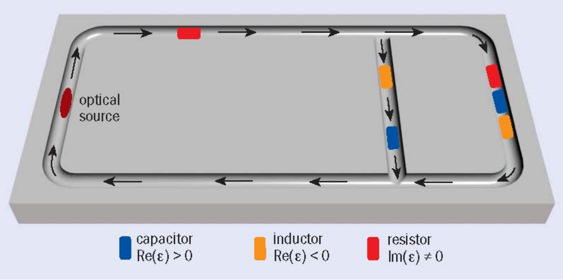
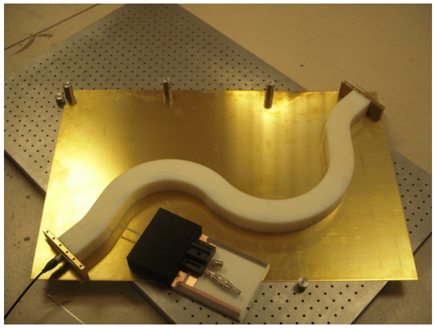
Of Light, Electrons and Metamaterials





Nader Engheta

Special Thanks to
Andrea Alu
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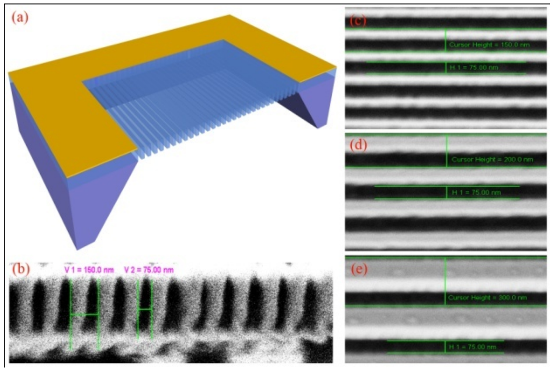
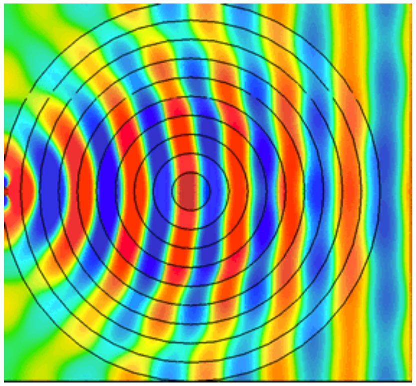
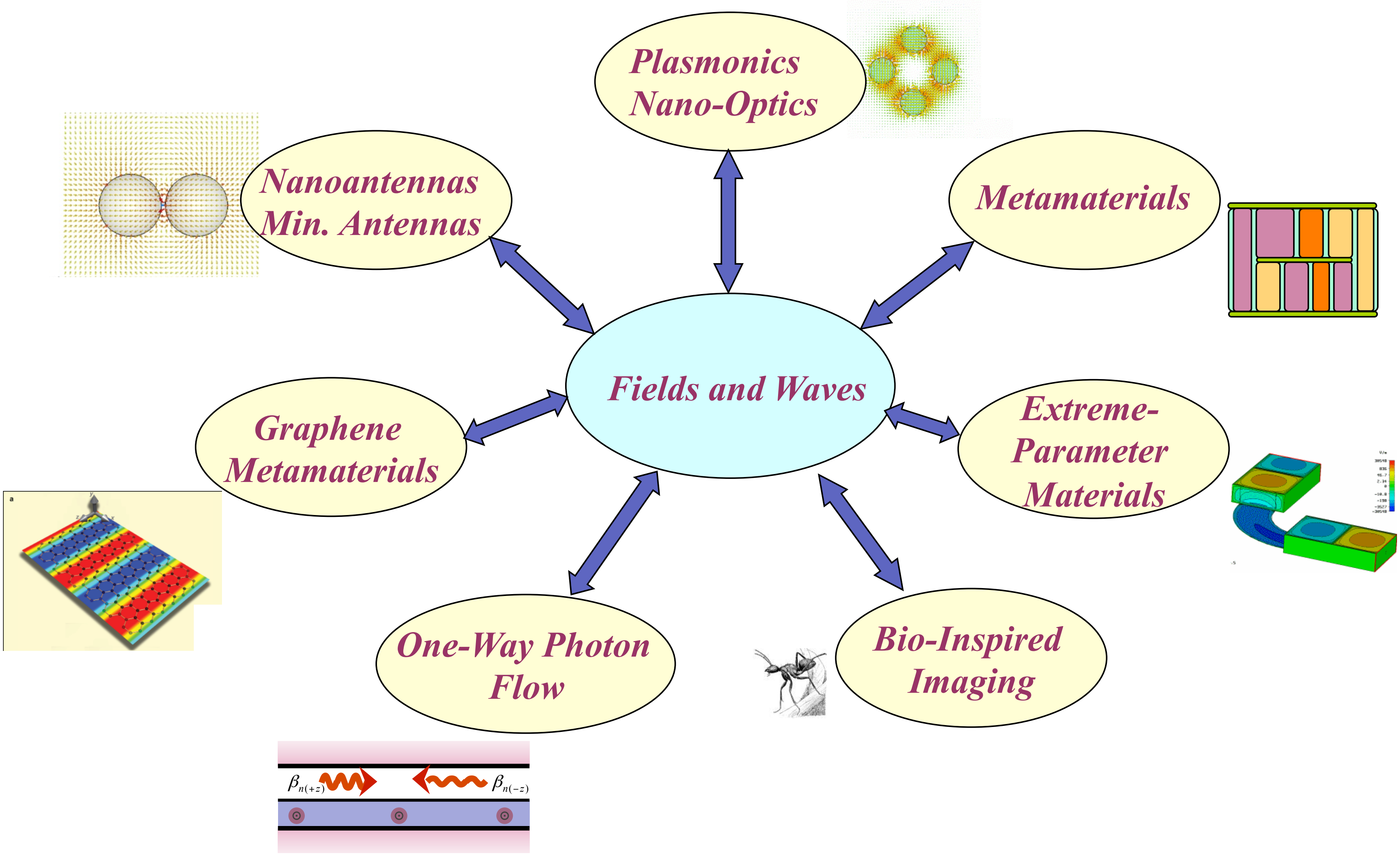
Uday Chettiar
Brian Edwards
Nikolina Jankovic
Mario Silveirinha
Yong Sun
Ashkan Vakil
Wenkan Zhu

February 15, 2012





Current Research Programs



Fields and Waves

Plasmonics Nano-Optics

Nanoantennas Min. Antennas

Metamaterials

Graphene Metamaterials

Extreme-Parameter Materials

One-Way Photon Flow

Bio-Inspired Imaging

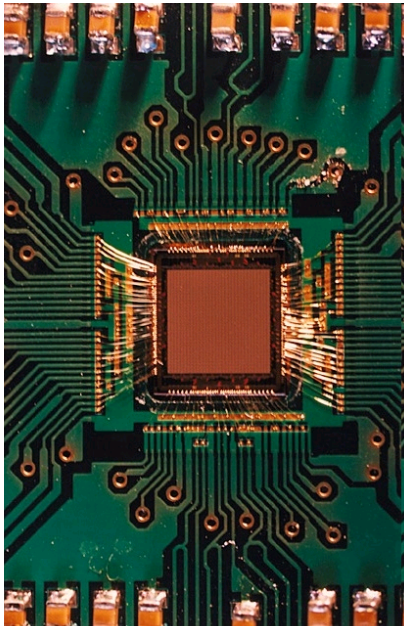
System Approach

Modularization

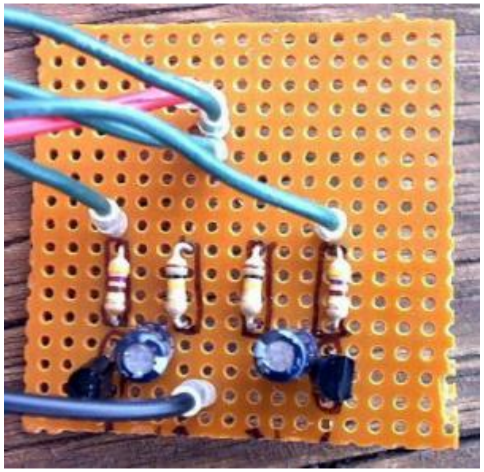
Parameterization

Standardization

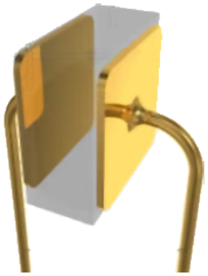
Electronic Modules



http://www.imrc.hw.ac.uk/New_versions/Home_files/Microelectronics.jpg



C



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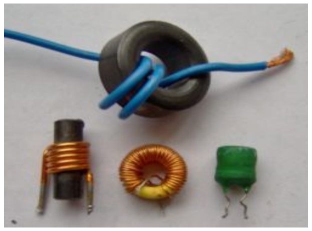
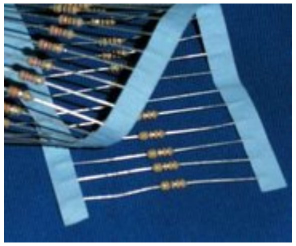
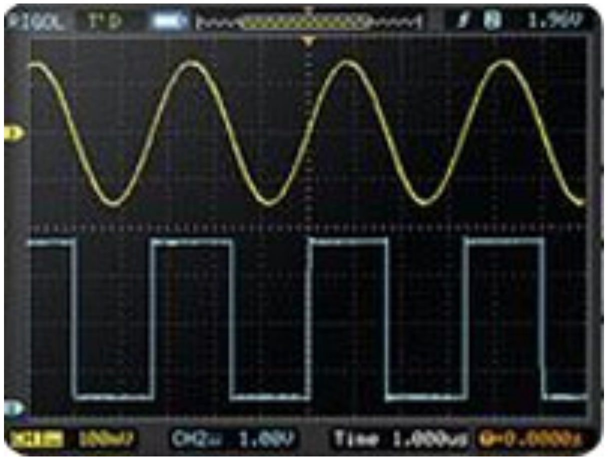
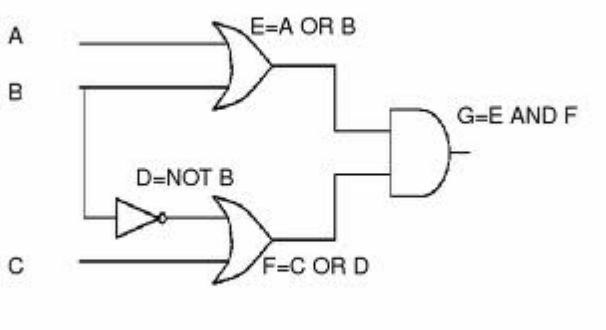


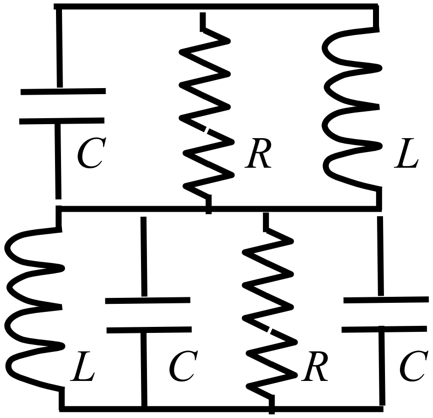
R



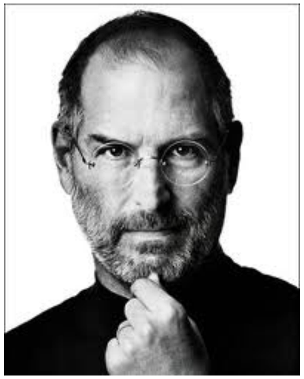
Analog vs Digital

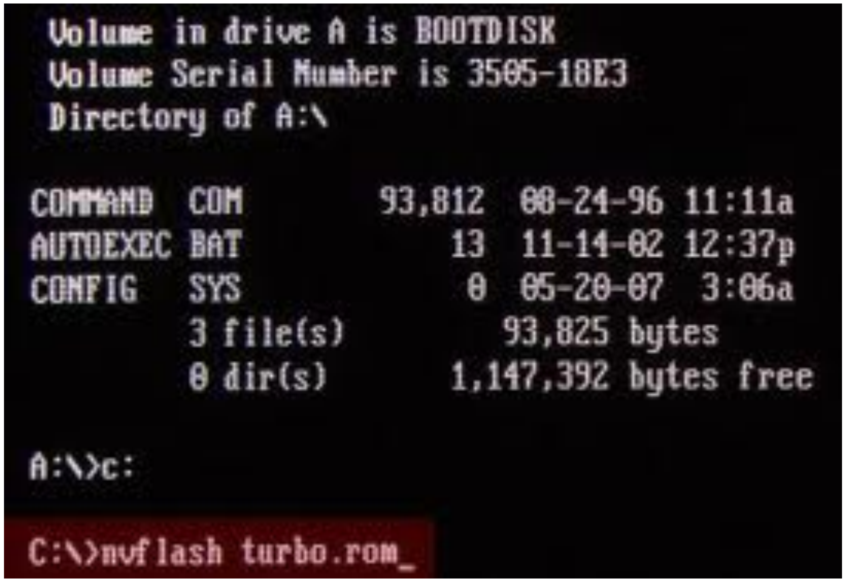






iPhone vs DOS

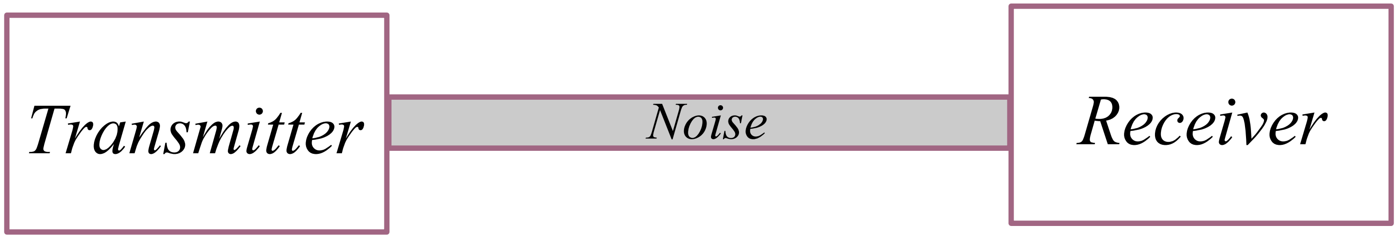




```
 Volume in drive A is BOOTDISK
 Volume Serial Number is 3505-18E3
 Directory of A:\

COMMAND  COM        93,812  08-24-96 11:11a
AUTOEXEC BAT            13  11-14-02 12:37p
CONFIG   SYS             0  05-20-07  3:06a
         3 file(s)          93,825 bytes
         0 dir(s)        1,147,392 bytes free

A:\>c:

C:\>nvflash turbo.rom_
```

http://t0.gstatic.com/images?q=tbn:ANd9GcQ2jC_aCeZHKyjVou0Q_xOq0LG3FkyuW963_OLqcM07rld4EHAUsA

Claude Shannon & Channel Capacity



Transmitter

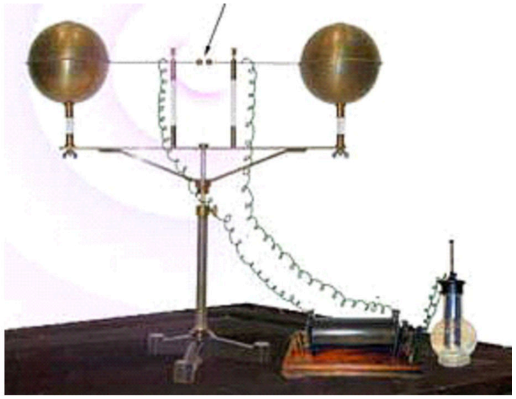
Noise

Receiver

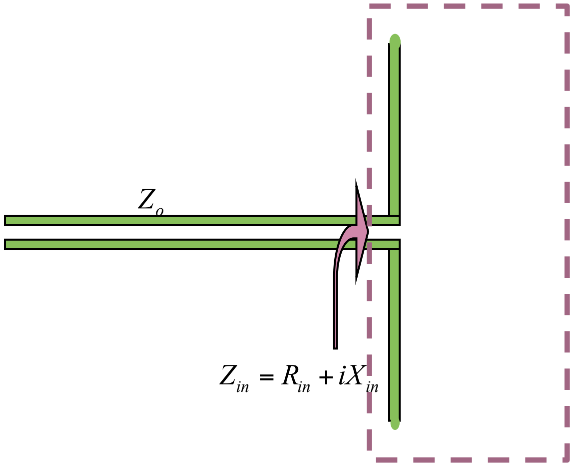
$$\text{Channel Capacity} = B\log_2\left(1+\frac{S}{N}\right)$$

Development of Antennas

a)



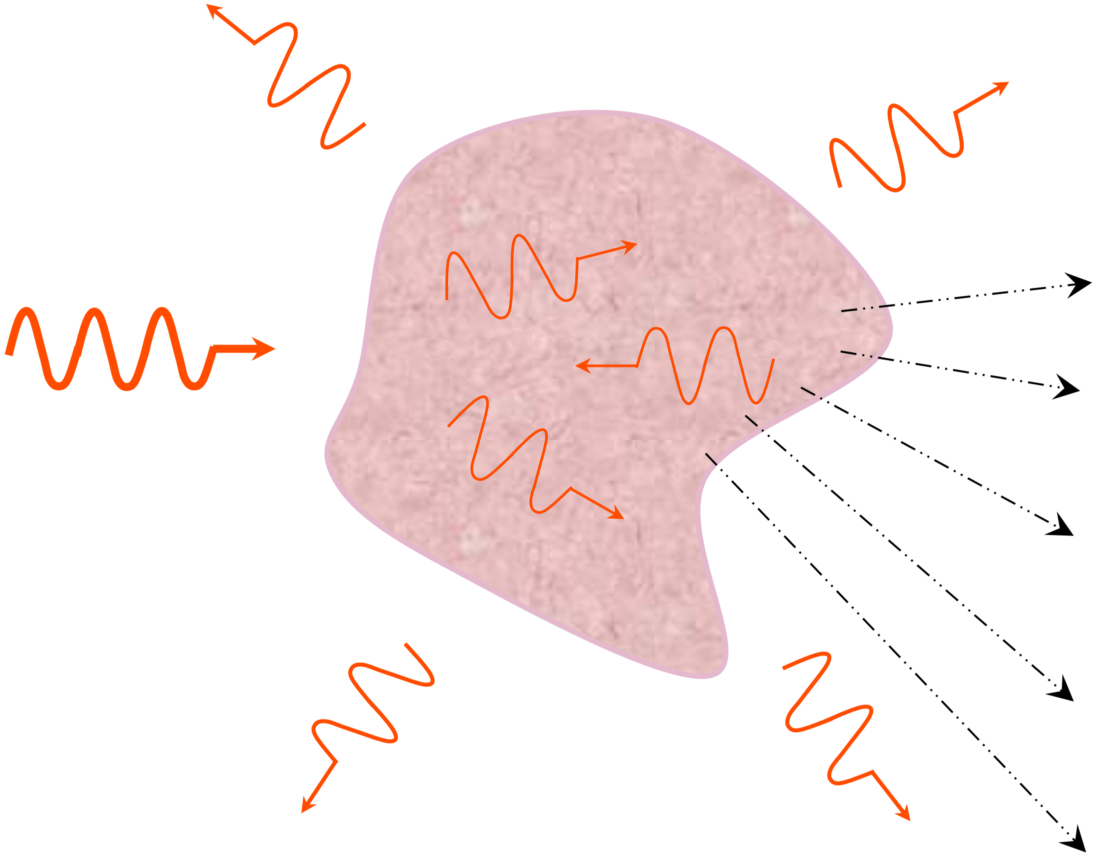
From: http://www.sparkmuseum.com



R. W. P. King

S. A. Schelkunoff

Light-Matter Interaction



ε

μ

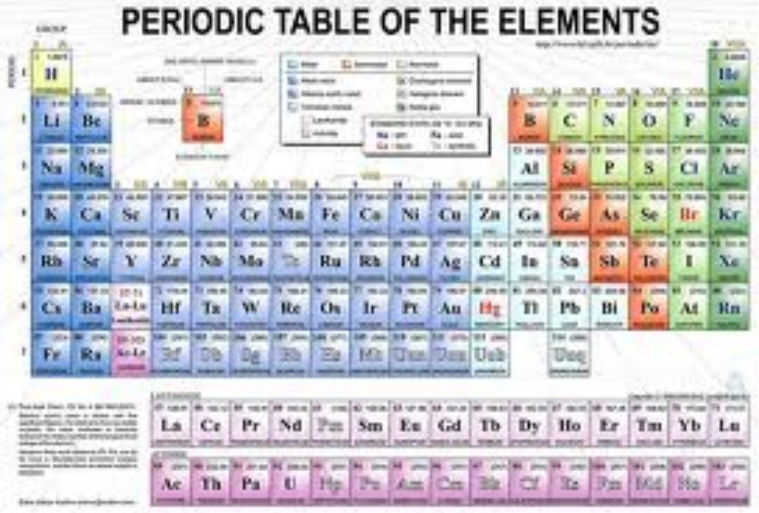
σ

$\chi^{(2)}, \ldots.\ \chi^{(3)}$

ξ

M

“Natural” Materials

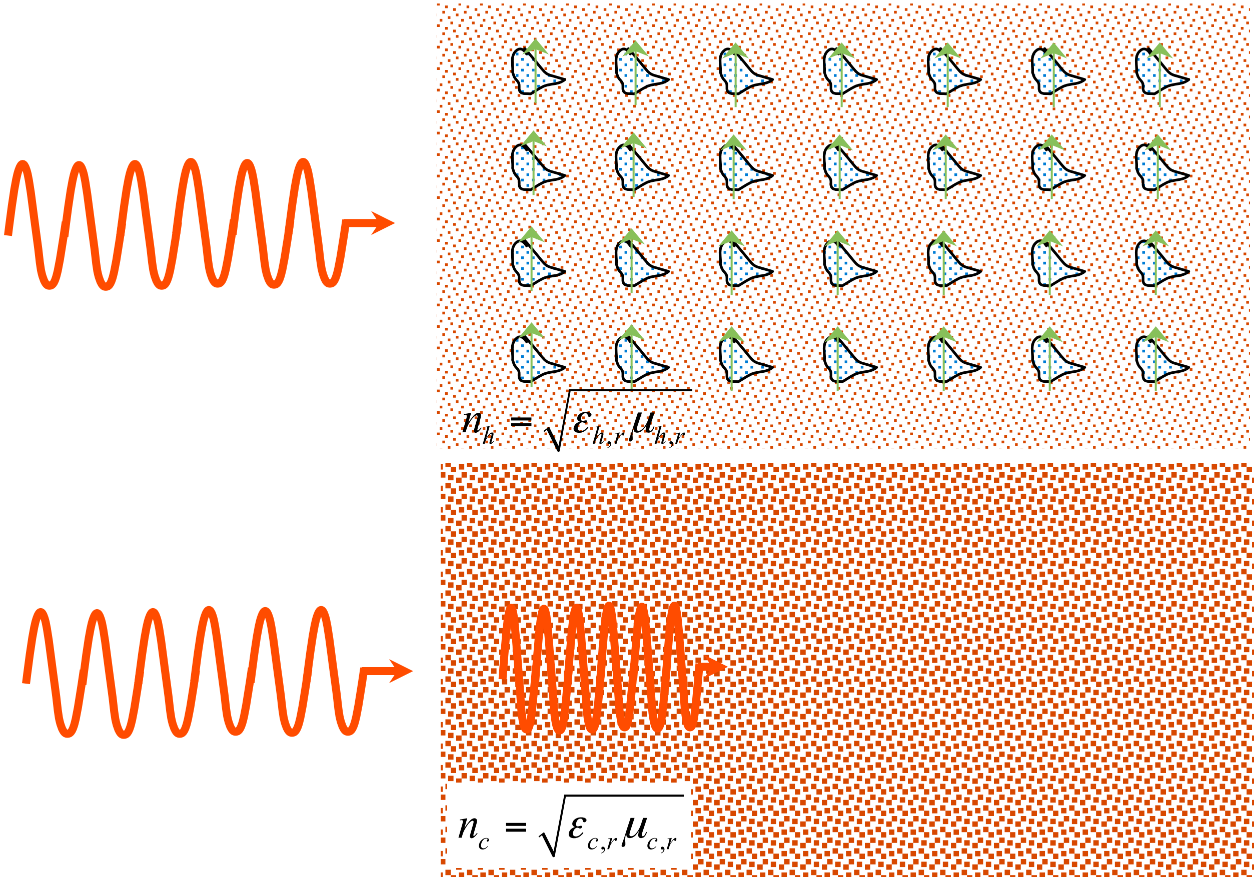


PERIODIC TABLE OF THE ELEMENTS

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La-Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub		Uuq				
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

"Artificially" Engineered Materials

- *Particulate Composite Materials*

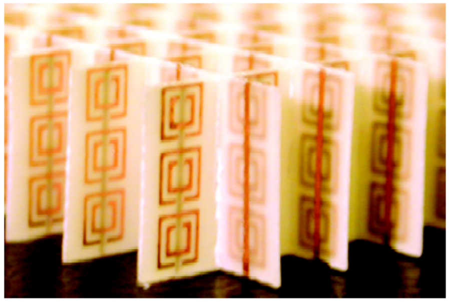


$$n_h = \sqrt{\varepsilon_{h,r}\mu_{h,r}}$$

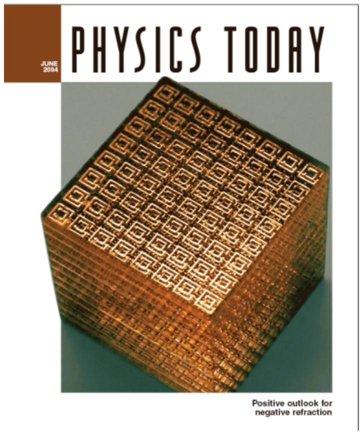
$$n_c = \sqrt{\varepsilon_{c,r}\mu_{c,r}}$$

- *Composition*
- *Alignment*
- *Arrangement*
- *Density*
- *Host Medium*
- *Geometry/Shape*

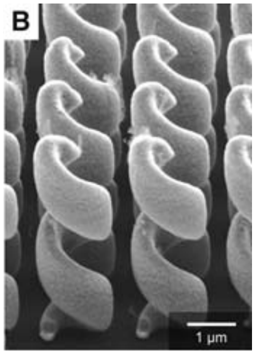
Recent Metamaterials (2000-2011)



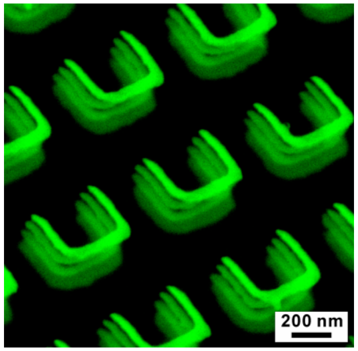
Smith, Schultz group (2000)



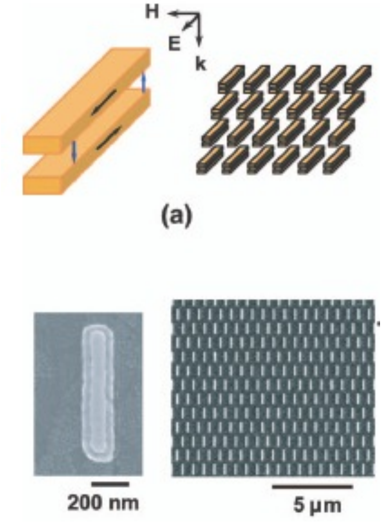
Boeing group



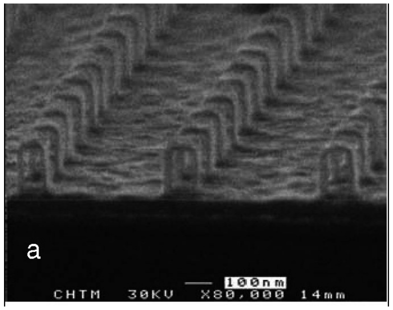
Wegener group (2009)



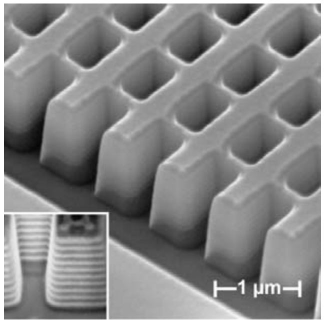
Giessen group (2008)



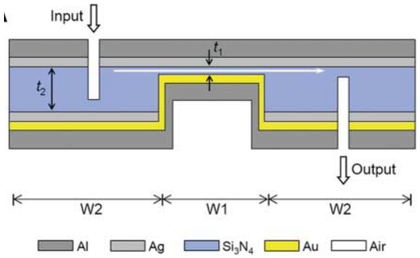
Shalaev group (2005)



Brueck group (2005)

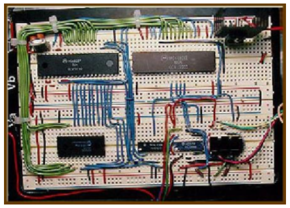


Zhang group (2008)



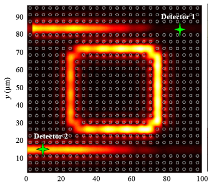
Atwater group (2007)

Topics vs Parameters



Electronics

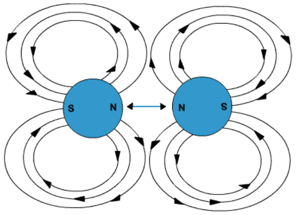
$$J = \sigma_e E$$



From: D. Prather's group

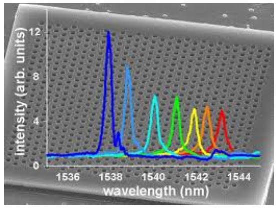
Photonics

$$D = \varepsilon E$$



Magnetics

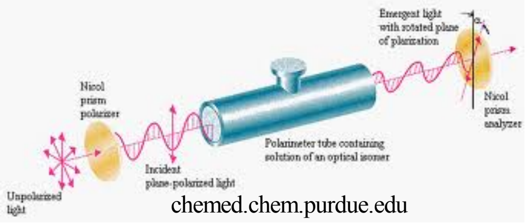
$$B = \mu H$$



logofanothemeA.jpg, lpn.cnrs.fr

Nonlin. Opt.

$$\chi^{(2)}, \ldots . \quad \chi^{(3)}$$



chemed.chem.purdue.edu

Opt. Activity

$$\xi$$

Metatronics vs Metamaterials

Photonics/ Microwaves → Concept of Metamaterials ← Electronics

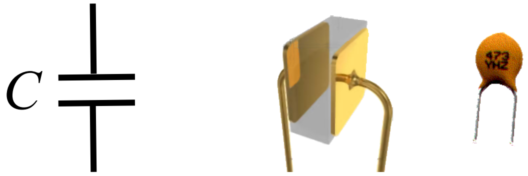
↓

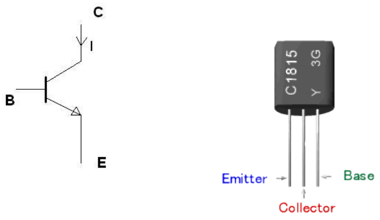
"Metatronics"

↓

Building Blocks for Metamaterials

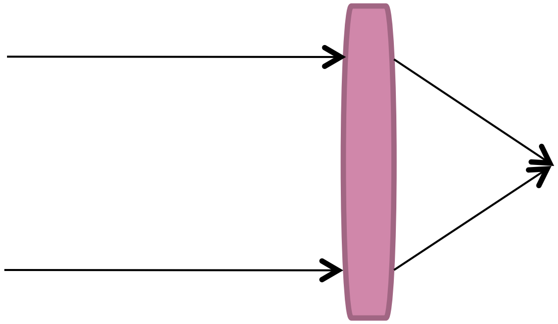
“Modular Blocks” in electronics



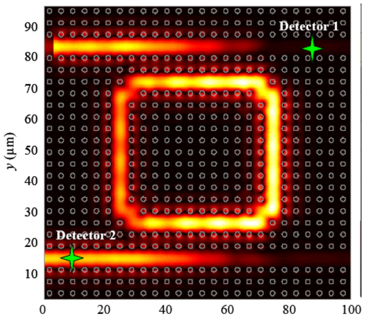


“Building Blocks” in Optics?

Waveguide

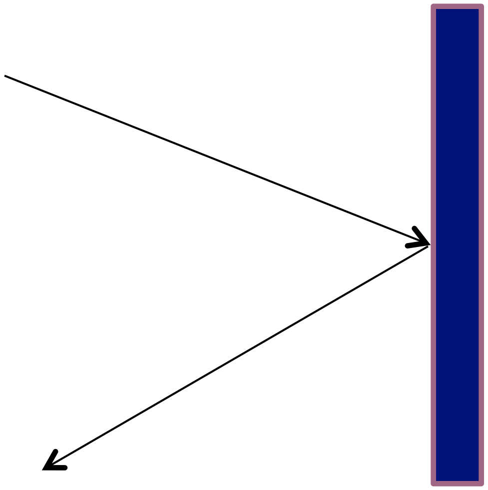


Lens



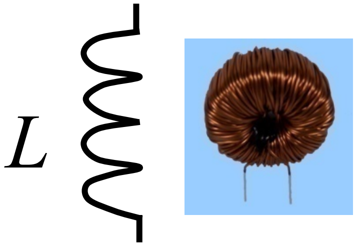
from: D. Prather's group

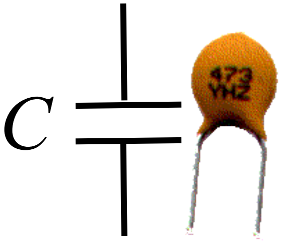
Optics

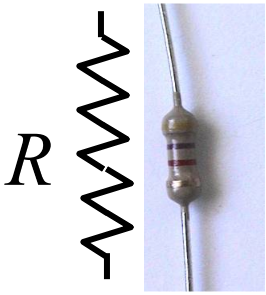


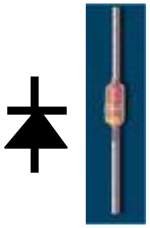
Mirror

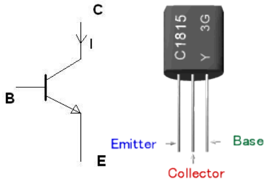
Can We Have "Lumped" Circuit Elements in Nano-Optics?











Radio Frequency (RF) electronics

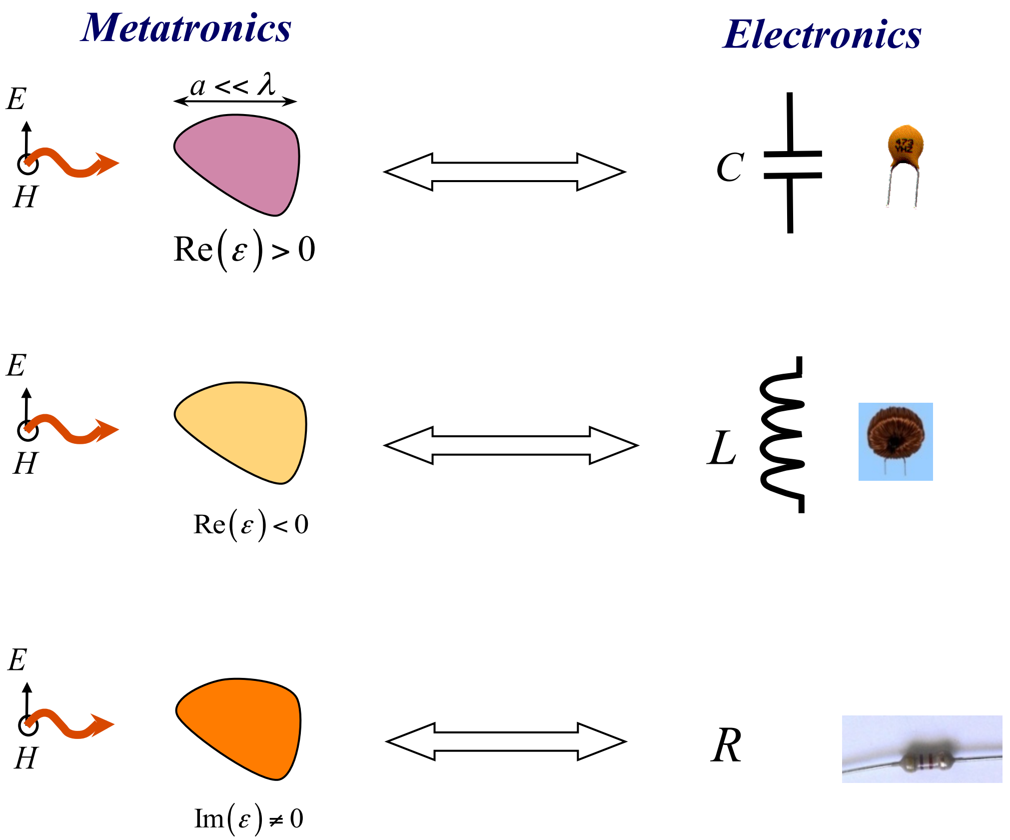
? ? ? ? ?

Nano-Optics

Optical Lumped Circuit Elements: Modular Blocks

$$\frac{\partial D}{\partial t} = -i\omega\varepsilon E$$

$$Z = \frac{\mathit{Optical\ Voltage}(E)}{\mathit{Optical\ Displacement}(D)}$$



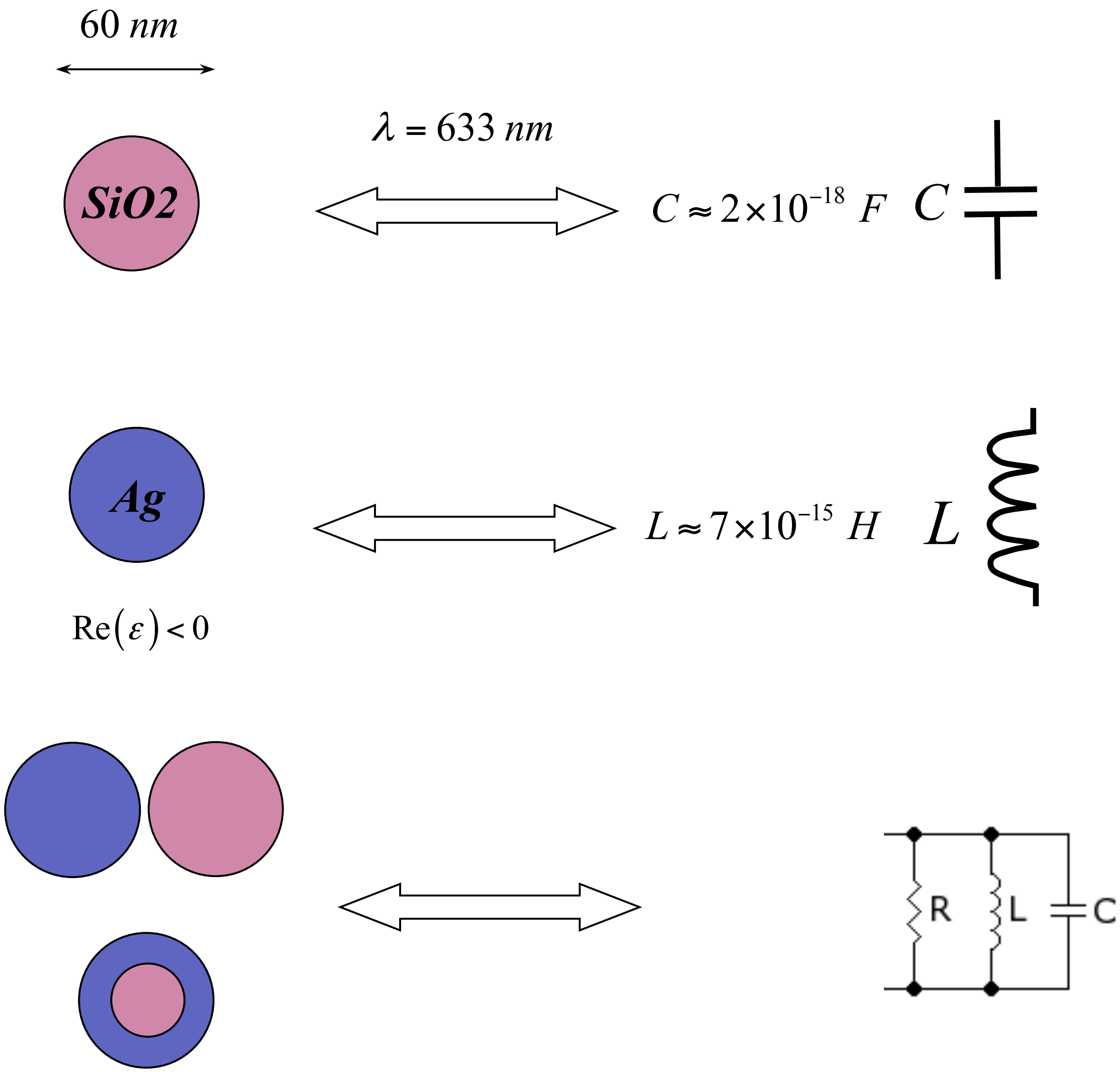
Metatronics ***Electronics***

Engheta, Physics World, 23(9), 31 (2010)

Engheta, Salandrino, Alu, Phys. Rev. Lett. 95 (2005)

Engheta, Science, 317, 1698 (2007)

Examples



$60\ nm$

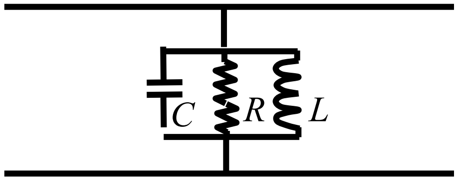
$\lambda = 633\ nm$

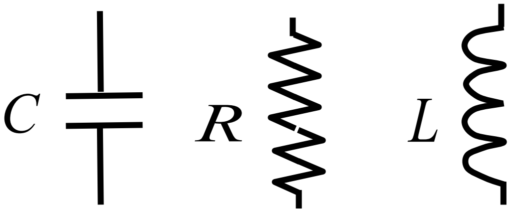
$C \approx 2\times10^{-18}\ F$ C

$L \approx 7\times10^{-15}\ H$ L

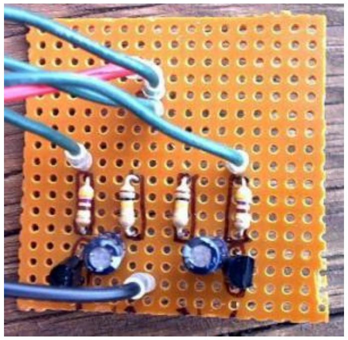
$\mathrm{Re}(\varepsilon) < 0$

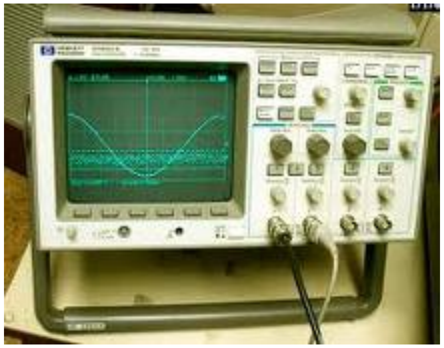
Electronic Circuit Design?



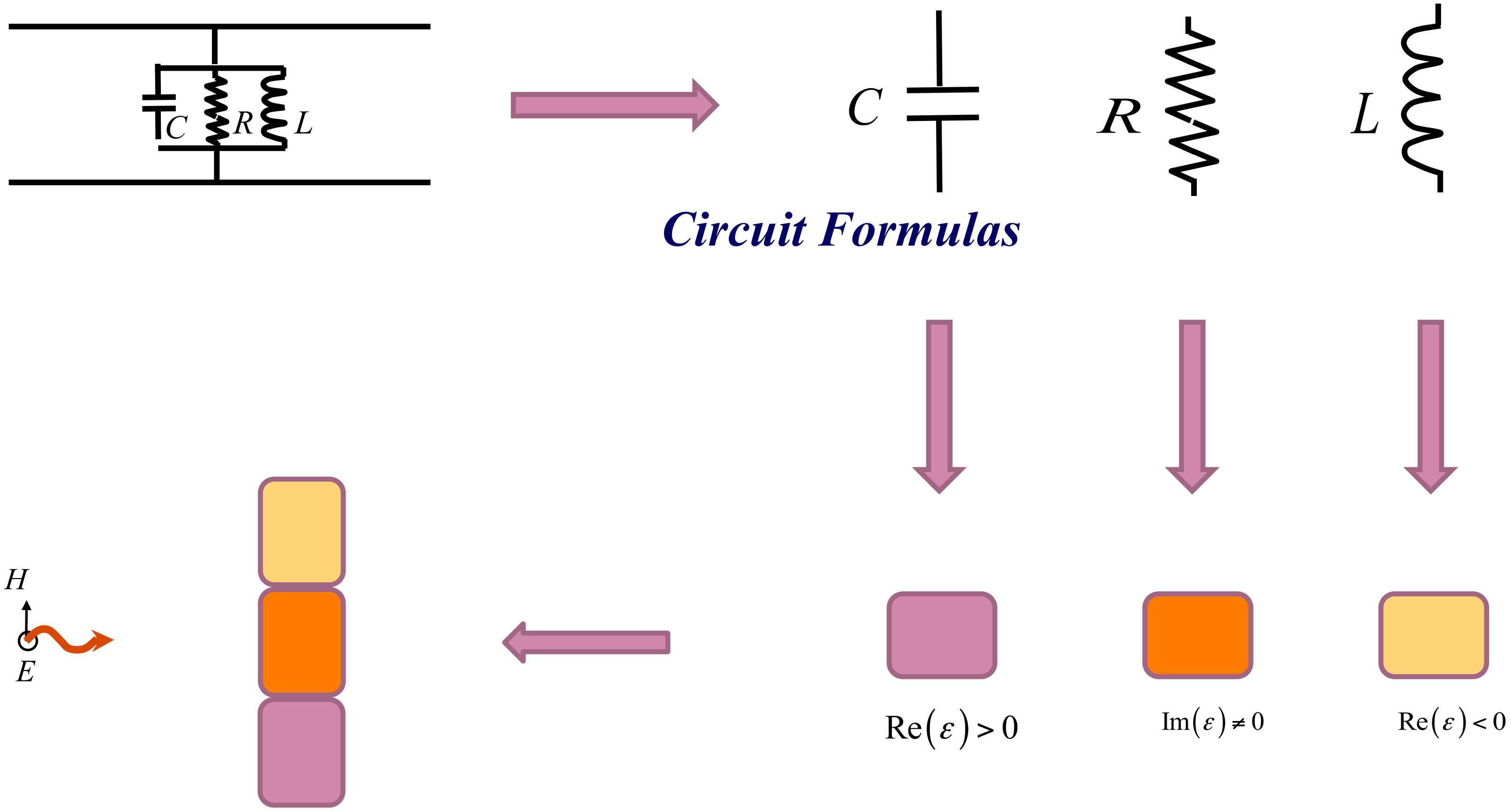


Circuit Formulas





Can we do this in Nano-Optics?



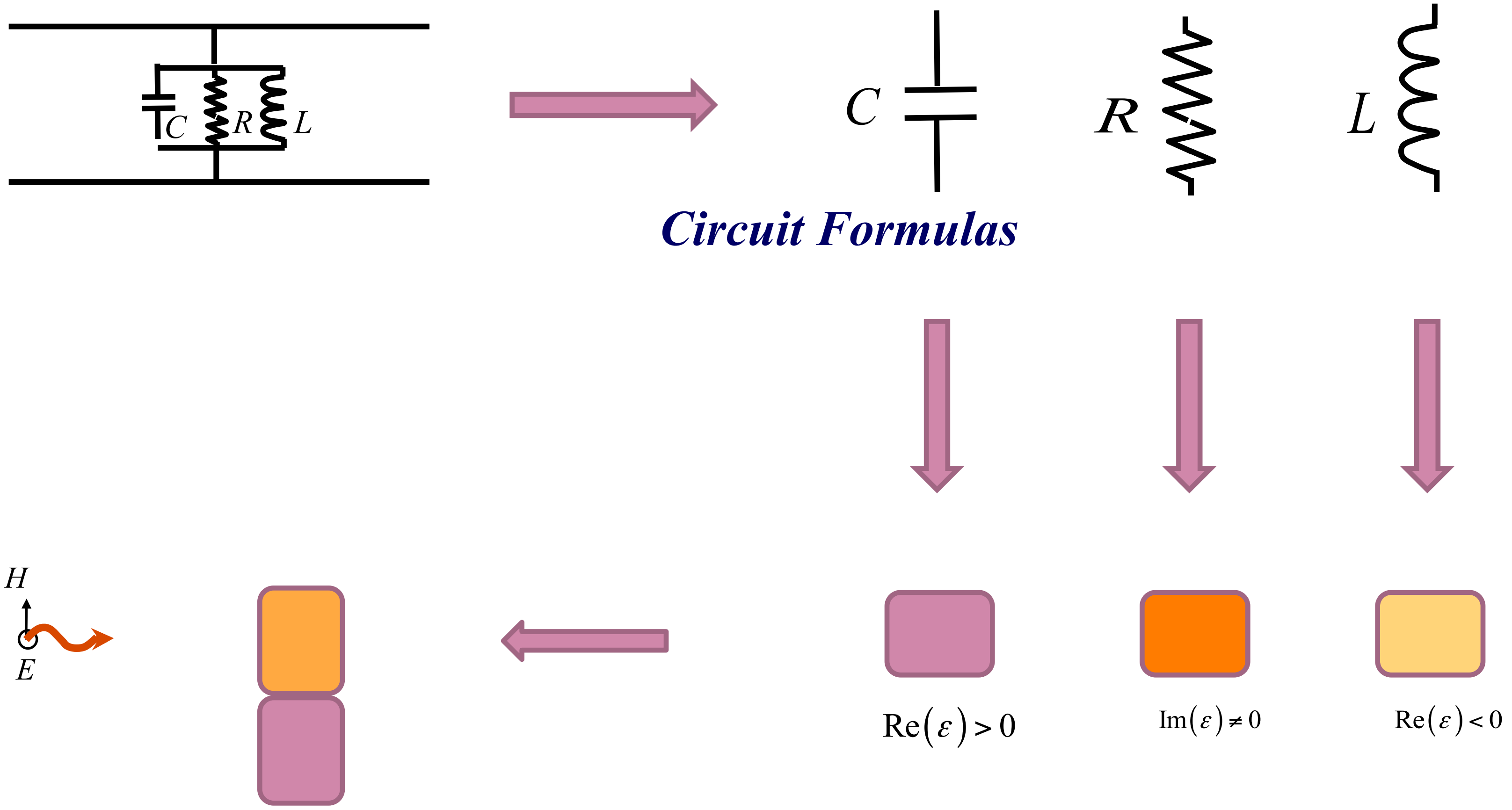
Circuit Formulas

$\mathrm{Re}(\varepsilon) > 0$

$\mathrm{Im}(\varepsilon) \neq 0$

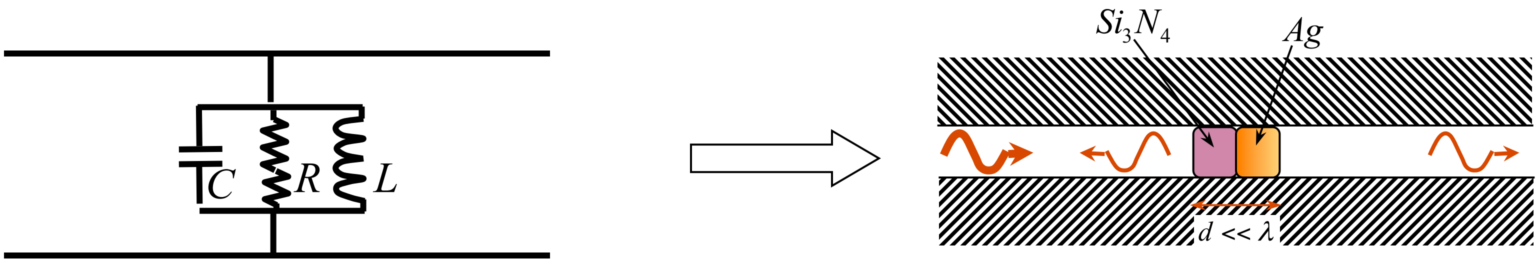
$\mathrm{Re}(\varepsilon) < 0$

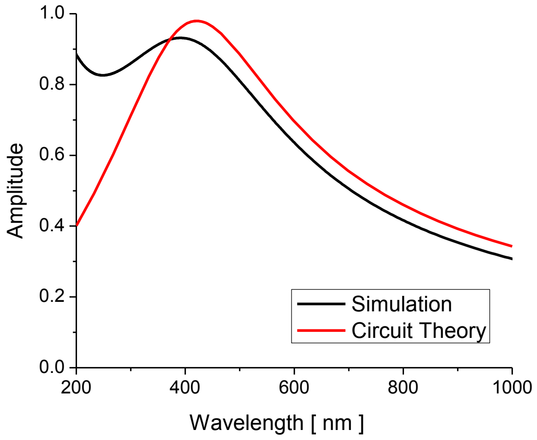
Can we do this in Nano-Optics?

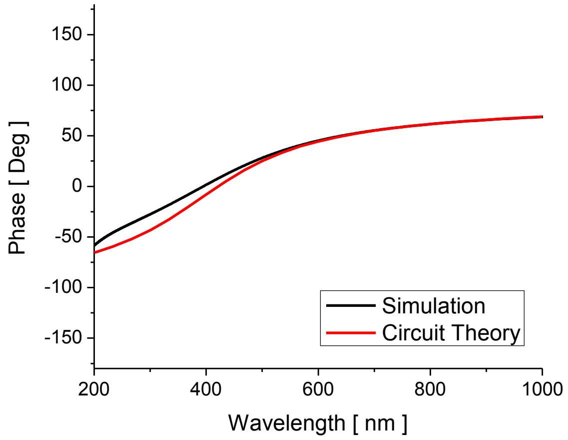


Circuit Formulas

Optical Filter with Nanorods



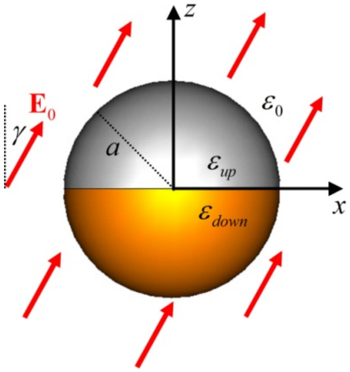


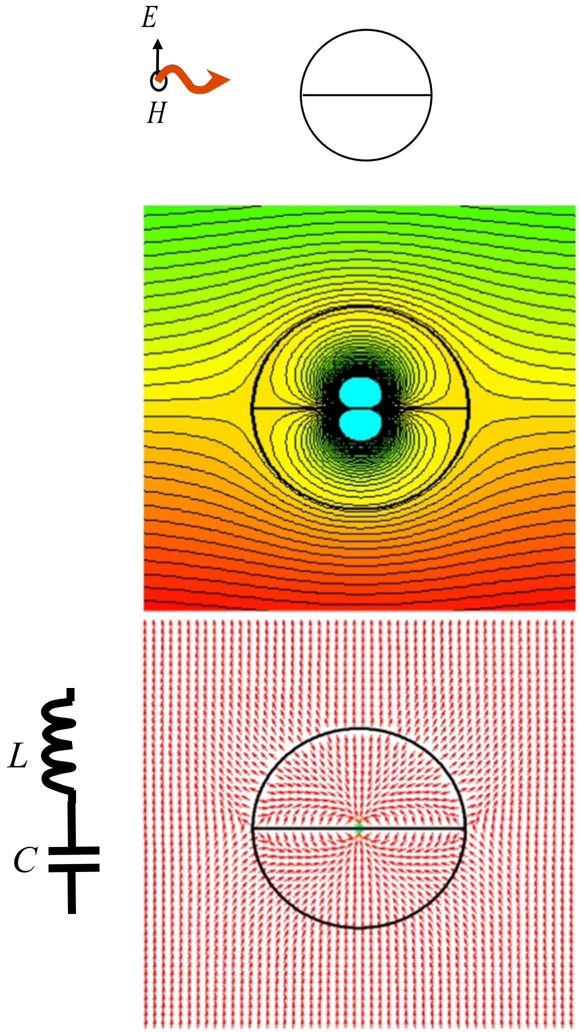


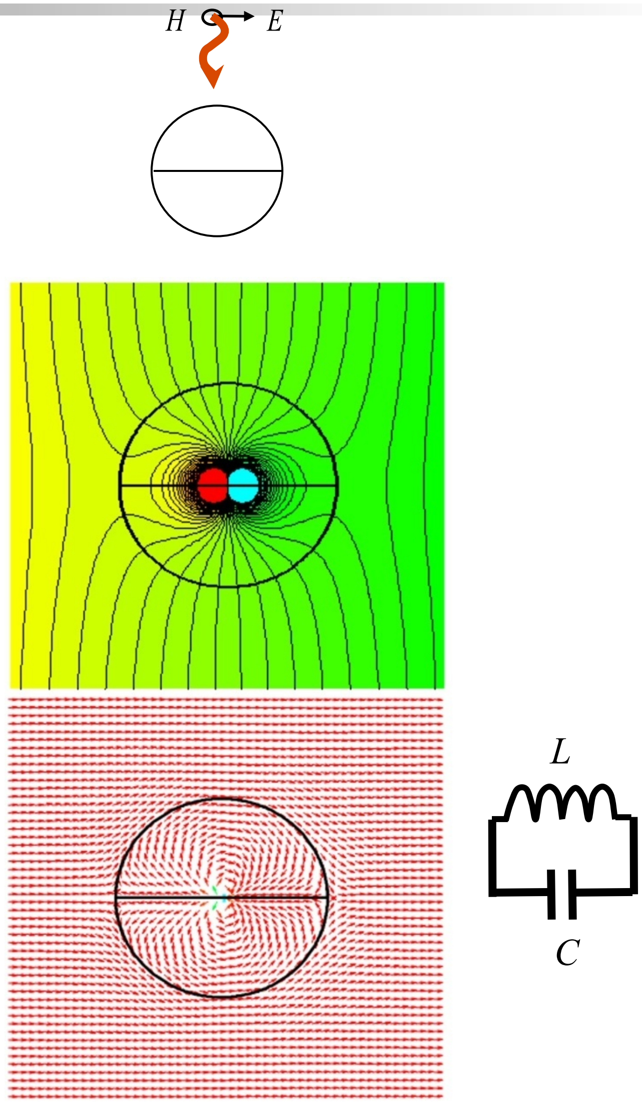
Engheta, Science, 317, 1698 (2007)

Alu, Young, and Engheta, Phys. Rev. B (2008)

"Stereo-Circuits"
Different "Circuits" for Different "Views"



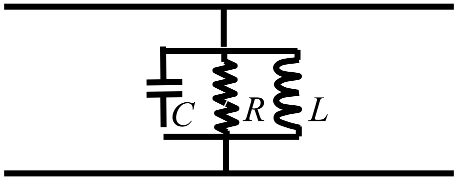


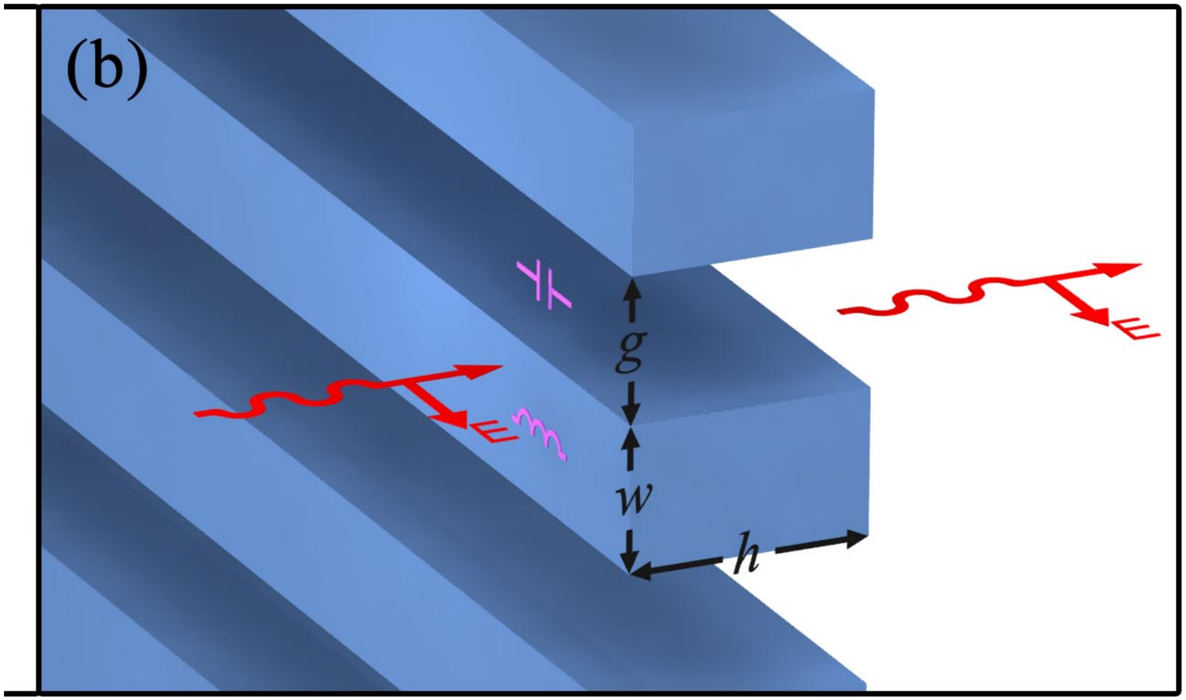


Salandrino, Alu, Engheta, JOSA B, Part 1, 2007
Alu, Salandrino, Engheta, JOSA B, Part 2, 2007

Alu and Engheta, New Journal of Physics, 2009

Experimental Verification at IR





$W = 75nm, 125nm, 225nm$

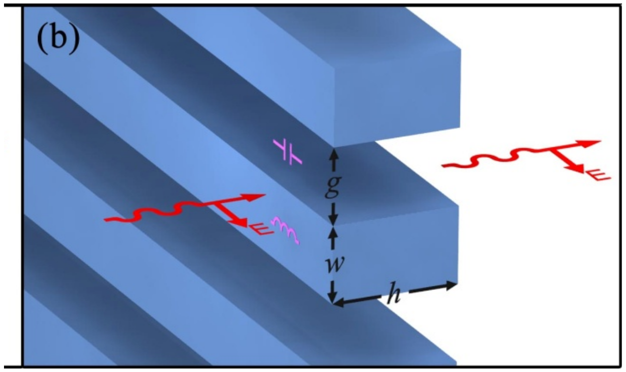
$g = 75nm$

$h = 175nm, 250nm, 325nm$

Y. Sun, B. Edwards, A. Alu, and N. Engheta, Nature Materials, Jan 29, 2012

Experimental Verification at IR

Circuit Theory Model



$$Z_{wire}^{par} \equiv \frac{i}{\omega h w \varepsilon_{Si_3N_4}}$$

$$Z_{air\text{-}gap}^{par} \equiv \frac{i}{\omega h g \varepsilon_{air}}$$

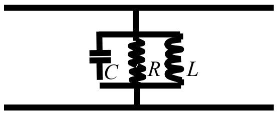
$$Z_{equivalent}^{par} \equiv \frac{Z_{wire}^{par} \cdot Z_{air\text{-}gap}^{par}}{Z_{wire}^{par} + Z_{air\text{-}gap}^{par}}$$

$$T^{par} = \left| \frac{Z_{equivalent}^{par}}{Z_{equivalent}^{par} + \left[\eta_o / \left(2 \left(W + g \right) \right) \right]} \right|^2$$

$g = 75nm$

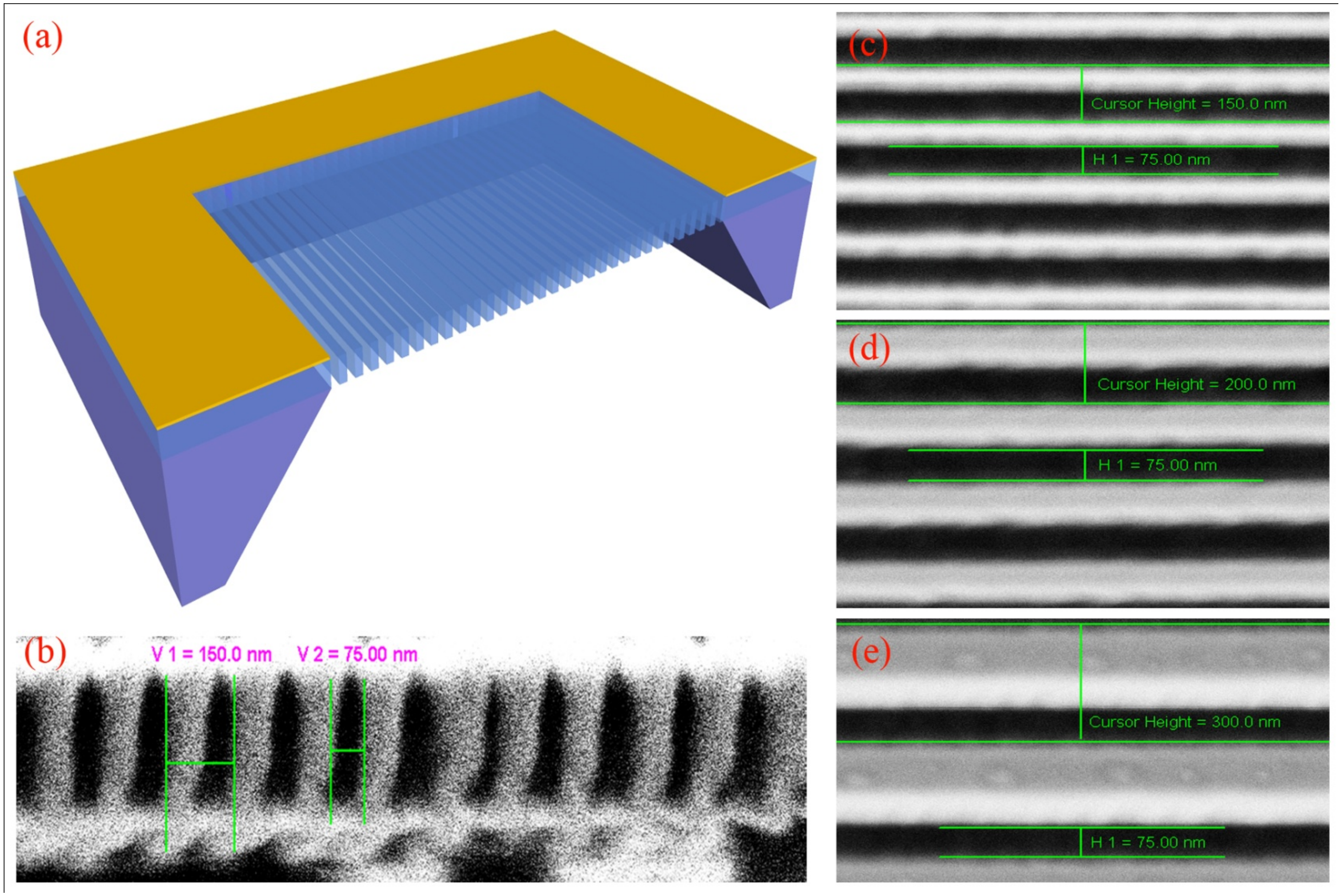
$h = 175nm, 250nm, 325nm$

$W = 75nm, 125nm, 225nm$



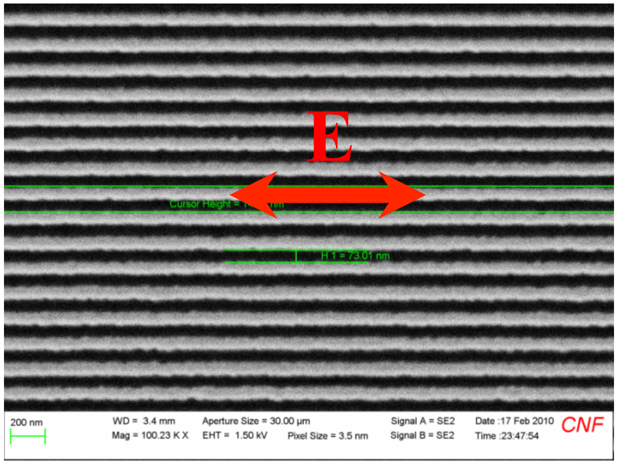
Y. Sun, B. Edwards, A. Alu, and N. Engheta, Nature Materials, Jan 29, 2012

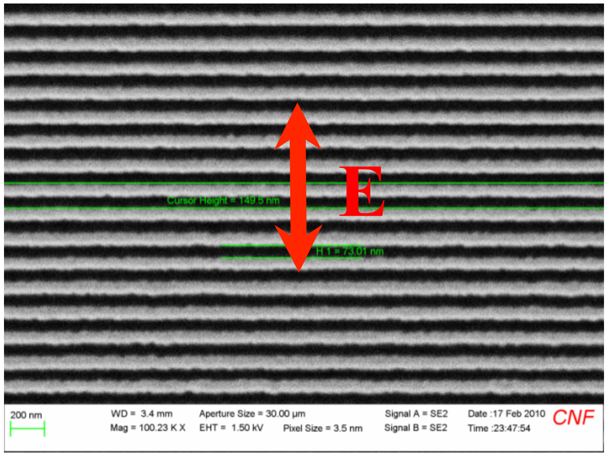
Our Samples

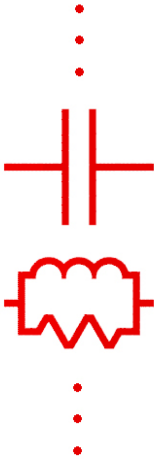


Y. Sun, B. Edwards, A. Alu, and N. Engheta, Nature Materials, Jan 29, 2012

“Parallel” and “Series” Optical Circuits

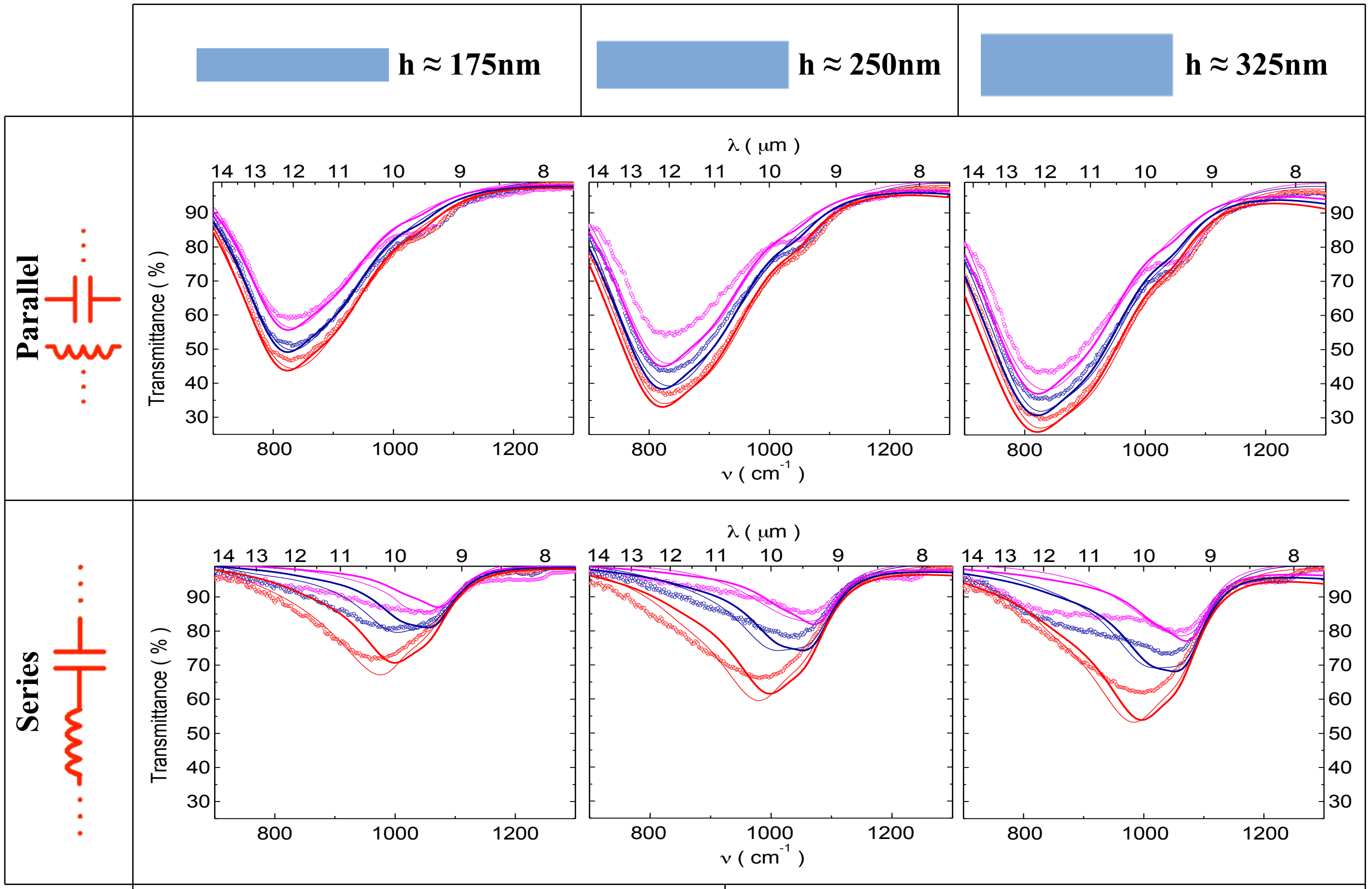






Y. Sun, B. Edwards, A. Alu, and N. Engheta, <u>Nature Materials,</u> Jan 29, 2012

Collective Results

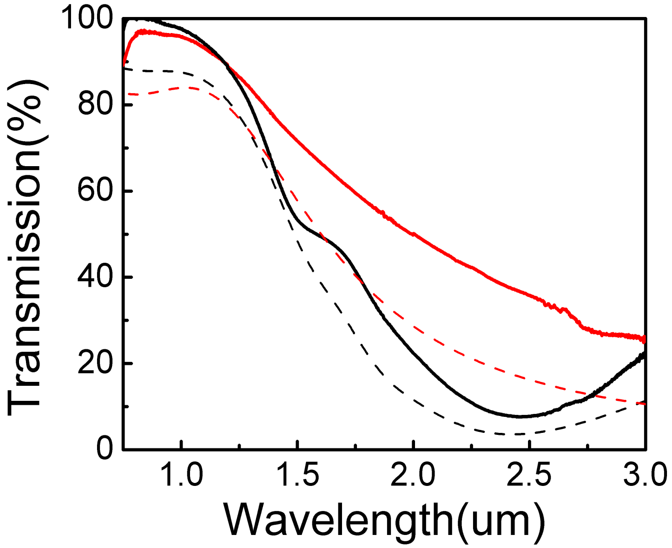


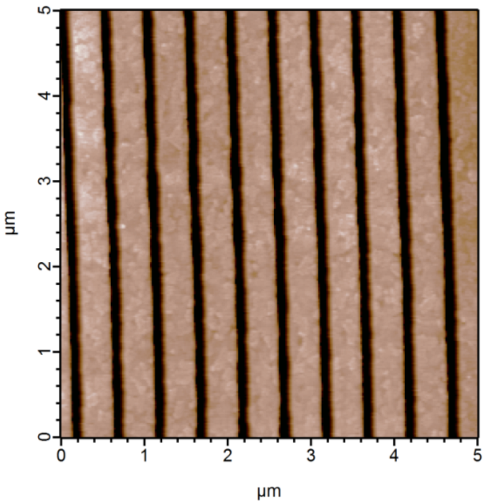
“empty circle”: Experimental data
“Thick line”: Circuit theory
“Thin line” : Full wave simulation

Magenta: w ~ 75 nm, g ~ 75 nm
Royal blue: w ~ 125 nm, g ~ 75 nm
Red: w ~ 225 nm, g ~ 75 nm

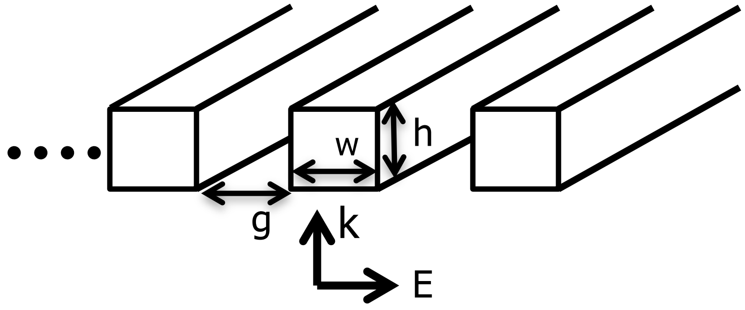
Y. Sun, B. Edwards, A. Alu, and N. Engheta, Nature Materials, Jan 29, 2012

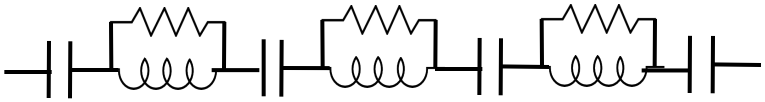
TCO NIR Metatronic Circuits
Fabrication and Experimental Results





w=380nm
g=120nm
h=150nm

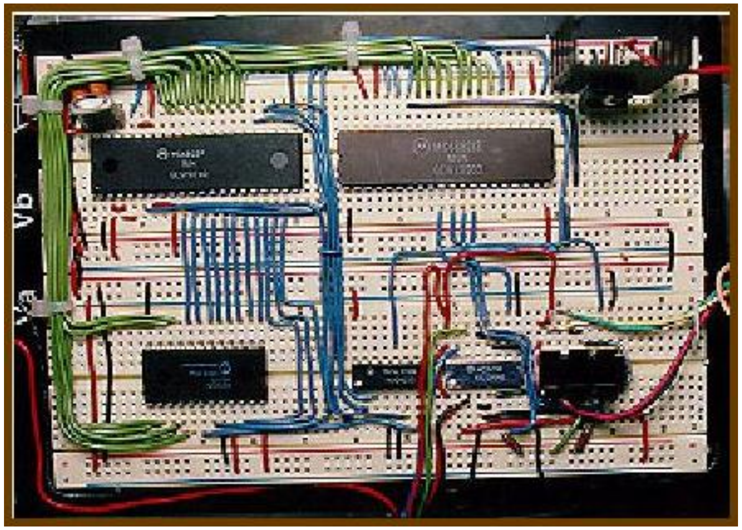




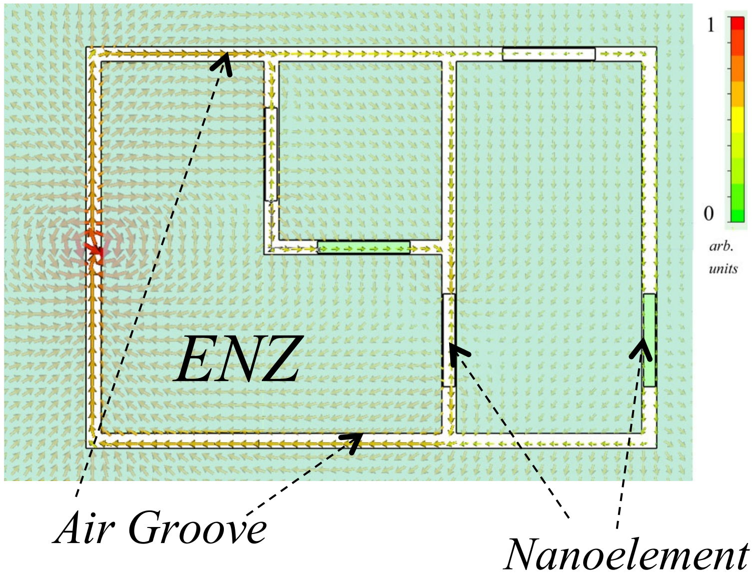
H. Caglayan, S.-H. Hong, C. Kagan, and N. Engheta, __manuscript in preparation__

Nano-Optics Circuit Boards

Electronic Circuit Board

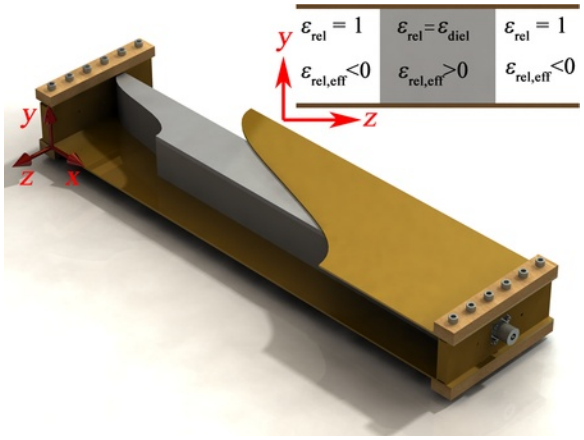


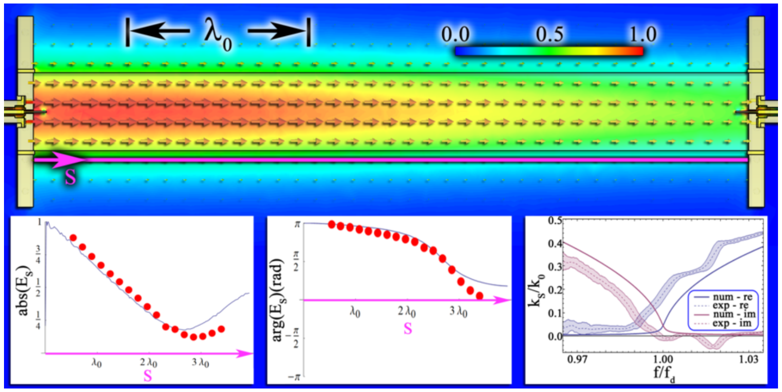
Metatronic Circuit Board

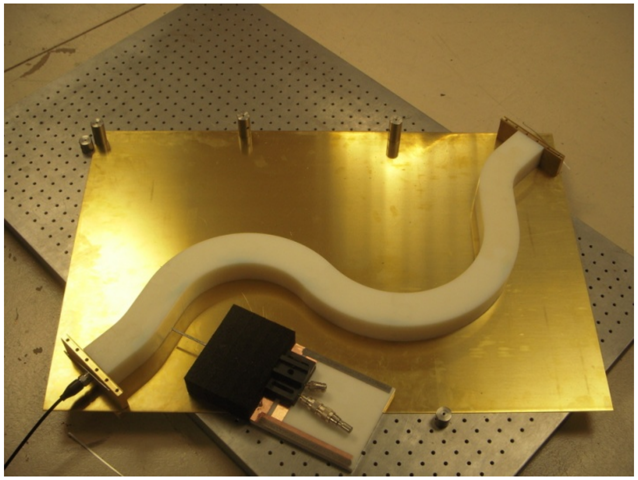


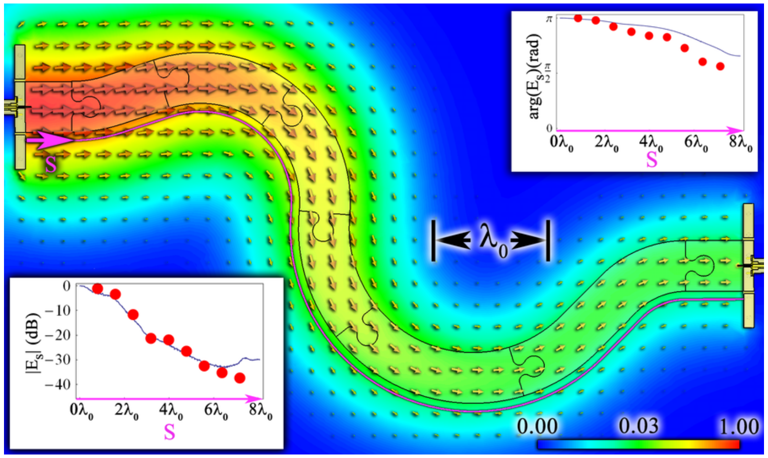
Alu and Engheta, Phys. Rev. Lett., 2009

Experimental Verification of Displacement-Current Wire



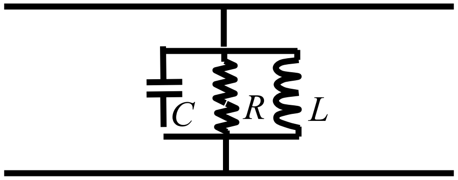


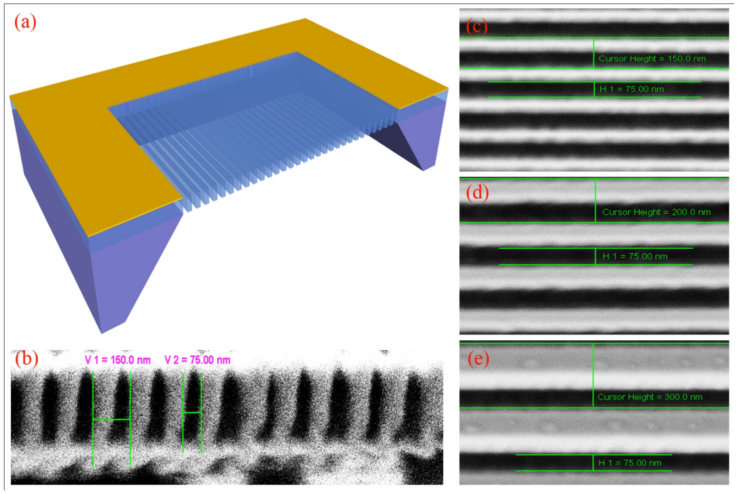




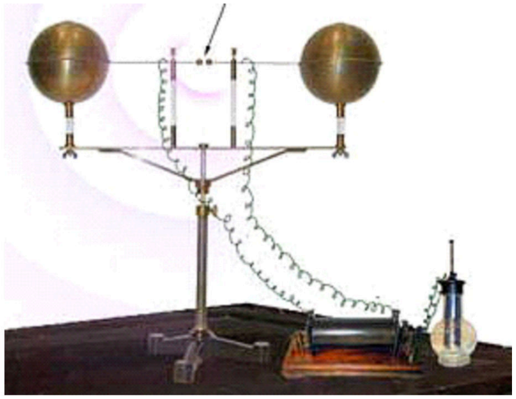
B. Edwards and N. Engheta, submitted

From a “Filter” to a “Filter”



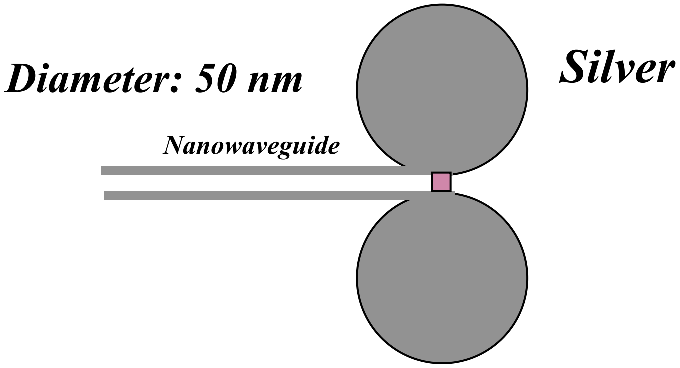


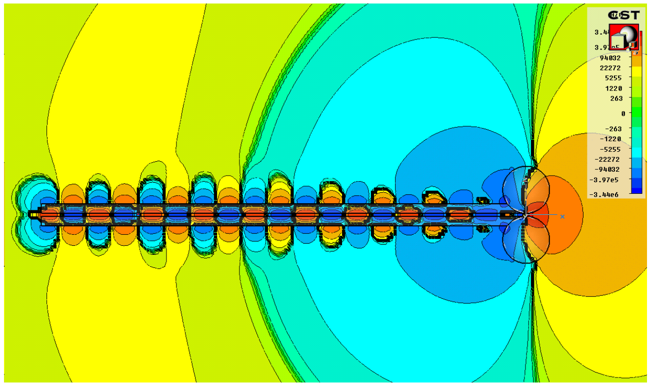
From an "Antenna" to an "Nanoantenna"



a)

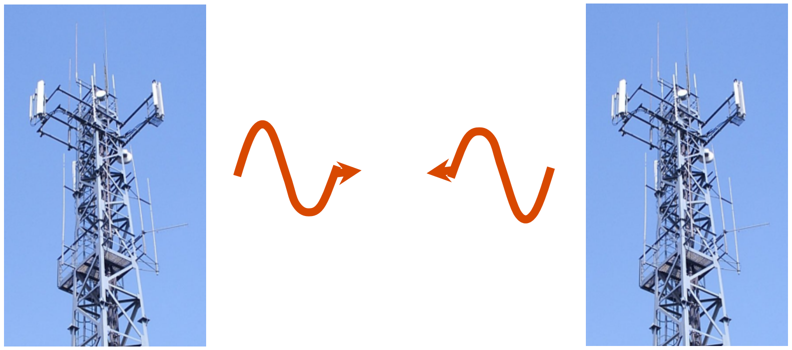
From: http://www.sparkmuseum.com





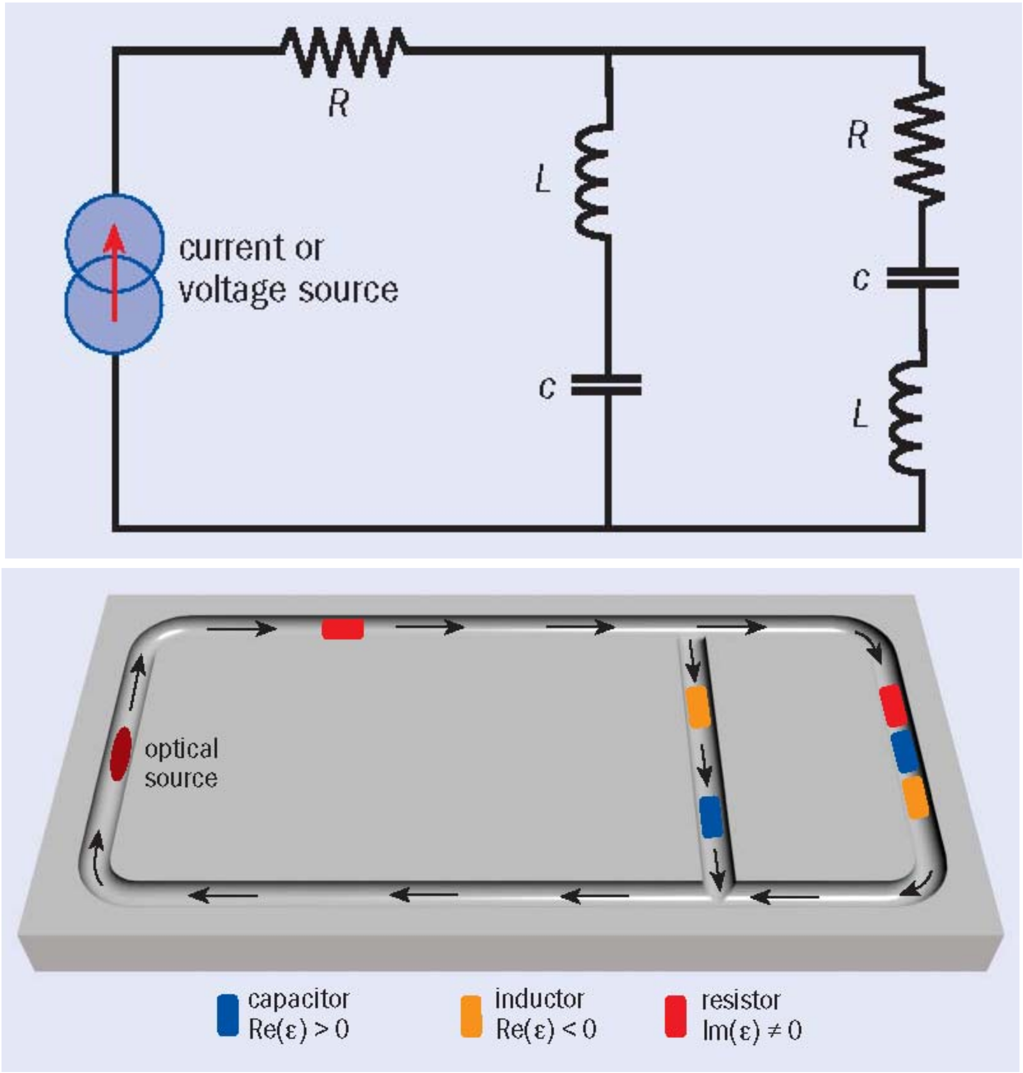
A. Alu and N. Engheta, Phys. Rev. B. 2008

From a ”Wireless Link” to a “Wireless Link” at the Nanosale

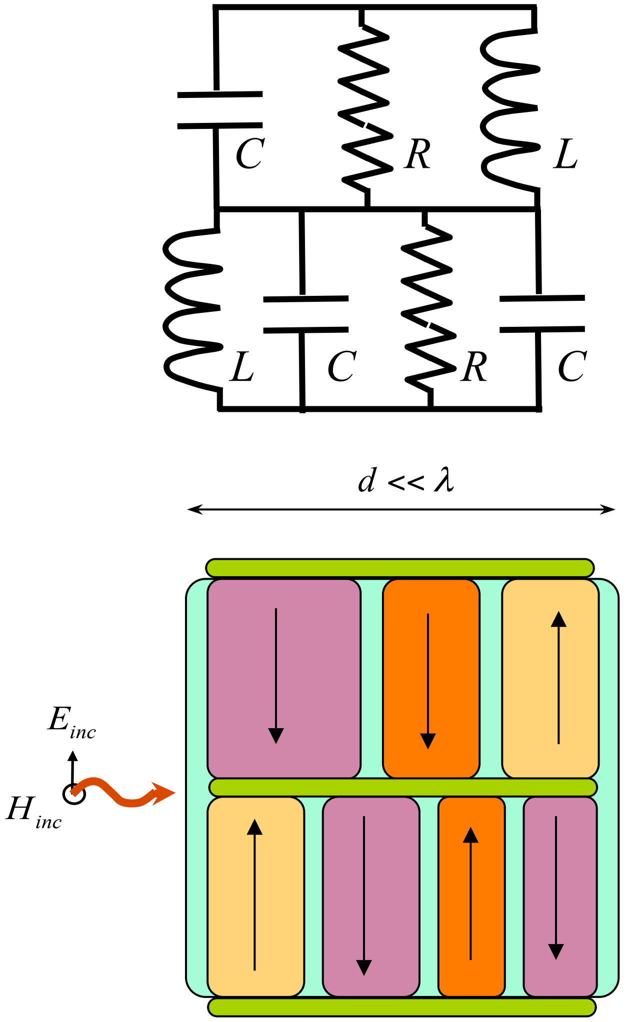


A. Alu and N. Engheta, Phys. Rev. Lett. 2010

Optical Metatronics



Engheta, <u>Physics Worlds,</u> 23(9), 31 (2010)

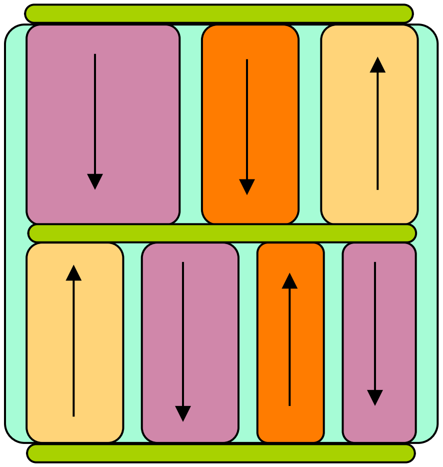


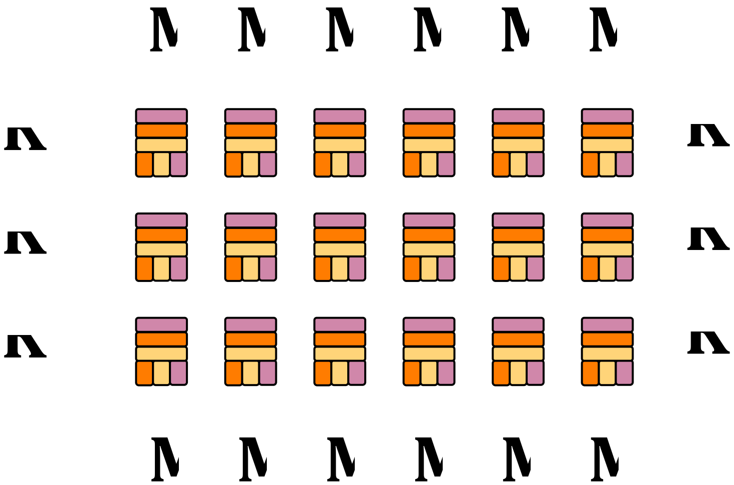
Engheta, <u>Science,</u> 317, 1698 (2007)

Metatronics vs Metamaterials

Metatronics

Building Blocks for Metamaterials



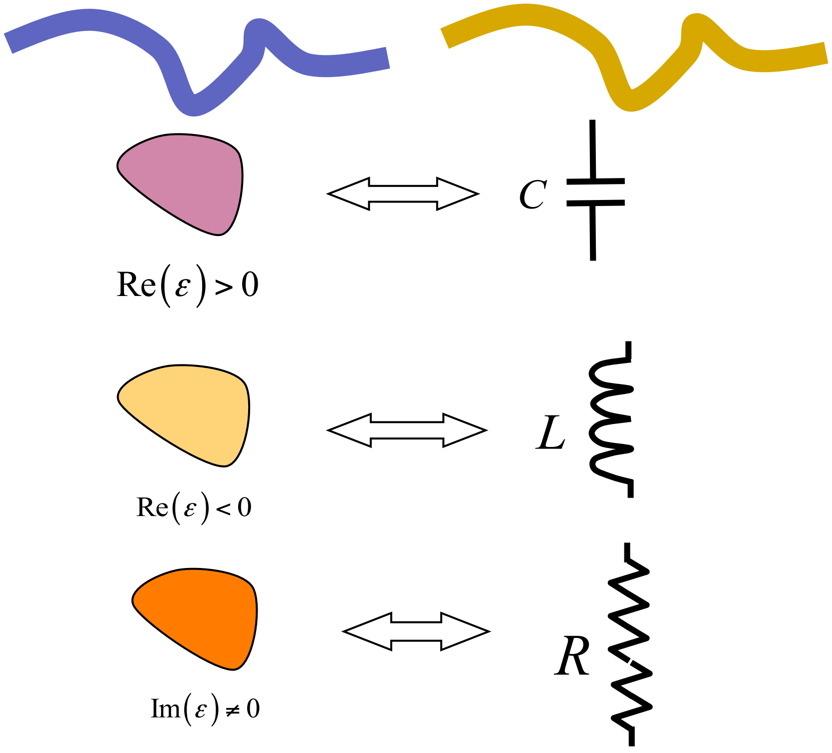


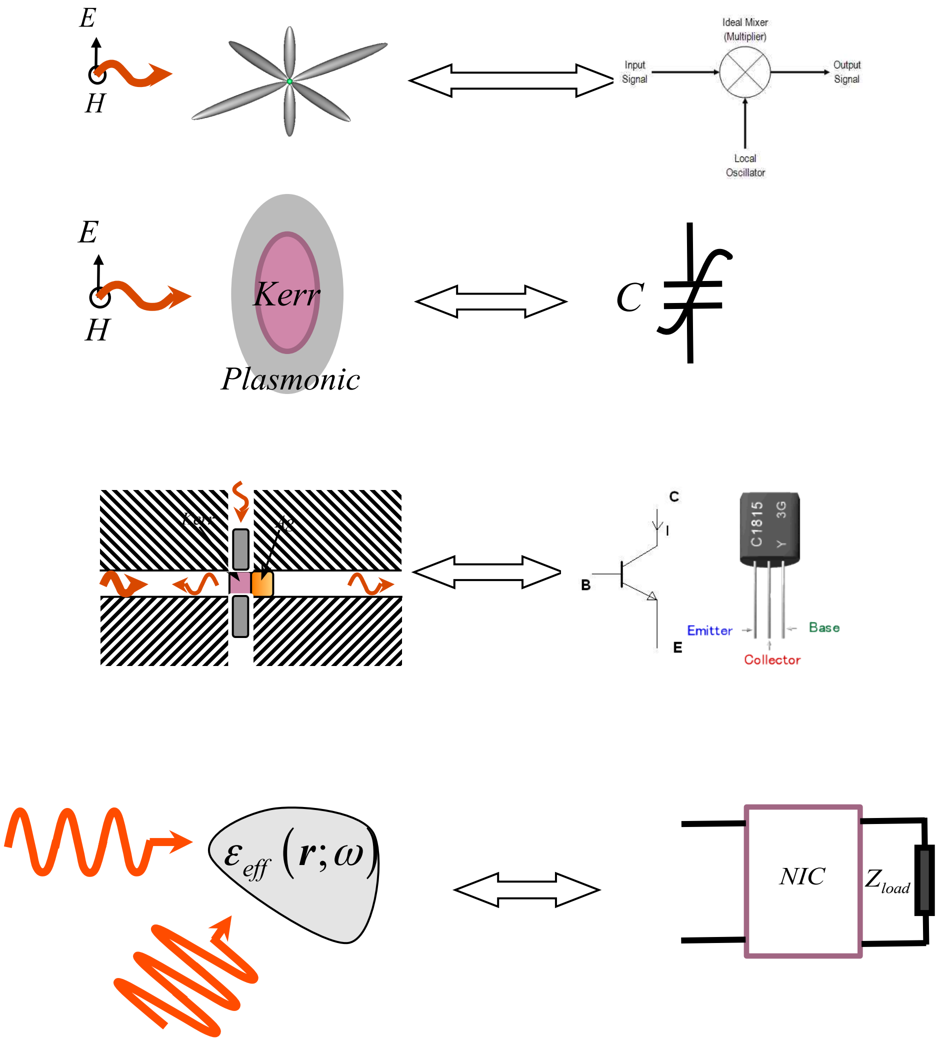
Nonlinear Metatronics

Metatronics | ***Electronics***

$$\dot{\boldsymbol{D}} = -i\omega\varepsilon \boldsymbol{E}$$

$$\boldsymbol{J} = \sigma \boldsymbol{E}$$





Back to Conductivity and Electronics

Electronics $\longrightarrow \boldsymbol{J} = \sigma_e \boldsymbol{E} \longrightarrow \quad \sigma_e > 0$

E-Displacement Current $\quad -i\omega\varepsilon\boldsymbol{E} \longrightarrow \quad \mathrm{Re}(\varepsilon) > 0 \qquad \mathrm{Re}(\varepsilon) < 0$

H-Displacement Current $\quad i\omega\mu\boldsymbol{H} \longrightarrow \quad \mathrm{Re}(\mu) > 0 \qquad \mathrm{Re}(\mu) < 0$

$$\sigma = \sigma_r + i\sigma_i$$

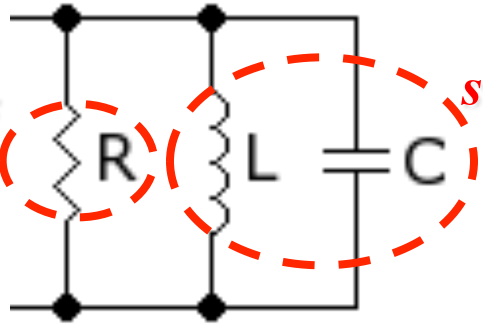
Graphene

$$J_s = \sigma_g E$$

$$I = \sigma_g V = Y \cdot V$$

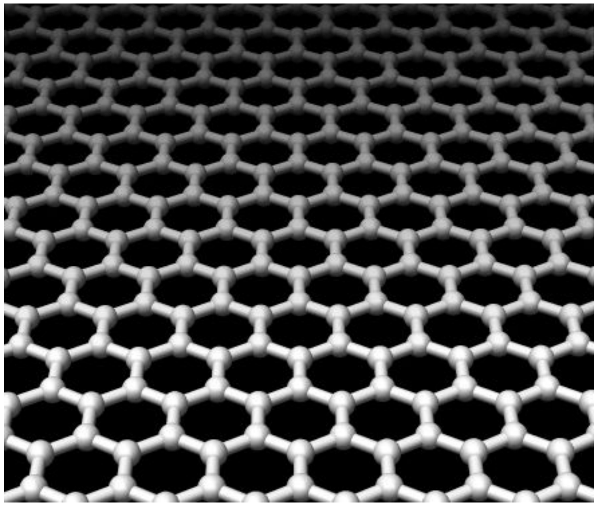
$$\underset{\displaystyle Y}{\underset{\downarrow}{\sigma_g}} = \underset{\displaystyle G}{\underset{\downarrow}{\overset{>0}{\sigma_{g,r}}}} + i\,\underset{\displaystyle B}{\underset{\downarrow}{\overset{>0 \text{ or } <0}{\sigma_{g,i}}}}$$

$$Y = G + i\,B$$



loss

stored energy



http://math.ucr.edu/home/baez/graphene.jpg

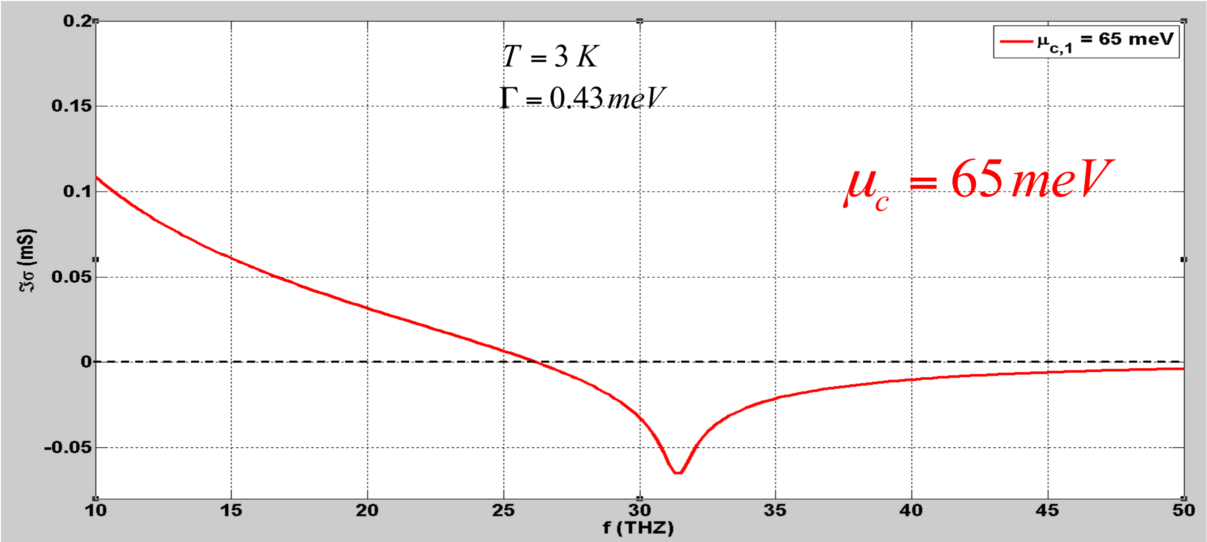
Graphene Conductivity

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

$$\sigma_{g,r} = f_1(\omega, \mu_c, \Gamma, T)$$

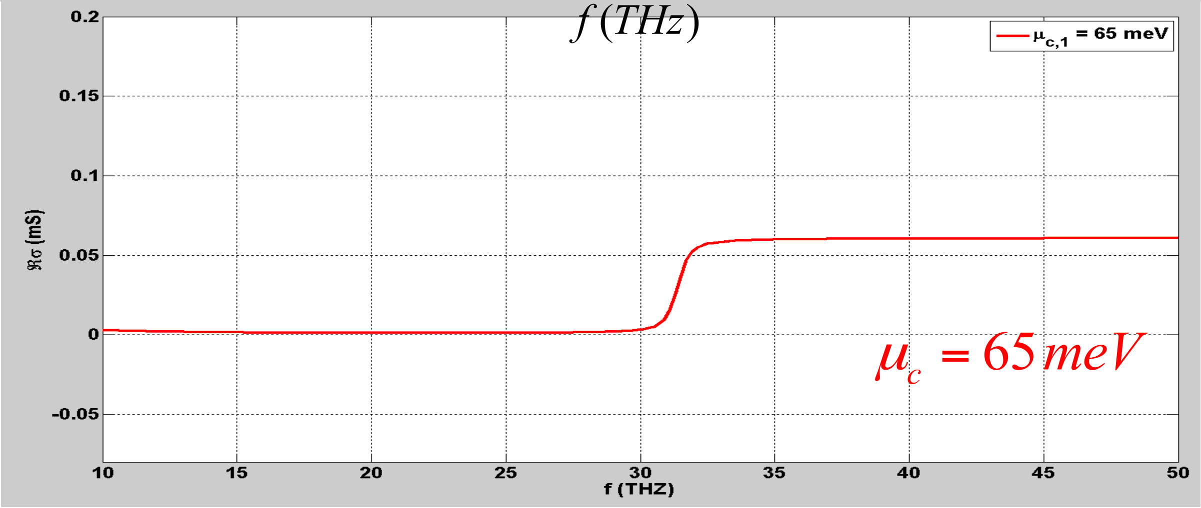
$$\sigma_{g,i} = f_2(\omega, \mu_c, \Gamma, T)$$

$\mathrm{Im}(\sigma_g)$



$f(THz)$

$\mathrm{Re}(\sigma_g)$



$f(THz)$

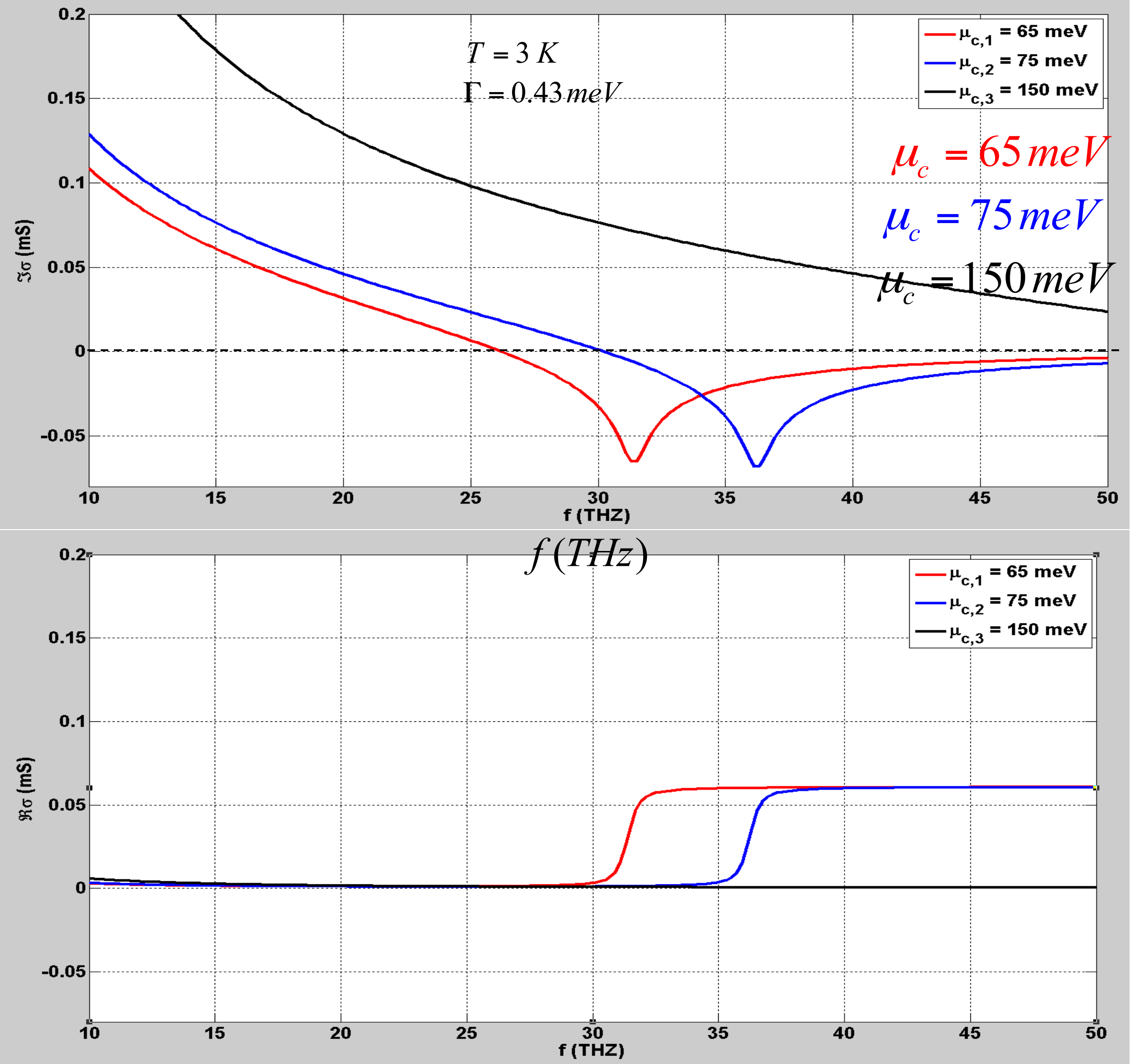
G. Hanson, J. Appl. Phys. 103, 064302 (2008)

Graphene Conductivity

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

$$\sigma_{g,r} = f_1(\omega, \mu_c, \Gamma, T)$$

$$\sigma_{g,i} = f_2(\omega, \mu_c, \Gamma, T)$$

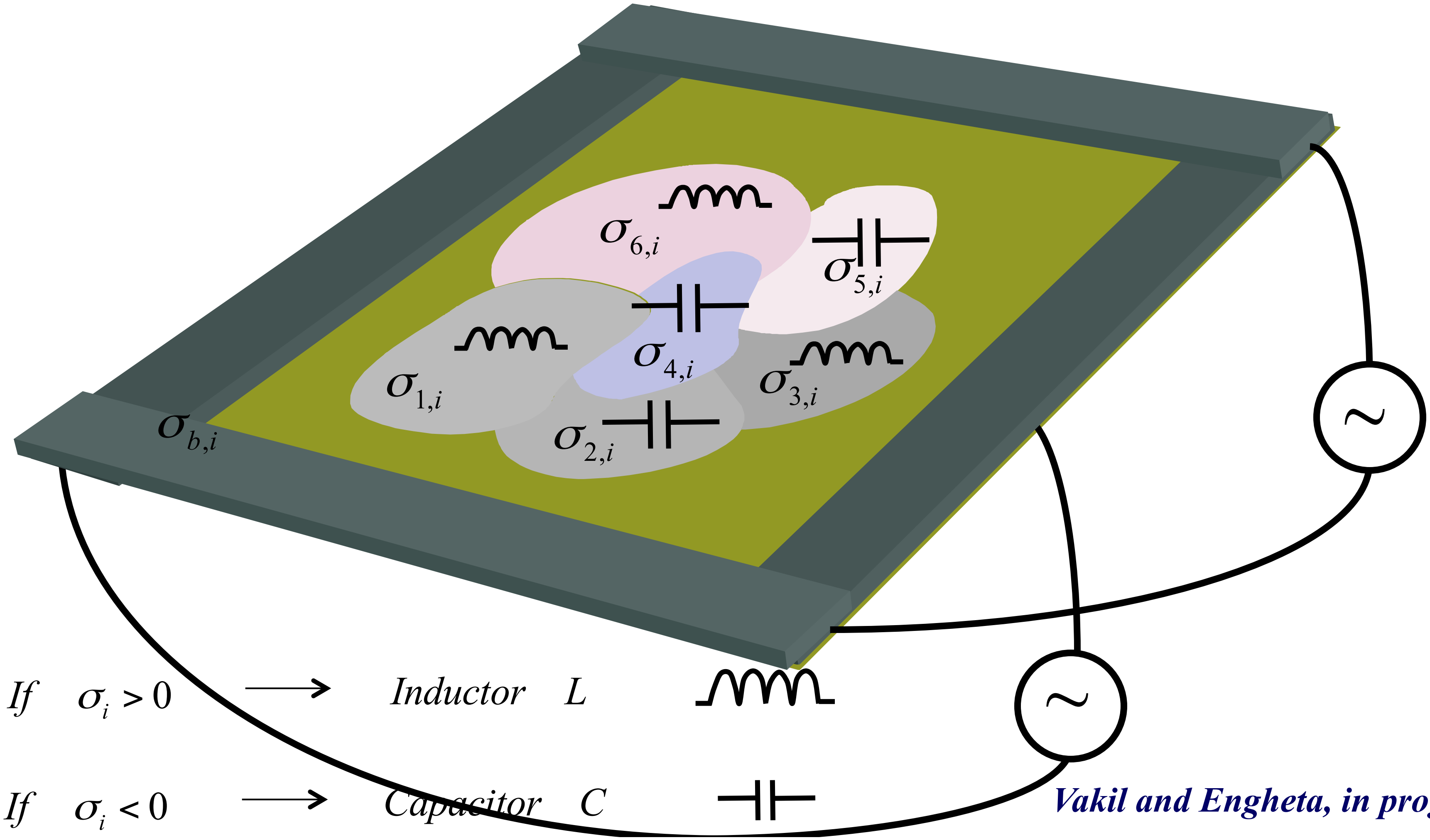


$f\,(THz)$

G. Hanson, J. Appl. Phys. 103, 064302 (2008)

Graphene Metatronics

One-Atom-Thick Stereo Circuits

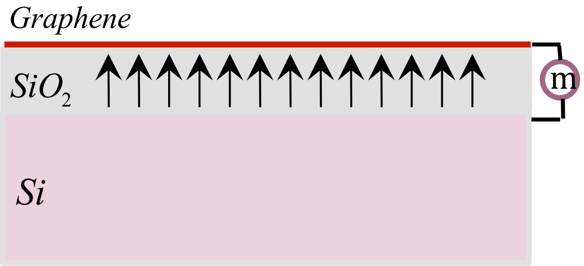


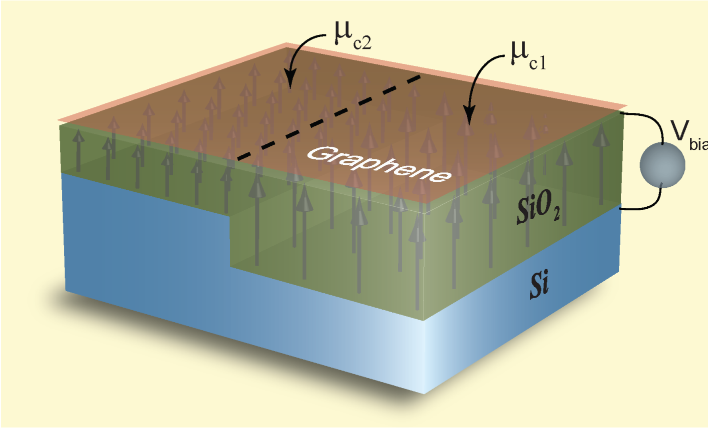
If $\sigma_i > 0$ $\longrightarrow$ *Inductor* L

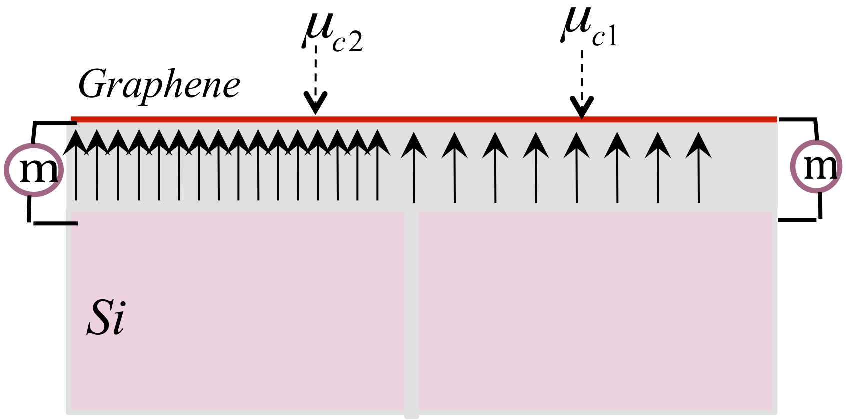
If $\sigma_i < 0$ $\longrightarrow$ *Capacitor* C

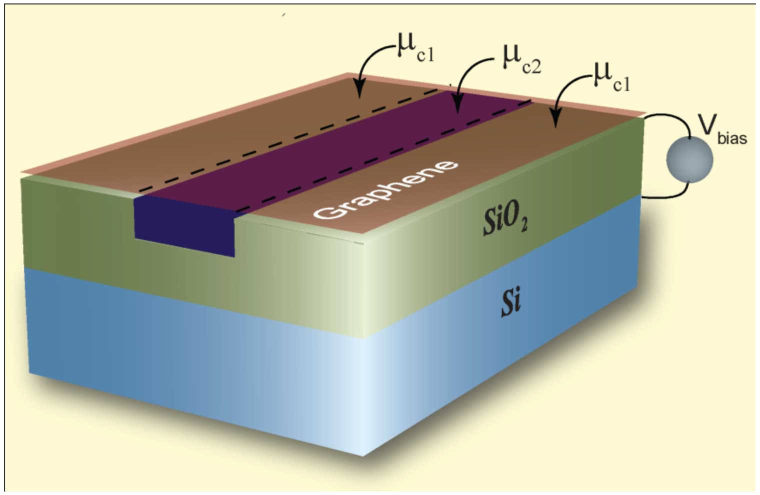
Vakil and Engheta, in progress

Inhomogeneous Conductivity across Graphene



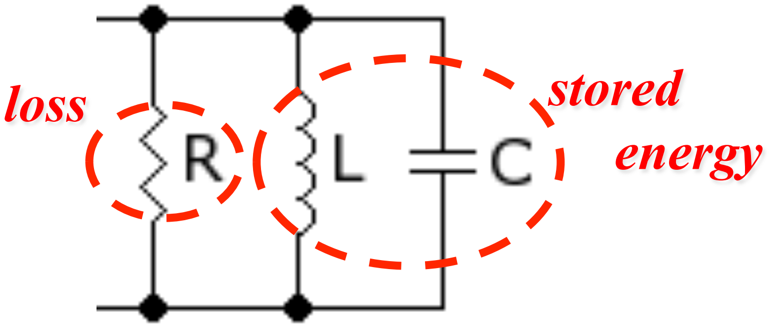


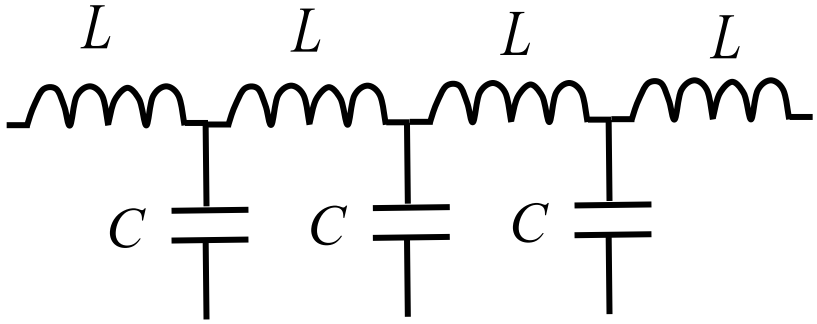


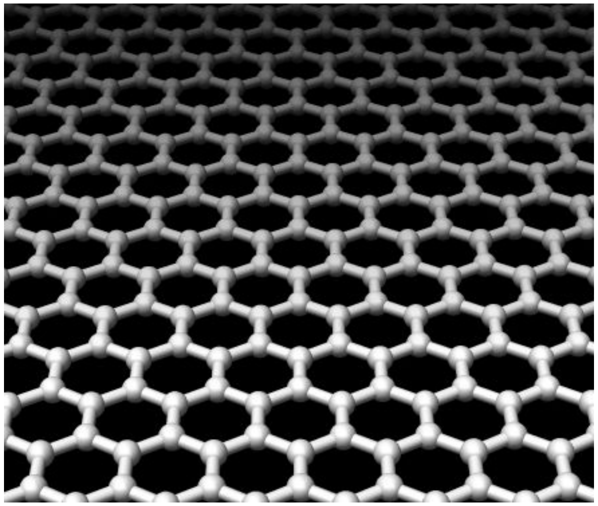


From Transmission Line to Graphene

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

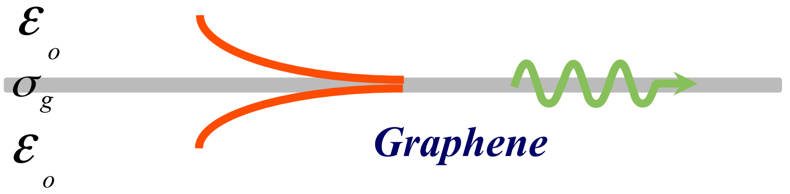






http://math.ucr.edu/home/baez/graphene.jpg

SPP along Graphene

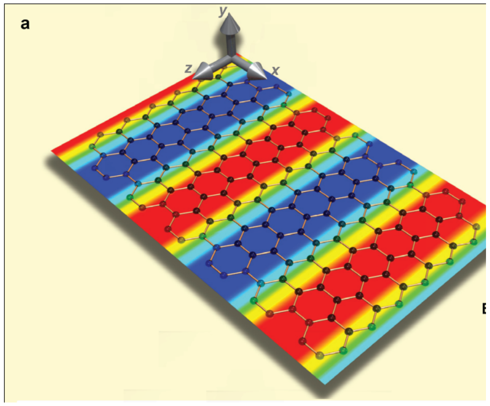


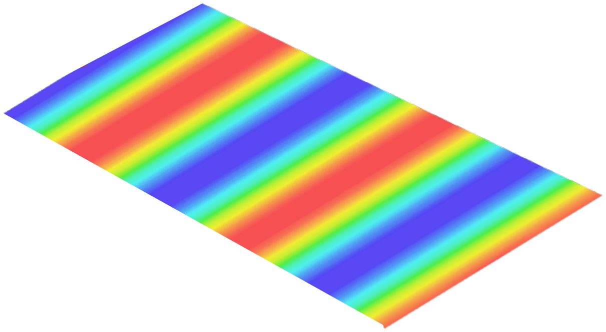
$$\beta_{SPP} = \omega\sqrt{\varepsilon_o\mu_o}\sqrt{1-\left(\frac{2}{\sigma_g\sqrt{\mu_o/\varepsilon_o}}\right)^2} \qquad \sigma_{g,i} > 0$$

$$\beta_{SPP} >> \omega\sqrt{\varepsilon_o\mu_o}$$

$$\lambda_{SPP} << \lambda_{free-space} \qquad \beta_{SPP} = n_{SPP}k_o$$

$$\lambda_{SPP} \approx \frac{\lambda_o}{70} \approx 144nm \qquad \beta_{SPP} \approx 70k_o$$





S. A. Mikhailov, K. Ziegler, Phys. Rev. Lett. 99, 016803 (2007)

G. Hanson, J. Appl. Phys. 103, 064302 (2008)

M. Jablan, H. Buljan, M. Soljacic, Phys. Rev. B., 80, 245435 (2010)

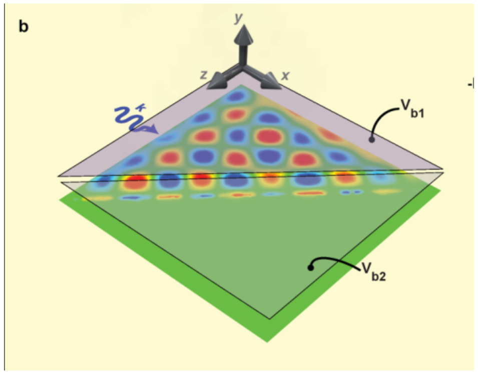
Inhomogeneous Conductivity

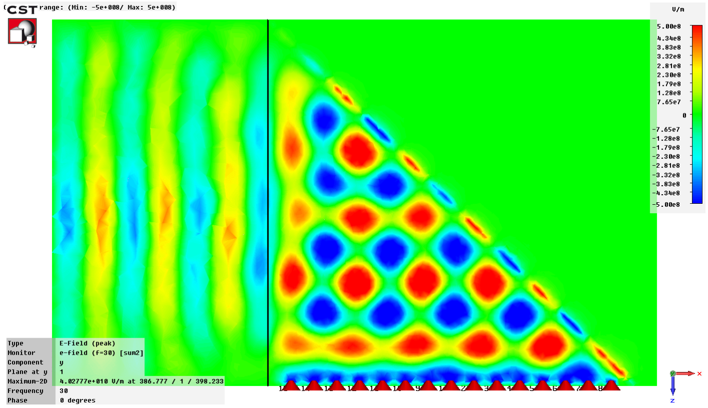
Region 1: $\sigma_{g,i} > 0$ $\sigma_{g1} = 0.0009 + i0.0765 \text{ mS}$

$\mu_{c1} = 150\, meV$

Region 2: $\sigma_{g,i} < 0$ $\sigma_{g2} = 0.0039 - i0.0324 \text{ mS}$

$\mu_{c1} = 65\, meV$



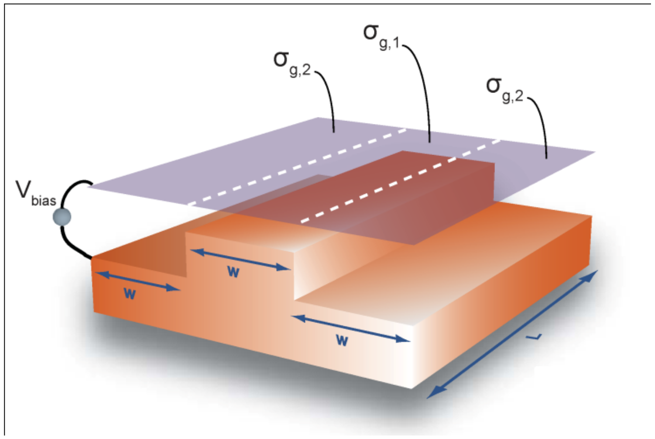


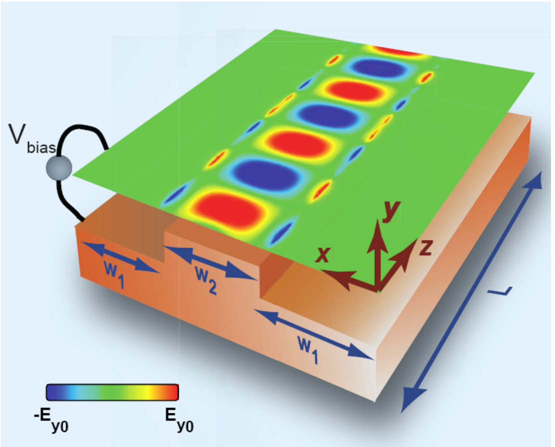
range: (Min: -5e+008/ Max: 5e+008)

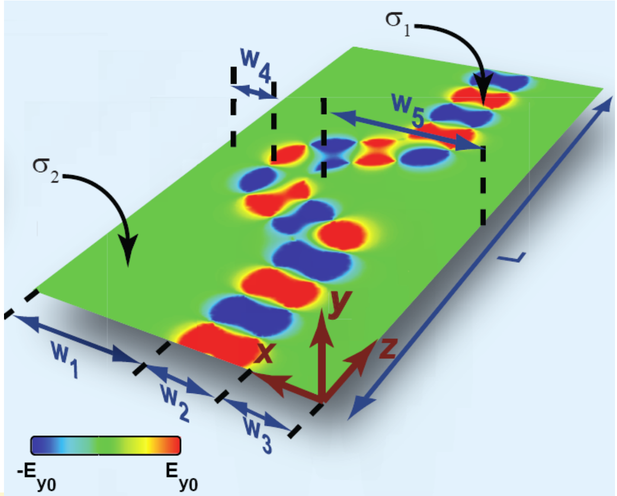
Type	E-Field (peak)
Monitor	e-field (f=30) [sum2]
Component	y
Plane at y	1
Maximum-2D	4.02777e+010 V/m at 386.777 / 1 / 398.233
Frequency	30
Phase	0 degrees

A. Vakil and N. Engheta, Science, 332, June 2011

One-Atom-Thick Waveguides





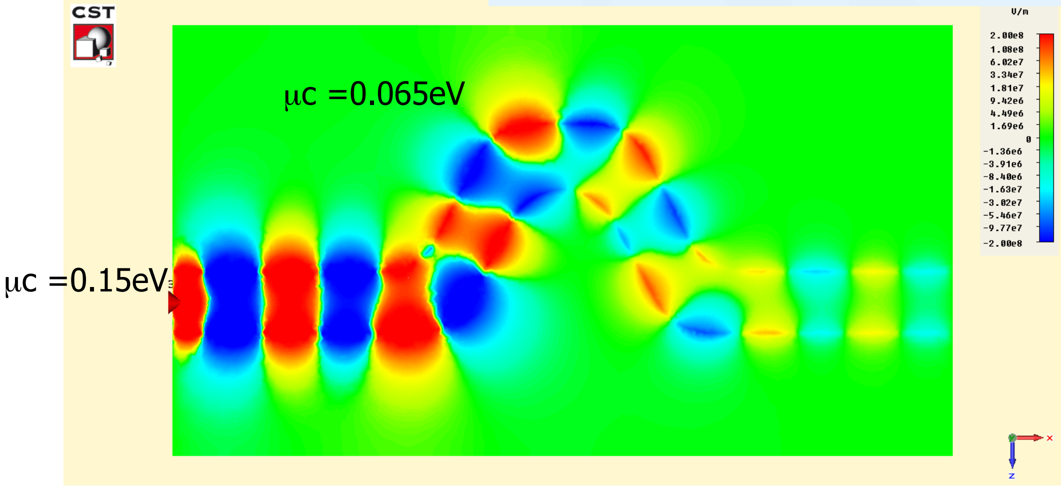


Region 1: $\sigma_{g,i} > 0$

$\mu_c = 150\ meV$

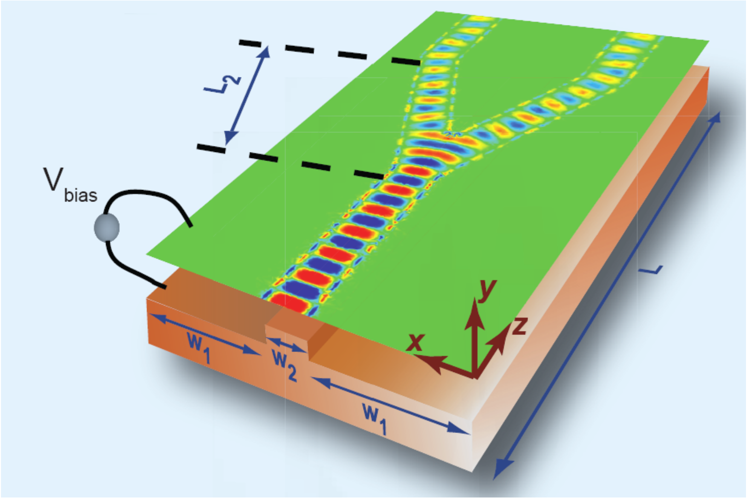
Region 2: $\sigma_{g,i} < 0$

$\mu_c = 65\ meV$



A. Vakil and N. Engheta, __Science,__ 332, June 2011

One-Atom-Thick IR Splitter

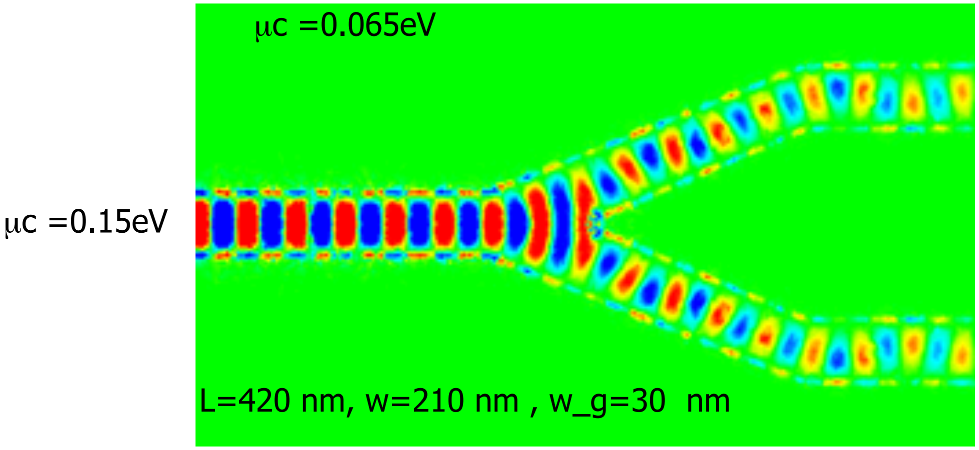


Region 1: $\sigma_{g,i} > 0$

$$\mu_c = 0.15\,eV$$

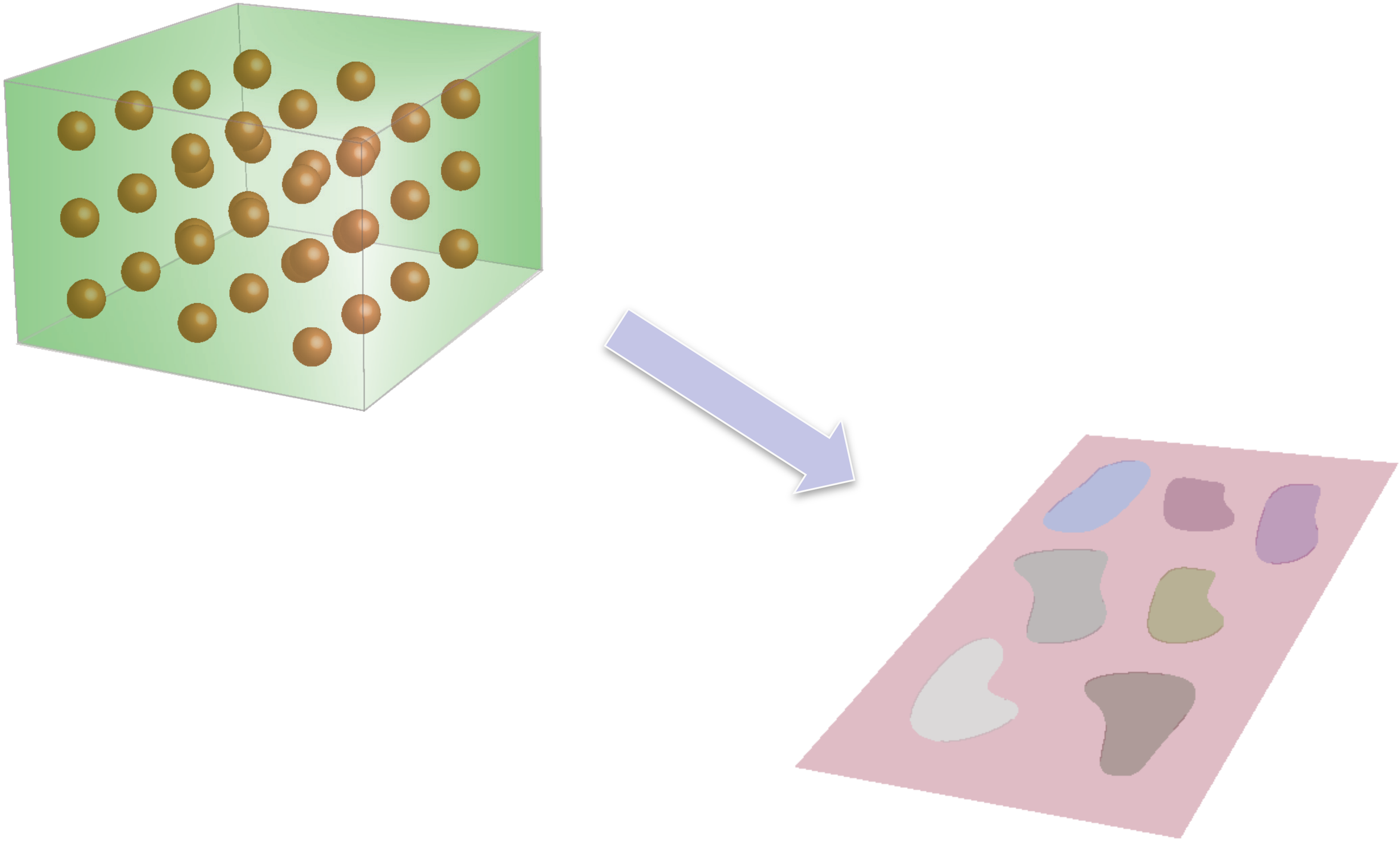
Region 2: $\sigma_{g,i} < 0$

$$\mu_c = 0.065\,eV$$



A. Vakil and N. Engheta, <u>Science,</u> 332, June 2011

Thinnest Metamaterials?



A. Vakil and N. Engheta, <u>Science,</u> 332, June 2011

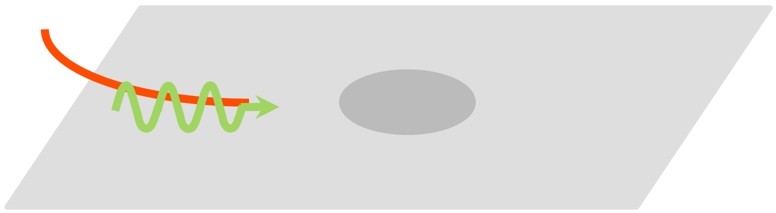
One-Atom-Thick Scatterer

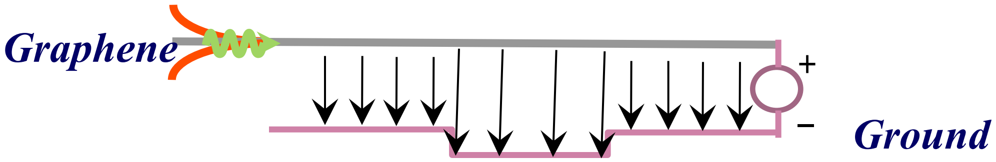
Region 1: $\sigma_{g,i} > 0$

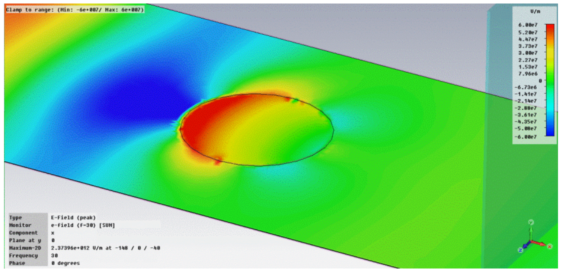
$$\mu_c = 150\, meV$$

Region 2: $\sigma_{g,i} < 0$

$$\mu_c = 65\, meV$$



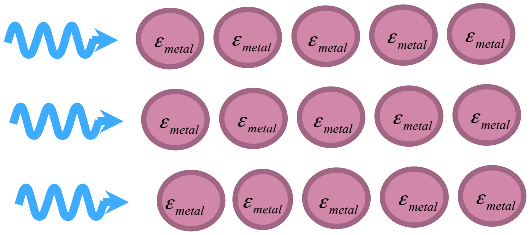


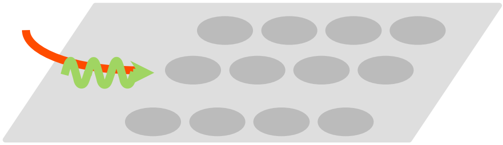


w=120nm
r=25nm

A. Vakil and N. Engheta, Science, 332, June 2011

One-Atom-Thick Metamaterials



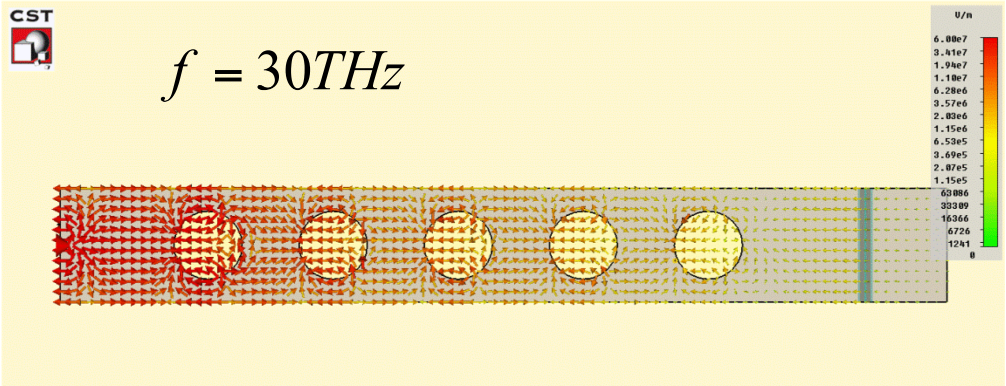


Region 1: $\sigma_{g,i} > 0$

$\mu_c = 150\, meV$

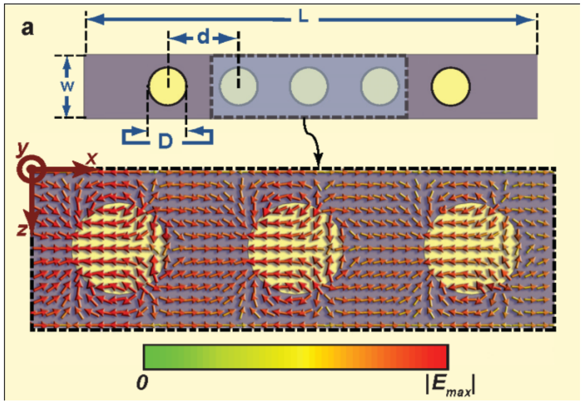
Region 2: $\sigma_{g,i} < 0$

$\mu_c = 65\, meV$



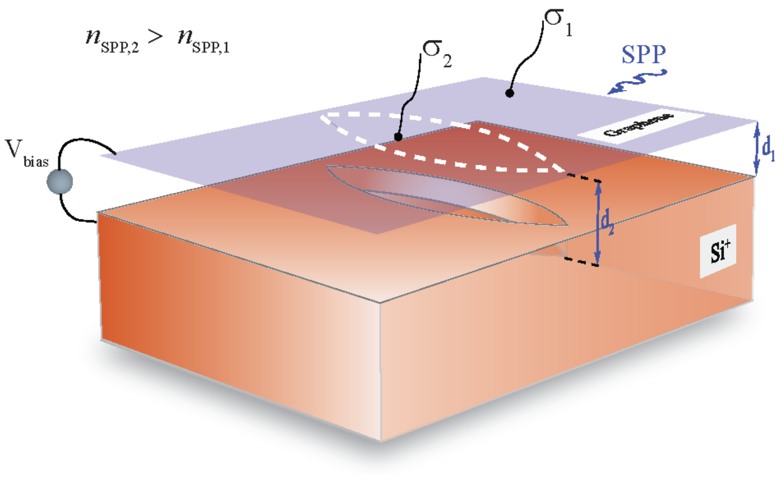
$f = 30THz$

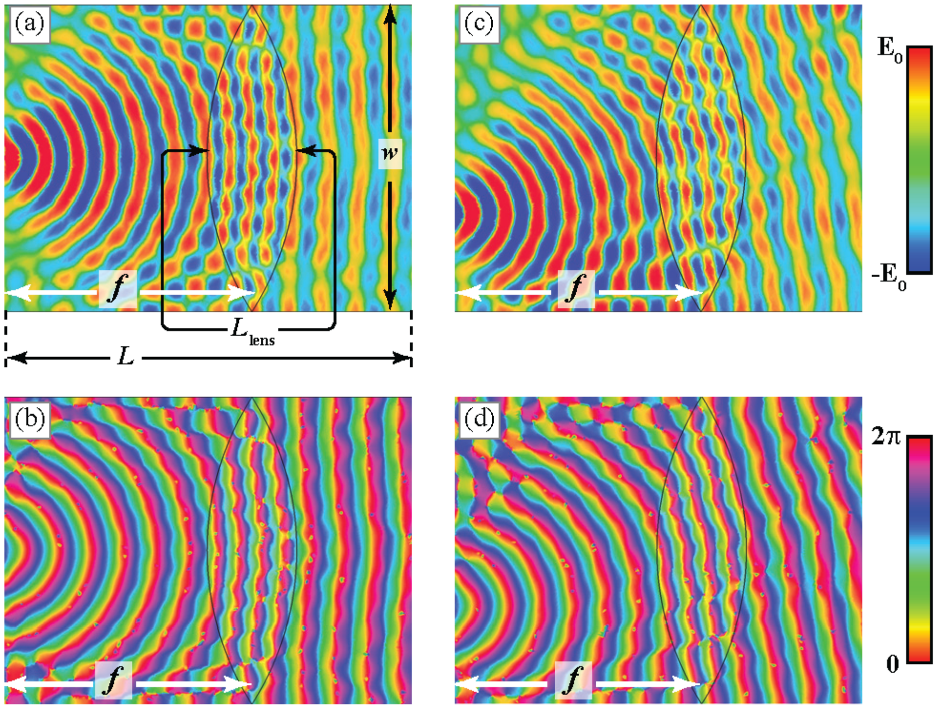
L=370 nm
d =55 nm
D=30 nm
w=55 nm



A. Vakil and N. Engheta, Science, 332, June 2011

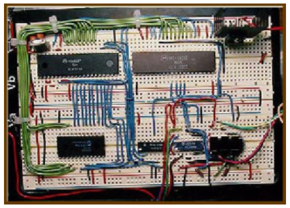
One-Atom-Thick Fourier Optics



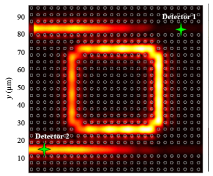


A. Vakil and N. Engheta, ArXiv, 2011

Summary

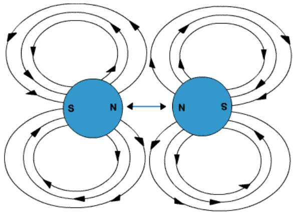


Electronics $\boldsymbol{J} = \sigma_e \boldsymbol{E}$

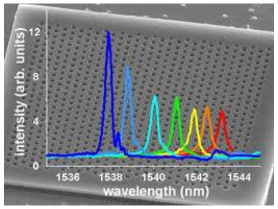


from: D. Prather's group

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

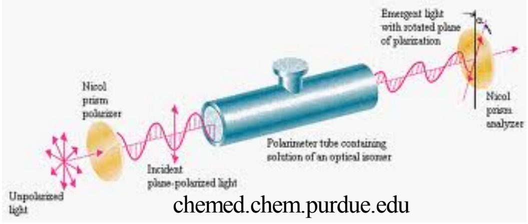


Magnetics $\boldsymbol{B} = \mu \boldsymbol{H}$



logofanothemeA.jpg, lpn.cnrs.fr

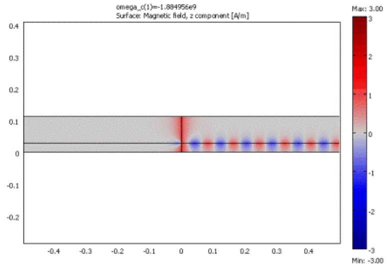
Nonlin. Opt. $\chi^{(2)}, \ldots . \; \chi^{(3)}$

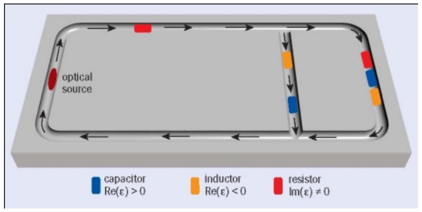


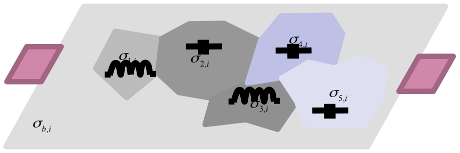
chemed.chem.purdue.edu

Opt. Activity ξ

Summary







Metatronics

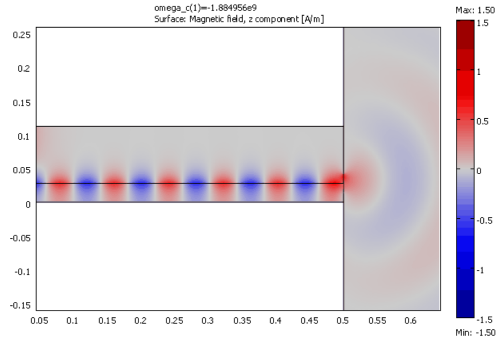
$$J = \sigma_e E$$

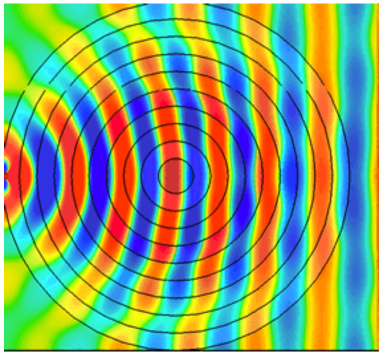
$$D = \varepsilon E$$

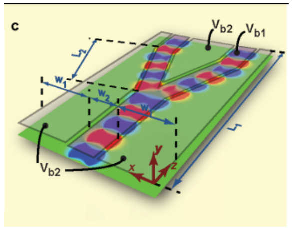
$$B = \mu H$$

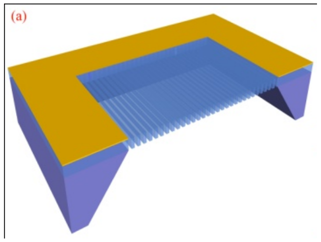
$$\chi^{(n)}$$

$$\xi$$









Thank you very much!