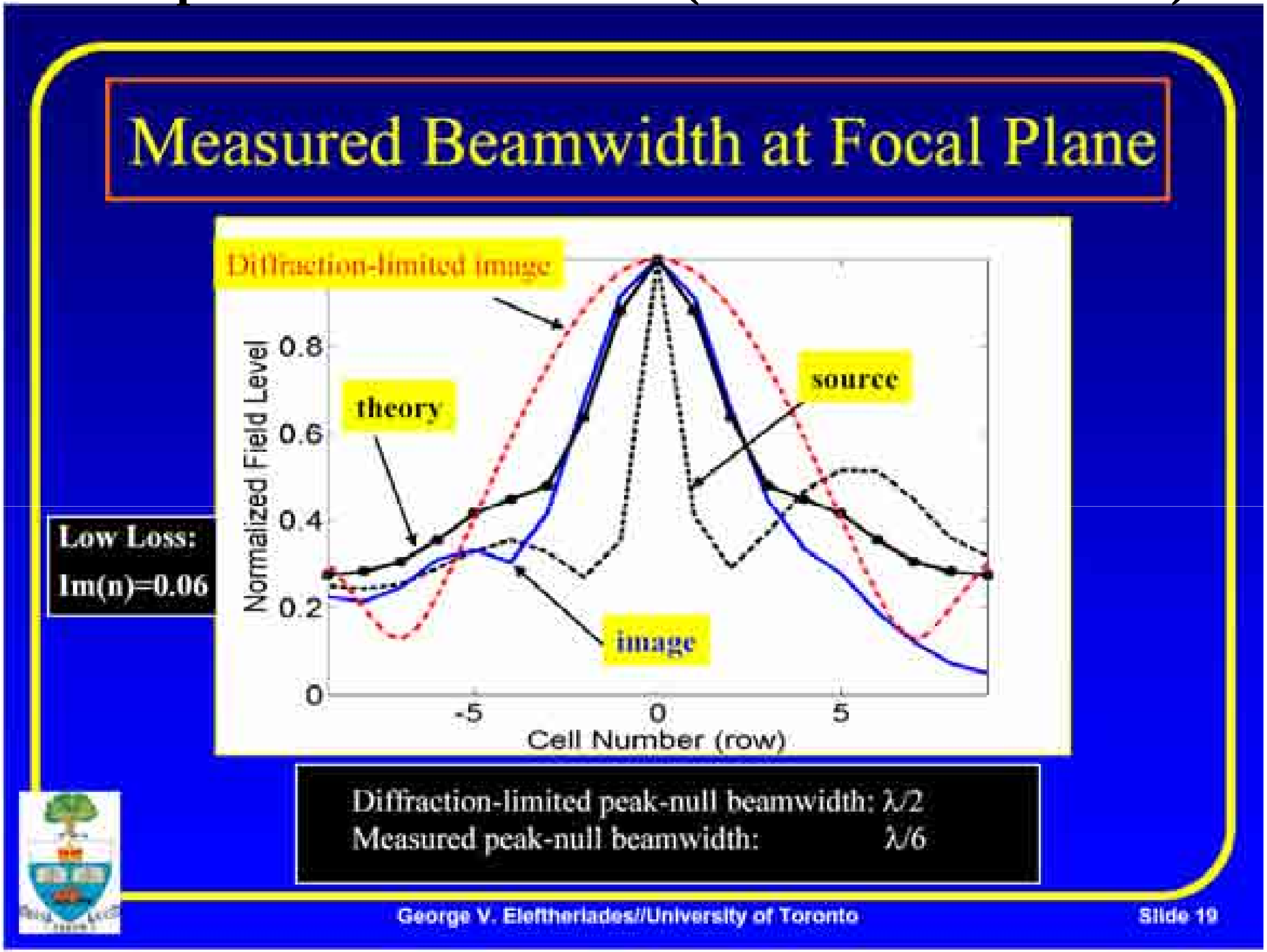
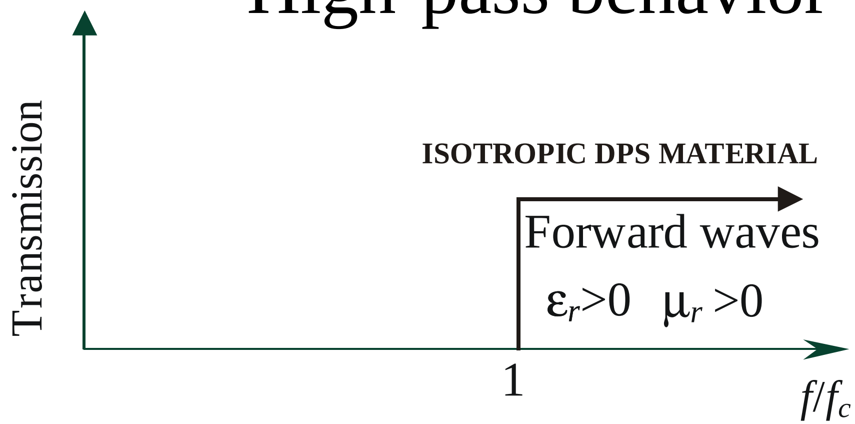


Figure taken from G. Eleftheriades (University of Toronto) presentation slides

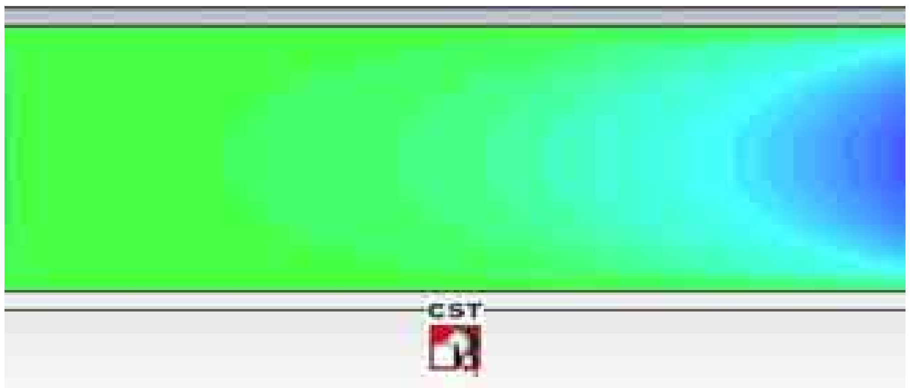
Potential Engineering Applications
I – Guiding of EM energy

Classical rectangular waveguide– Electrical field distribution (TE case)

•High-pass behavior

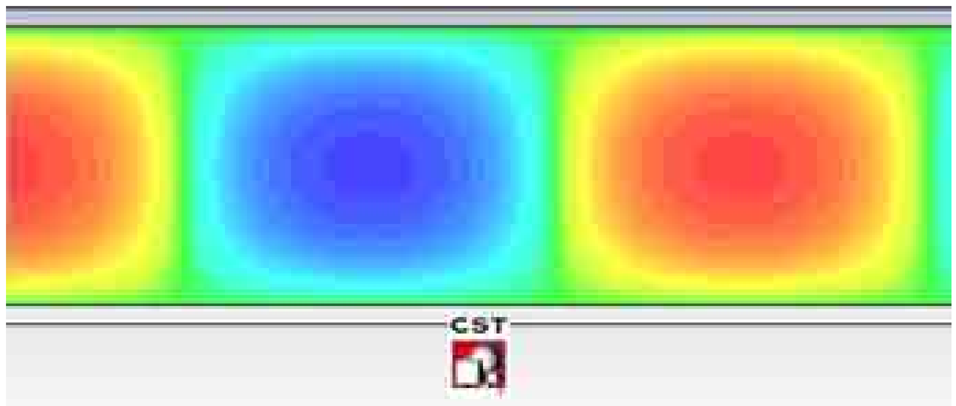


•f < f_c, Evanescent **E** field



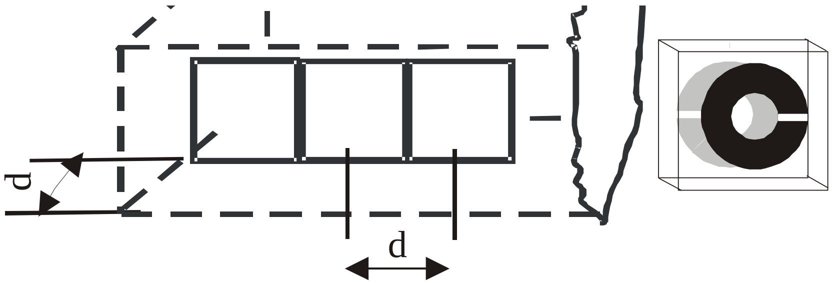
•**P**, **k**

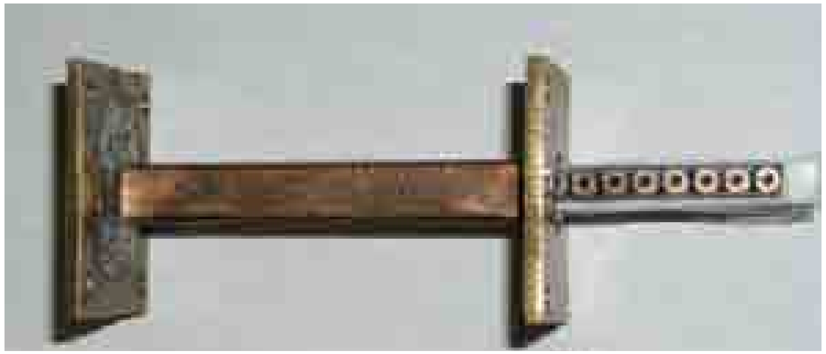
•f > f_c, Propagating **E** field

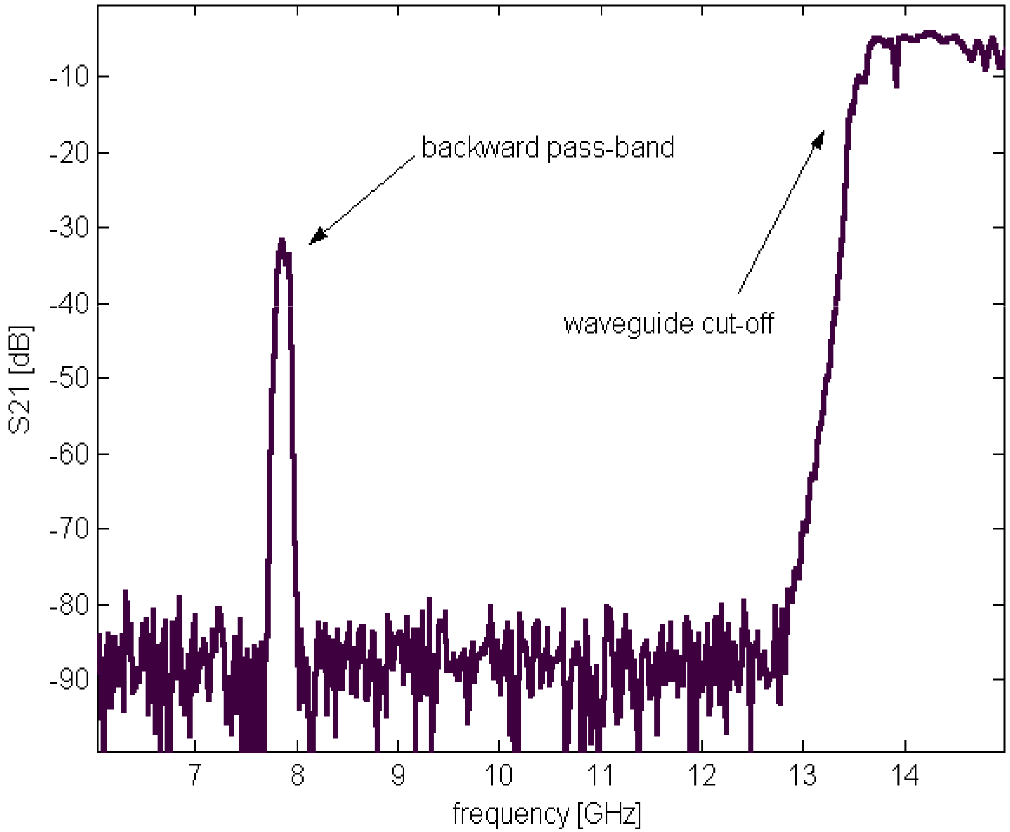


•**P**, **k**

Miniaturized Waveguide based on Anisotropic Meta-material (Hrabar, Bartolic, Sipus; 2003)

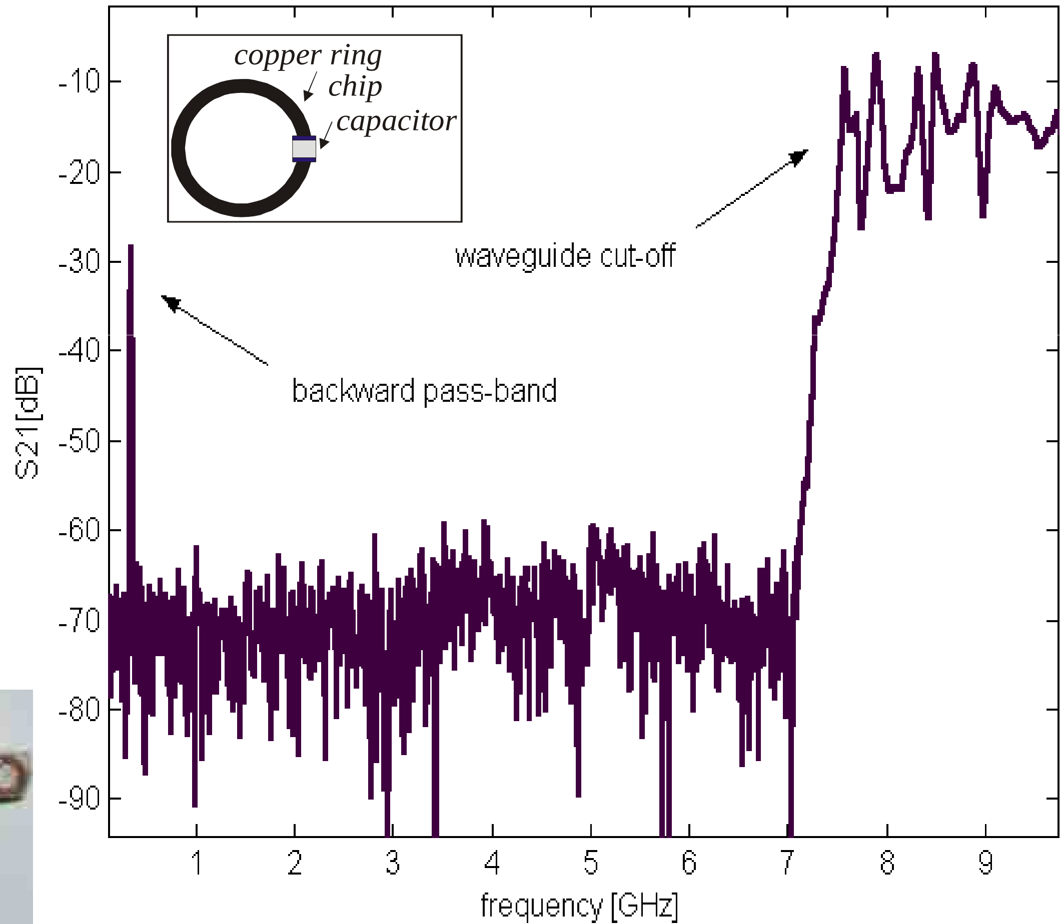






Miniaturized Waveguide based on Negative Permeability Metamaterial
(transversal dimension reduced down to 25%)

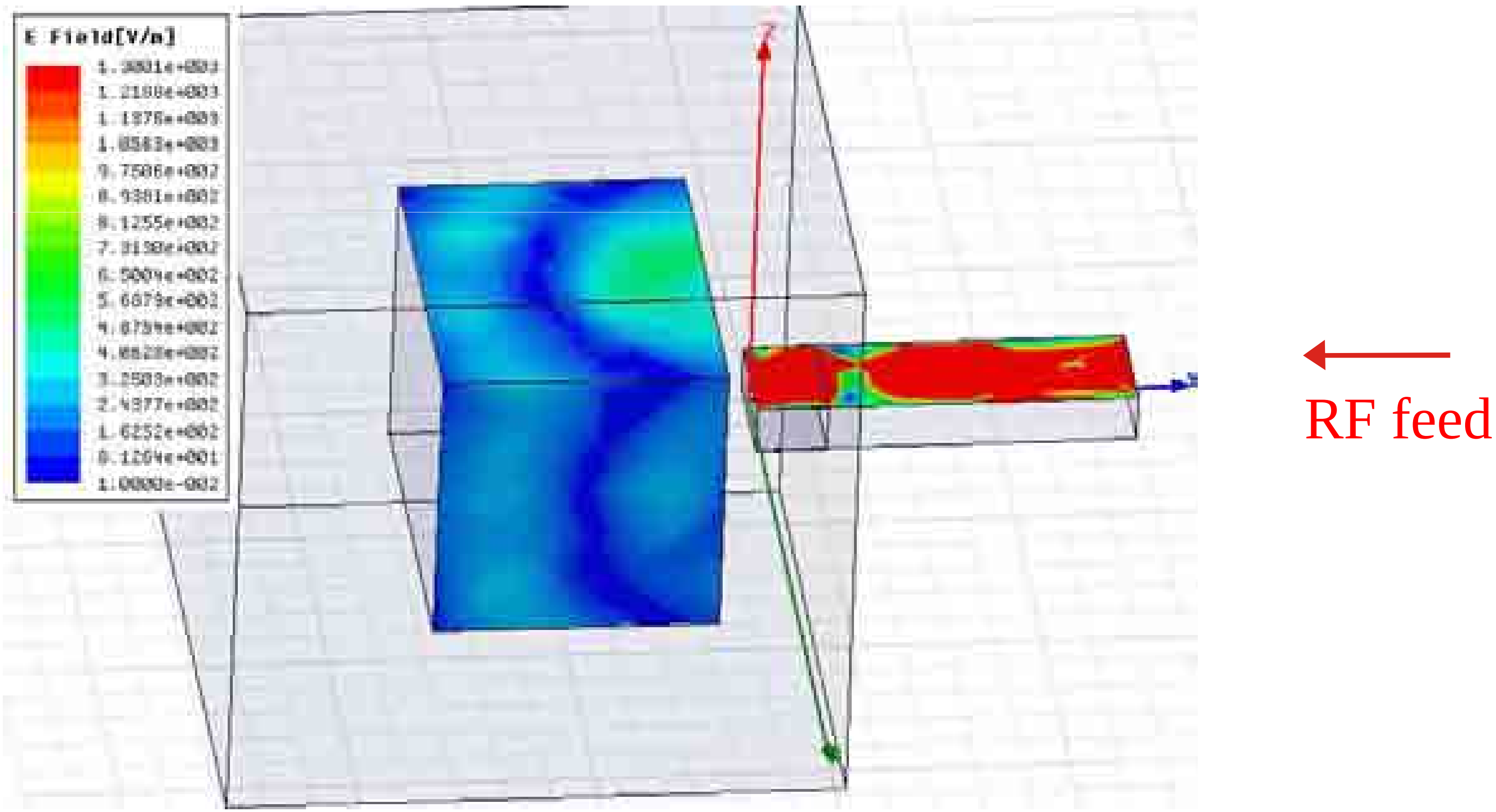
Miniaturized waveguide (a=15 mm) filled with capacitively loaded rings – the transversal width reduced down to 4% !



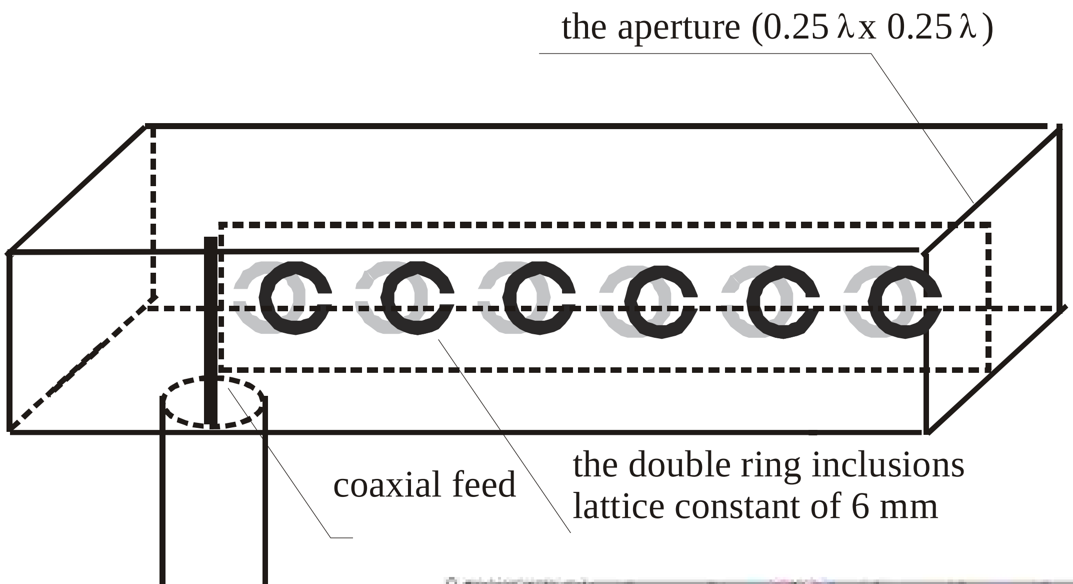
Potential Engineering Applications II – Antennas

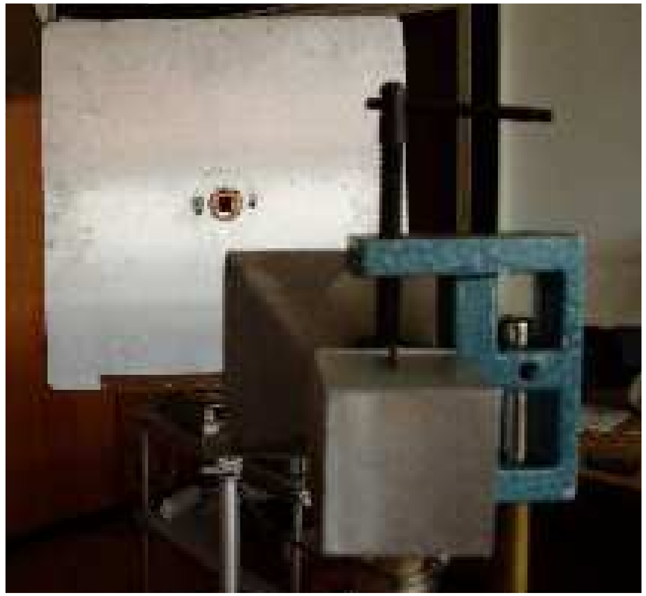
Does an open-ended SNG-filled miniaturized waveguide radiate into a free space ? (Hrabar, Zivkovic; 2005)

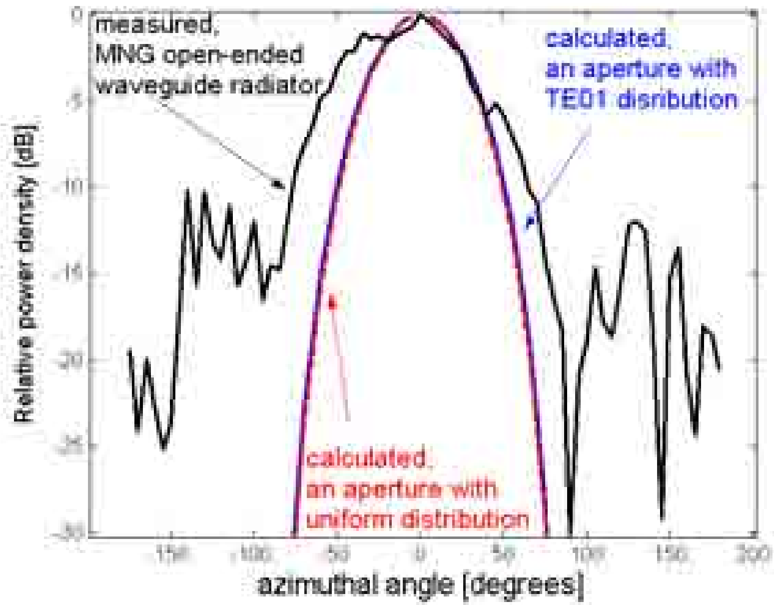
The simulated radiation (BW mode, k<0)



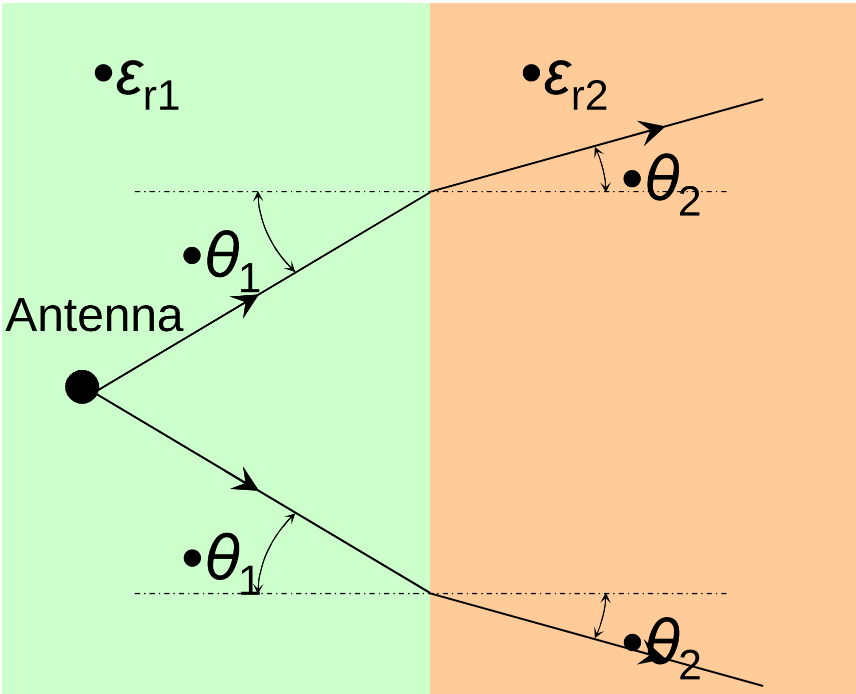
Experiemental Miniaturized Open-ended MNG Waveguide Radiator (Hrabar, Jankovic 2005)







Phenomenon of ultra-refraction



$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{\sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}}}$$

- If medium 2 is air

$$\theta_2 = \sin^{-1}\left(\sqrt{\varepsilon_{r1}}\,\sin(\theta_1)\right)$$

$$\text{if } \varepsilon_r = 0 \Rightarrow \theta_2 = 0.$$

2582 MICROWAVE AND OPTICAL TECHNOLOGY LETTERS / Vol. 48, No. 12, December 2006 DOI 10.1002/mop

EXPERIMENTAL INVESTIGATION OF RADIATION PROPERTIES OF AN ANTENNA EMBEDDED IN LOW PERMITTIVITY THIN-WIRE-BASED METAMATERIAL

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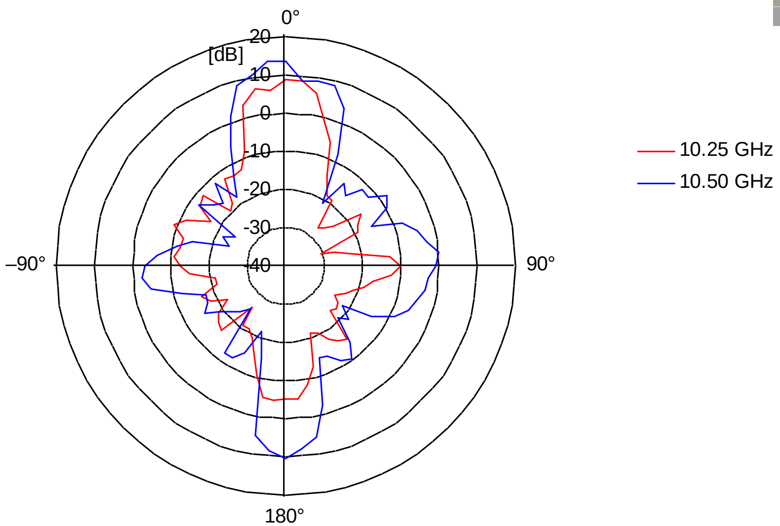
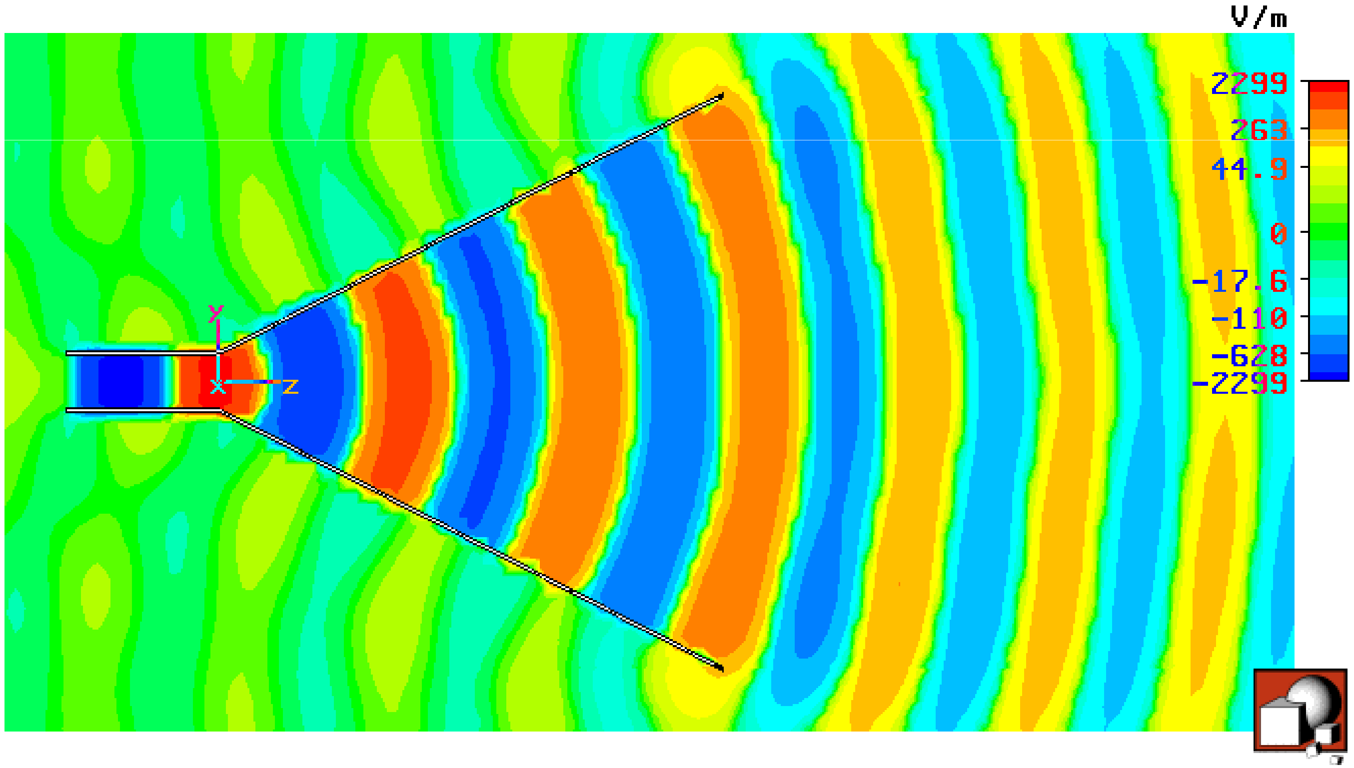
Received 12 June 2006



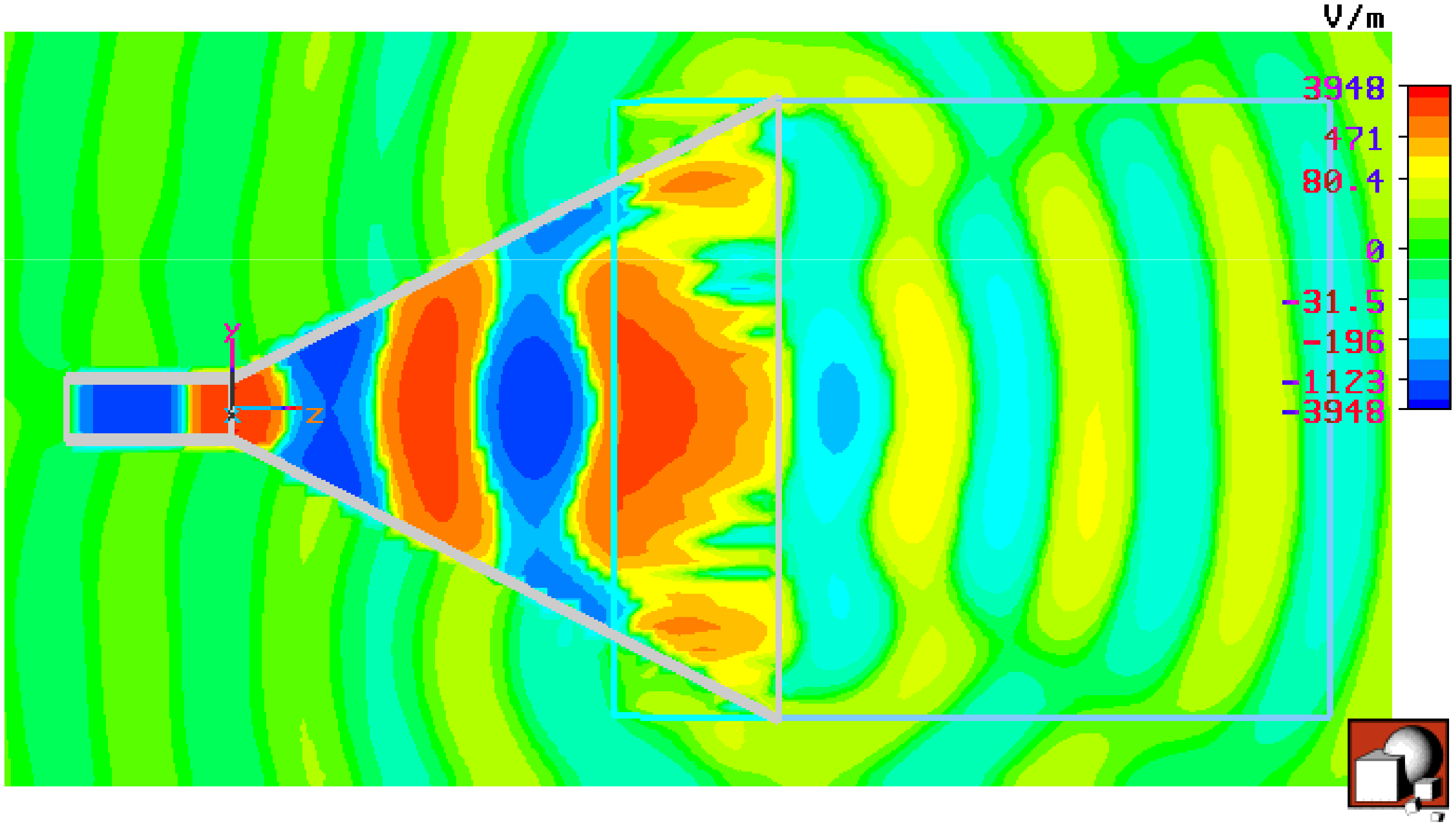
- Figures copied from the original article

Shortened Horn with ENZ Metamaterial (Hrabar, Bonefacic, Muha, 2008)

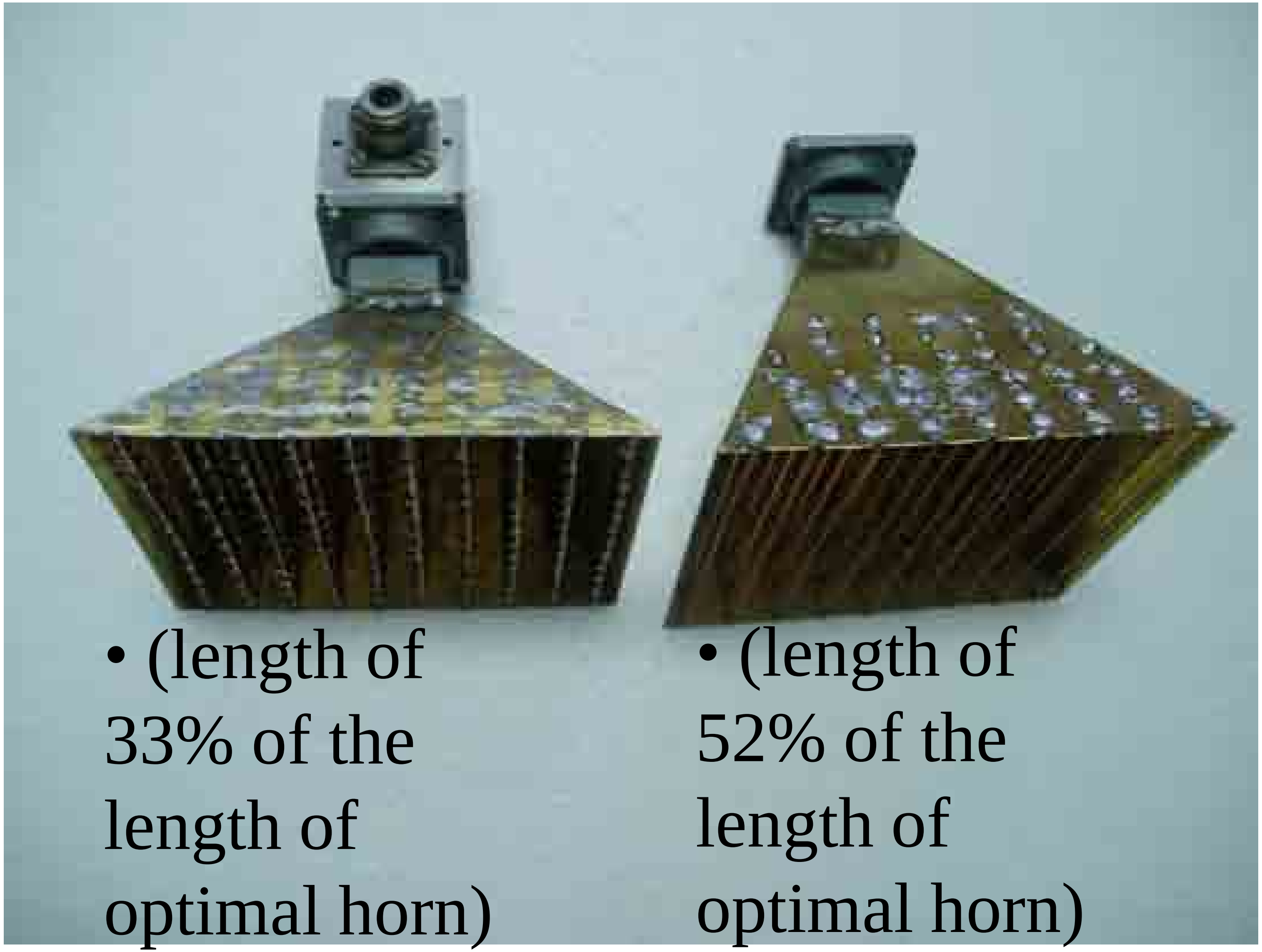
Simulated magnitude of the y-componnet of electric field of the shortened horn



•Simulated magnitude of the y-componnet of electric field of the shortened horn with ENZ slab



•Comparison of prototyped shortened horns



• (length of 33% of the length of optimal horn)

• (length of 52% of the length of optimal horn)

TELECOM // WIRELESS

NEWS

Metamaterials Arrive in Cellphones

LG Chocolate BL40 is first cellphone to use a metamaterials antenna

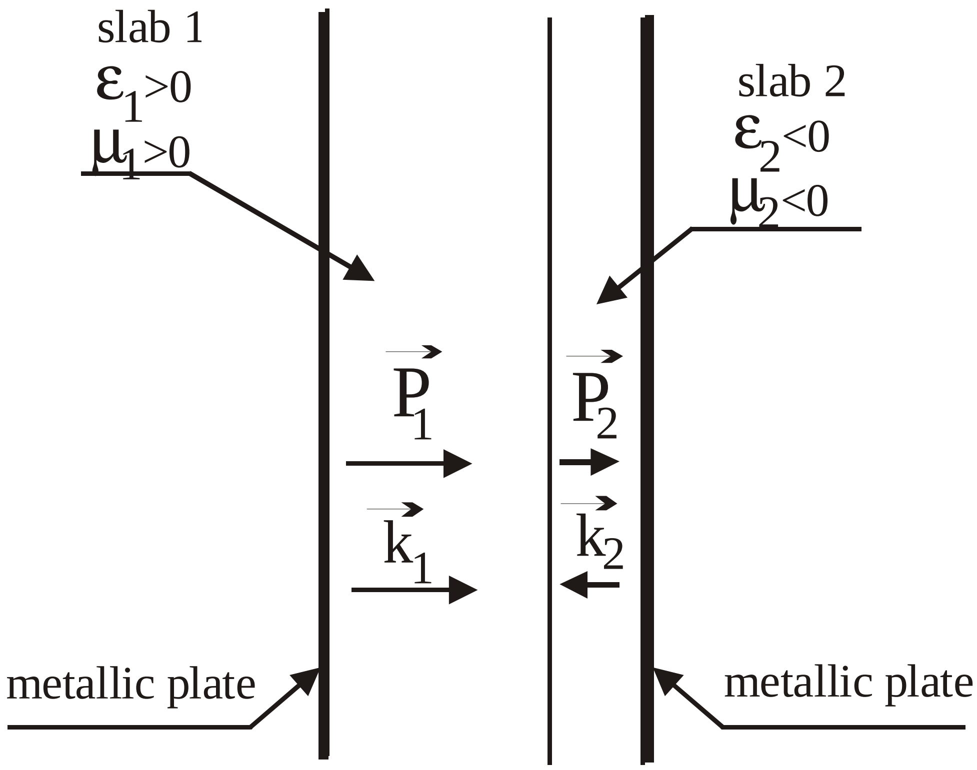
Image: LG

BY SASWATO R. DAS // OCTOBER 2009

28 October 2009—The quest to build more-powerful multiband mobile handsets has gotten a boost from a relatively new class of materials. Called metamaterials, they are specifically engineered to have properties that do not occur naturally, such as the ability to bend light the wrong way. For manufacturers of mobile devices, recent advances in metamaterials promise a way to shrink size while still retaining multiband functionality.

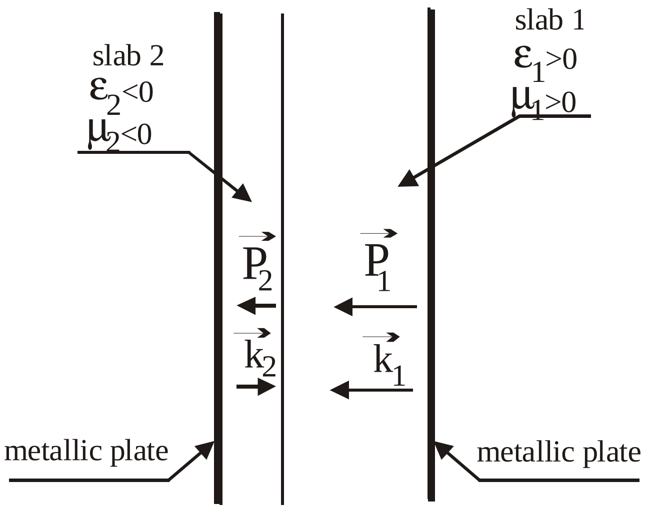
Potential Engineering Applications III – Resonators

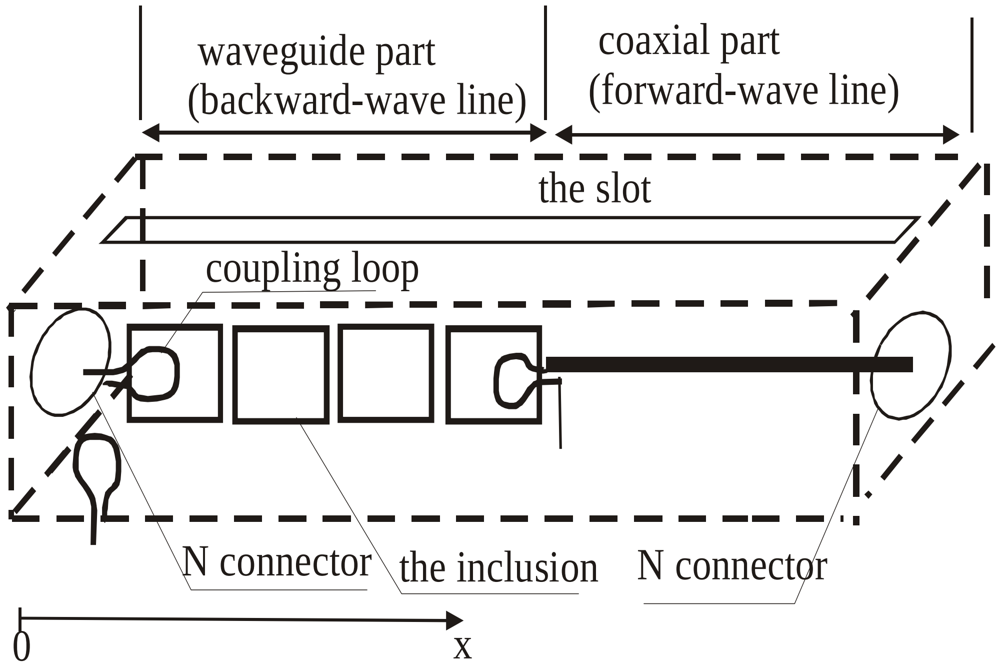
Sub-wavelength Resonator
(Engheta, 2001)



•The resonance frequency depends on d_2/d_1instead of d_2+d_1 which would hold in ordinary materials

Experimental verification of Engheta's resonator (Hrabar et al., 2004)





(f=350 MHz)

overall length

~ $\lambda/30$

Potential Engineering Applications IV – Going optical!

Going Optical - Approach I
Scaling Down the Size of Inclusions

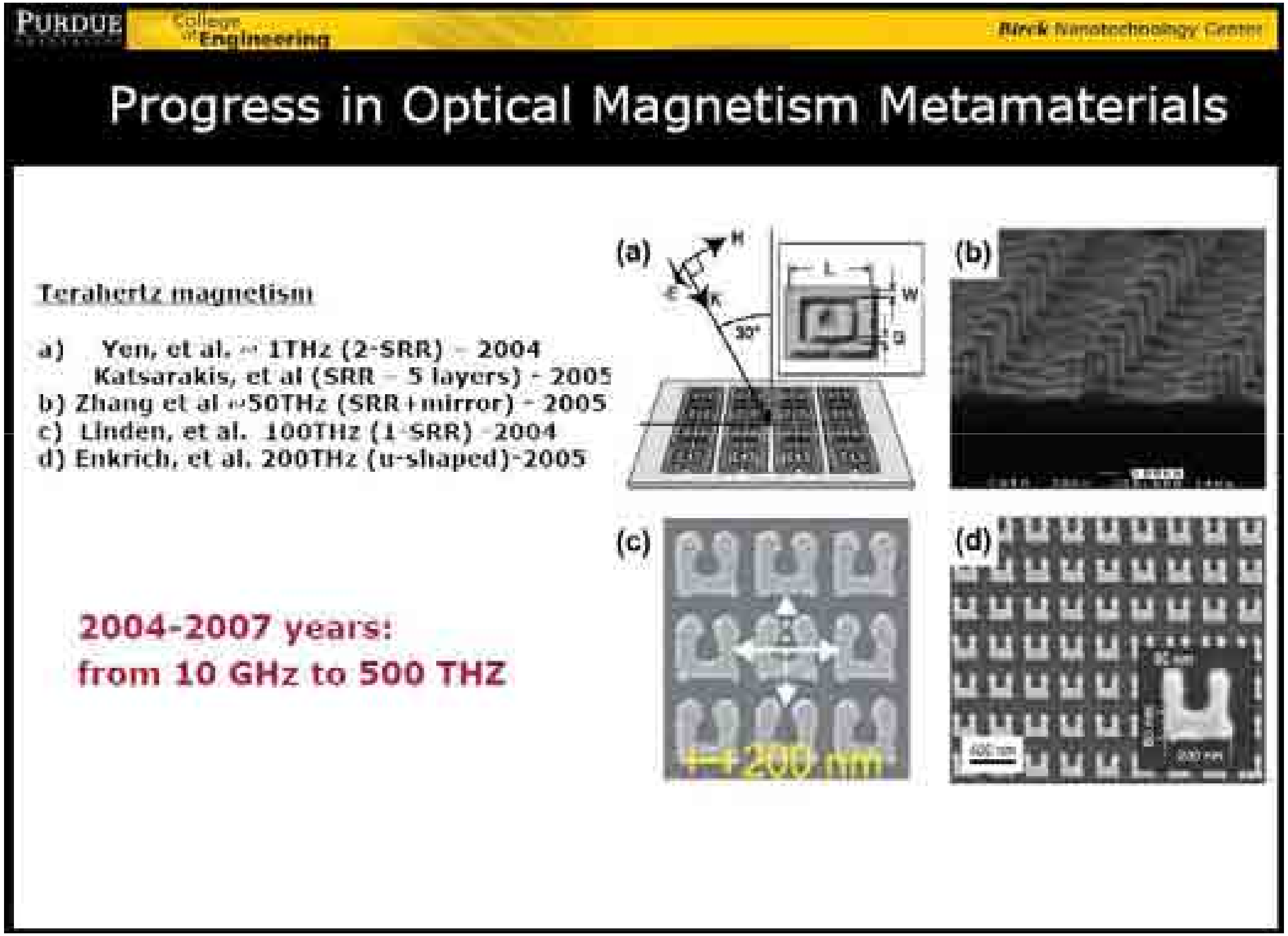
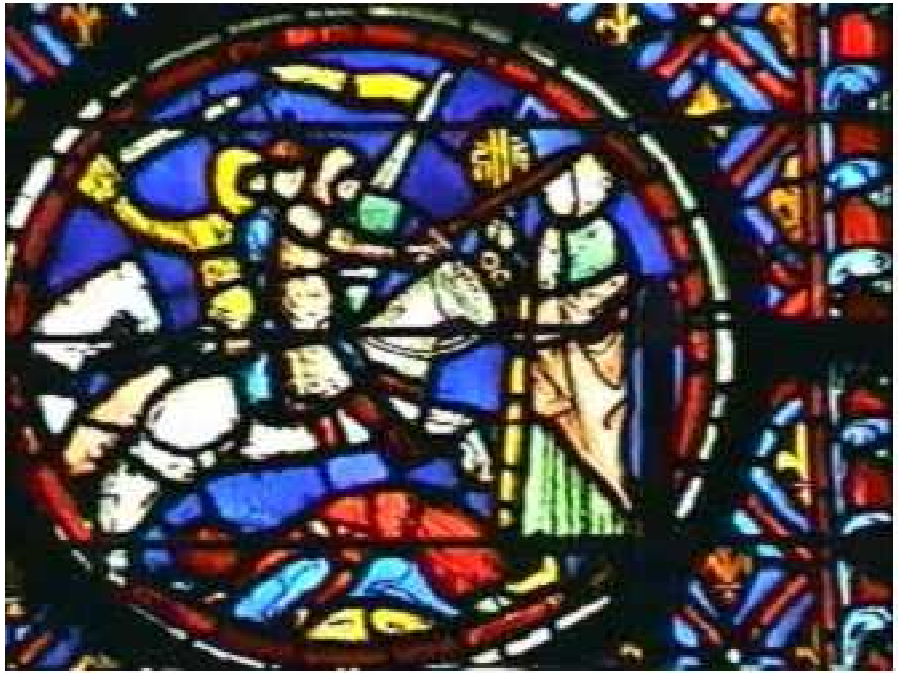


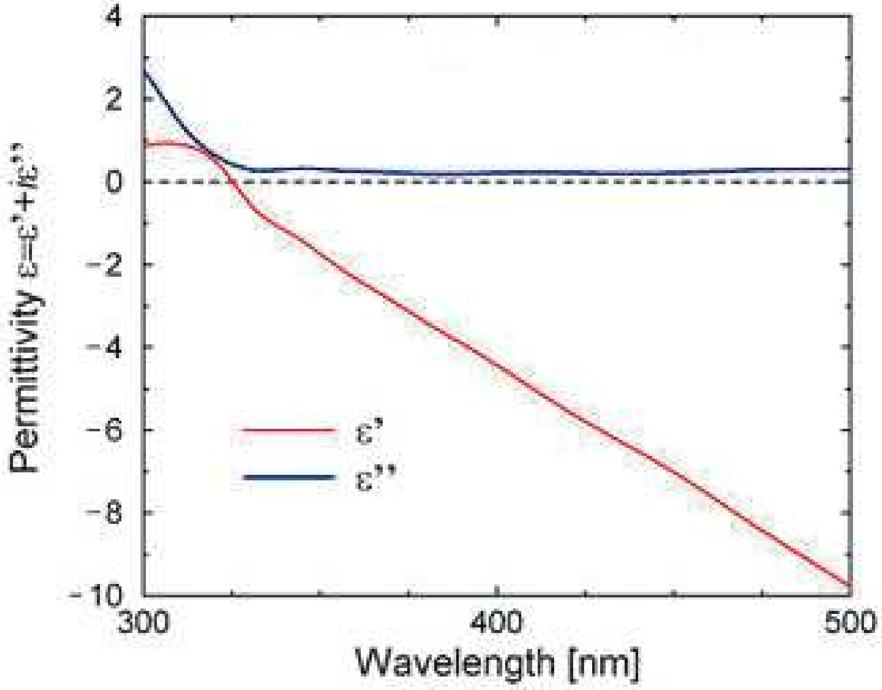
Figure taken from V. Shalaev (Purdue University) presentation slides

Going Optical –Approach II
Make Use of Surface Plasmons



The Lycurgus Cup (glass; British Museum; 4th century A. D.)

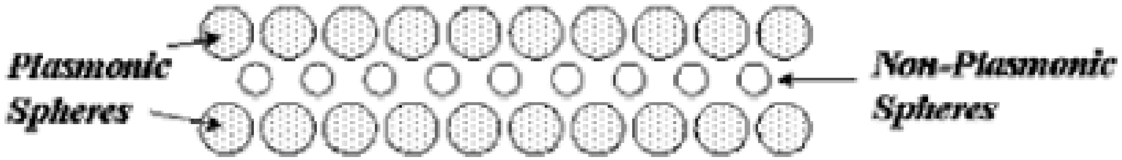
Going Optical – A 'Soft' Approach
Make Use of Surface Plasmons



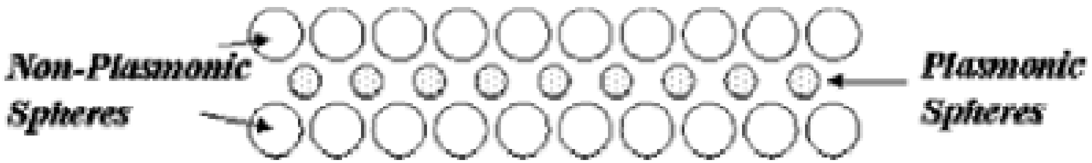
Permittivity of silver

From Plasmonic Spheres to Nano-circuit Elements in Optical Domain (Alu, Engheta; 2005)

Nano-transmission-lines



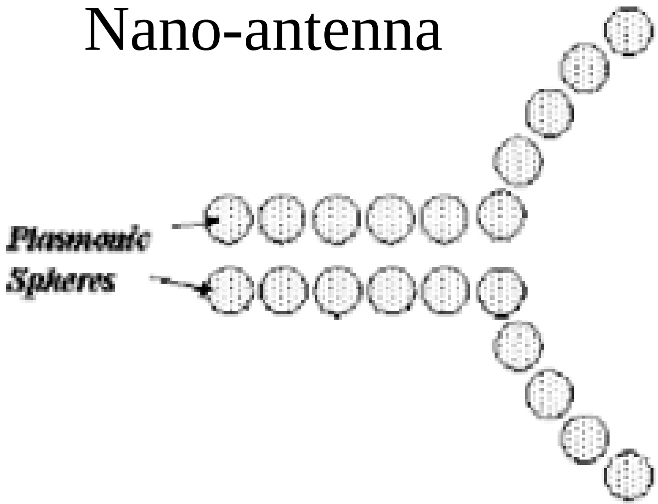
Forward-wave

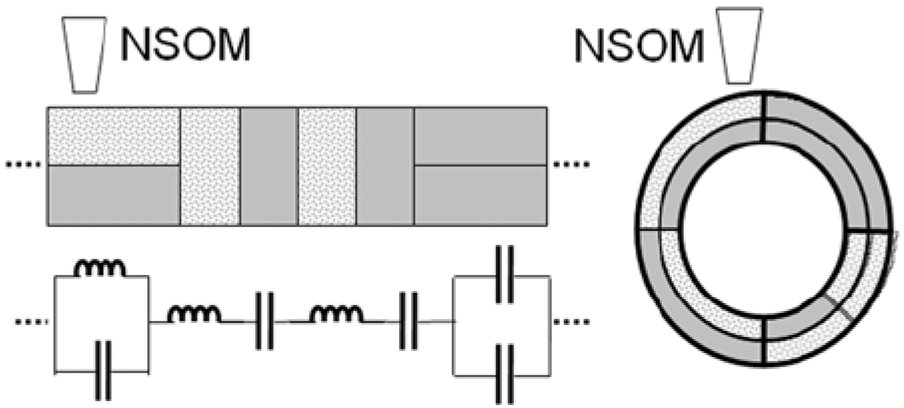


Backward-wave

Nano-circuit

Nano-antenna

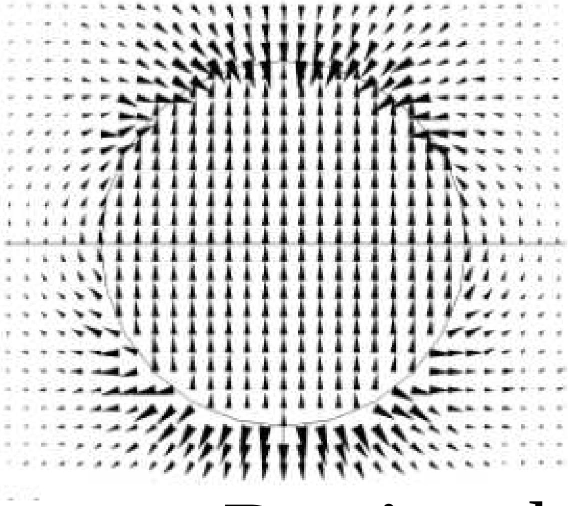




New Idea - Scaled RF Replicas of Plasmonic Structures

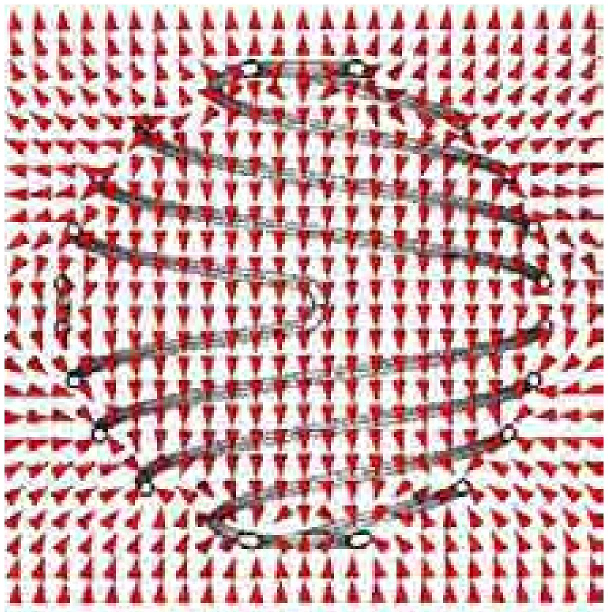
Prototyping of 'RF replicas' of plasmonic spheres

(Hrabar, Eres; Kumric, 2007)

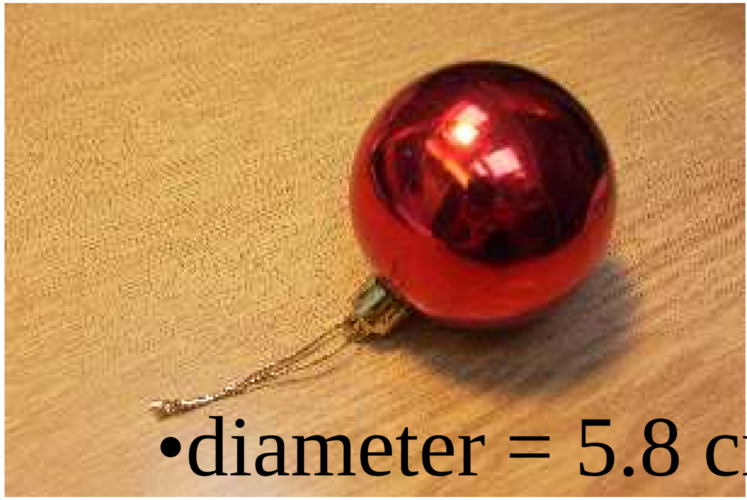


Simulated E-field distribution of ideal plasmonic nanosphere

Best's spherical resonator



Prototyping of “Plasmonicc” spheres



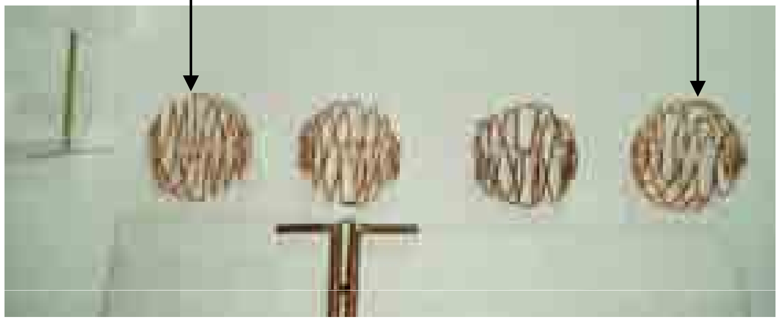
•diameter = 5.8 cm

Measurement of E-field phase distribution along four-sphere chains (RF replicas of plasmonic WG)

•Measuring points

•L

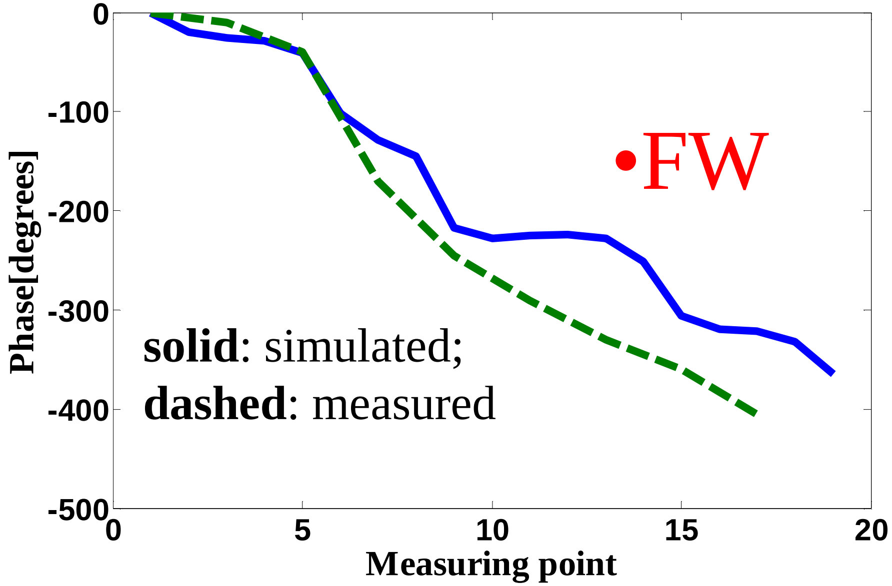
•1 •20

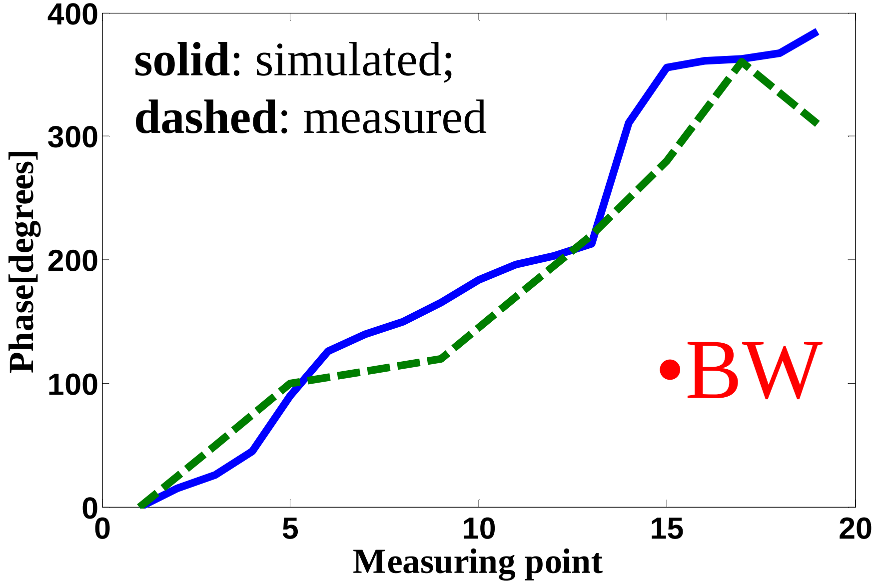


•T

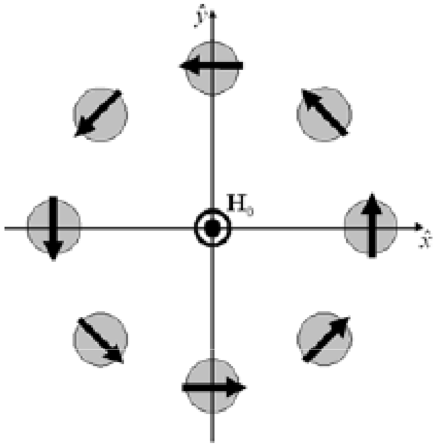
•1 •20

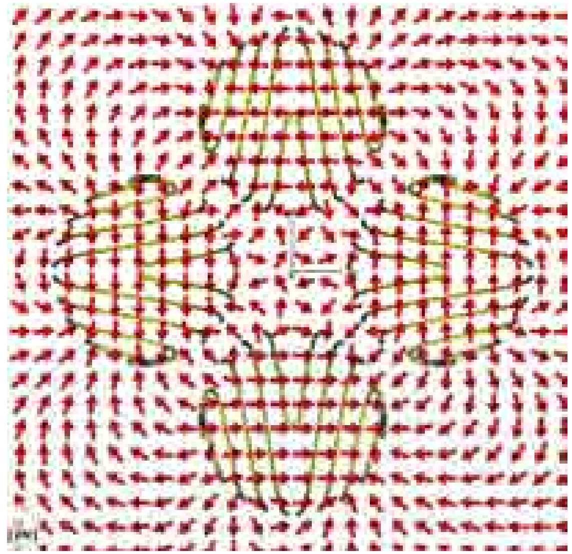
•Measuring points

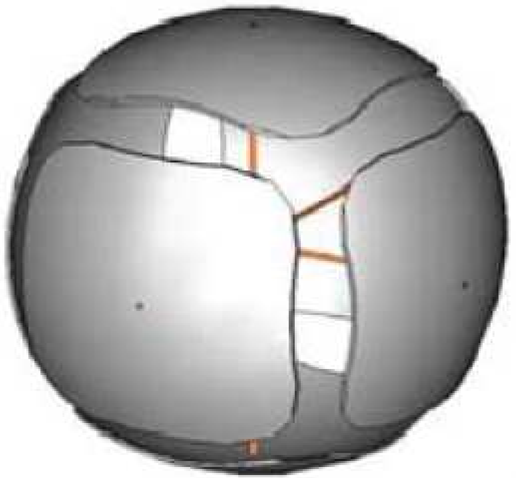




Prototyping of ‘RF analog of ‘plasmonic circular cluster ‘ (Hrabar, Muha, Zaluski, Mlakar, 2010)

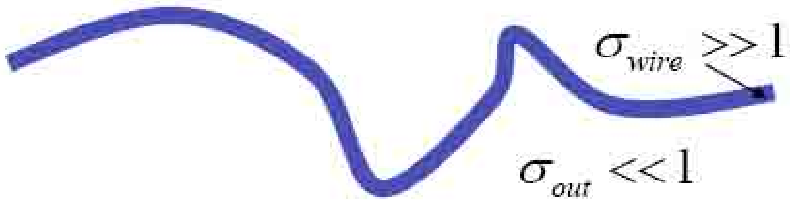






Current Confinement?

RF



$\sigma_{wire} >> 1$

$\sigma_{out} << 1$

$J_{out} = \sigma_{out} E \simeq 0$

$\boldsymbol{D} = \varepsilon \boldsymbol{E}$

Nano-Optics ?

$\varepsilon_{wire} >> 1$

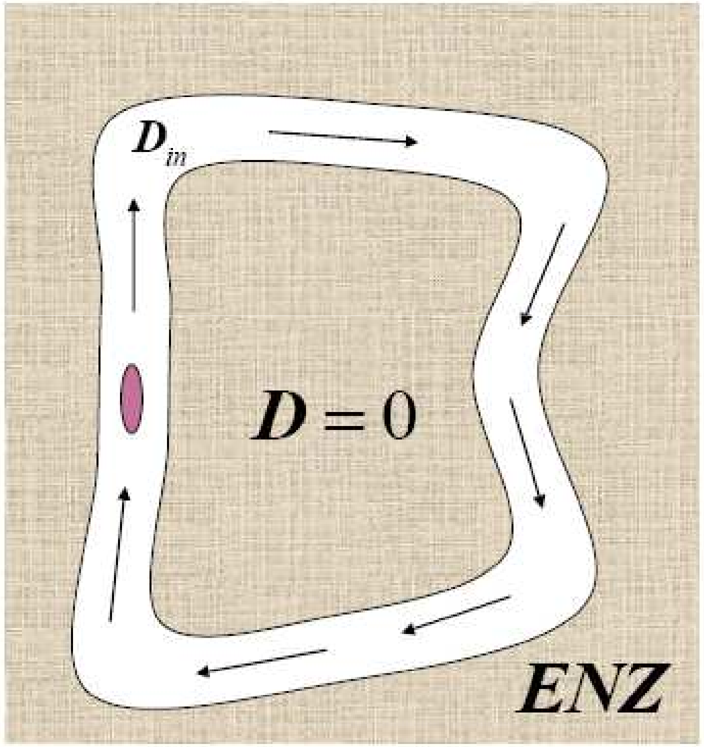
$\varepsilon_{substrate} << 1$

$D_{out} = \varepsilon_{out} E \simeq 0$

Alu, Engheta, Optics Express, 15, 13773 (2007)

Figure taken from N. Engheta (University of Pennsylvania) presentation slides

Grooves in ENZ



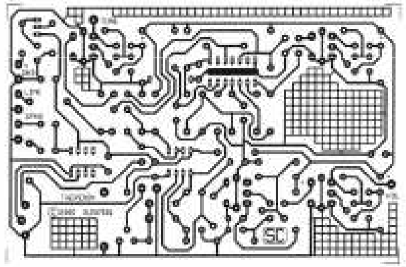


Figure taken from N. Engheta (University of Pennsylvania) presentation slides

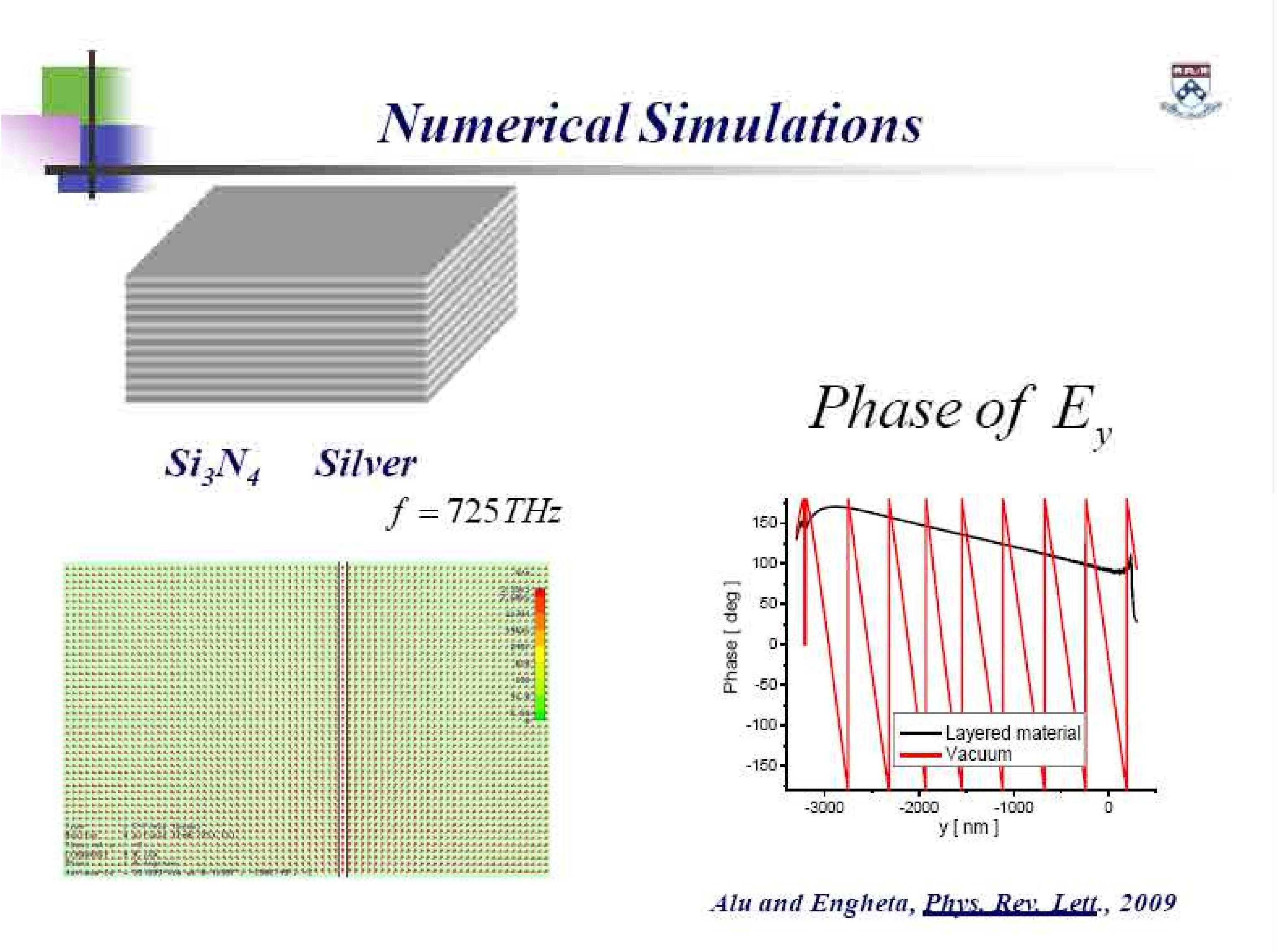
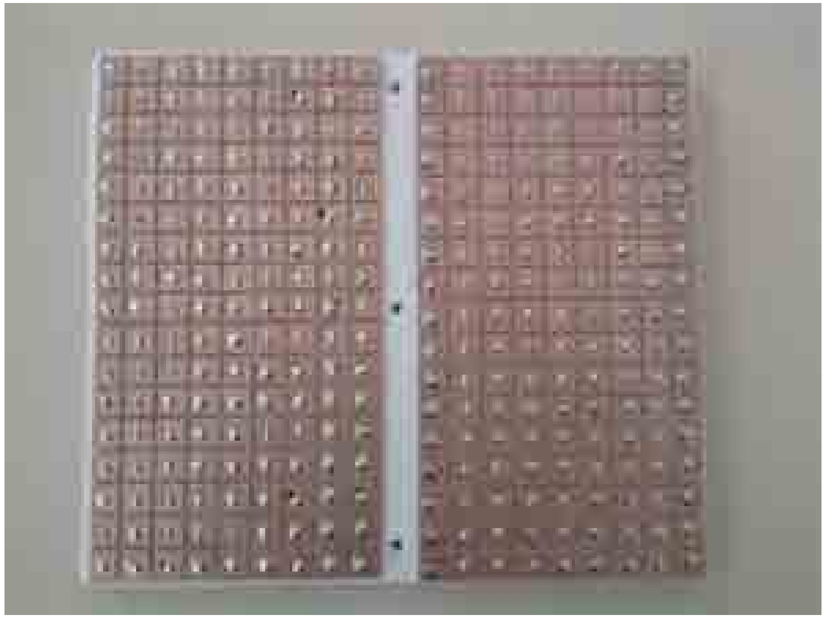
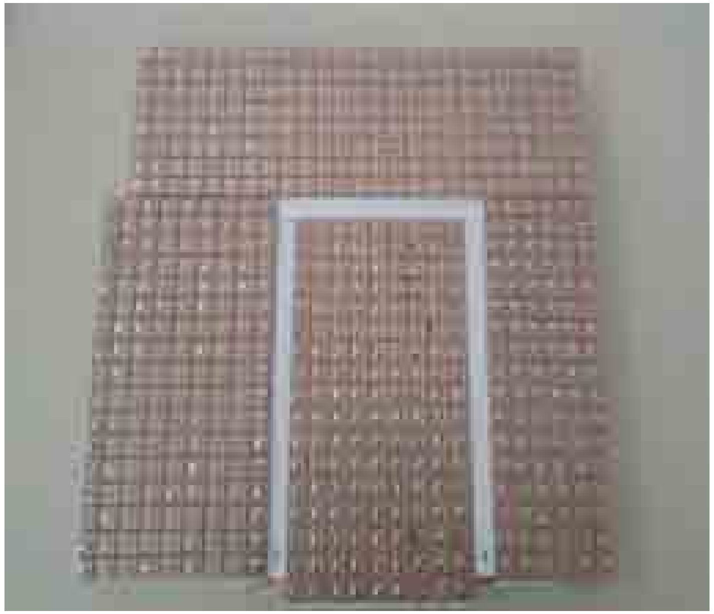
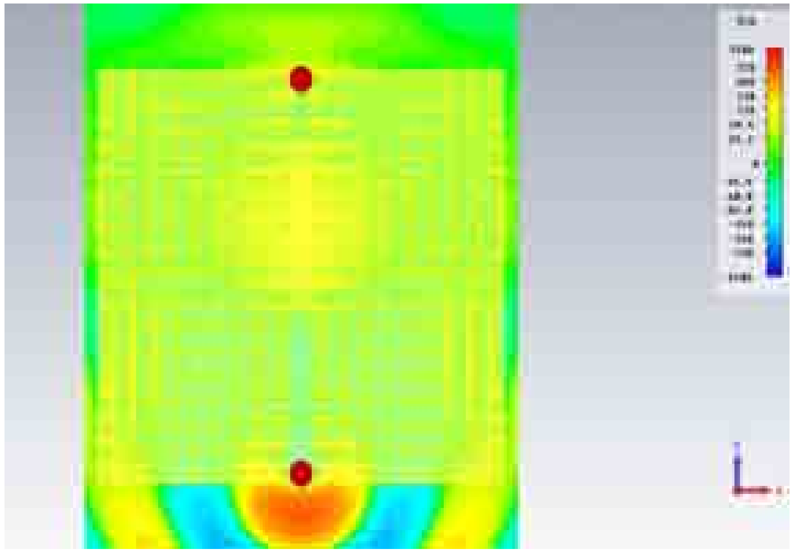


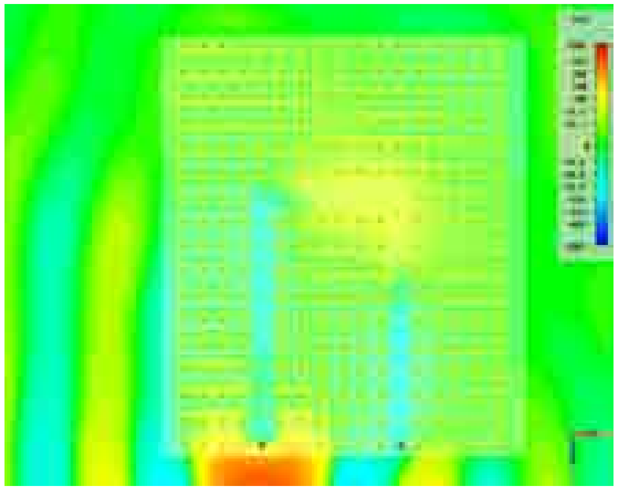
Figure taken from N. Engheta (University of Pennsylvania) presentation slides

Scaled prototype of optical D-dot wire (Muha, Hrabar et al. 2011)









Near-field Superlens

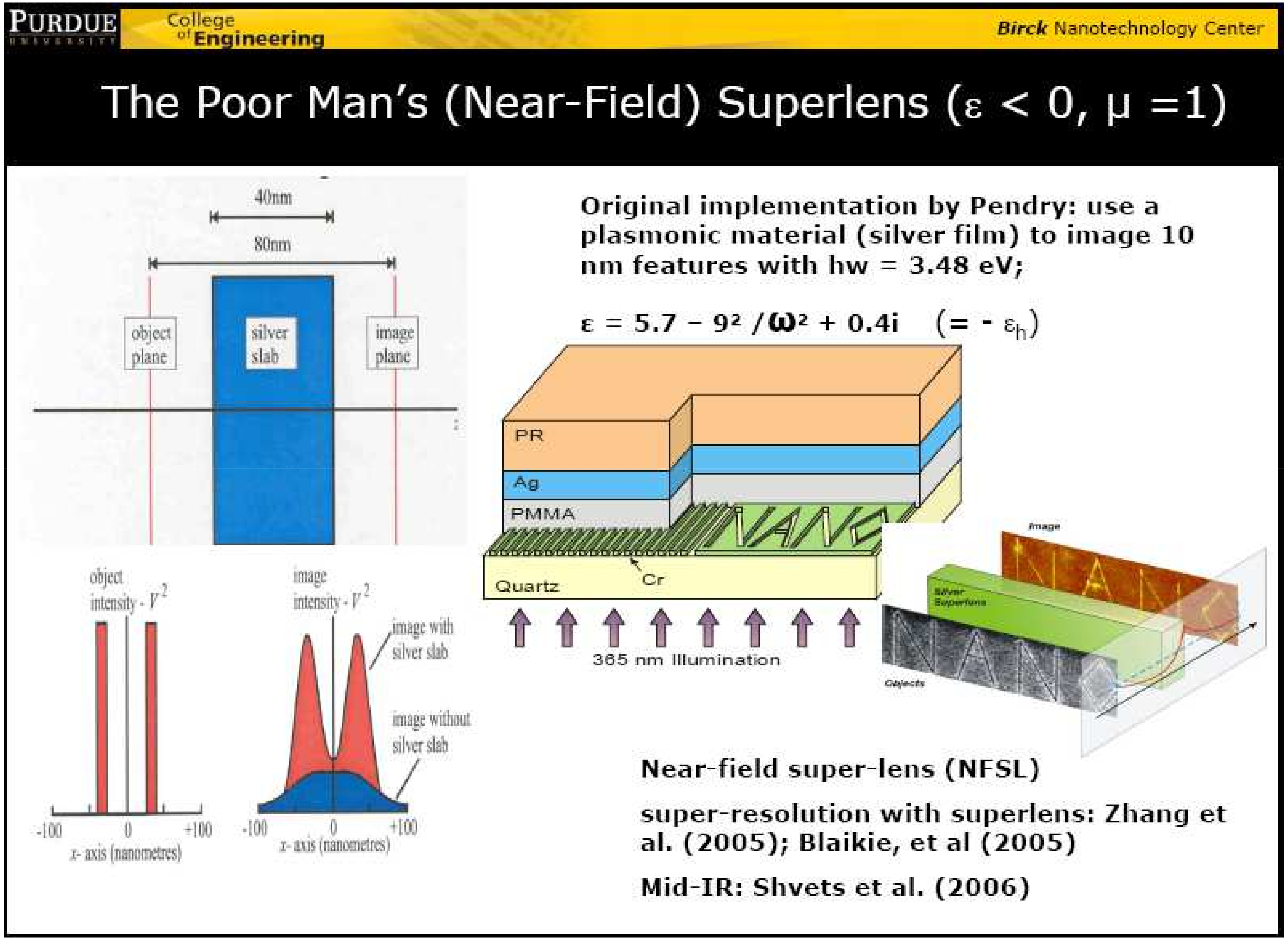


Figure taken from V. Shalaev (Purdue University) presentation slides

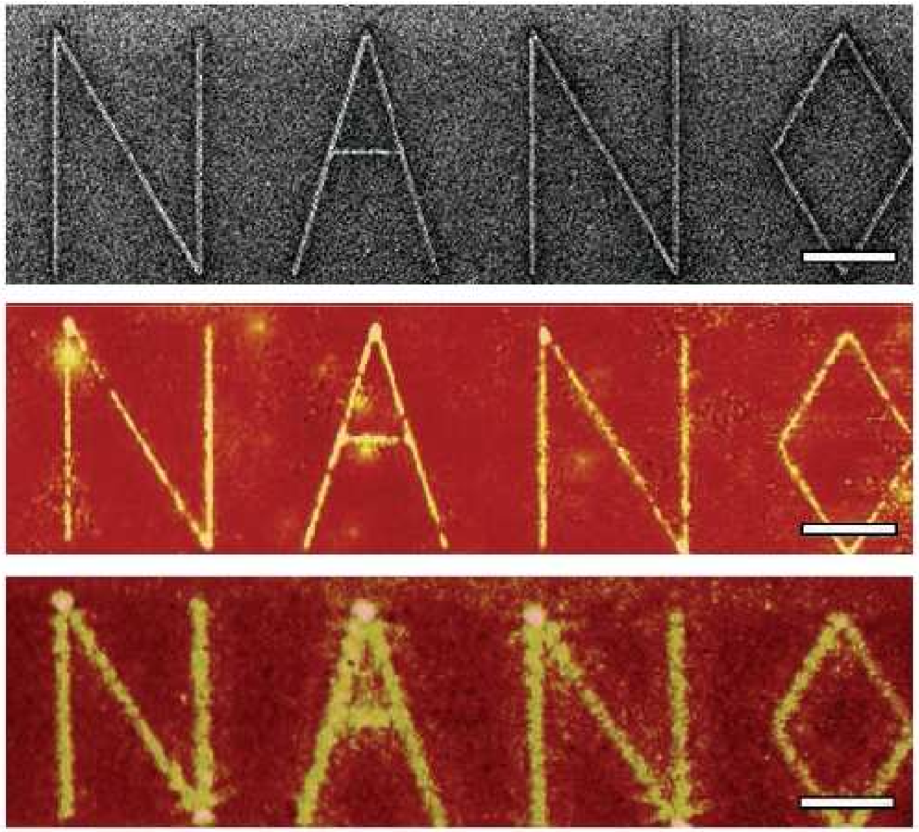
Experimentally achieved images

N. Fang, H. Lee, C. Sun, X. Zhang, Science **308, 534,** (2005).

written object (**top)**

optical image (**center)**

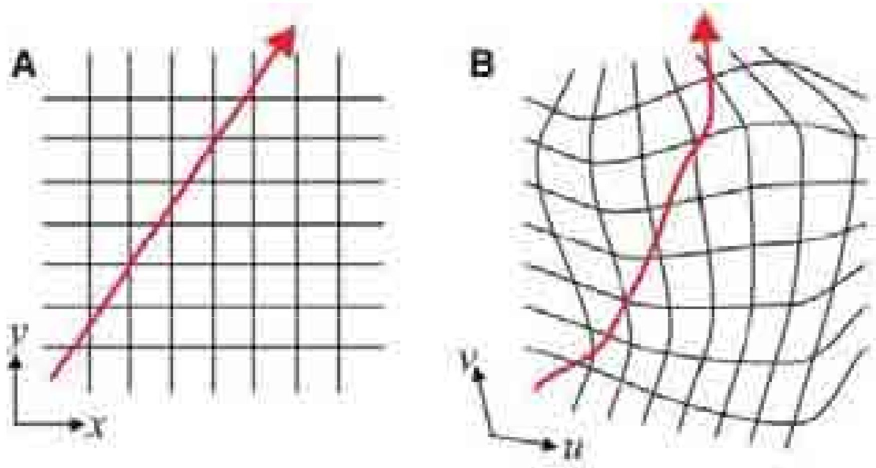
optical image without super- lens

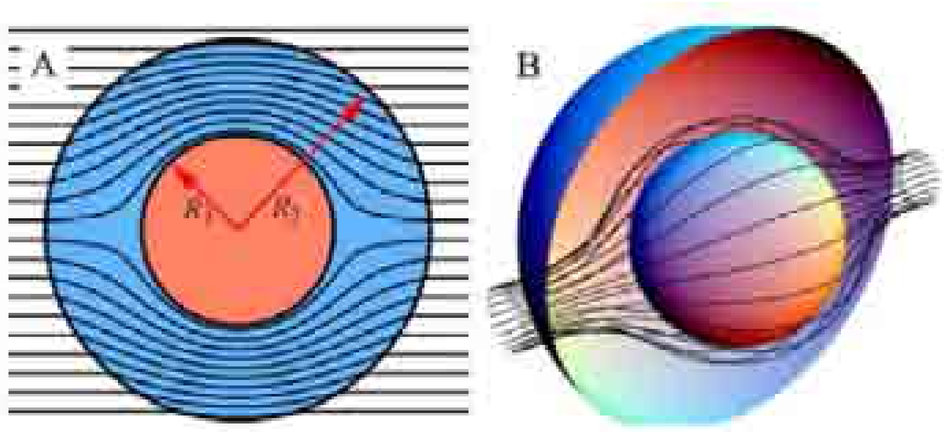


Potential Engineering Applications V – Is it feasible to be invisible?

Figure taken from V. Shalaev (Purdue University) presentation slides

‘Transformation Electromagnetics’
(Dollin 1961, Pendry 2006)

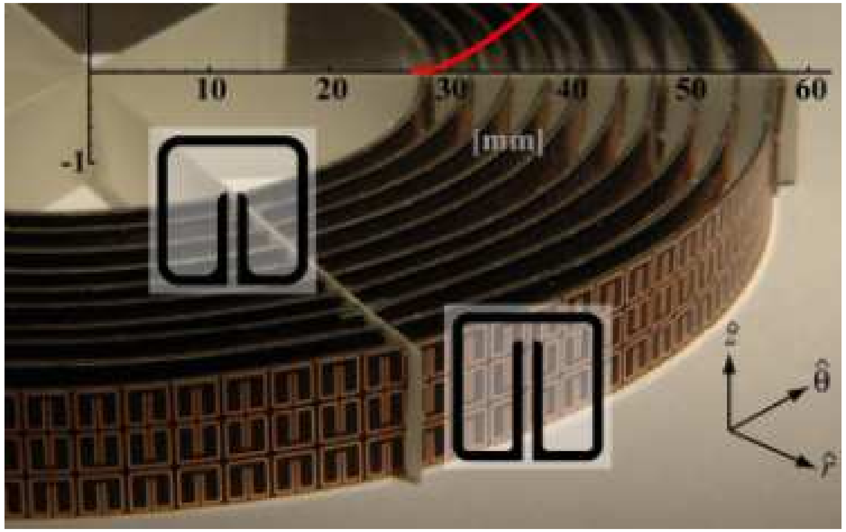


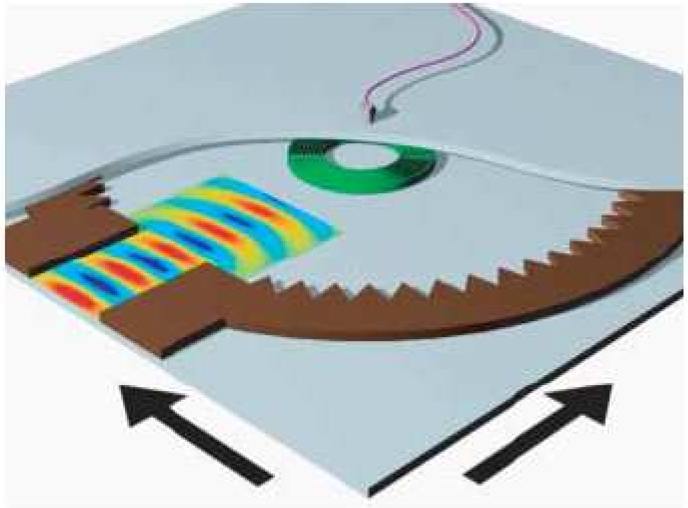


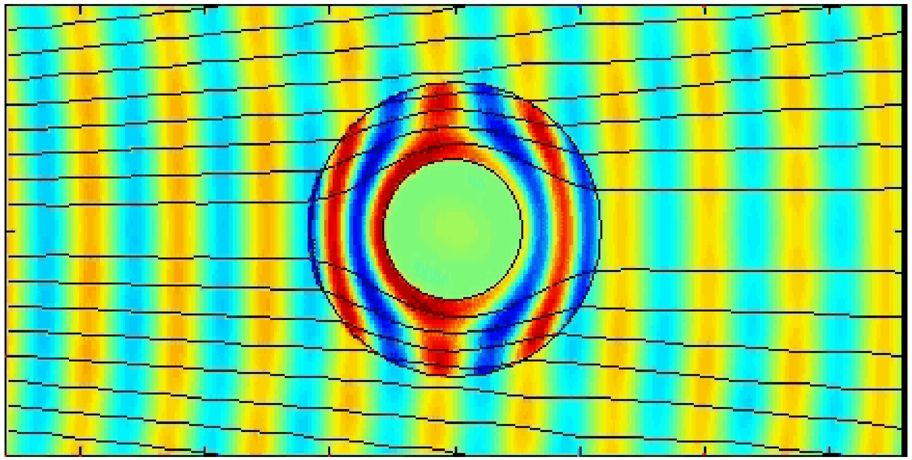
www.sciencexpress.org / 25 May 2006

•Experimental verification already reported

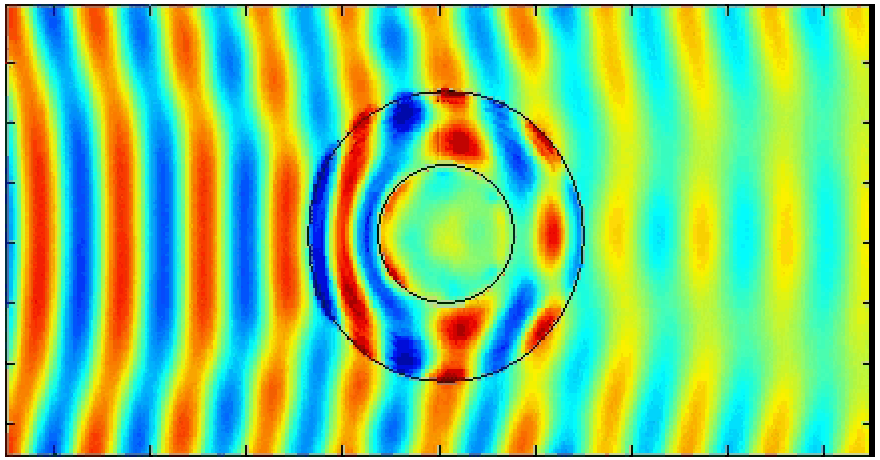
First Experimental Results (Schurig 2006)







Simulations

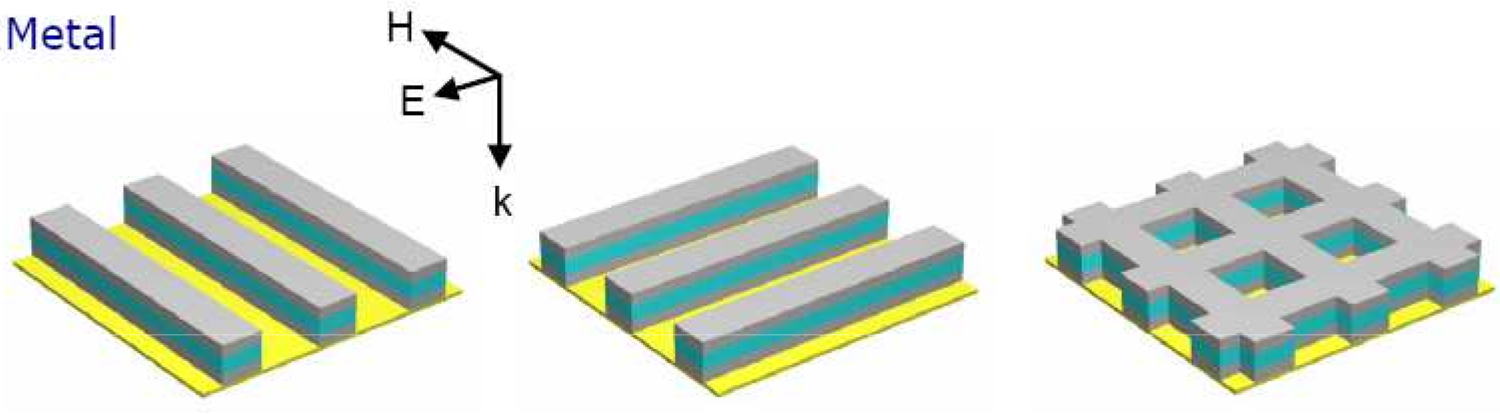


Measurements

PURDUE UNIVERSITY College of Engineering Birck Nanotechnology Center

Negative permeability and negative permittivity

- Dielectric
- Metal



Nanostrip pair (TM)	Nanostrip pair (TE)	Fishnet
$\mu < 0$ (resonant)	$\varepsilon < 0$ (non-resonant)	ε and $\mu < 0$

Figure taken from V. Shalaev (Purdue University) presentation slides *S. Zhang, et al., PRL (2005)*

Problem 1 All these structures are again extremely narrowband!

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Birck Nanotechnology Center

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=|n'|/n"*	*Structure used*
2005:					
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
2006:					
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

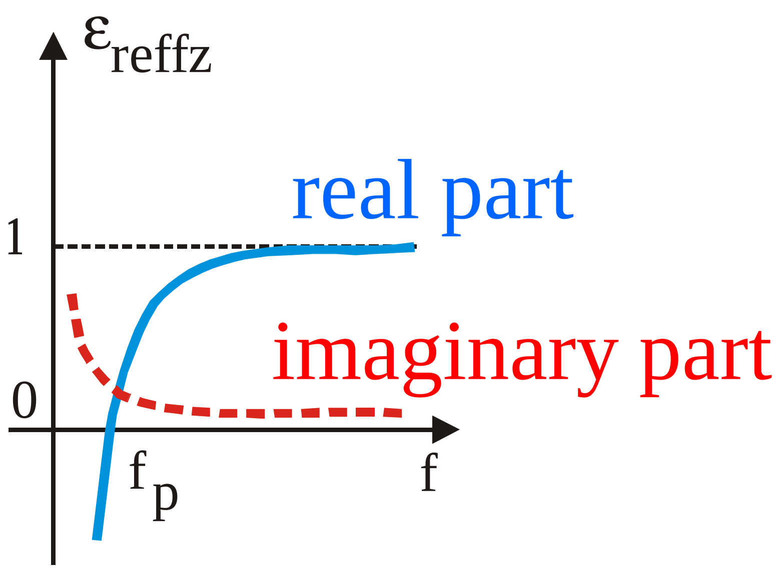
see review: Nature Photonics v. 1, 41 (2007)

Problem 2 All these structures have significant loss !

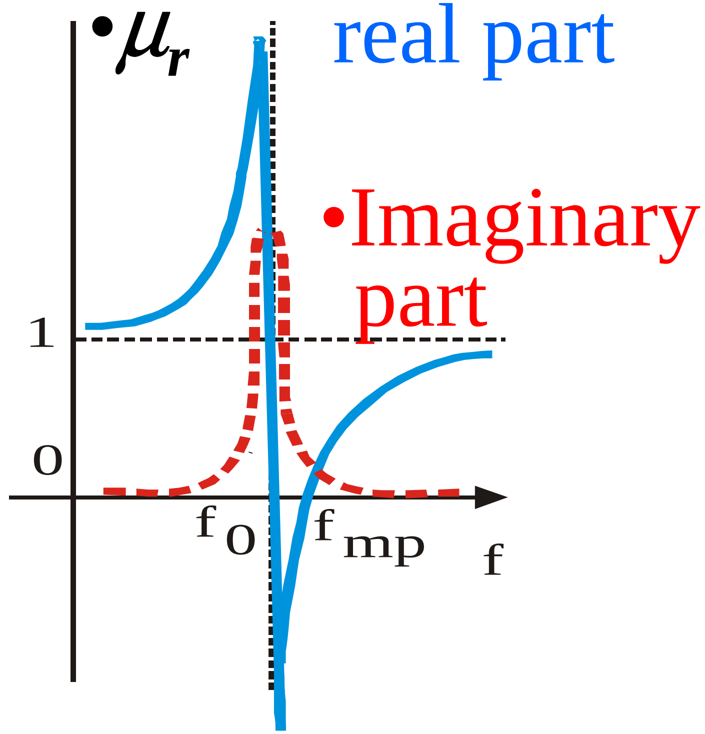
Figure taken from V. Shalaev (Purdue University) presentation slides

Dispersion models of passive materials (metamaterials) with $\varepsilon_r<1$ or $\mu_r<1$

•Drude model

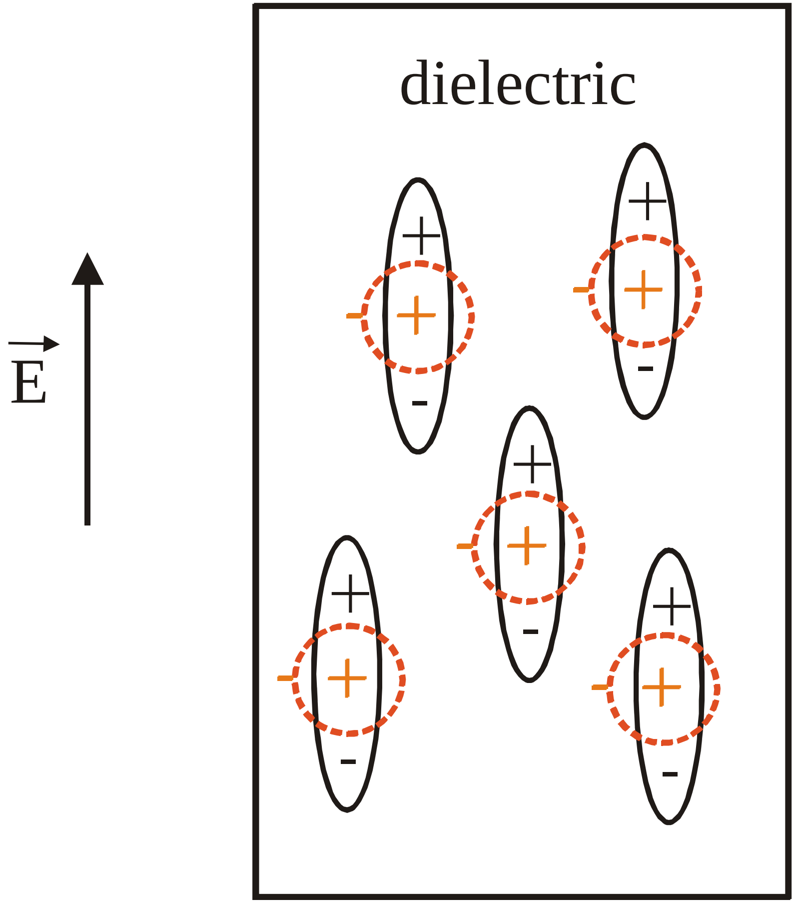


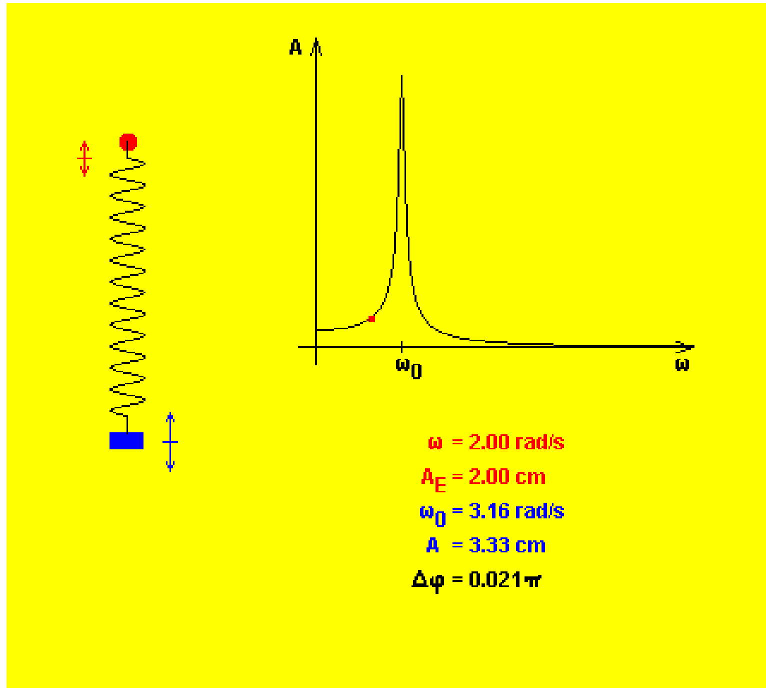
•Lorentz model

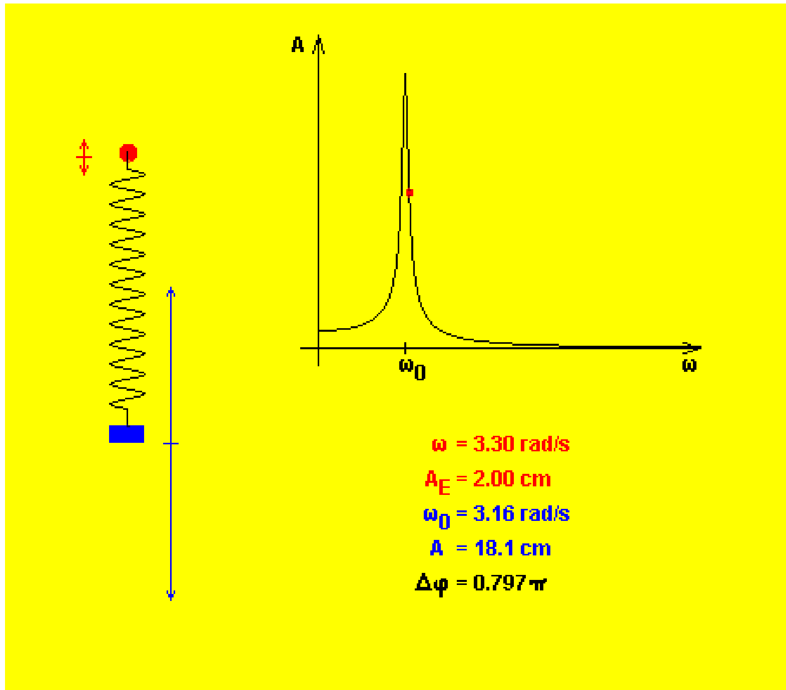


Both of these models are highly dispersive for $0<\varepsilon_r<1$ (or $0<\mu_r<1$)

Resonance is always present in passive metamaterials – WHY?)







- URL: http://www.walter-fendt.de/ph14e/resonance.htm

Can one go around the dispersion-energy limitations?

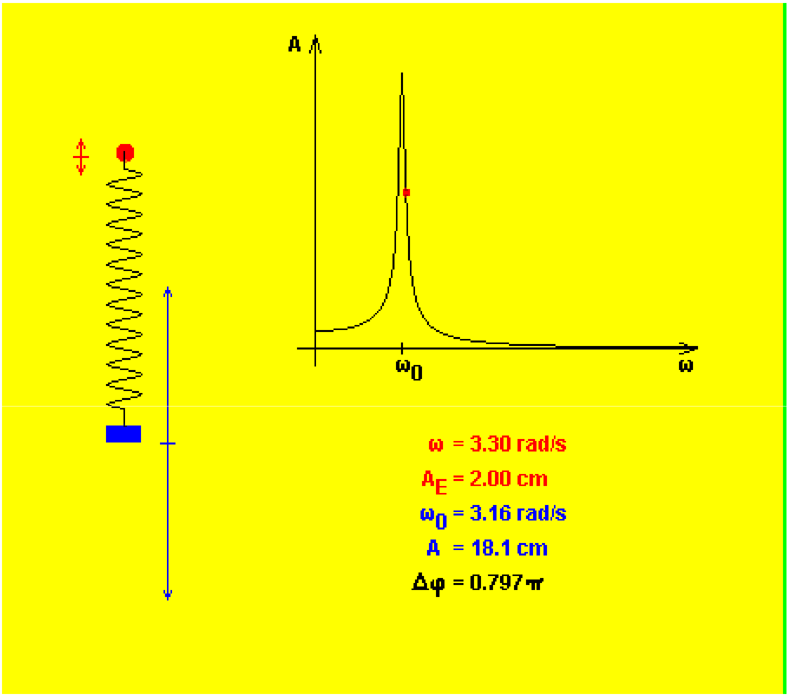
$$W = W_e + W_m = \frac{1}{2}\varepsilon_0 \frac{\partial(\omega\varepsilon_r)}{\partial\omega} E^2 + \frac{1}{2}\mu_0 \frac{\partial(\omega\mu_r)}{\partial\omega} H^2$$

$$\frac{\partial(\omega\varepsilon_r)}{\partial\omega} > 0, \frac{\partial(\omega\mu_r)}{\partial\omega} > 0.$$

W<0, ???

The only way is to use active medium (i.e. to introduce active elements) !

Active medium should introduce 'assisting negative restoring force' !

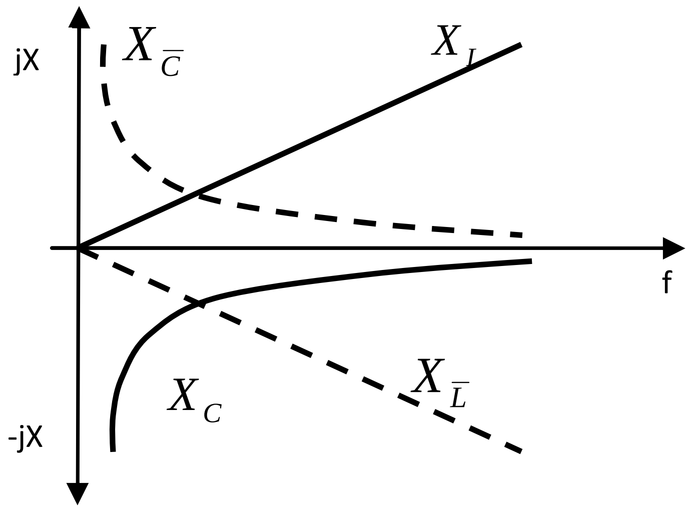


F_{as}

- **One would need a 'negative spring' or a'negative mass'**

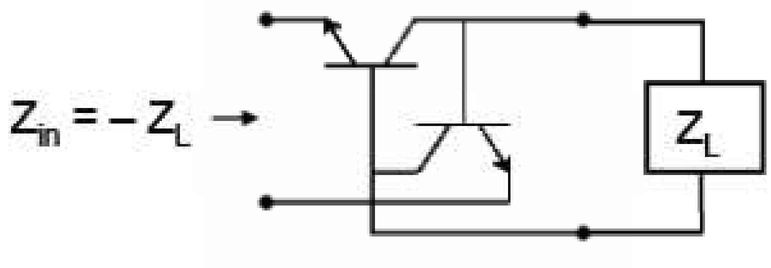
•URL: http://www.walter-fendt.de/ph14e/resonance.htm

•Going Active - Non-Foster reactive elements (negative C and negative L)



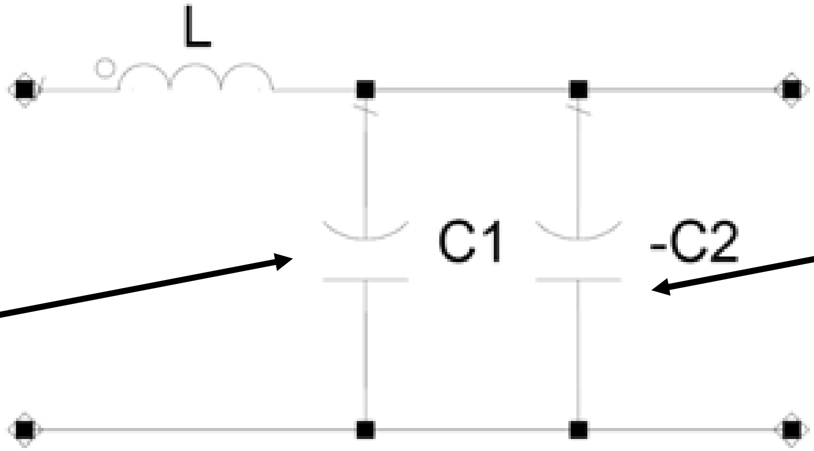
$$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{-V_l}{I_l} = -Z_l$$

Floating negative impedance
(Linvill, 1953)



New idea : Introduction of negative capacitance into TL (Hrabar et al , APS 2008)

•Positive capacitance



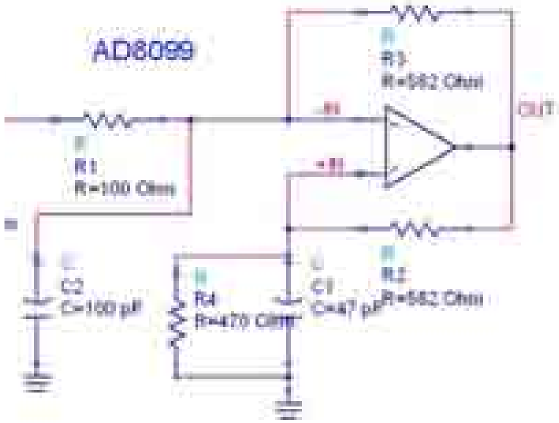
•**Negative capacitance**

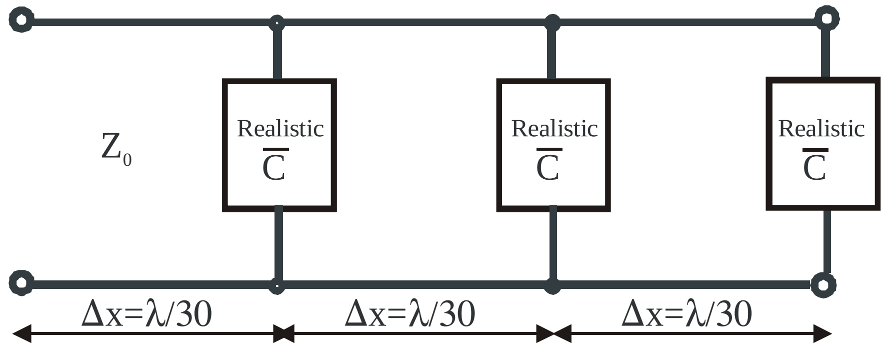
$$C = C_1 + C_2$$

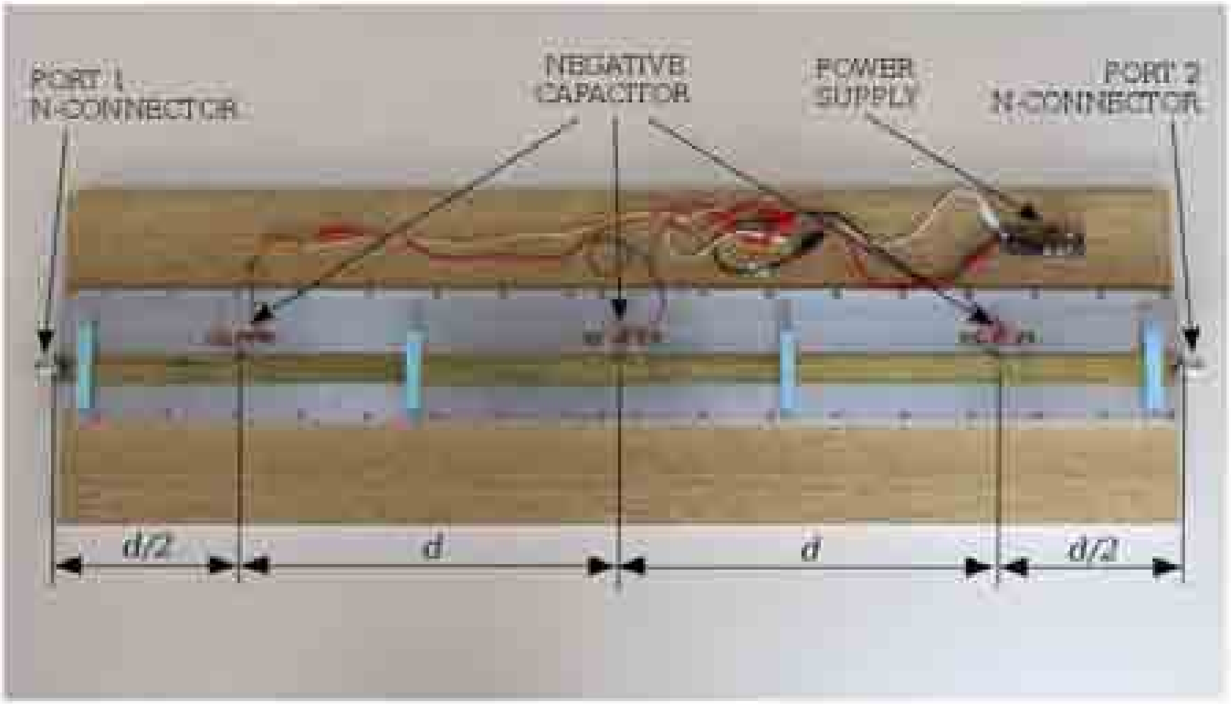
$$C_e = C_+ + C_- = |C_+| - |C_-|$$

$$\varepsilon_e = \varepsilon_0 + \varepsilon_- = \varepsilon_0 - |\varepsilon_-| \quad \Rightarrow \quad 0 < \varepsilon < 1$$

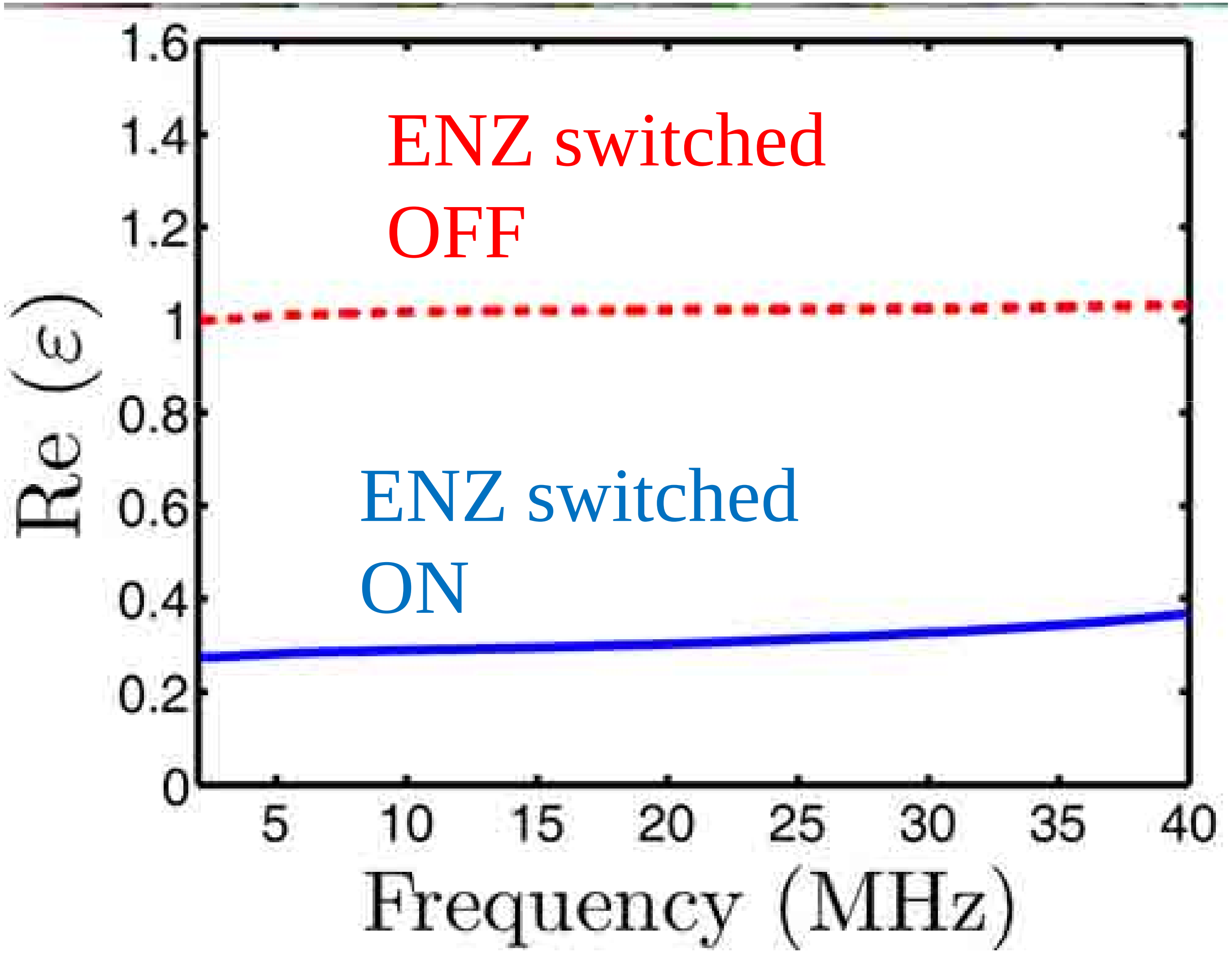
•Experimental RF Active ENZ TL with Three Unit Cells (l = 1 m), (Hrabar et.al 2011)





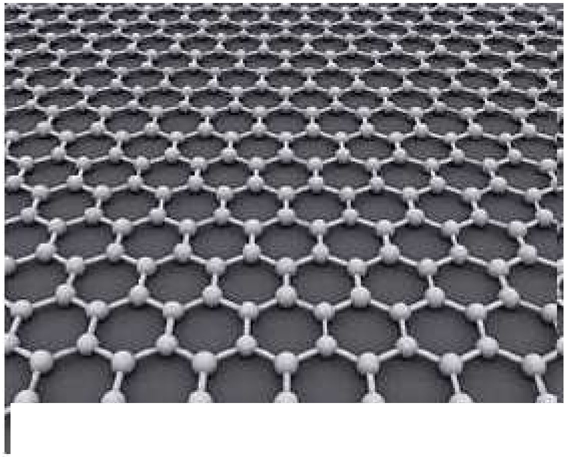


•**Measurement of effective permittivity of ENZ Active TL with Three Unit Cells** (Hrabar et.al 2011)



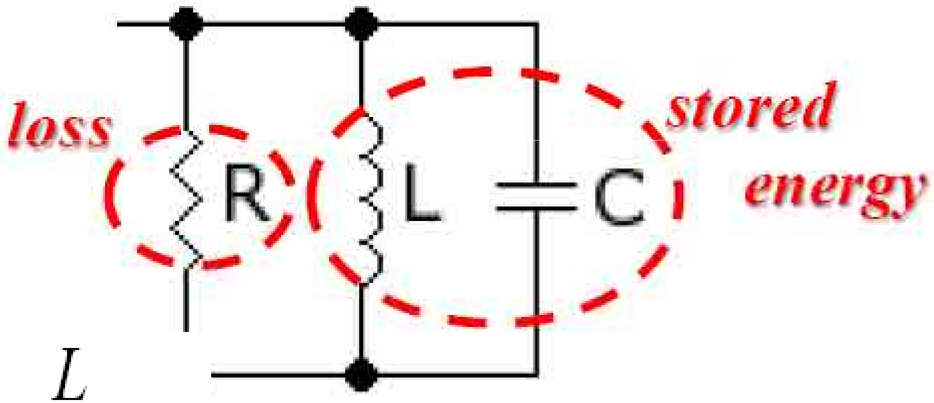
Potential Engineering Applications VI – Going nano?

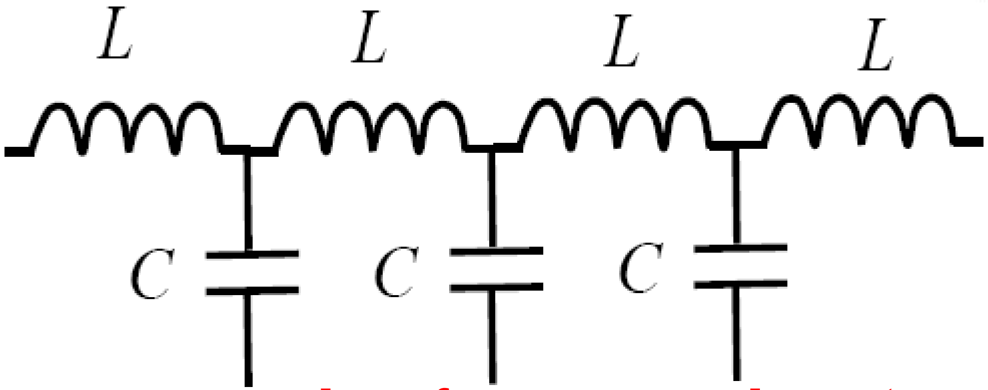
Graphene-based One-atom-thick Metamaterials



2010 Nobel Prize !

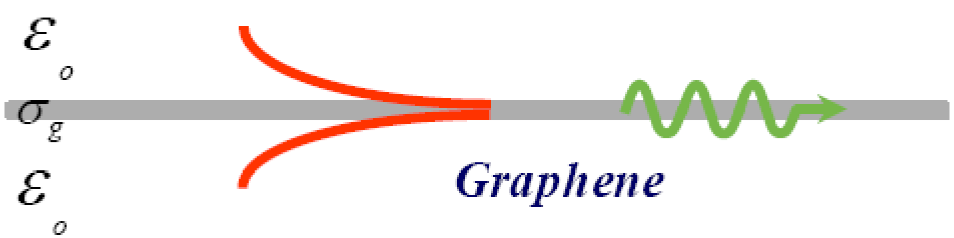
$$\sigma_g = \sigma_{g,r} + i\sigma_{g,i}$$

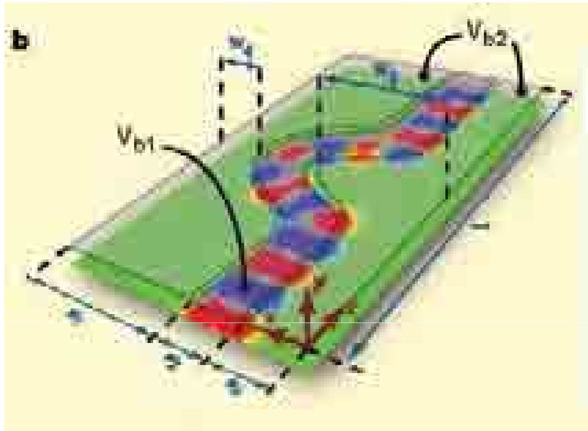


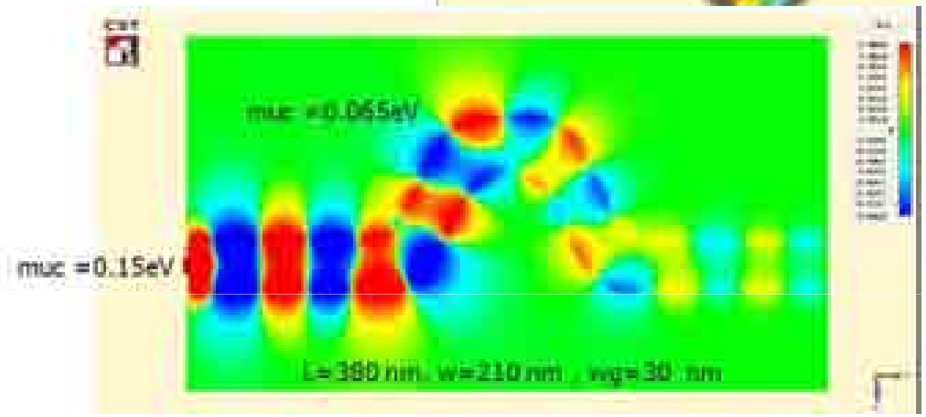


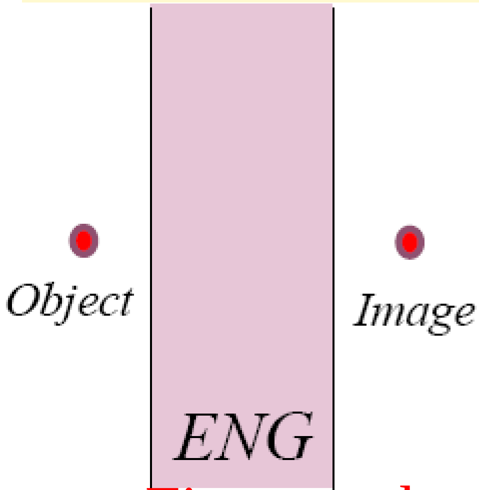
Figures taken from N. Engheta (University of Pennsylvania) presentation slides

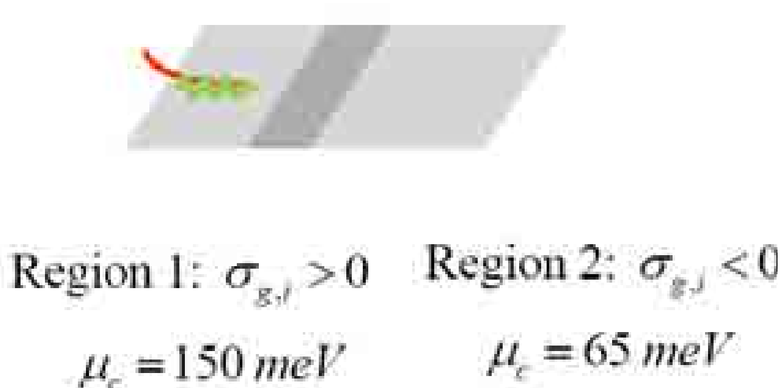
Graphene-based Metamaterials

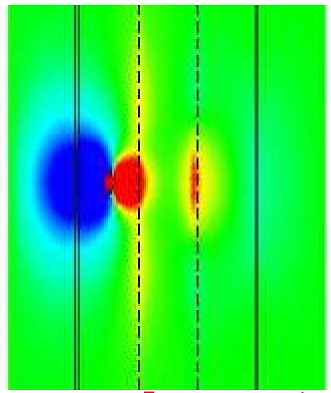












Figures taken from N. Engheta (University of Pennsylvania) presentation slides

What’s next?

- Nanotechnolgy + metamaterials (plasmonics, ,photonics, lasing, gain materials, superluminal materials, graphene, nano-spheres and nano-films)

- Gravity, matter, acoustics + metamaterials (black hole metamaterials, seismic metamaterials, acoustic lenses)

Conclusions

- Metamaterials offer new exciting physical phenomena, which are very often counter-intuitive !
- In author’s opinion, this area is not in its infant phase any more and applications, that make use of new intriguing phenomena are expected to come in coming years!
- It is an interdisciplinary field which needs extensive collaboration of different worlds (math, physics, engineering, at least!)