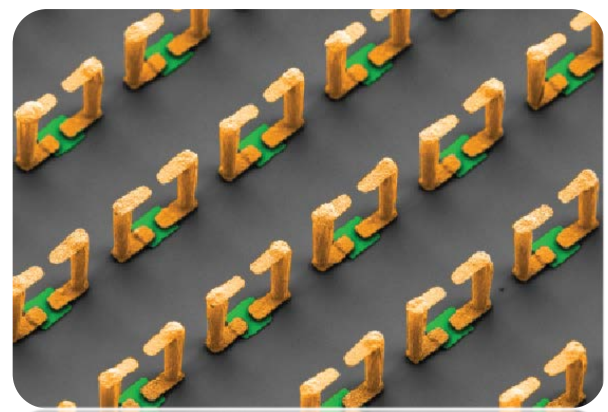
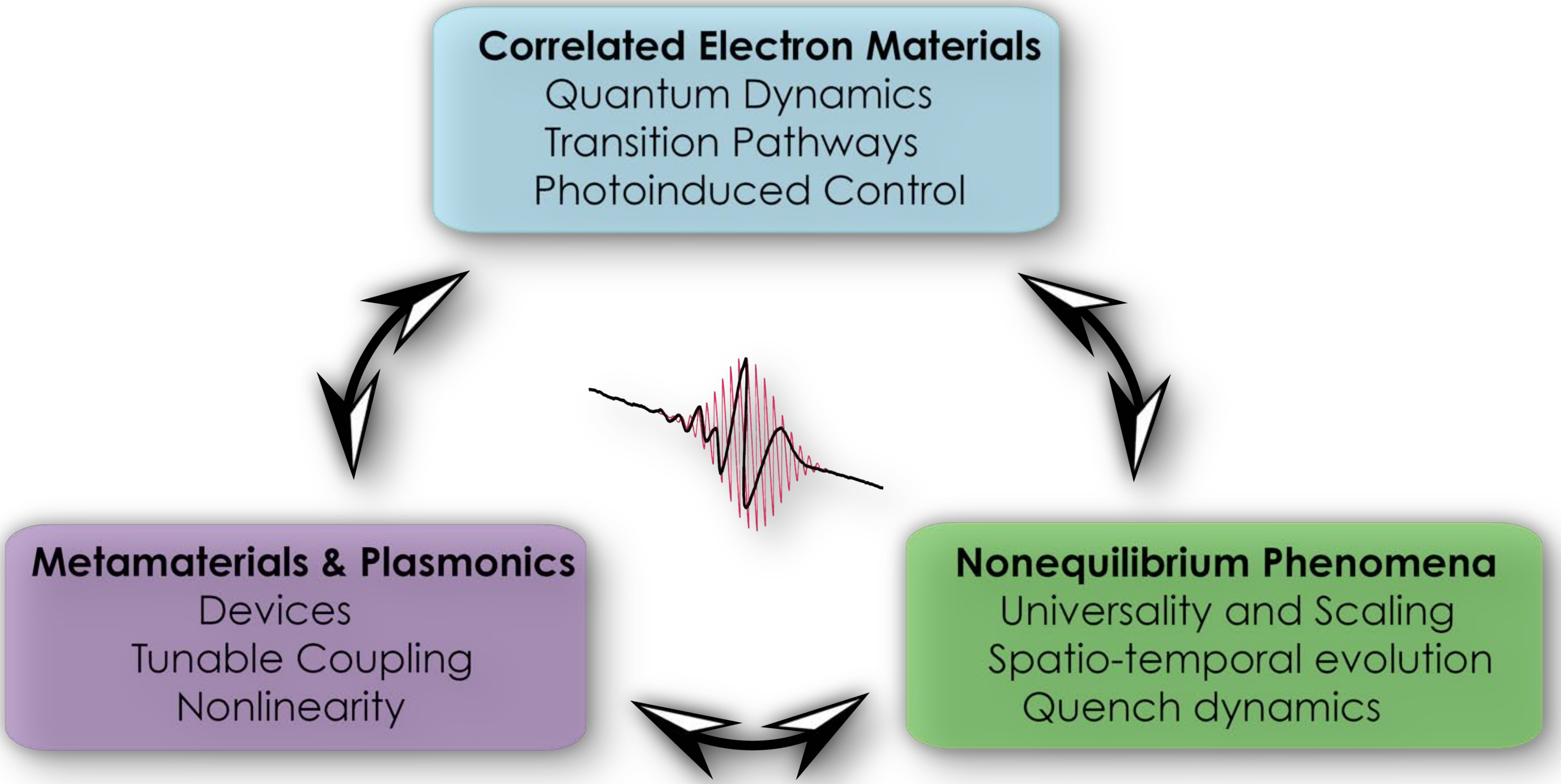
Introduction to Metamaterials

Richard D. Averitt

BOSTON UNIVERSITY

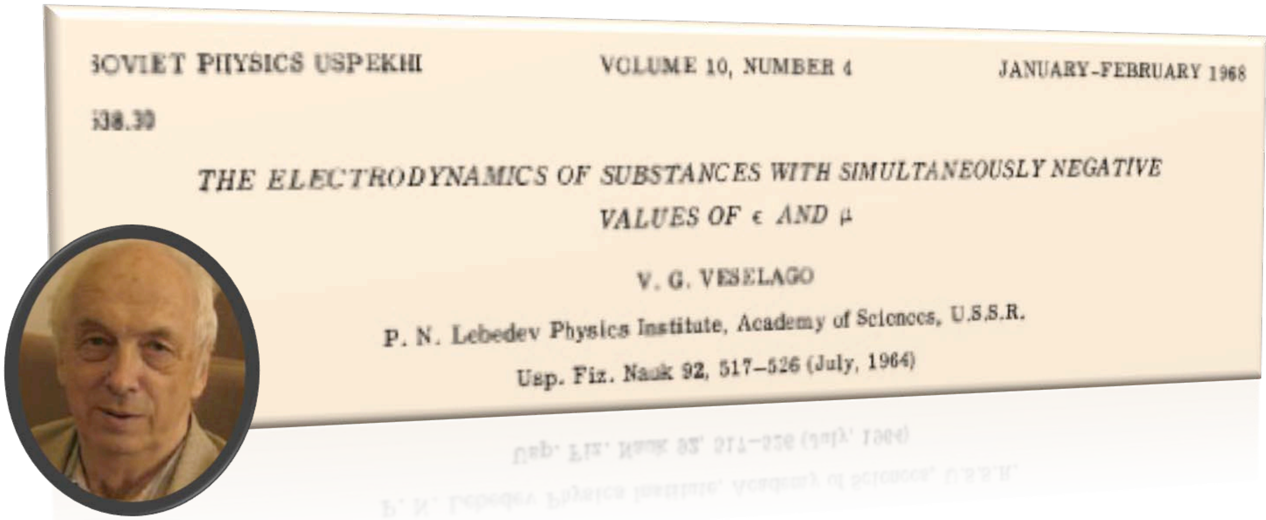


Research Themes



"Equilibrium is when all of the fast stuff has happened, and all of the slow stuff hasn't."
-Feynman

Metamaterials: a new field


SOVIET PHYSICS USPEKHI VOLUME 10, NUMBER 4 JANUARY-FEBRUARY 1968

538.30

THE ELECTRODYNAMICS OF SUBSTANCES WITH SIMULTANEOUSLY NEGATIVE VALUES OF ϵ AND μ

V. G. VESELAGO

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Usp. Fiz. Nauk 92, 517–526 (July, 1964)

D. R. Smith, et al.,
Phys. Rev. Lett. 84, 4184 (2000)

J. B. Pendry, A. J. Holden, D. J. Robbins, W. J. Stewart, "Magnetism from conductors and enhanced non-linear phenomena," IEEE Trans. MTT 47, 2075 (1999)

The Irresistible Fantasy of the Invisible Man, and Machine

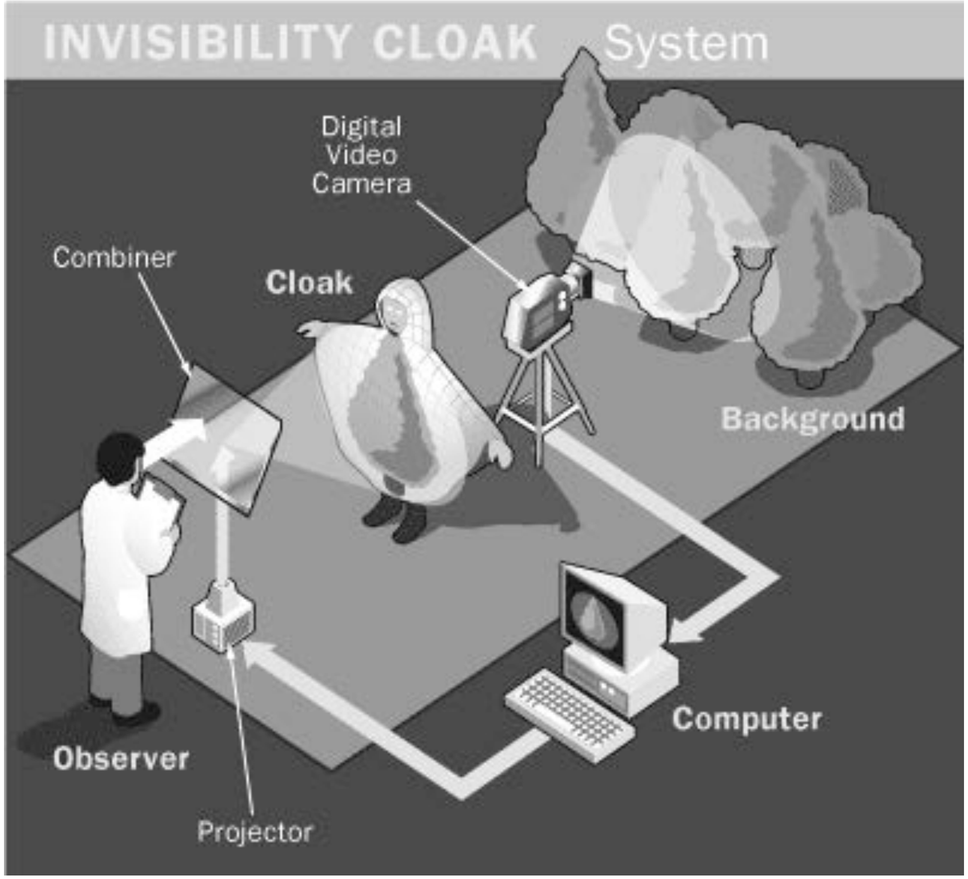
New York Times, 2007

The Chameleon

The Stealth Fighter:
Invisible to Radar?

Very small radar cross section: shape and absorbing paint

A camera and a projector



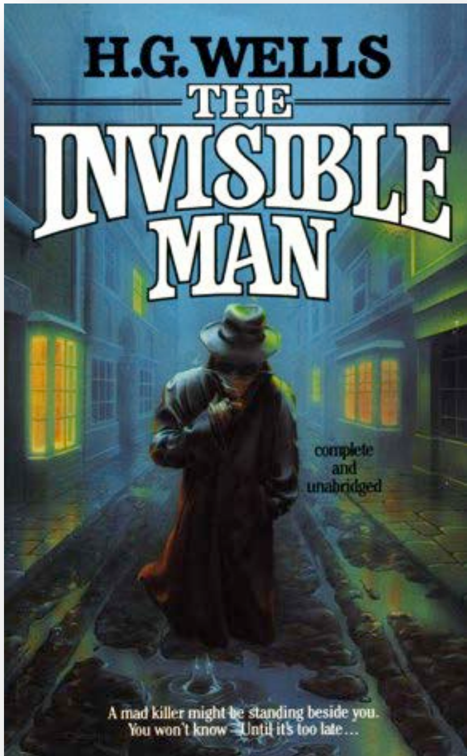
From: http://www.star.t.u-tokyo.ac.jp

Fantastic 4: The Invisible Woman

by Lee & Kirby (1961)

"... she achieves these feats by bending all wavelengths of light in the vicinity around herself ... without causing any visible distortion." -- Introduction from Wikipedia

The Invisible Man by H.G. Wells (1897)

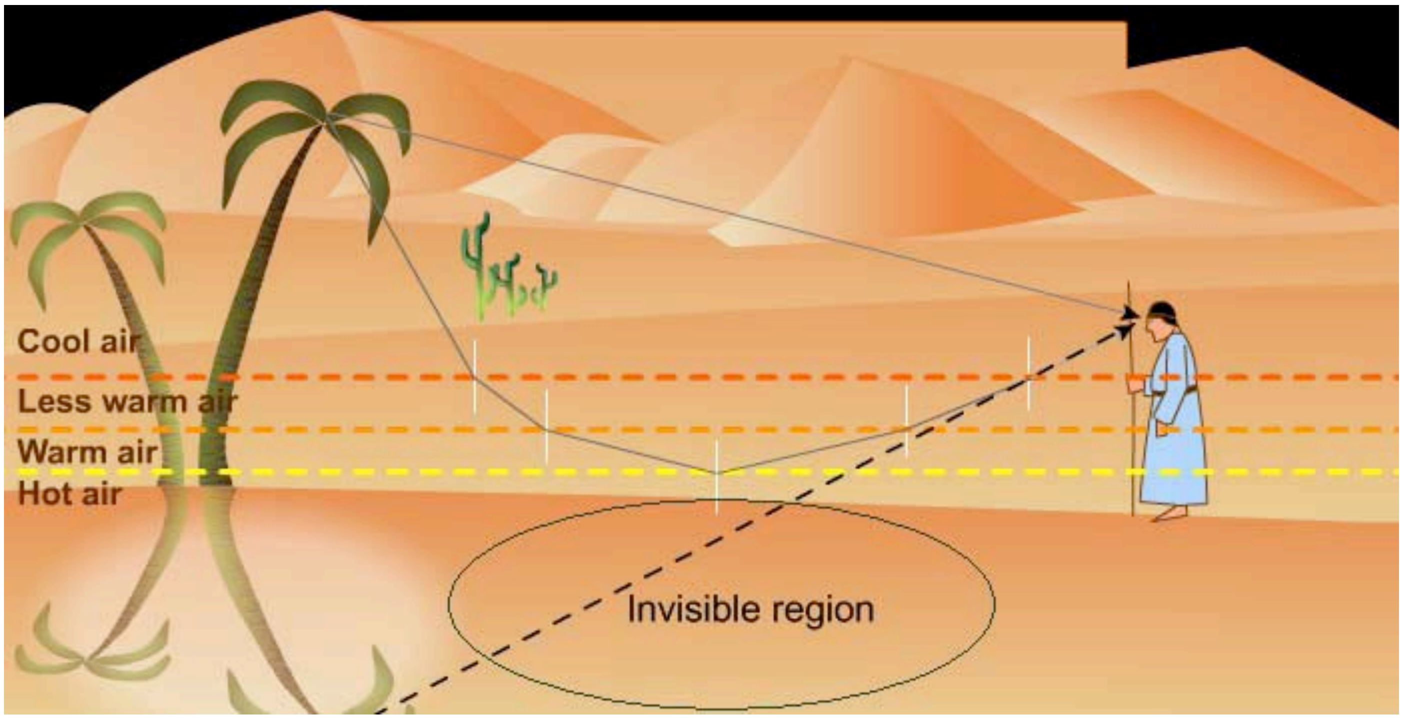


"… it was an idea … to lower the refractive index of a substance, solid or liquid, to that of air — so far as all practical purposes are concerned." -- Chapter 19 "Certain First Principles"

Key Concept:
The Refractive Index → n

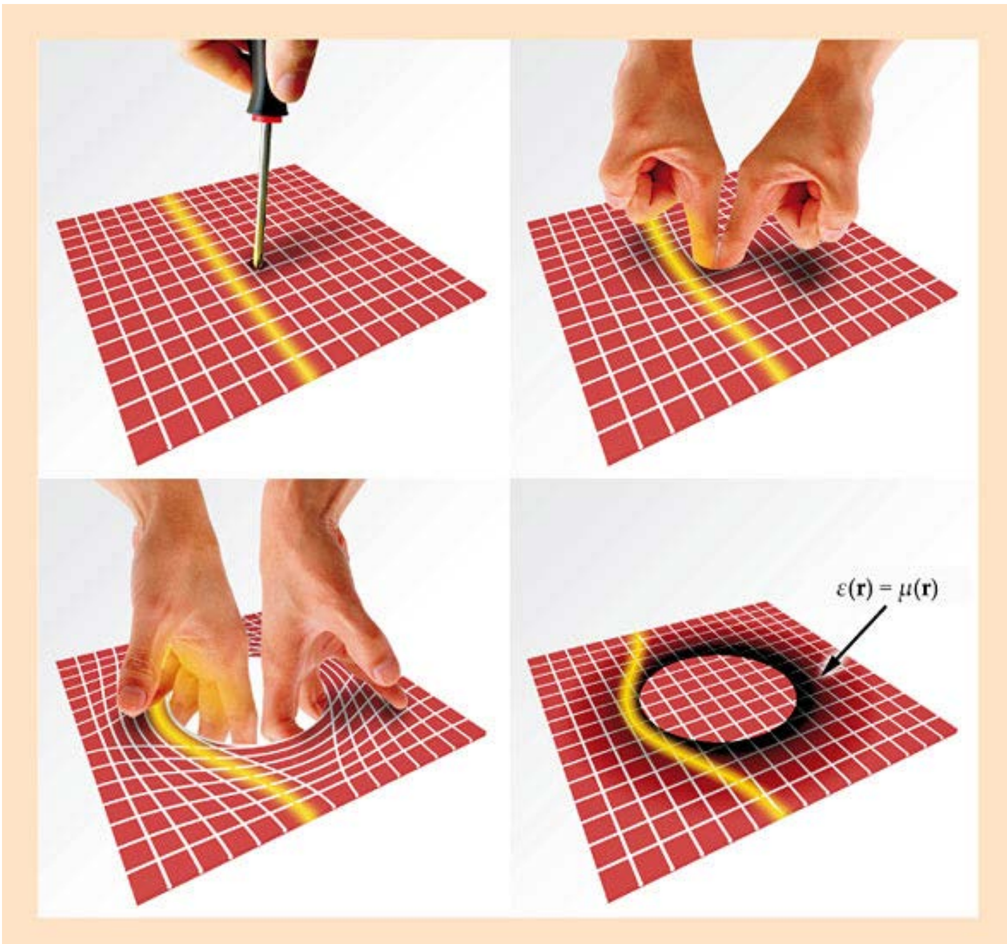
Velocity of light in free space: c
In a material: c/n

Mirage: Optical Illusion



The bending of light due to the gradient in refractive index in a desert mirage

Tearing Space: conformal map



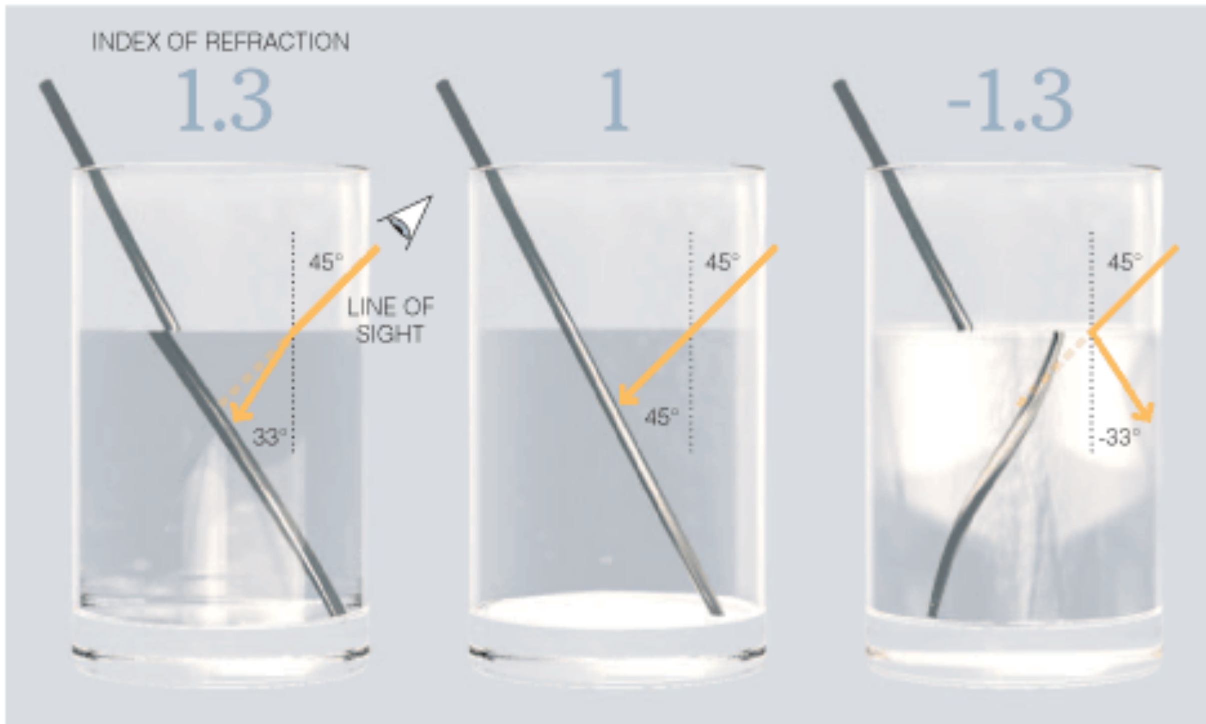
We can't tear space:

Mimic by shaping the refractive index n

Wegner, Linden in **Physics Today**, 2010

The Bending of Light

When rays of light cross a boundary from air to another material, they bend according to the material's index of refraction. Below, how water and two hypothetical liquids bend light.



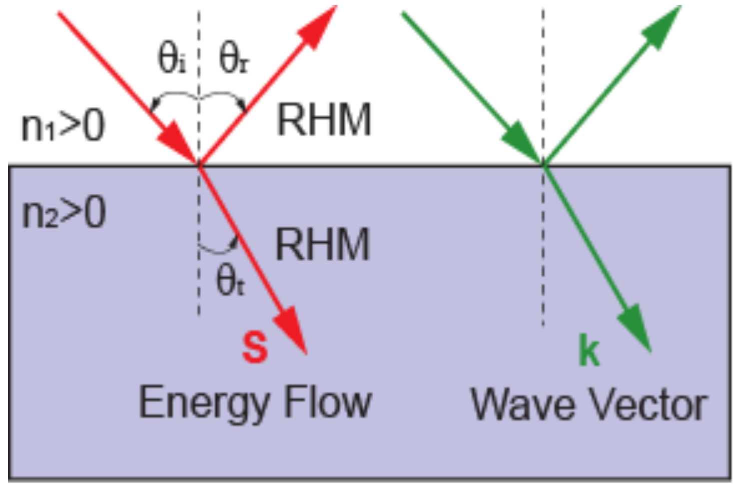
POSITIVE REFRACTION
With a refraction index of 1.3, water bends light inward, closer to the perpendicular.

NO REFRACTION
A hypothetical liquid with a refraction index of 1, the same as the surrounding air, would not distort light.

NEGATIVE REFRACTION
A hypothetical liquid with a negative refraction index would bend light the "wrong" way.

The New York Times; 3-D model by Christoph Hormann and Gunnar Dolling, Karslruhe University

Snell's Law

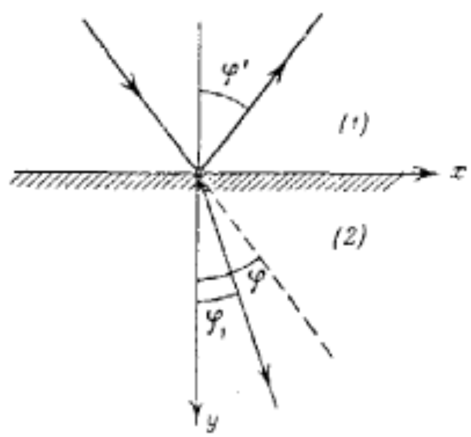


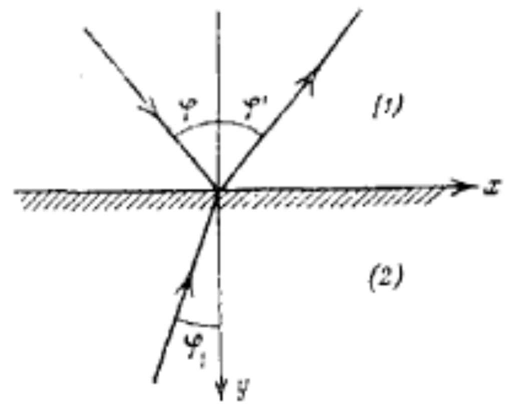
- Reflection: $\theta_i = \theta_r$
- Refraction: $n_1 \sin\theta_i = n_2 \sin\theta_t$

The refraction beam is at the other side of the incident normal.

Negative Refractive Index: A long history

- A. Schuster, An Introduction to the Theory of Optics, (1904)
  - Discussed in the context of anomalous dispersion as occurs at any absorption band.
- L.I. Mandelshtam, May 5 1944 (last lecture)

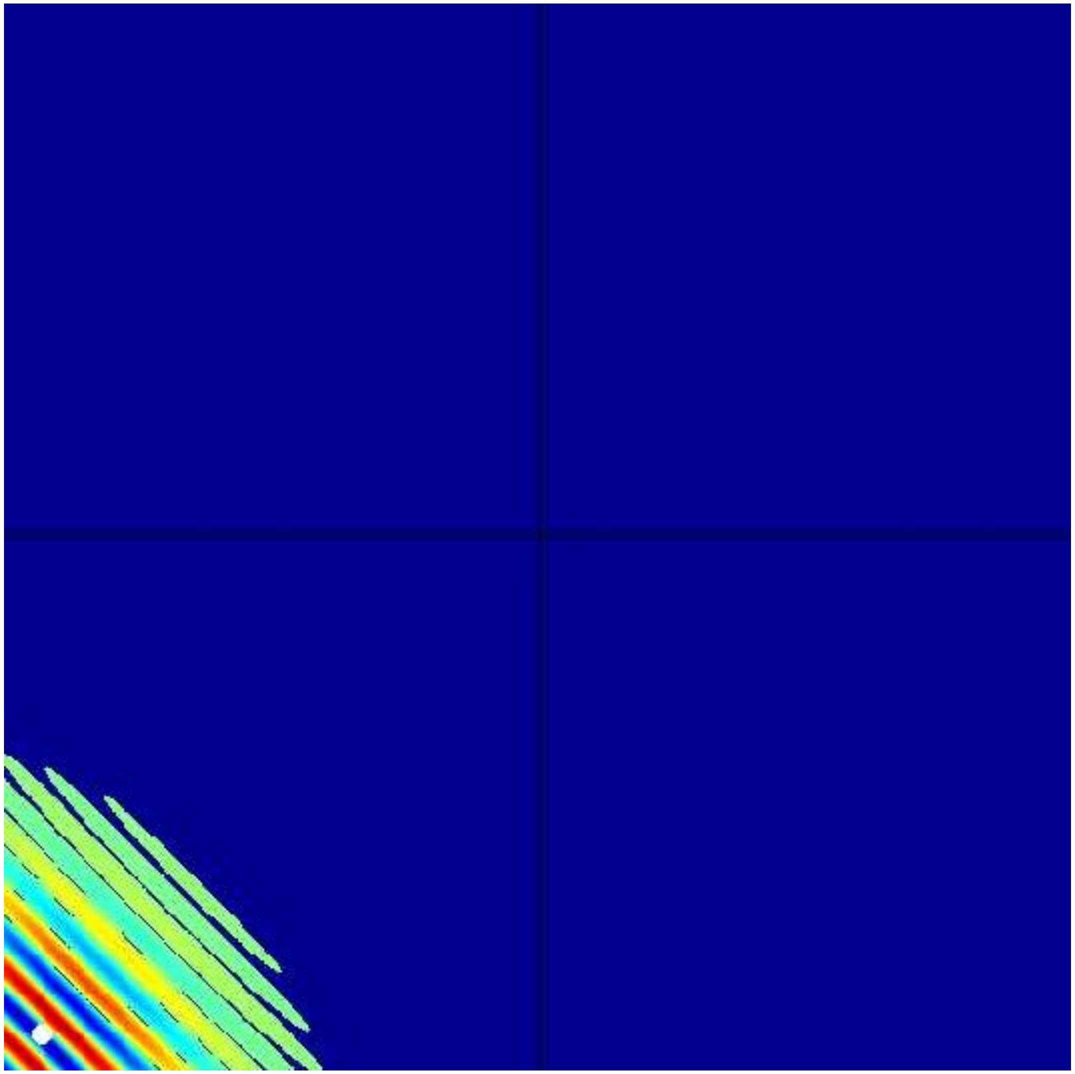




"In fact, the direction of wave propagation is determined by its phase velocity, while energy is transported at the group velocity."

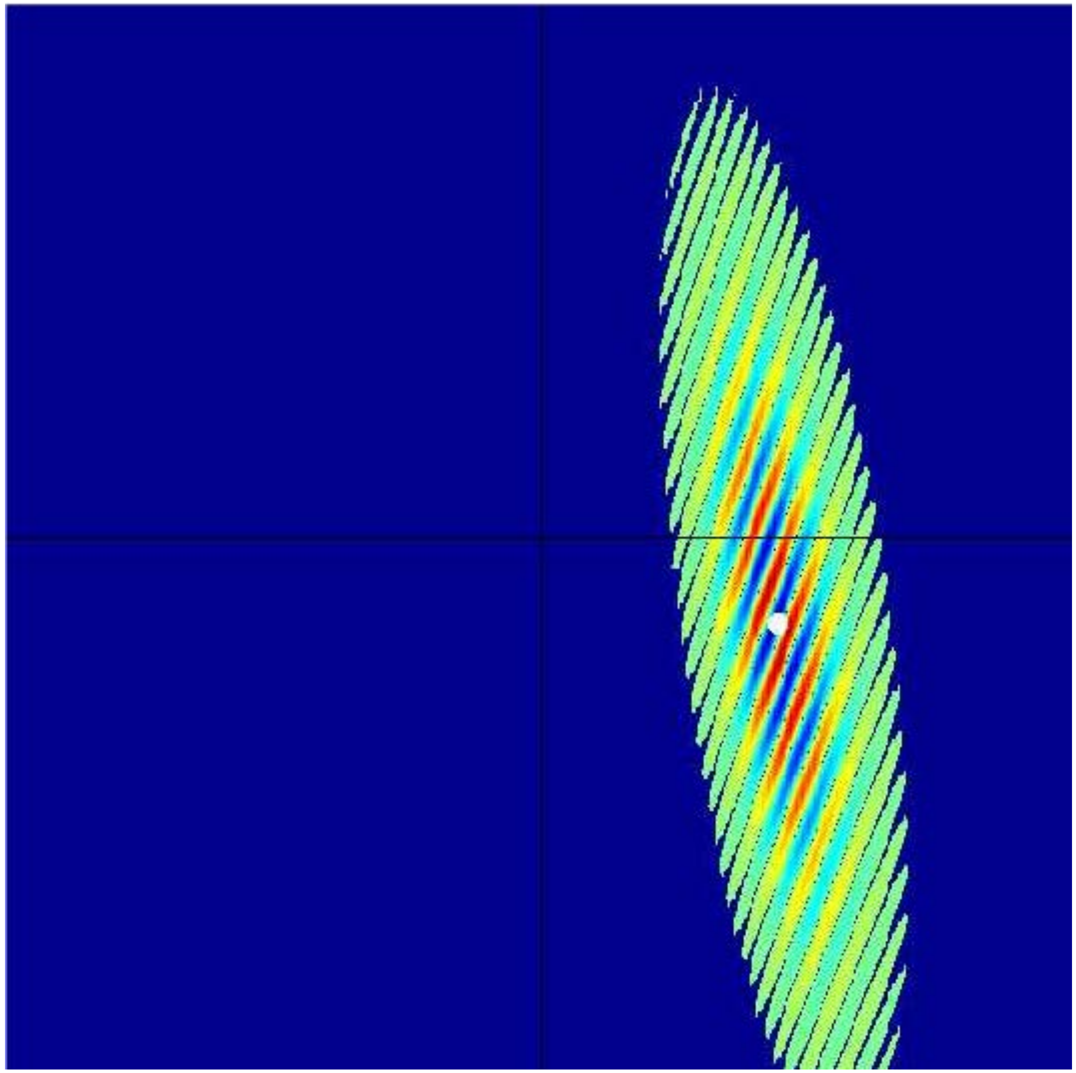
- Translated by E. F. Keuster

Positive Refraction



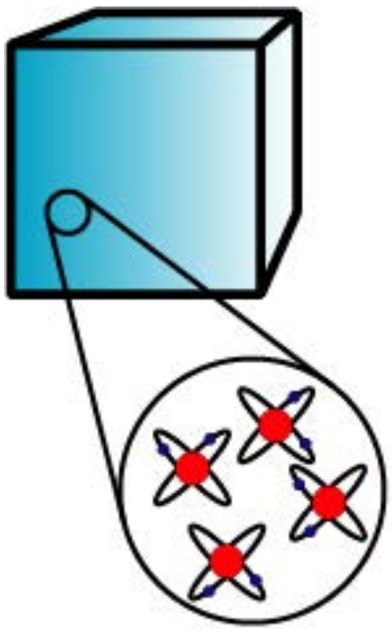
X. Huang, W. L. Schaich, Am. J. Phys.72, 1232 (2004)

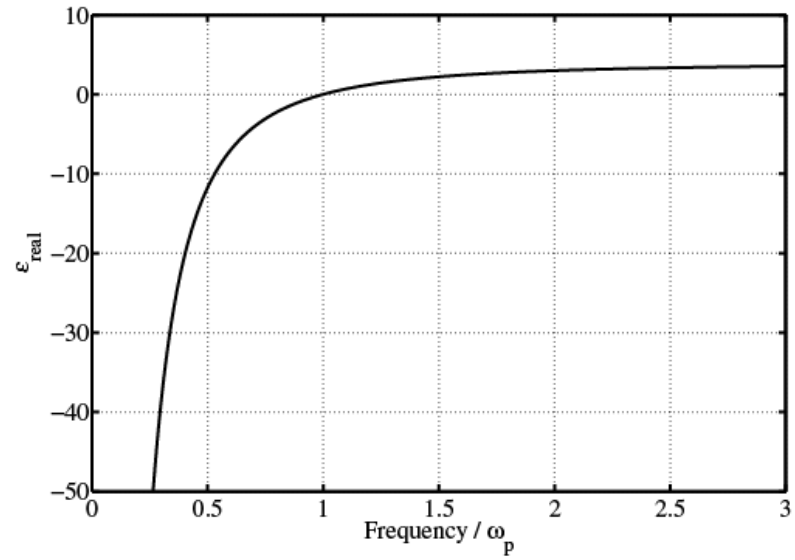
Negative Refraction



X. Huang, W. L. Schaich, Am. J. Phys.72, 1232 (2004)

Sir John Pendry – leading theorist in the area:

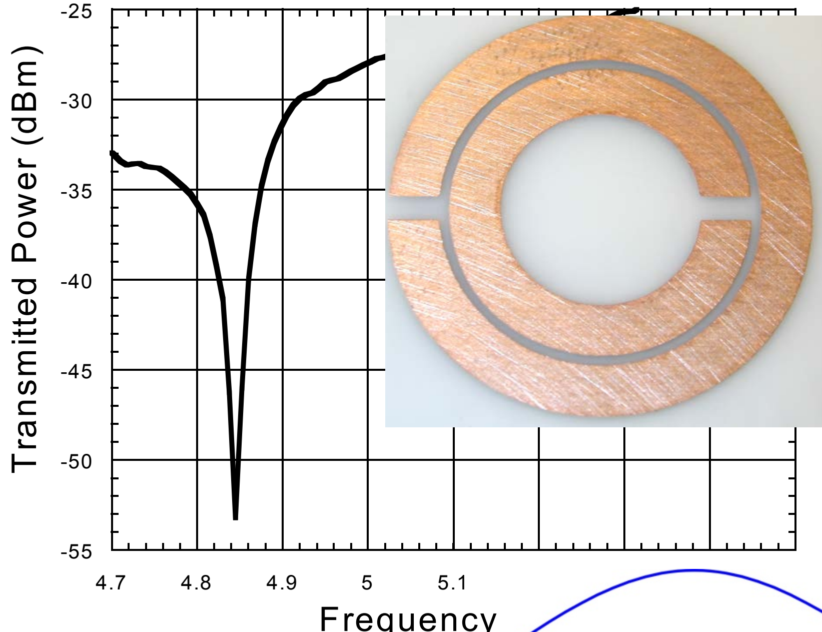




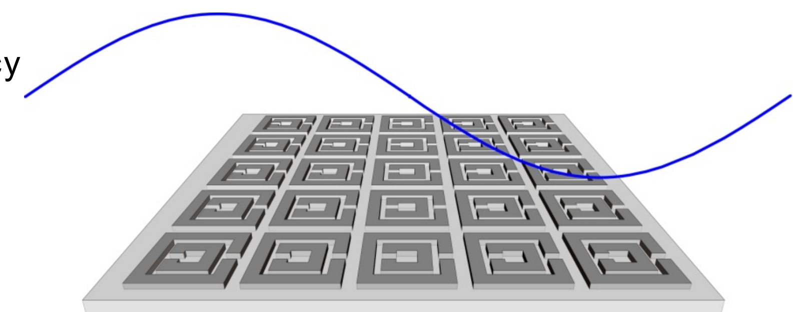
In conventional materials, the dielectric response derives from the constituent atoms. As discussed, negative or positive $\varepsilon(\omega)$ is possible over a broad spectral range. However, natural materials with a resonant magnetic permeability $\mu(\omega)$ don't exist above a few THz (e.g. Ferromagnetic resonance in Fe at microwave frequencies, or antiferromagnetic resonance in MnF_2 at ~2THz).

Pendry, Contemporary Physics

Metamaterials: Expanding our Space



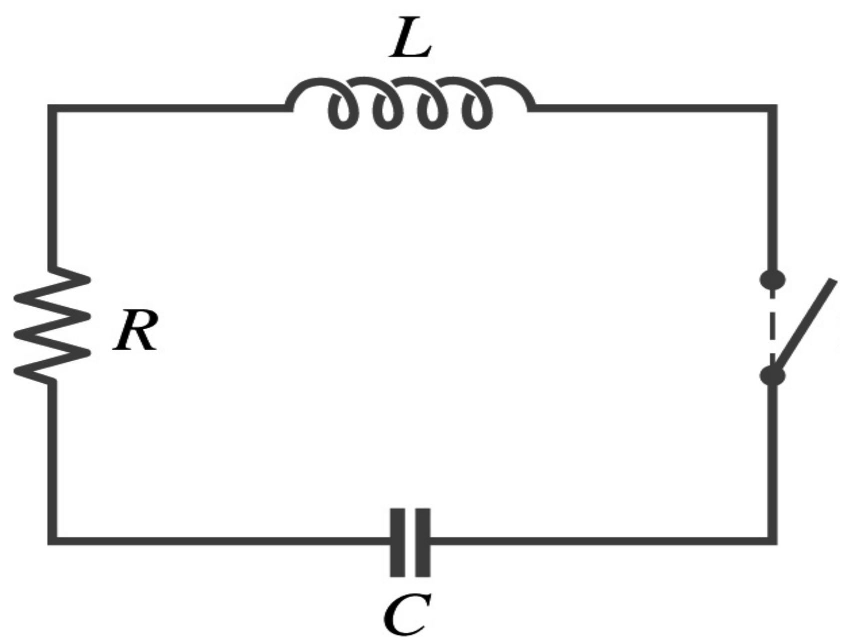
Pendry et al. suggested that an array of ring resonators could respond to the magnetic component light.



J. B. Pendry, A. J. Holden, D. J. Robbins, W. J. Stewart, “Magnetism from conductors and enhanced non-linear phenomena,” *IEEE Trans. MTT* **47**, 2075 (1999).

LCR circuits

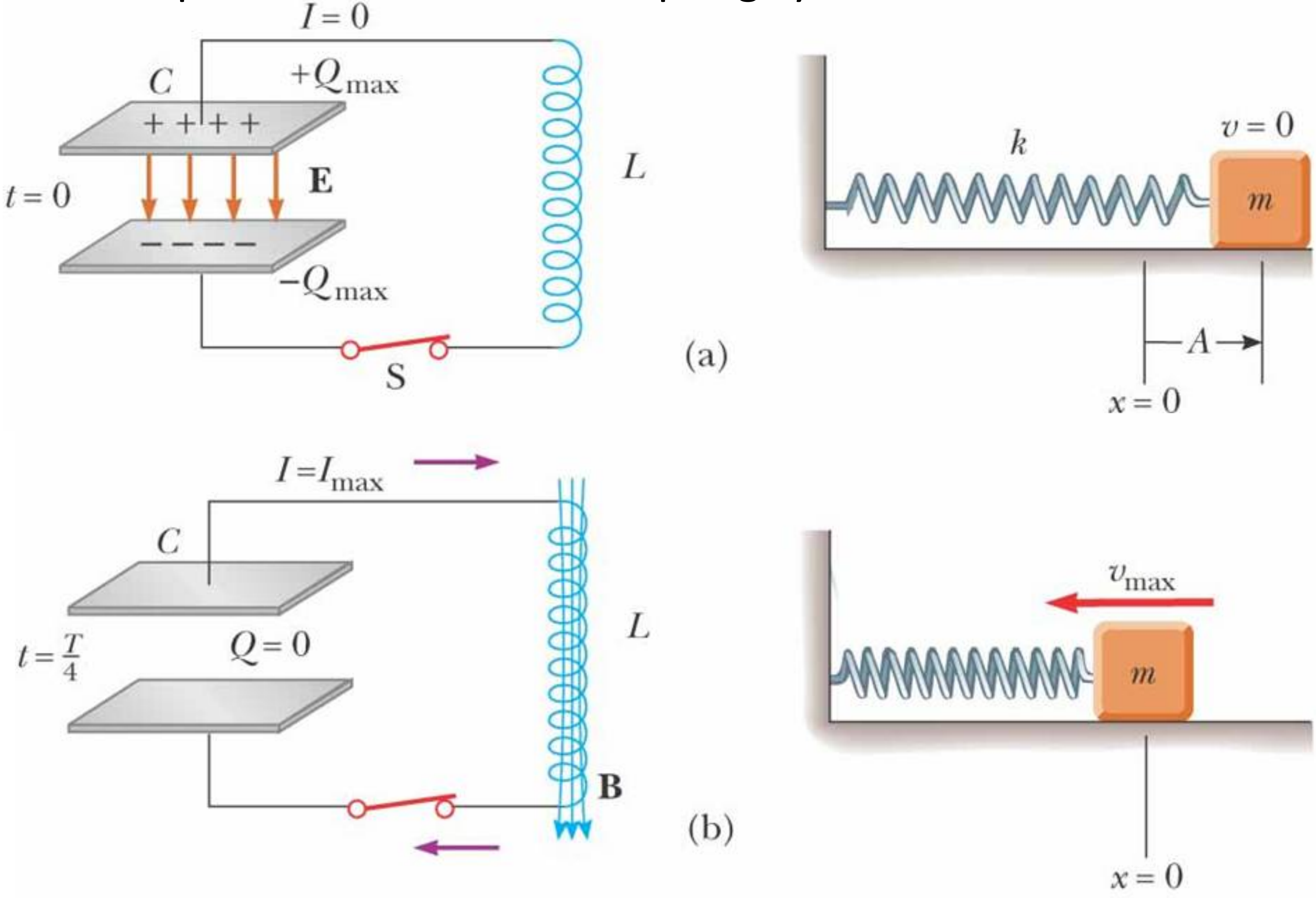
- A circuit with an inductor (L) and capacitor (C) satisfies the same equation as the mass spring system for simple harmonic oscillation.
- If we added a resistor (R) that we get the damped oscillator equation.
  - as for the mechanical oscillator, the solution can be
    - under damped: ($\gamma < 2\omega_0$)
    - critically damped: ($\gamma = 2\omega_0$)
    - over damped: ($\gamma > 2\omega_0$)
- We can choose the values of L, C, and R to determine which kind of damping we have.

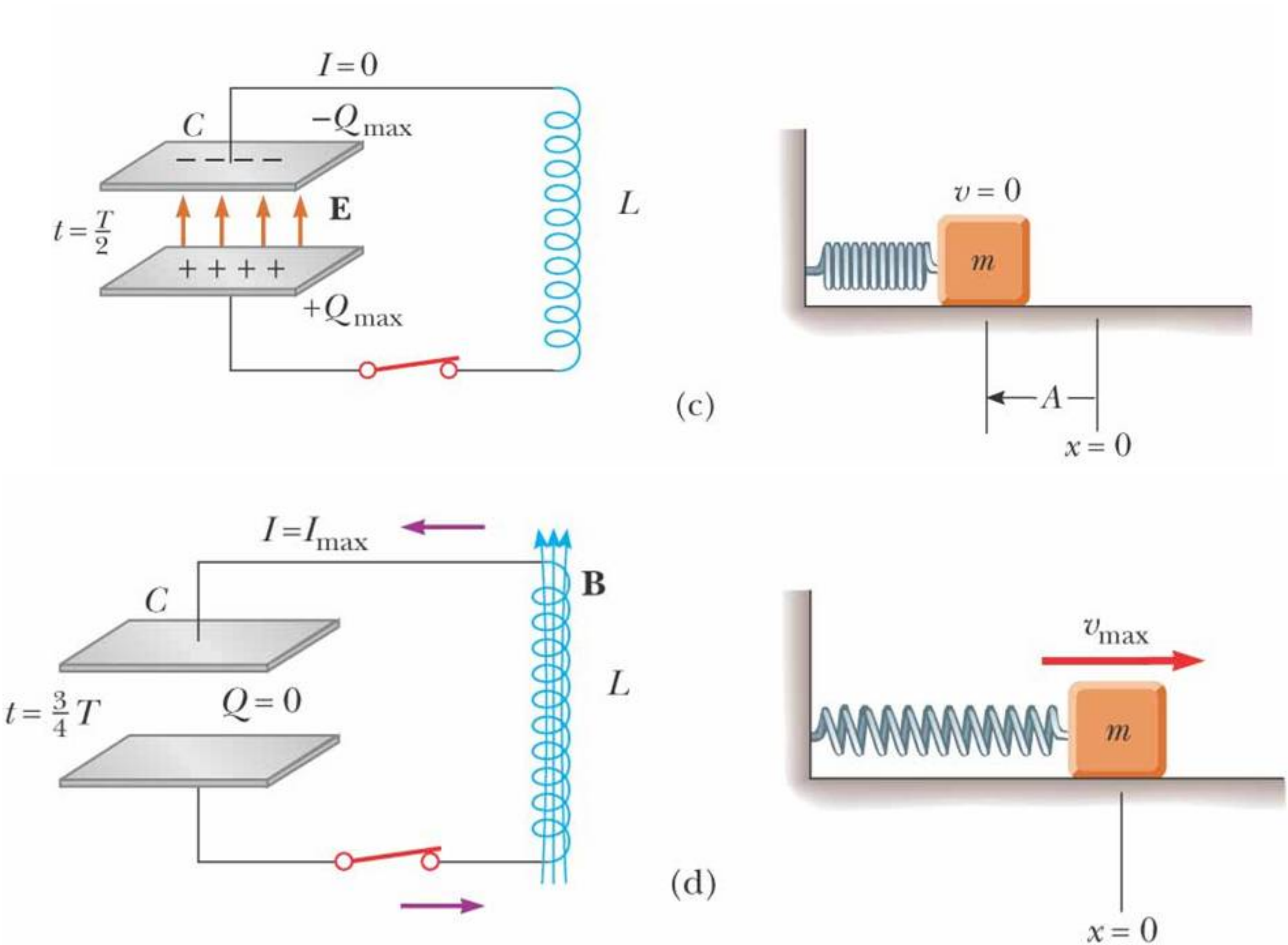


$$\frac{d^2q}{dt^2} + \frac{R}{L}\frac{dq}{dt} + \frac{1}{LC}q = 0$$

$$\gamma = \frac{R}{L}; \quad \omega_0^2 = \frac{1}{LC}$$

Comparison between mass-spring systems and LCR circuits.

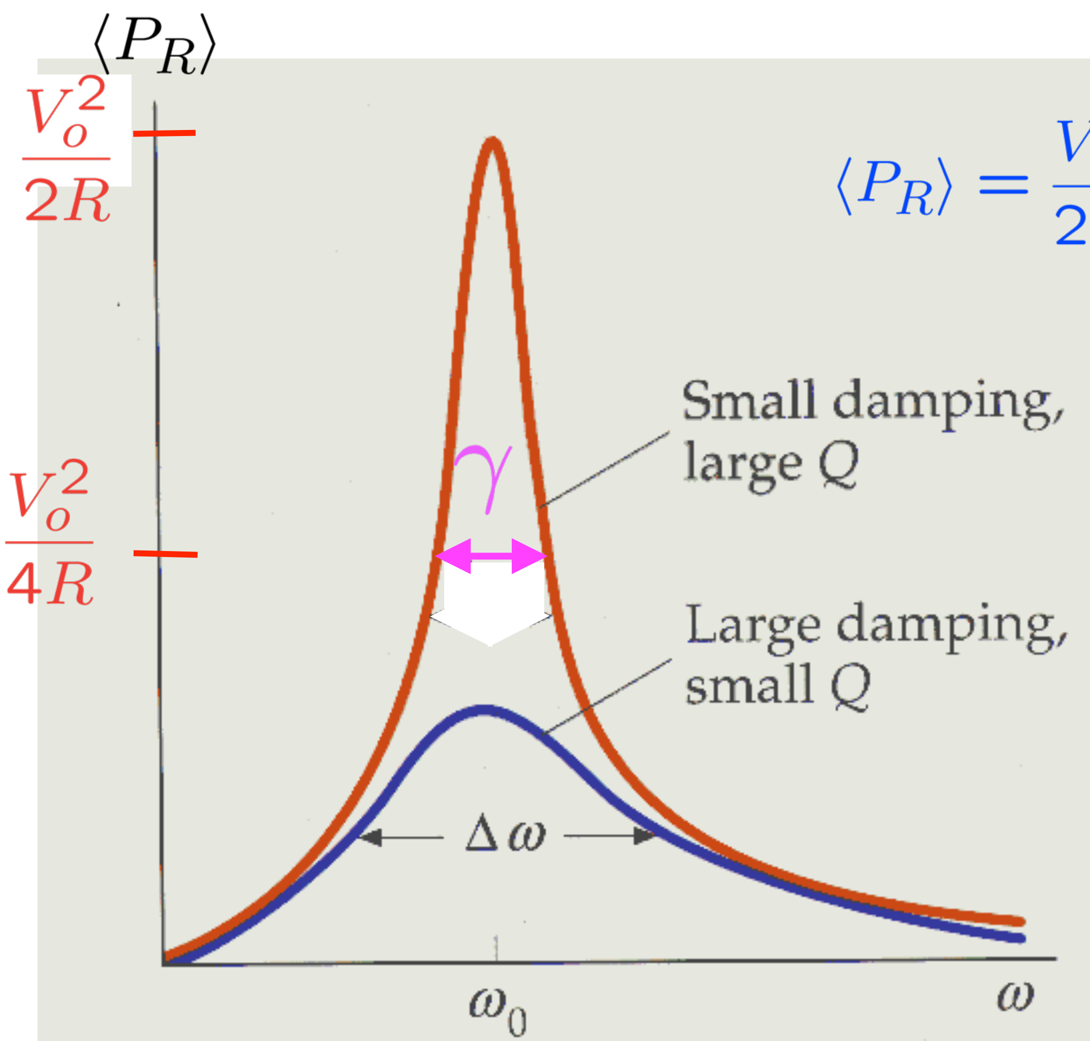




$I = 0$
C
$-Q_{max}$
L
$\mathbf{E}$
$t = \frac{T}{2}$
$+Q_{max}$
$v = 0$
m
A
$x = 0$
(c)
$I = I_{max}$
$\mathbf{B}$
C
L
$t = \frac{3}{4}T$
$Q = 0$
v_{max}
m
$x = 0$
(d)

γ is the full-width half maximum (fwhm) of the power absorption curve

quality factor Q : $$Q \simeq \frac{\omega_o}{\gamma}$$



$$\langle P_R \rangle = \frac{V_o^2}{2R}\left(\frac{\gamma^2\omega^2}{(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2}\right)$$

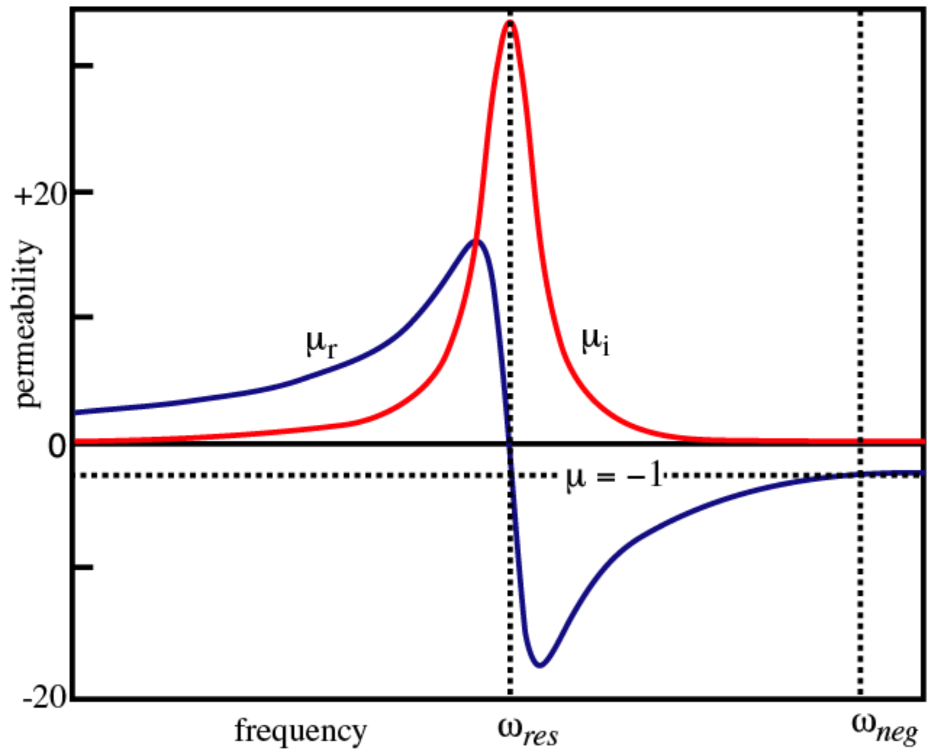
$$\gamma = \frac{R}{L}; \quad \omega_0^2 = \frac{1}{LC}$$

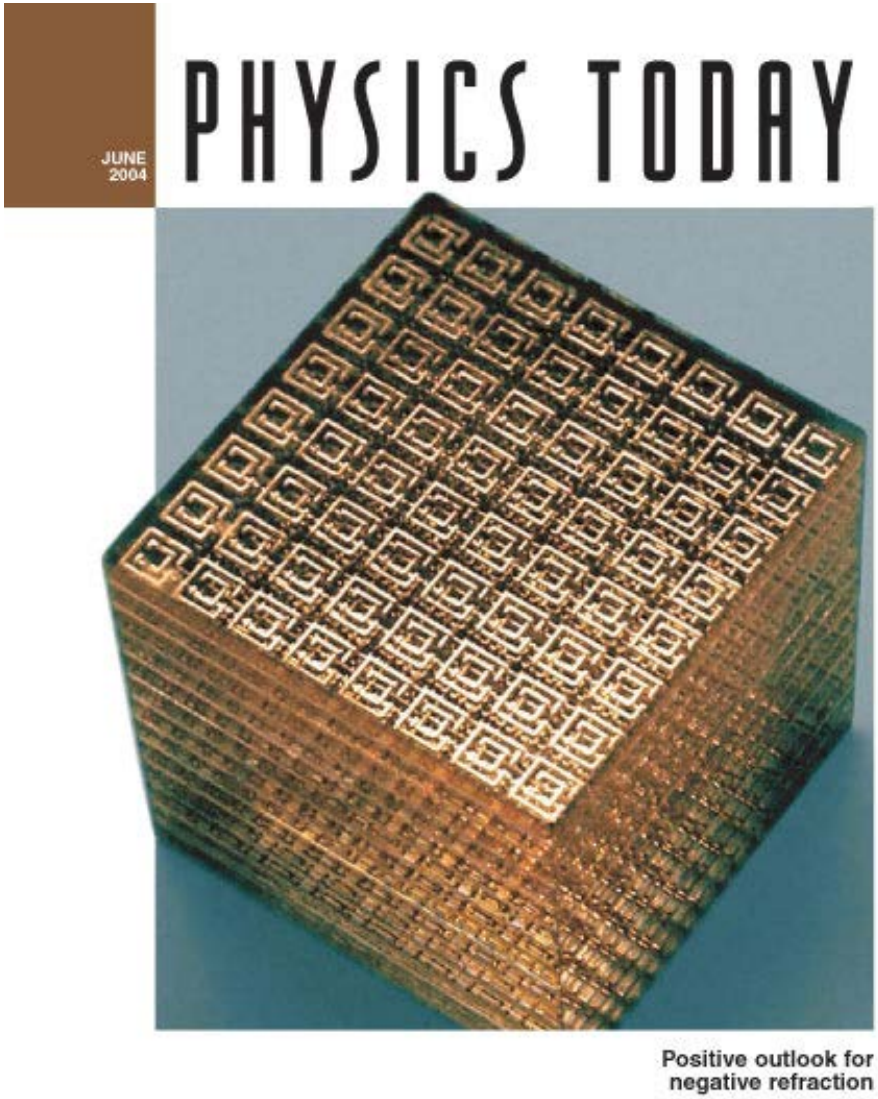
Magnetic Metamaterials: Shaping a resonance

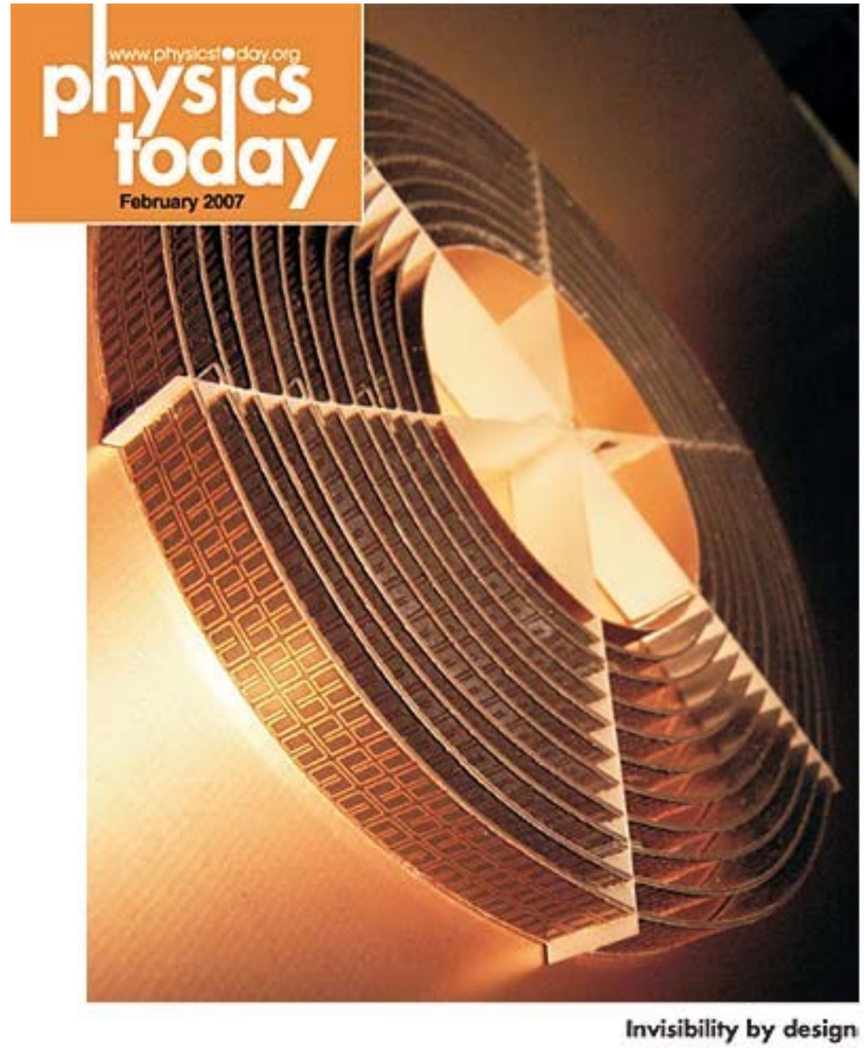
Dimensions < λ

Effective Medium: $\mu(\omega)$

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




JUNE
2004
PHYSICS TODAY
Positive outlook for
negative refraction

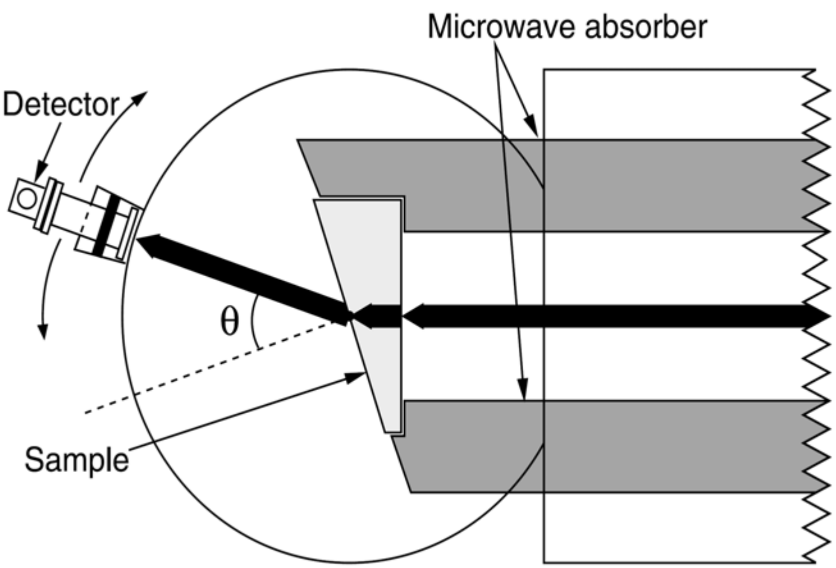

www.physicstoday.org
physics
today
February 2007
Invisibility by design

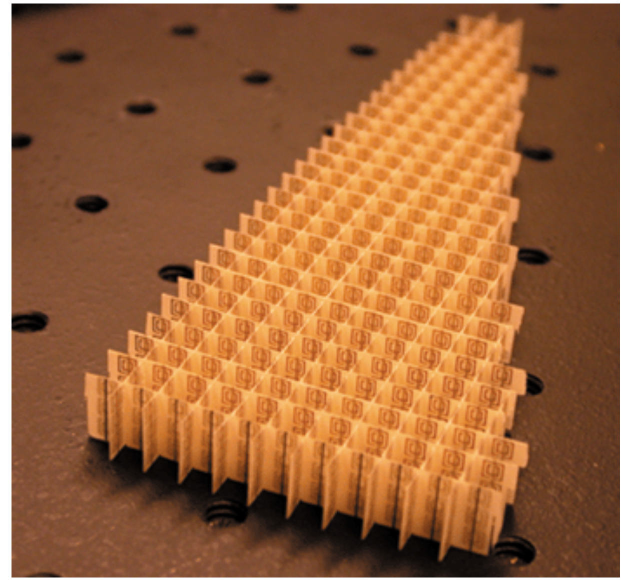
The first negative index material, meta or otherwise!

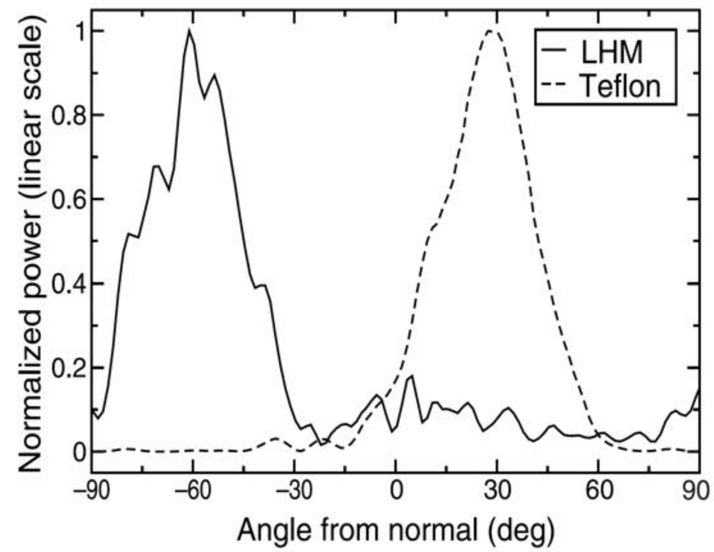
D. R. Smith, W. J. Padilla, et al, Phys. Rev. Lett. 14, 234 (2000)

Experimental Demonstration of NI

<u>Microwave:</u> ease of fabrication

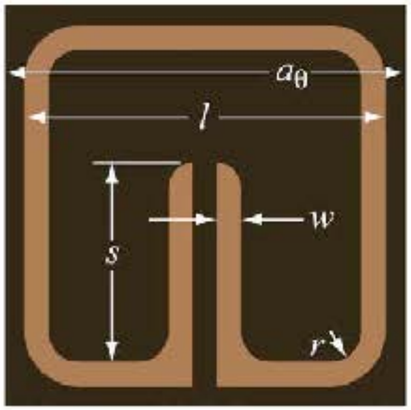




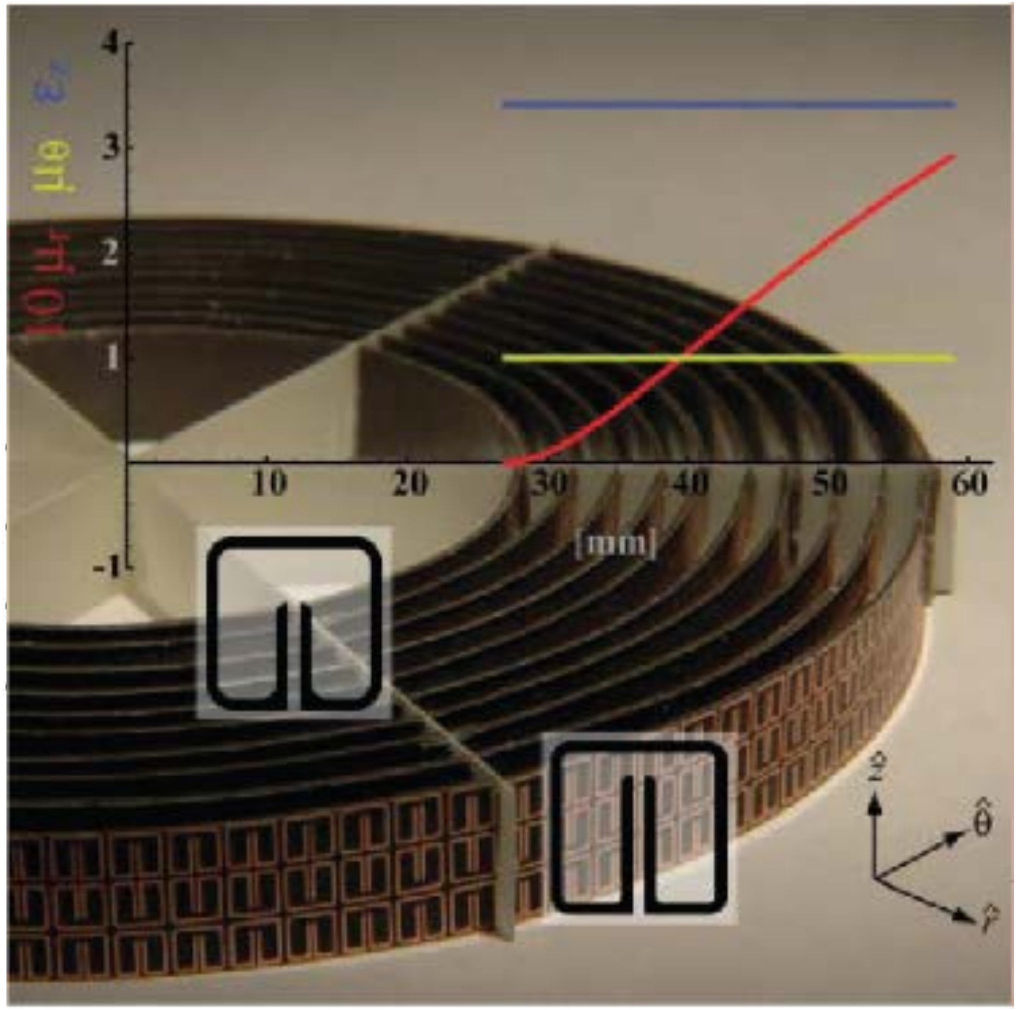


R. A. Shelby, D. R. Smith, S. Schultz, Science **84**, 4184 (2001)

The Electromagnetic Cloak (2006)

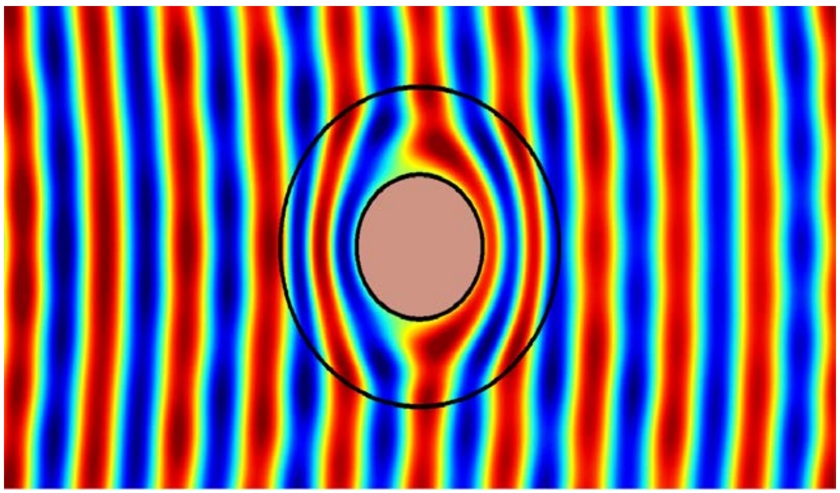


cyl.	r	s	μ_r
1	0.260	1.654	0.003
2	0.254	1.677	0.023
3	0.245	1.718	0.052
4	0.230	1.771	0.085
5	0.208	1.825	0.120
6	0.190	1.886	0.154
7	0.173	1.951	0.188
8	0.148	2.027	0.220
9	0.129	2.110	0.250
10	0.116	2.199	0.279

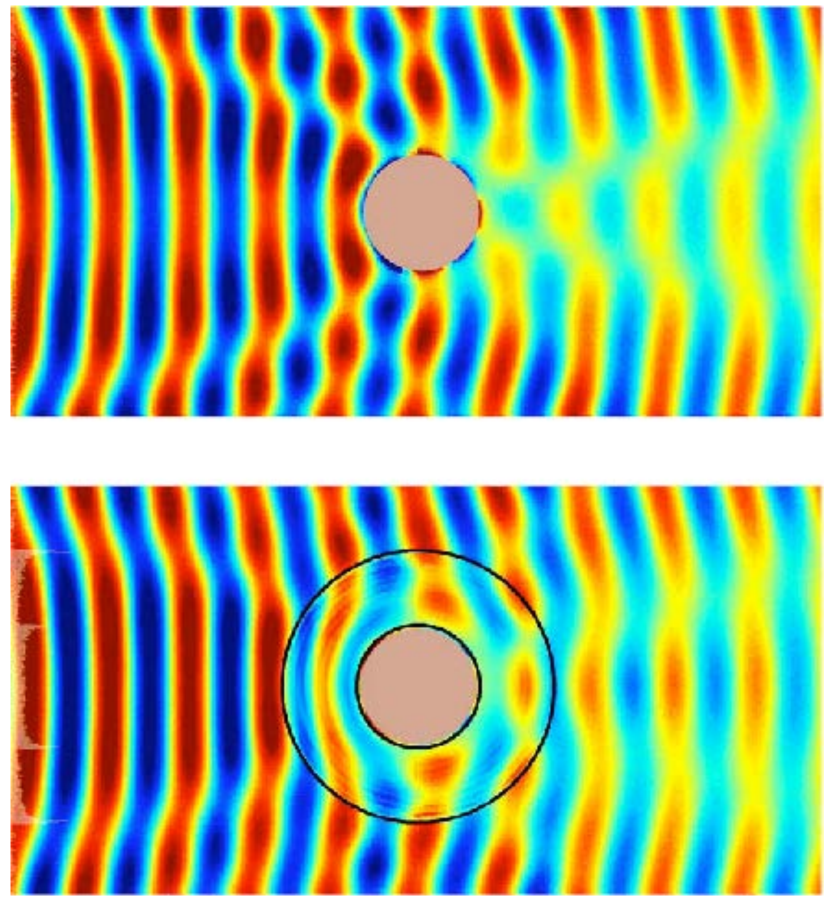


The Electromagnetic Cloak

Simulation



Experiment



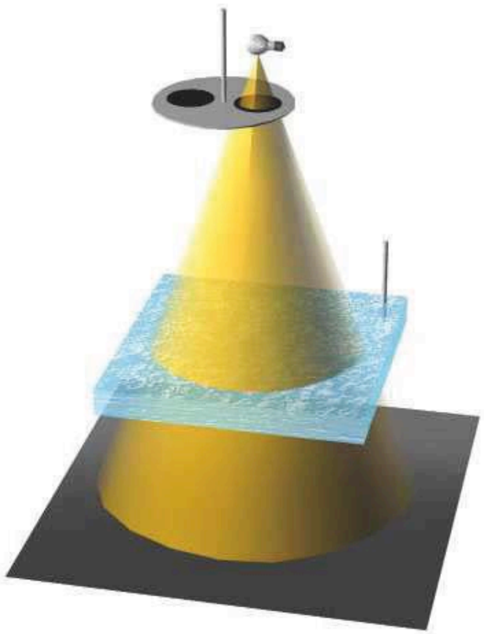
J. B. Pendry, et al., Science 312, 1780 (2006)
D. Schurig, et al., Science, 314, 2006.

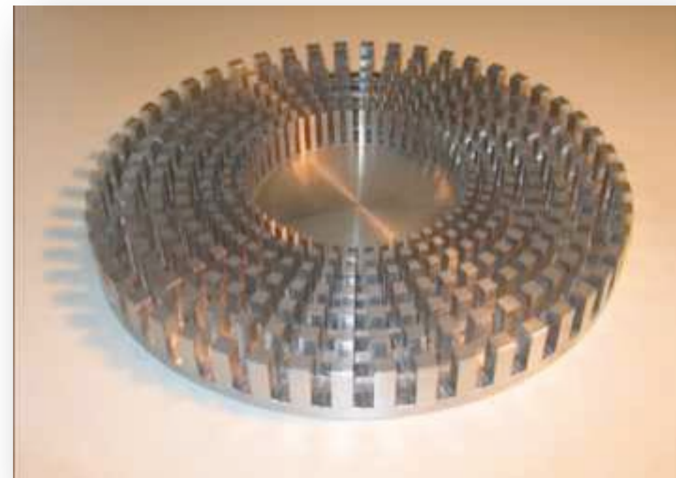
Would you believe?........

Cloaking Other Waves:
Sound, Water, Earth

The Cone of Silence

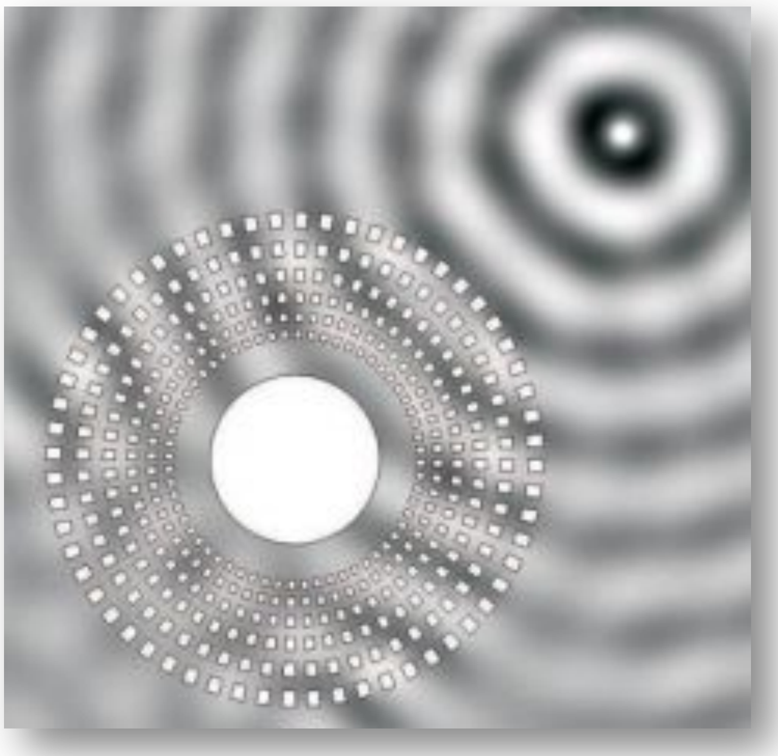
Cloaking Water Waves

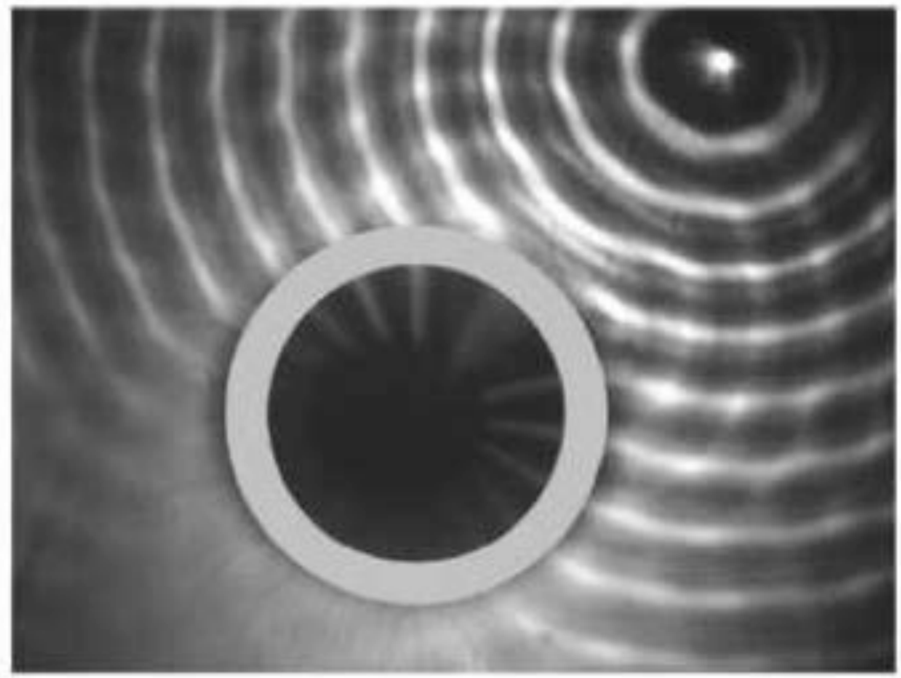




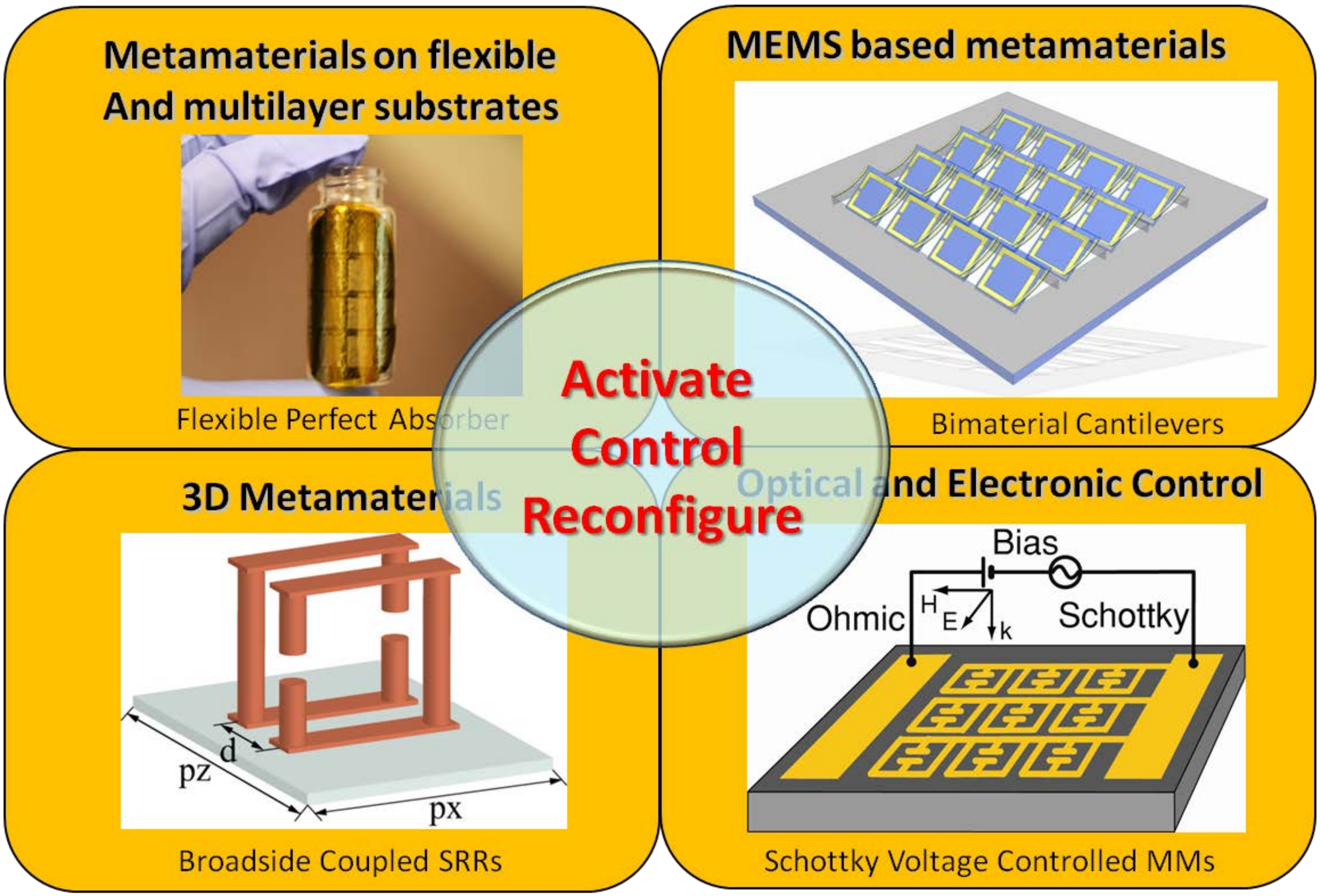
M. Farhat, S. Enoch, S. Guenneau, and A. B. Movchan, "Broadband cylindrical acoustic cloak for linear surface waves in a fluid", ***Physical Review Letters*** **101,.134501 (2008).**

Cloaking Water Waves



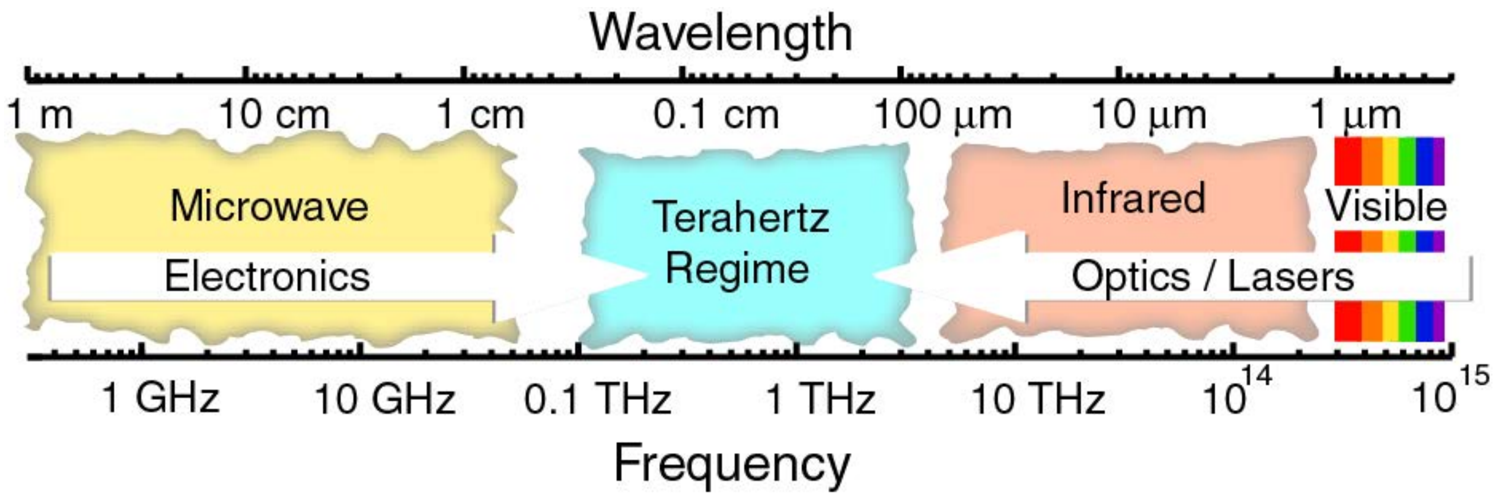


Metamaterials at BU



Terahertz

1 THz → 4 meV → 48K → 300 μm → 33 cm^{-1}



- **Microwave**

Electronics: Antenna, high speed transistor circuits for microwave generation, detection, control and manipulation

Applications: wireless communications, radar…

- **Terahertz gap**

Progress in sources and detectors. Also need functional devices such as filters, switches, modulators which largely do not exist

- **Infrared and visible**

Photonics:

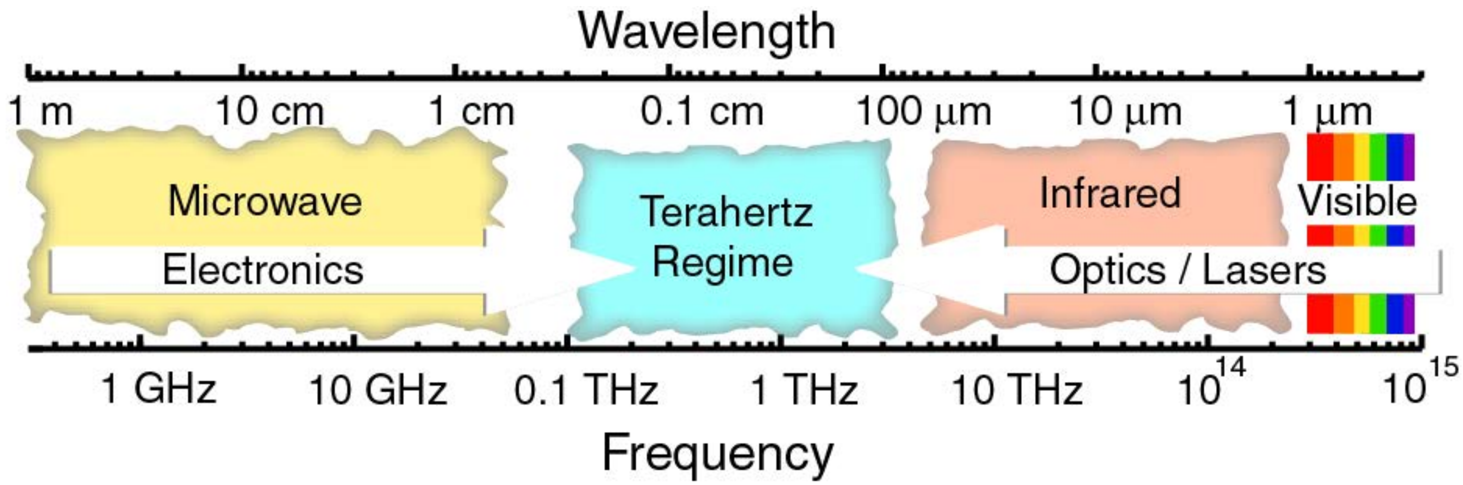
Source: lasers, LEDs

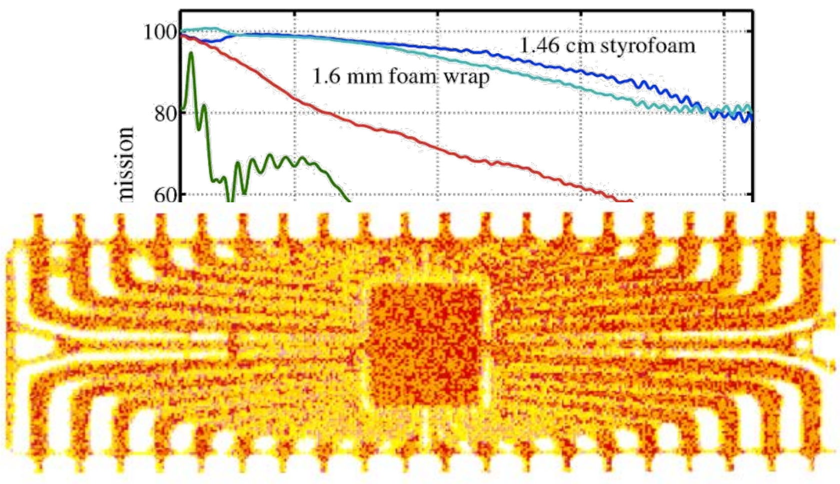
Detector: Photodiodes

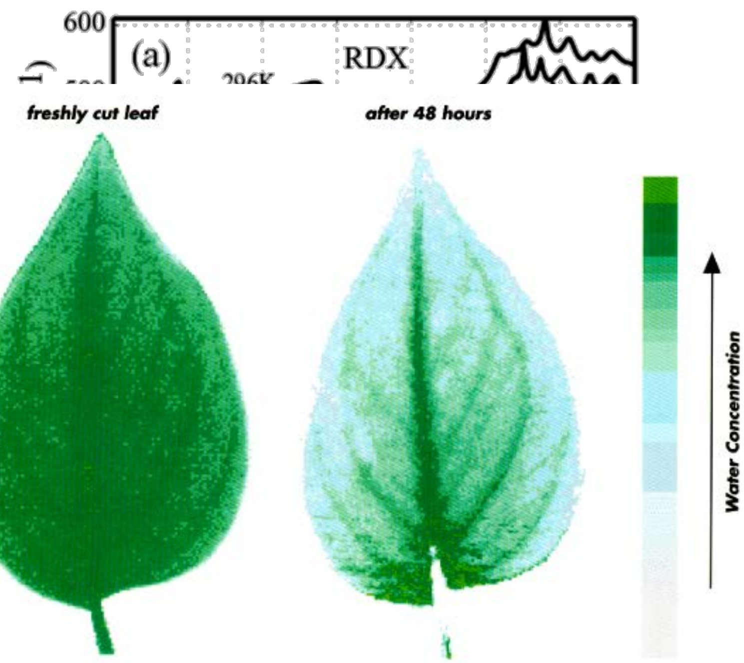
Functional: lens, polarizer, optical switch

Applications: optical fiber communications…

Terahertz Region of the EM Spectrum

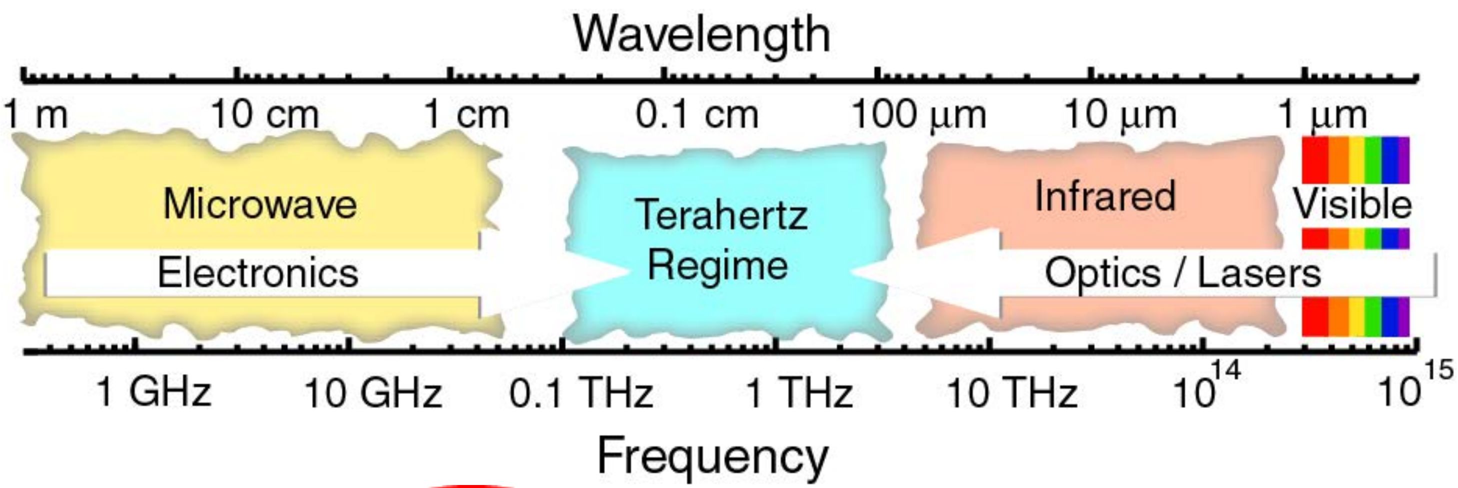






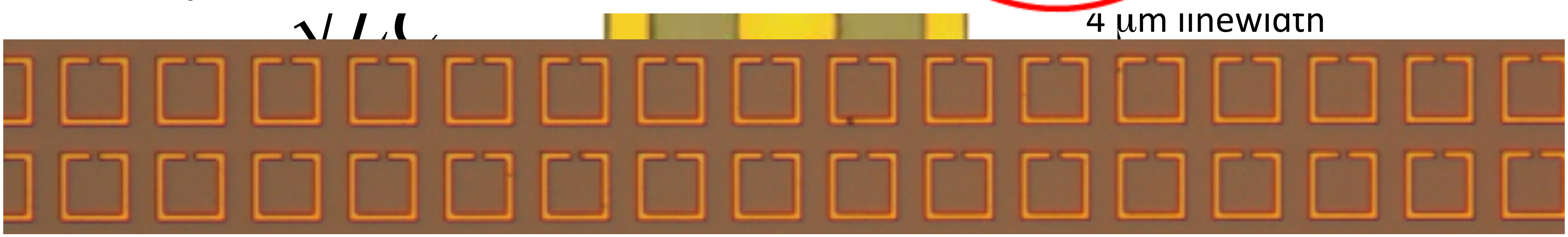
B.B. Hu, M. Nuss, Opt. Lett. 20, 1716 (1995)

THz Metamaterials

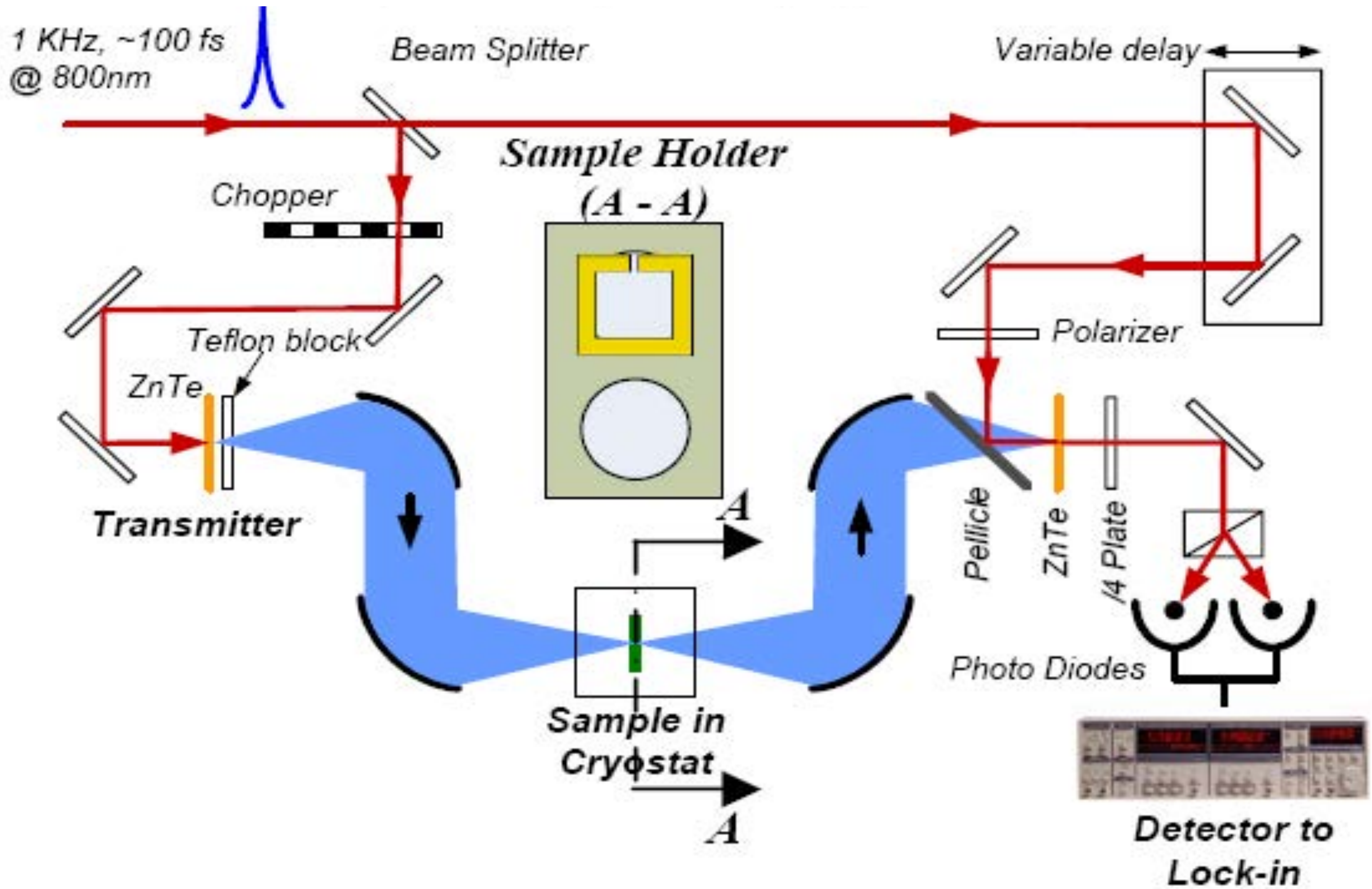


$\omega_0 =$

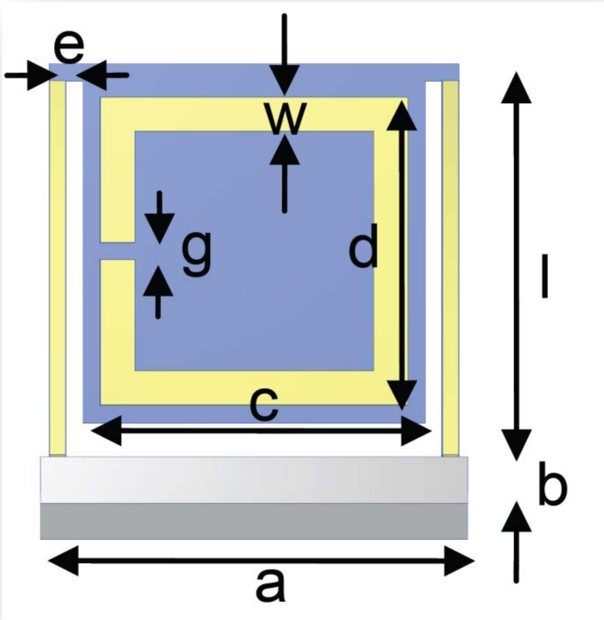
4 μm linewidth

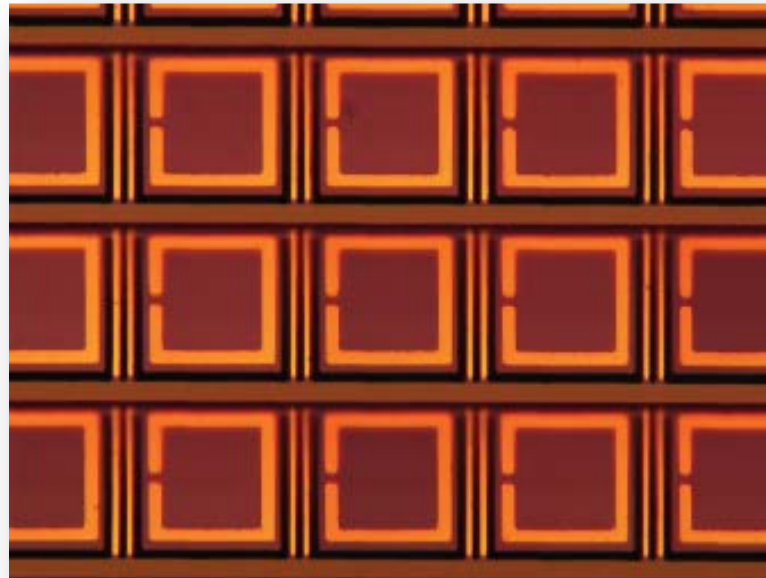


Experimental Setup: THz-TDS



Bi-material Cantilever Based Metamaterials
A Mechanical Chameleon



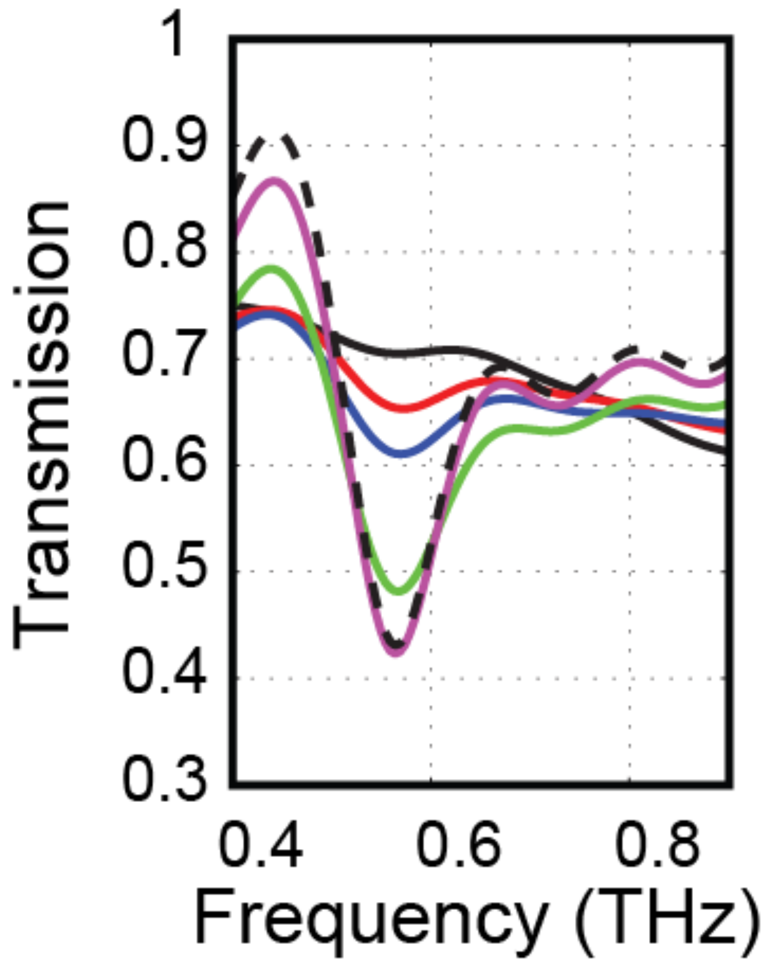


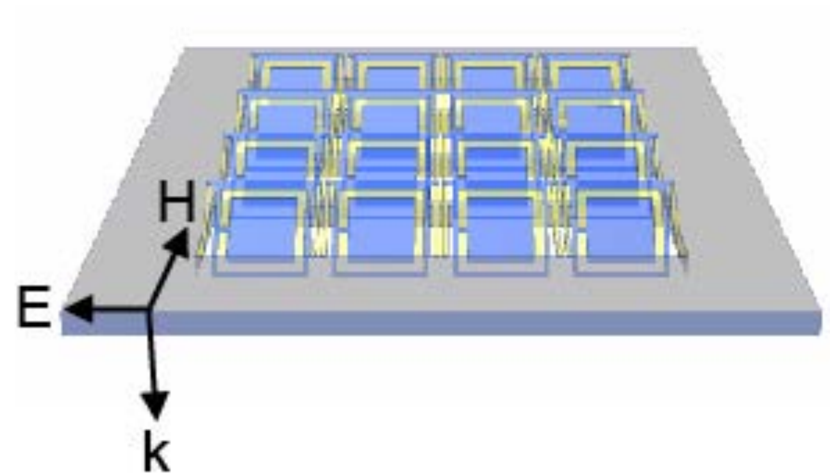
Au / Silicon nitride cantilever arrays: Thermal Actuation

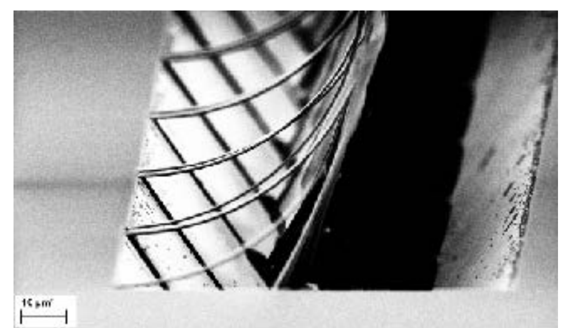
The SRRs are 72 μm X 72 μm with an in-plane periodicity of 100 μm and an overall dimension of 1 cm X 1cm.

Phys. Rev. Lett. **103**, 147410 (2009)

Turning On The Refractive Index Mechanically





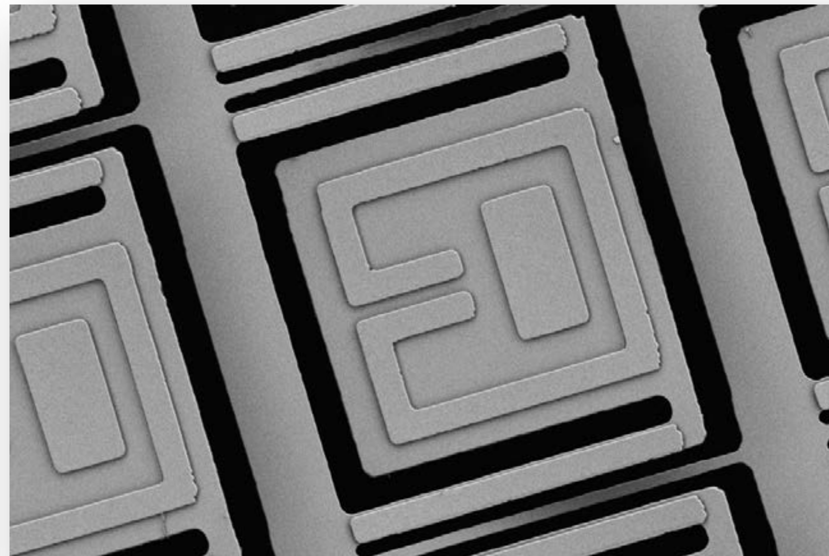


Control of the EM response at the unit cell level

Resonant Detectors Fabricated at 95 and 690 GHz

95 GHz

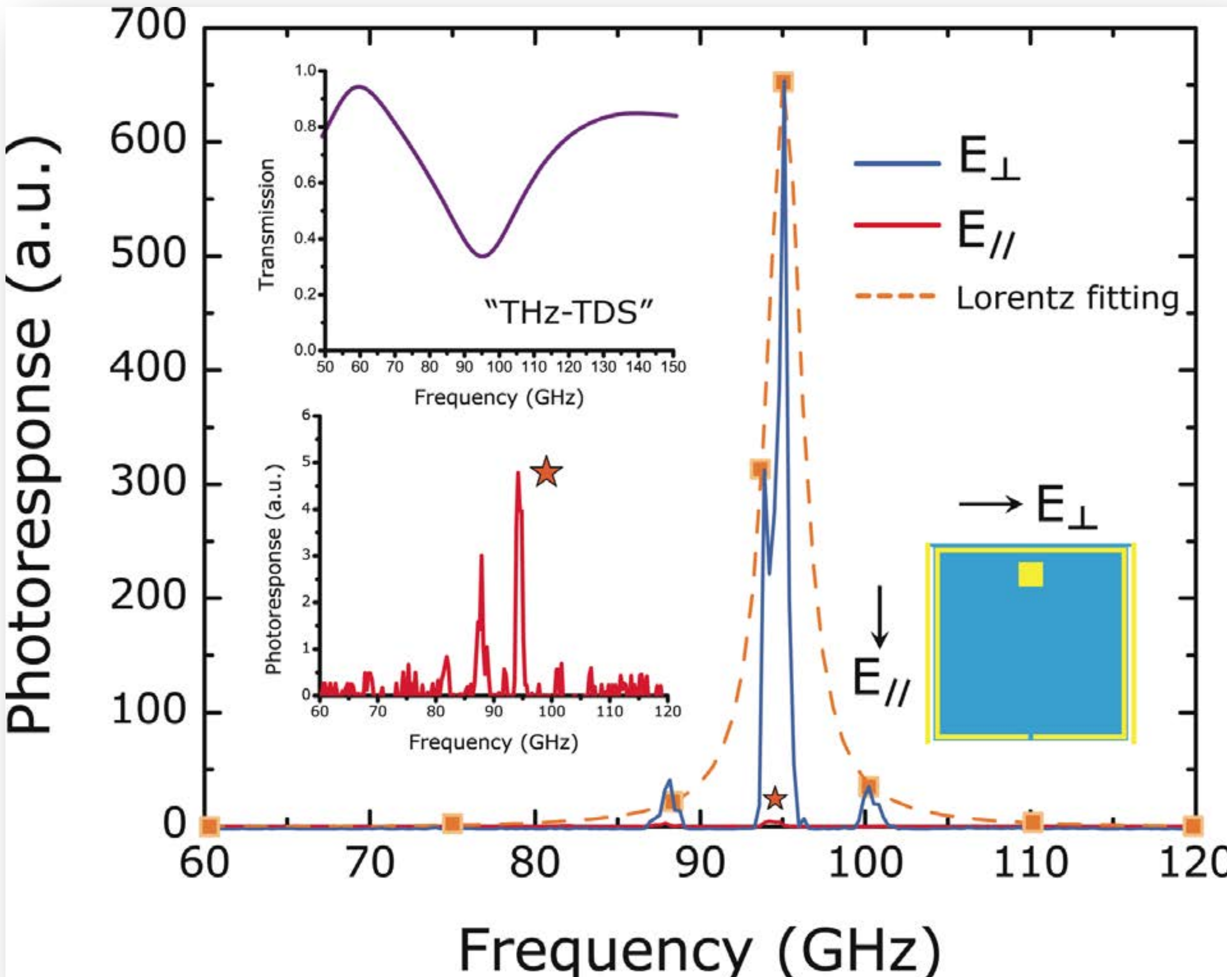
690 GHz



	a	b	c	d	e	f	g	h	i	w
95 GHz	435	415	395	10	50	50	10	–	–	10
690 GHz	80	67	49	5	13	26	2.5	16	51	5

All units are in microns.

95 GHz MM-Based Thermal Detector: Single Pixel Characterization



- Room T
- Ambient
- Optical Readout
- 15 Hz

Spectrally Selective and Polarization Sensitive!

FILED UNDER *Science*

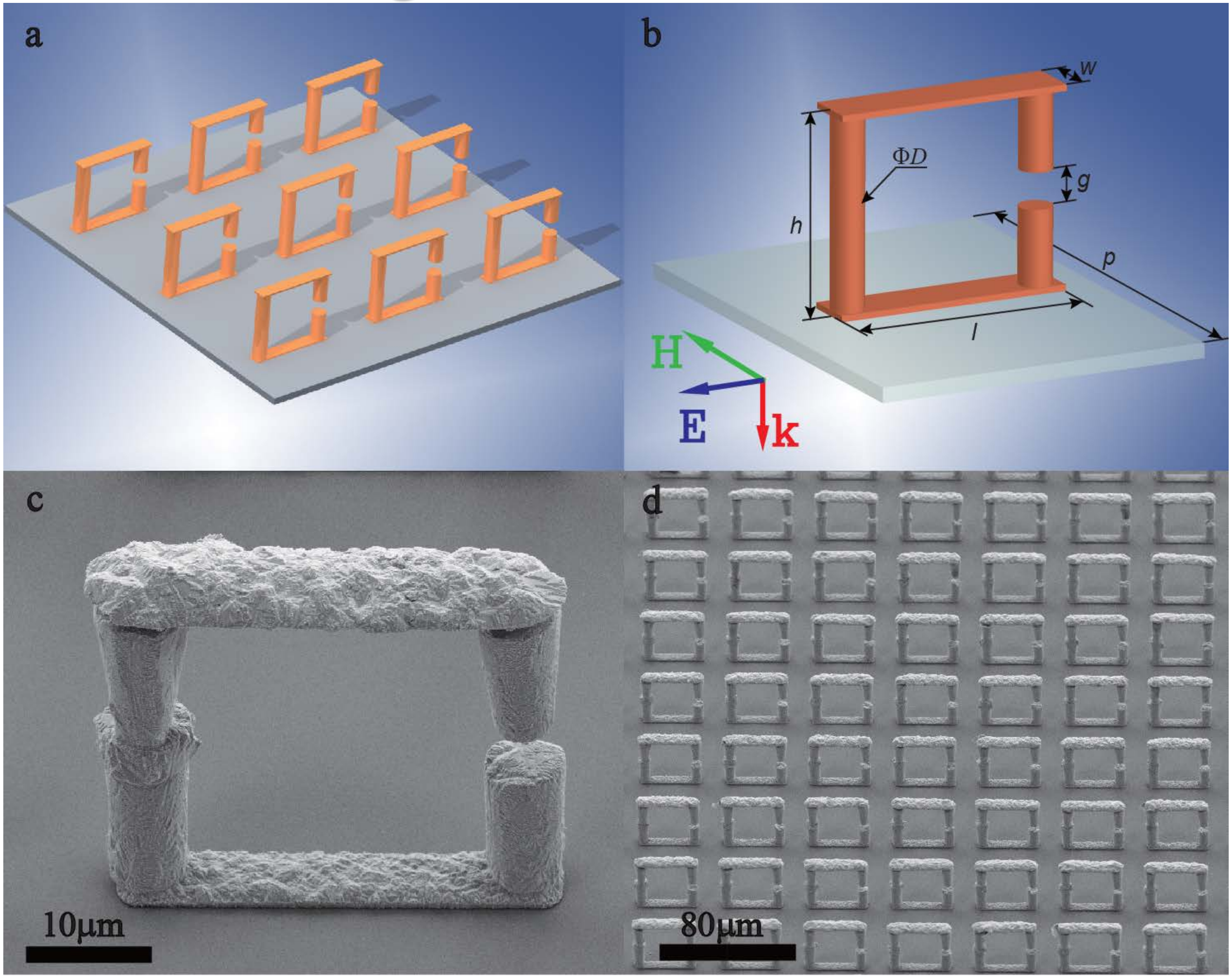
Terahertz radiation and metamaterials combine to form super X-Ray specs

By Tim Stevens *posted May 8th 2010 3:41PM*

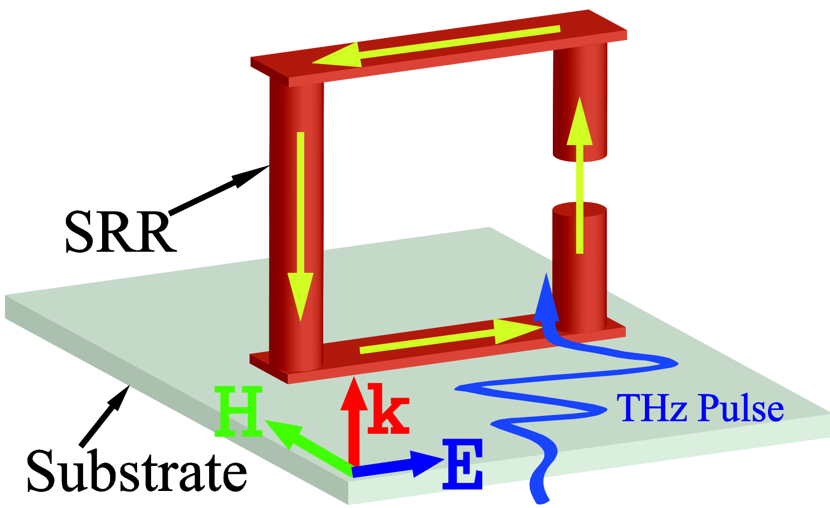
PR

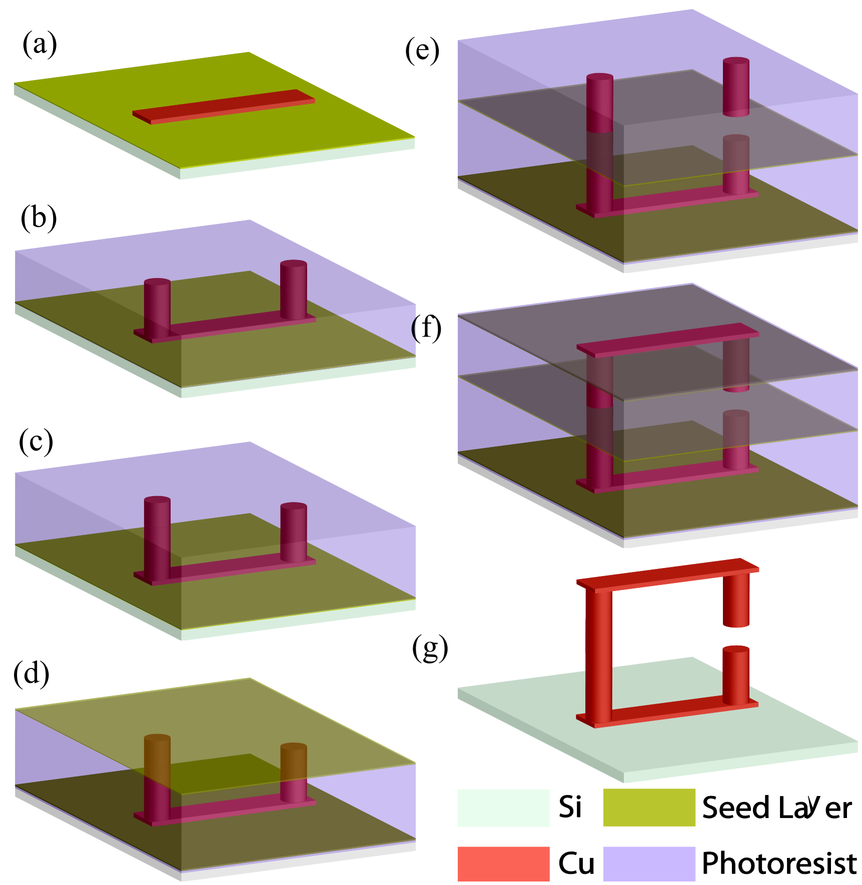
It looks like *somebody* actually coughed up the extra dollar for the De Luxe model X-Ray specs in the back of *Mad Magazine*, then reverse-engineered 'em in the name of science. That somebody is Richard Averitt, whose team at Boston University has come up with a way to use metamaterials and terahertz transmissions to see through you. We've seen metamaterials plenty of times before, typically being used for nefarious deeds on the opposite end of the spectrum: invisibility cloaks. Here they form pixels for a digital imager that can be activated by THz radiation. If you're not familiar with THz radiation, it's a (supposedly perfectly safe) form of energy waves that pass through materials -- much like X-Rays but without all the nasty DNA-shattering effects on the way through. There's just one problem: nobody (not even this guy) has made a powerful enough THz emitter just yet, meaning we're all safely naked under our clothes for at least another few years.

Magnetic Metamaterials



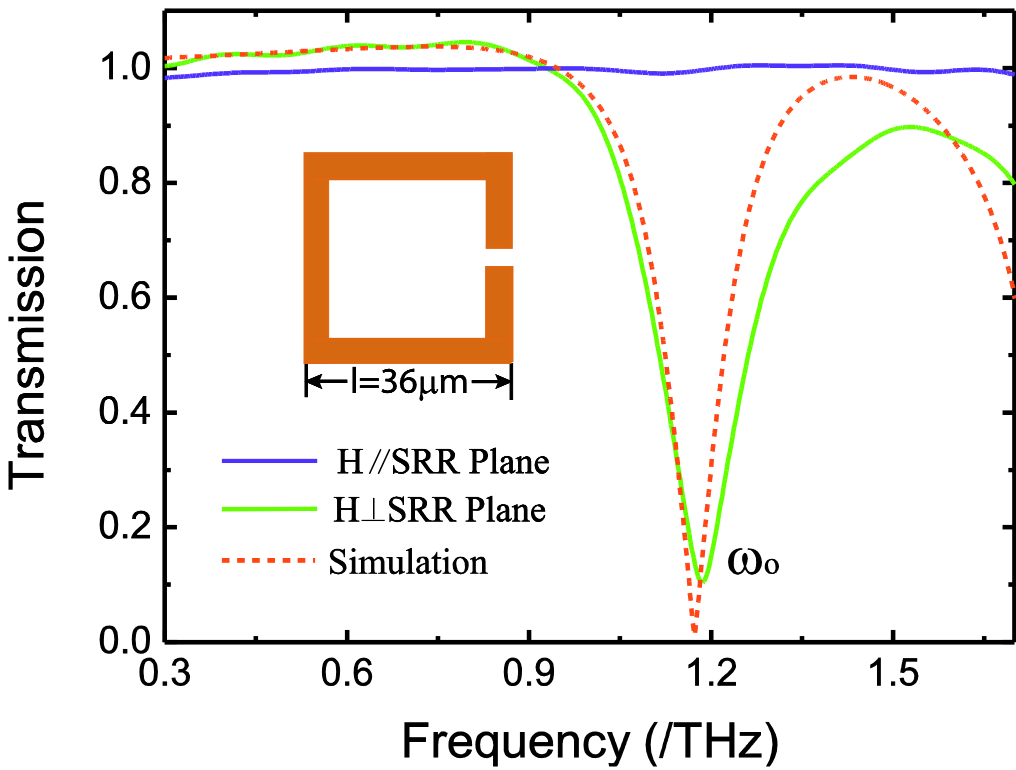
3D Stand-up Metamaterials: Pure Magnetic Excitation at Terahertz Frequencies

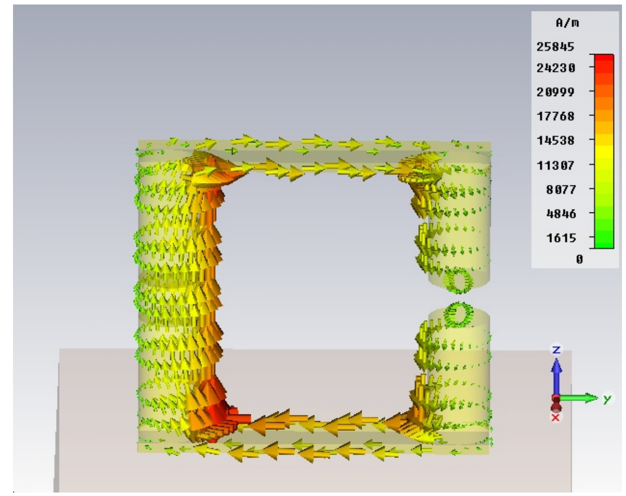


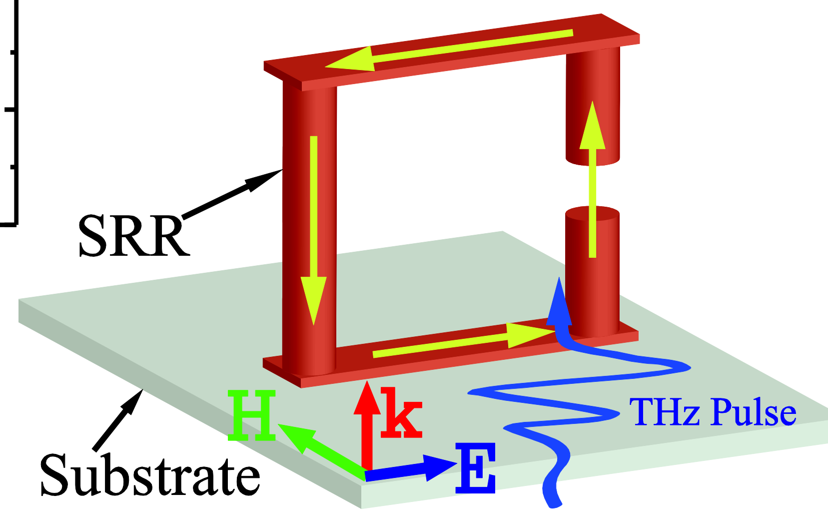


Cu electroplating with Cu/Ti seed layers

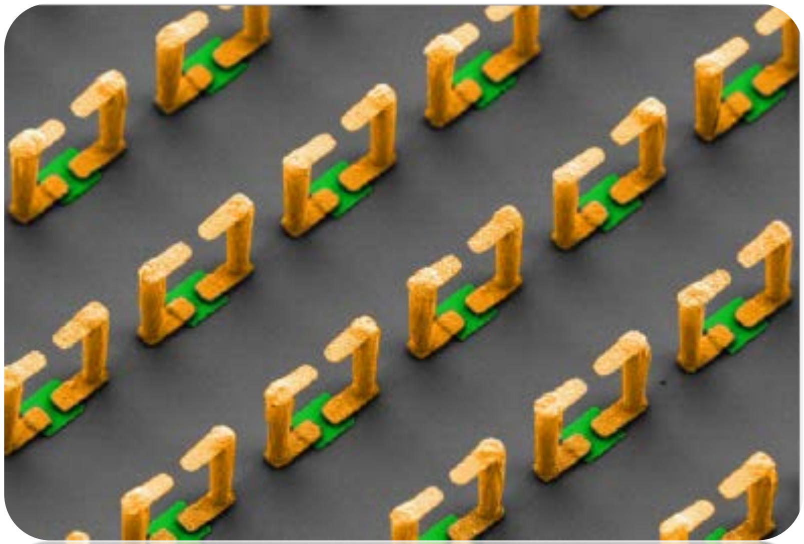
3D Stand-up Metamaterials: Pure Magnetic Excitation at Terahertz Frequencies

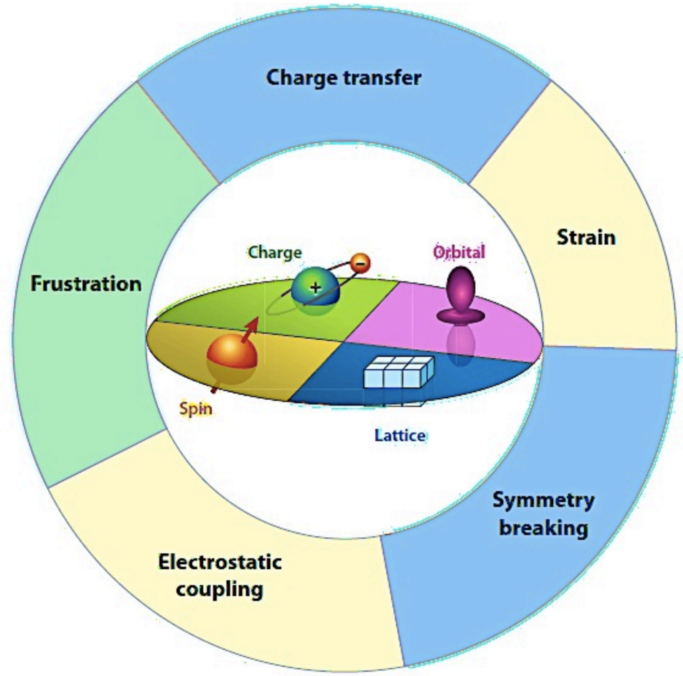






Create complex materials by combining metamaterials with other materials including transition metal oxides





Metamaterials

Sub-λ "LC" Resonators
Array → effective n(λ)

+

Correlated Electron Matter

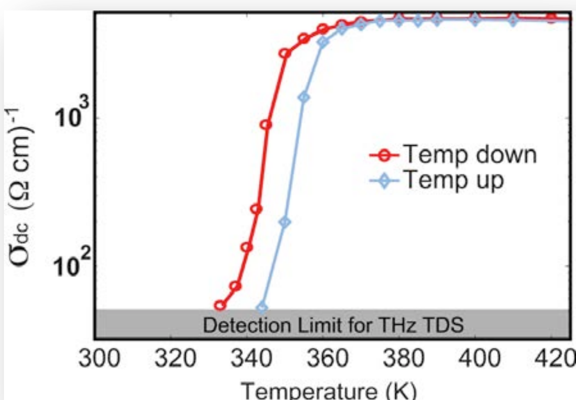
Competing DOF
Mode selec. excitation→
Phase control

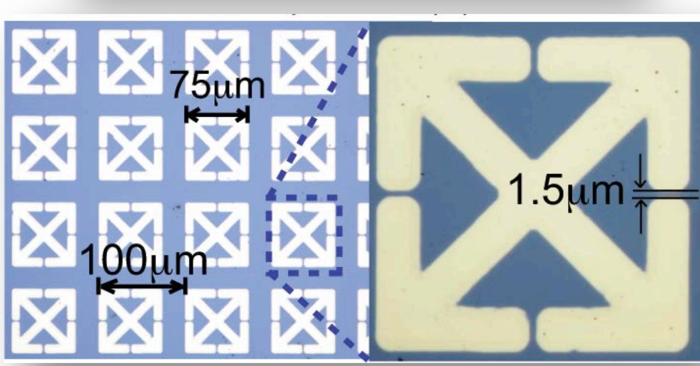
LETTER

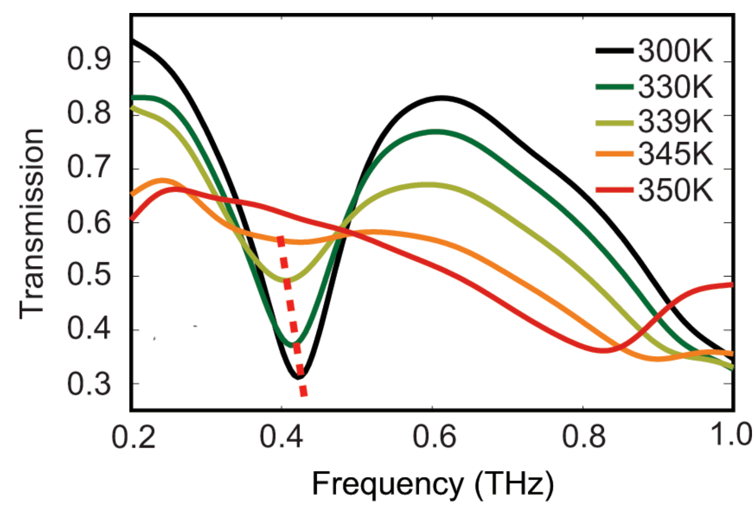
doi:10.1038/nature11231

Terahertz-field-induced insulator-to-metal transition in vanadium dioxide metamaterial

Mengkun Liu[1]*, Harold Y. Hwang[2]*, Hu Tao[3], Andrew C. Strikwerda[1], Kebin Fan[4], George R. Keiser[1], Aaron J. Sternbach[1], Kevin G. West[5], Salinporn Kittiwatanakul[5], Jiwei Lu[5], Stuart A. Wolf[5,6], Fiorenzo G. Omenetto[3], Xin Zhang[4], Keith A. Nelson[2] & Richard D. Averitt[1]

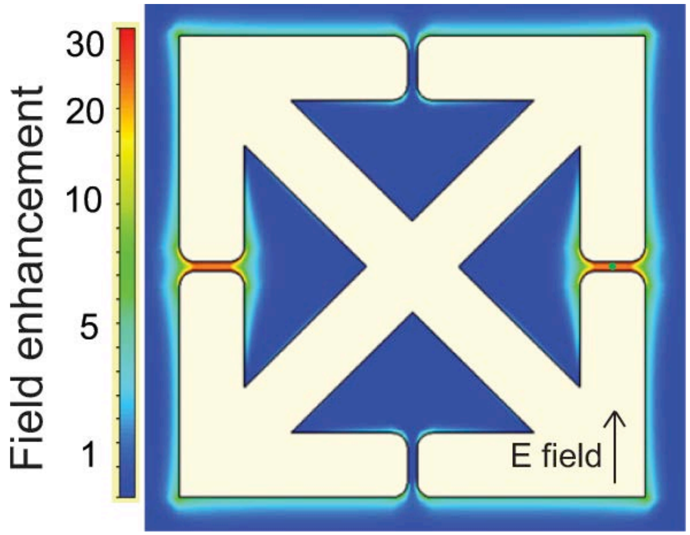


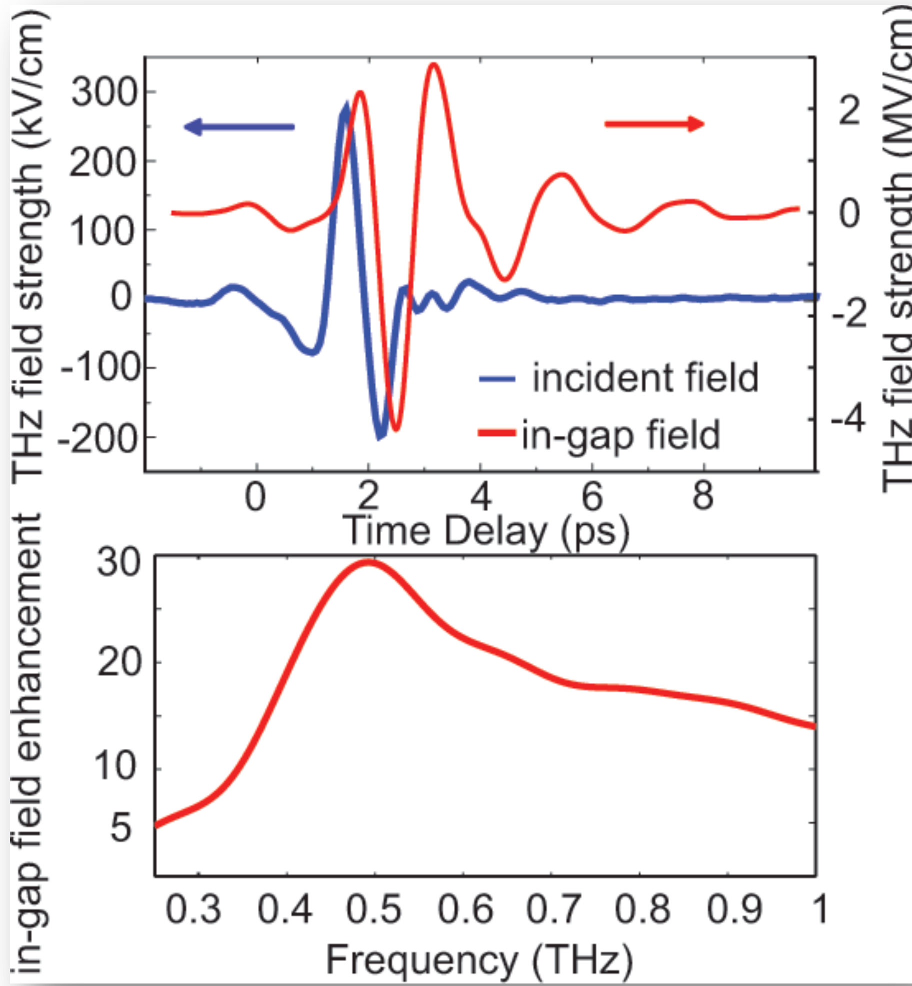




M. K. Liu, et al, Nature 487, 345 (2012)

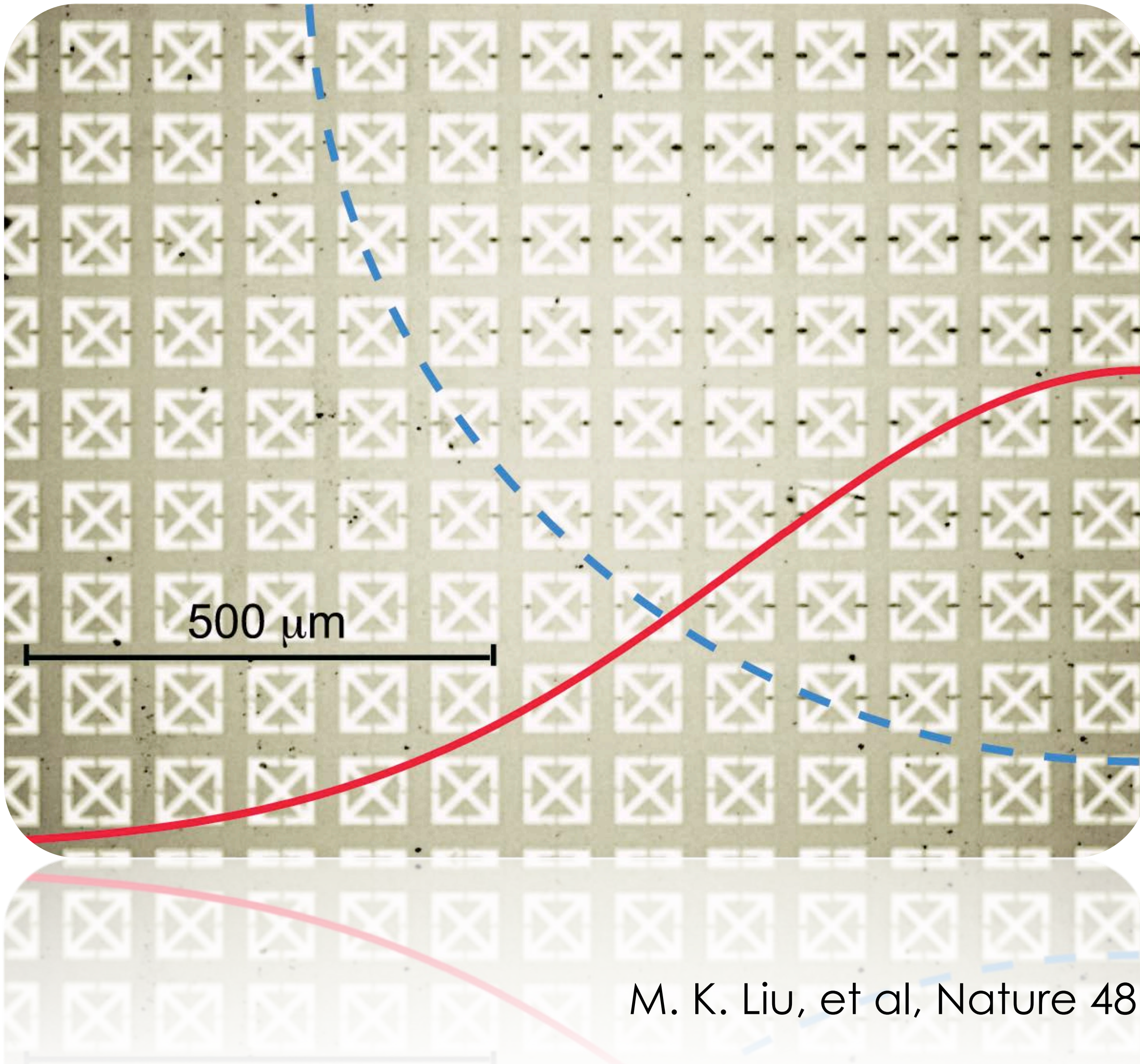
Field enhancement in the capacitive gaps





- Large field enhancement
- Extreme sub-λ regime
- Separation of E and H

Above Damage Threshold: ~4 MV/cm



M. K. Liu, et al, Nature 487, 345 (2012)