URSI Commission B School
for Young Scientists

Fields and Waves in Metamaterials

Lecture Notes

August 16-17, 2014

Beijing Conference Center

Beijing, China

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[1] This School is organized during the "XXXI URSI General Assembly and Scientific Symposium" (URSI GASS 2014), August 16-23, 2014, Beijing, China.

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Preface

The “URSI Commission B School for Young Scientists” is organized by URSI Commission B and is arranged on the occasion of the “XXXI URSI General Assembly and Scientific Symposium” (URSI GASS 2014) in Beijing, China. This School is a two-day event held during URSI GASS 2014, and is sponsored jointly by URSI Commission B and the URSI GASS 2014 Local Organizing Committee. The School offers a short, intensive course, where a series of lectures will be delivered by a leading scientist in the Commission B community. Young scientists are encouraged to learn the fundamentals and future directions in the area of electromagnetic theory from these lectures.

Program

1. Course Title

Fields and Waves in Metamaterials

2. Course Instructor

Professor Nader Engheta
University of Pennsylvania
Philadelphia, PA, USA

3. Course Program

Lecture 1

- Date and Time: 14:00-18:00, Saturday August 16, 2014
- Venue: Meeting Room 12, 2nd floor, Conference Building
  Beijing Conference Center, Beijing, China
- Lecture Topics:
  Metamaterials: Basic Principles
  Metasurfaces and Graphene
  Optical Metatronics

Lecture 2

- Date and Time: 8:00-12:00, Sunday August 17, 2014
- Venue: Meeting Room 12, 2nd floor, Conference Building
  Beijing Conference Center, Beijing, China
- Lecture Topics:
  Extreme-parameter metamaterials
  Metamaterial Guided and Radiating Structures
  Cloaking

Lecture Abstract

Fields and Waves in Metamaterials

Nader Engheta
H. Nedwill Ramsey Professor
University of Pennsylvania
Philadelphia, PA 19104, USA
Email: engheta@ee.upenn.edu
Web: http://www.seas.upenn.edu/~engheta/

Metamaterials and Plasmonic structures provide mechanisms for controlling and taming electromagnetic fields and waves in unprecedented ways. New directions, novel vistas and new applications are appearing in the horizon in the fields of metamaterials and its 2-D version, metasurfaces. In particular, when the extreme scenarios are considered, e.g., ultrathin structures (graphene), extreme near field (vortex in subwavelength near field), and extreme parameters (epsilon-near zero (ENZ), mu-near-zero (MNZ), epsilon-and-mu-near-zero (EMNZ)), numerous exciting possibilities for the interaction of waves with matter may occur. These may include design of metamaterials for scattering management in numerous applications where low or high scattering is desired, "metafunctional platforms" that can be formed on the metamaterial paradigms, and new functionalities may result from proper combinations of meta-systems and metamaterials. We have been exploring various features and characteristics of these concepts, topics, and directions in metamaterials, and we have been investigating new classes of applications such paradigms may provide. Some of the features of interest include nonlinearity, anisotropy, chirality, non-reciprocity, and non-locality. In this School, we will discuss the following topics:

Lecture 1
Metamaterials: Basic Principles
Metasurfaces and Graphene
Optical Metatronics

Lecture 2
Extreme-parameter metamaterials
Metamaterial Guided and Radiating Structures
Cloaking

Biographical Sketch of Course Instructor

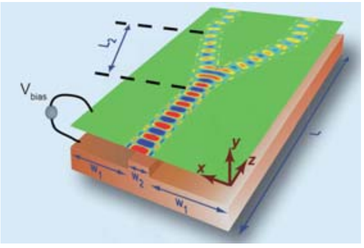
Nader Engheta is the H. Nedwill Ramsey Professor at the University of Pennsylvania in Philadelphia, with affiliations in the Departments of Electrical and Systems Engineering, Bioengineering, Physics and Astronomy, and Materials Science and Engineering. He received his B.S. degree from the University of Tehran, and his M.S and Ph.D. degrees from Caltech. Selected as one of the *Scientific American Magazine 50 Leaders in Science and Technology* in 2006 for developing the concept of optical lumped nanocircuits, he is a Guggenheim Fellow, an IEEE Third Millennium Medalist, a Fellow of IEEE, American Physical Society (APS), Optical Society of America (OSA), American Association for the Advancement of Science (AAAS), and SPIE-The International Society for Optical Engineering, and the recipient of numerous awards for his research including *2014 Balthasar van der Pol Gold Medal from the International Union of Radio Science (URSI), 2013 Benjamin Franklin Key Award, 2013 Inaugural SINA Award in Engineering, 2012 IEEE Electromagnetics Award*, 2008 *George H. Heilmeier Award for Excellence in Research*, the *Fulbright Naples Chair Award*, *NSF Presidential Young Investigator award*, the *UPS Foundation Distinguished Educator term Chair*, and several teaching awards including the *Christian F. and Mary R. Lindback Foundation Award, S. Reid Warren, Jr. Award* and *W. M. Keck Foundation Award*. His current research activities span a broad range of areas including nanophotonics, metamaterials, nano-scale optics, graphene optics, imaging and sensing inspired by eyes of animal species, optical nanoengineering, microwave and optical antennas, and engineering and physics of fields and waves. He has co-edited (with R. W. Ziolkowski) the book entitled "*Metamaterials: Physics and Engineering Explorations*" by Wiley-IEEE Press, 2006. He was the Chair of the Gordon Research Conference on Plasmonics in June 2012.

Fields and Waves in Metamaterials

August 16-17, 2014

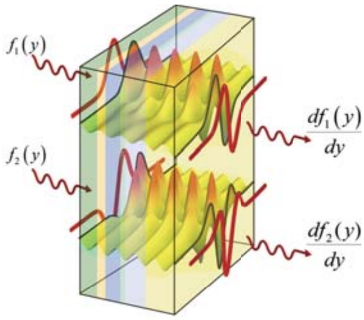
Professor Nader Engheta
University of Pennsylvania
Philadelphia, Pennsylvania
USA

Fields and Waves in Metamaterials Part 1



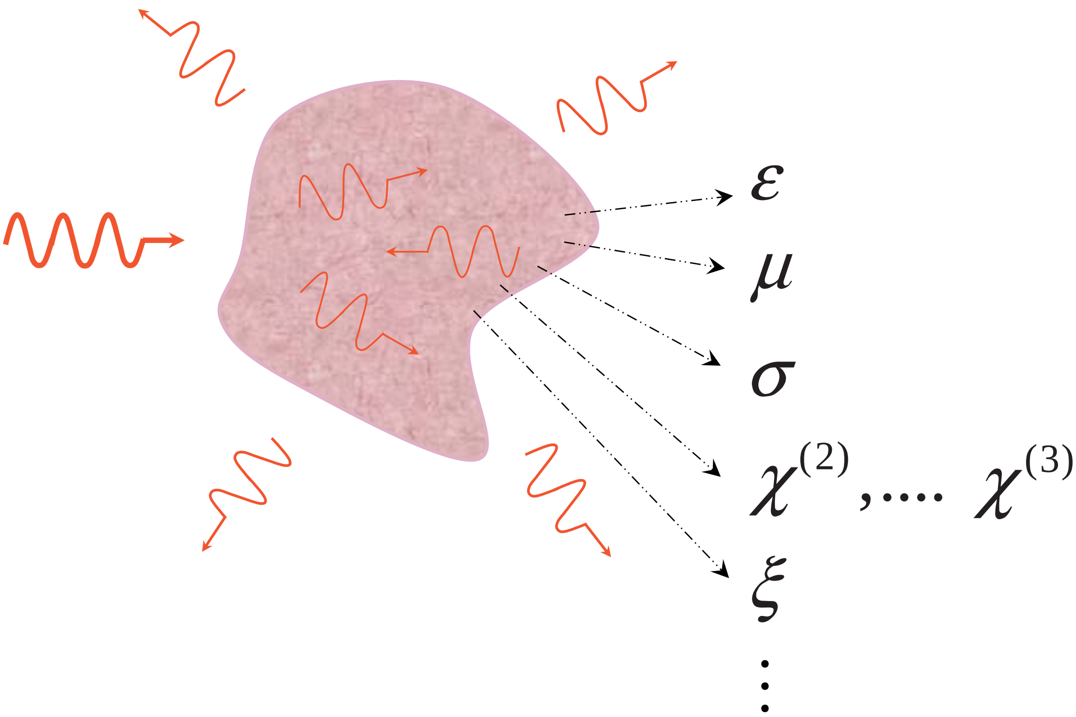
Nader Engheta

University of Pennsylvania
Philadelphia, PA 19104, USA



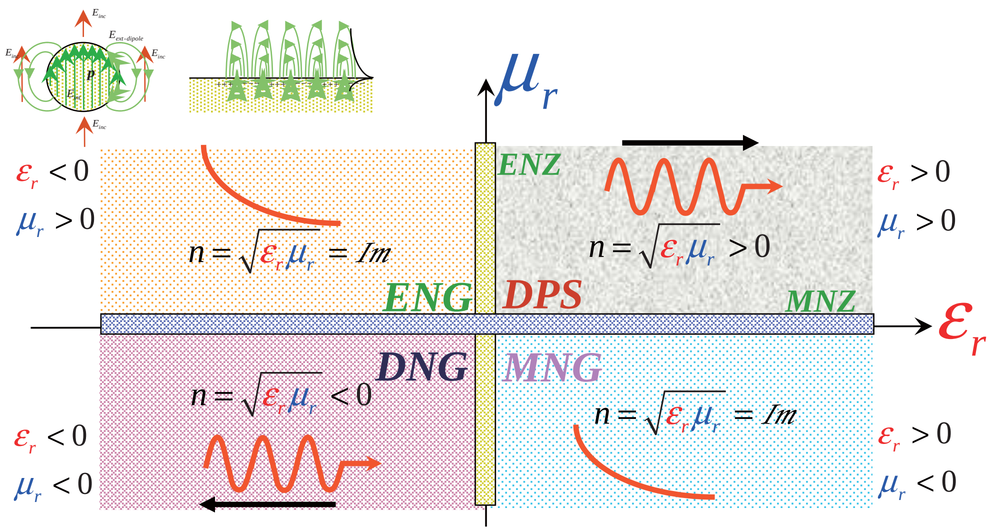
August 16-17, 2014

Light-Matter Interaction

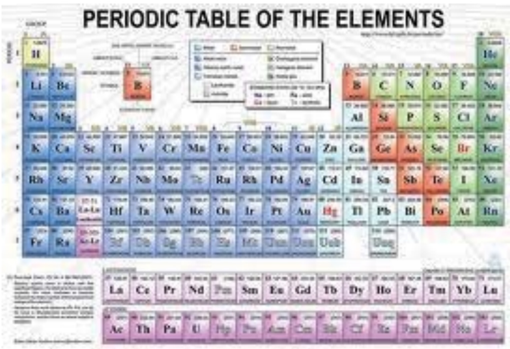


Metamaterials and Plasmonic Phenomena

$$\boldsymbol{E} = \boldsymbol{E}_o e^{ikz} e^{-i\omega t} \qquad k = \omega\sqrt{\varepsilon\mu} = \frac{2\pi}{\lambda} \qquad n = \sqrt{\varepsilon_r \mu_r}$$

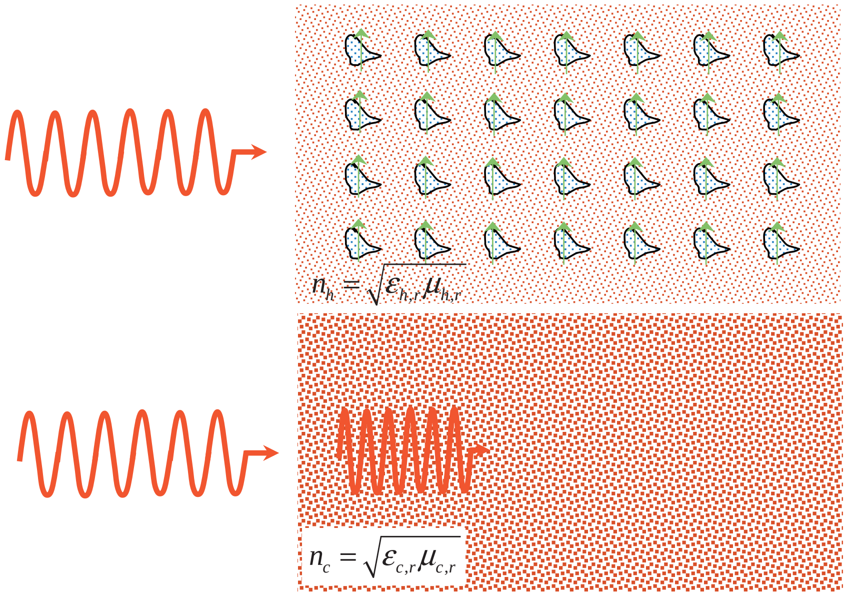


"Natural" Materials



"Artificially" Engineered Materials

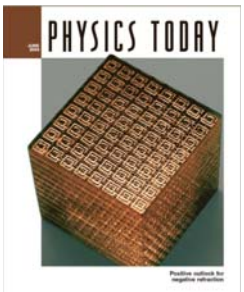
- *Particulate Composite Materials*



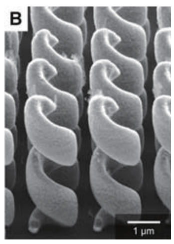
- *Composition*
- *Alignment*
- *Arrangement*
- *Density*
- *Host Medium*
- *Geometry/Shape*

Metamaterials Samples (2000-2013)

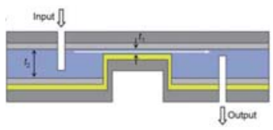
Smith, Schultz group (2000)



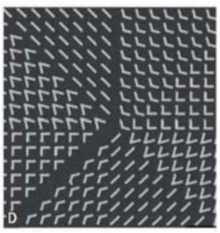
Boeing group



Wegener group (2009)

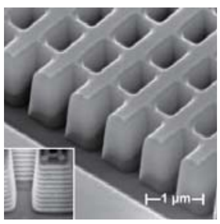


Atwater group (2007)

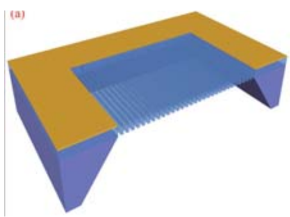


Capasso group (2011)

Shalaev group (2011)



Zhang group (2008)



Engheta group (2012)

Metamaterial Applications (2000-2013)

Cloaking

Ultrathin Cavities

Perfect Lens

Transformation Optics

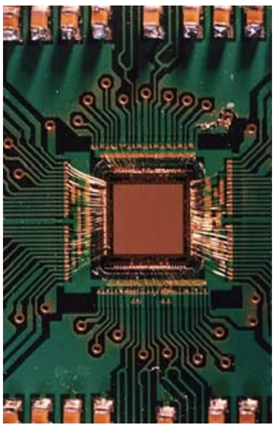
Hyperlens

ENZ & MNZ

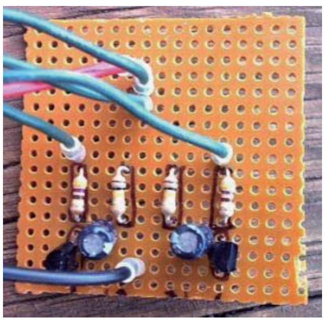
Metasurfaces

Metatronics

Electronic Modules



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



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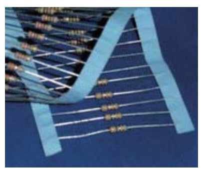
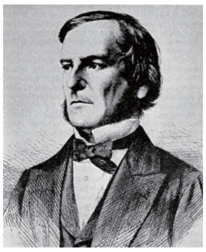
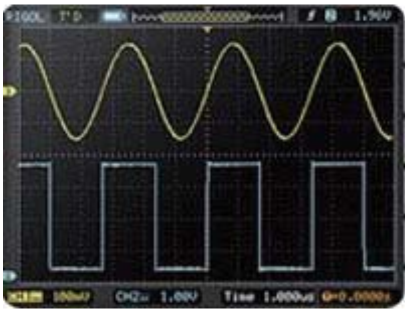
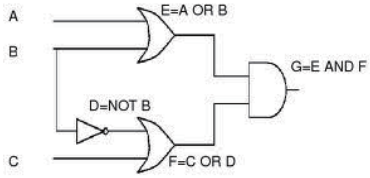


Analog vs Digital



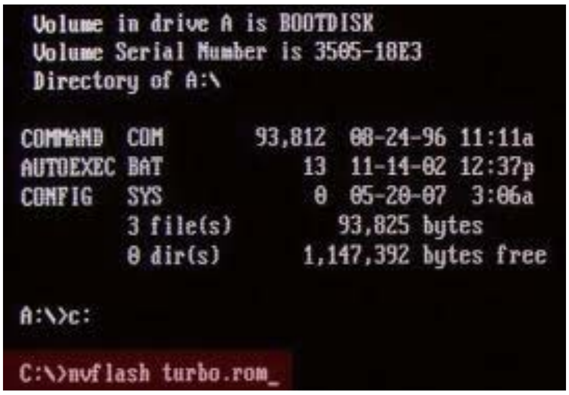
George Boole



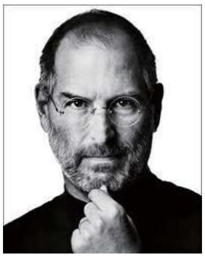


$$f(t) = \sin(\omega t) \qquad u(t) = 1\,0\,0\,1\,1\,1\,0\cdots$$

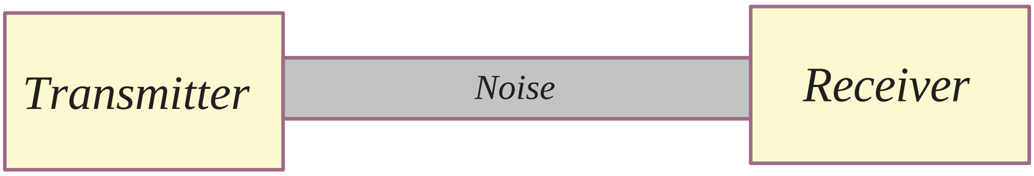
iPhone *DOS*

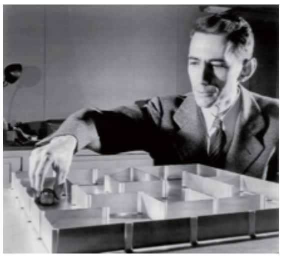


http://t0.gstatic.com/images?q=tbn:ANd9GcQ2jC_aCeZHKyjVou0Q_xOq0LG3FkyuW963_OLqcM07rld4EHAUsA



Claude Shannon & Channel Capacity

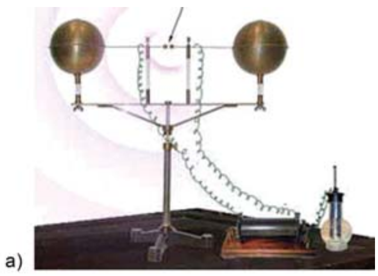




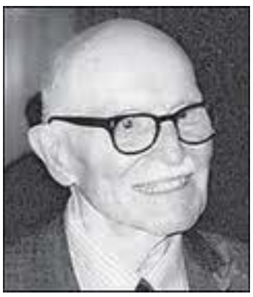
$$Channel\ Capacity = B\log_2\left(1+\frac{S}{N}\right)$$

C. Shannon

Development of Antennas

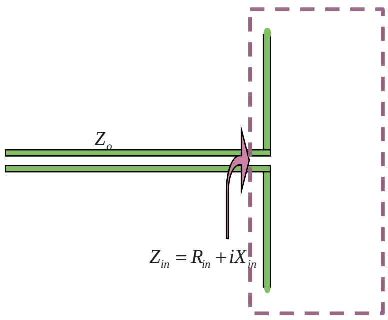


From: http://www.sparkmuseum.com



R. W. P. King

S. A. Schelkunoff



How about Metamaterials?

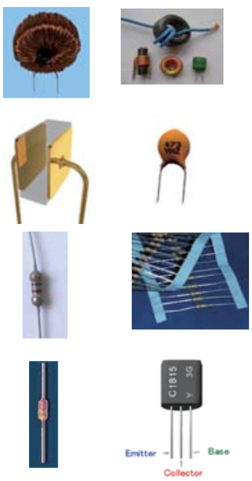
Complexity vs Simplicity

Modularization
Parameterization
Conceptualization
Cross Breeding

→

Metamaterials

Metamaterial Gadgets?



L

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Metamaterial Gadgets?

ε

μ

σ

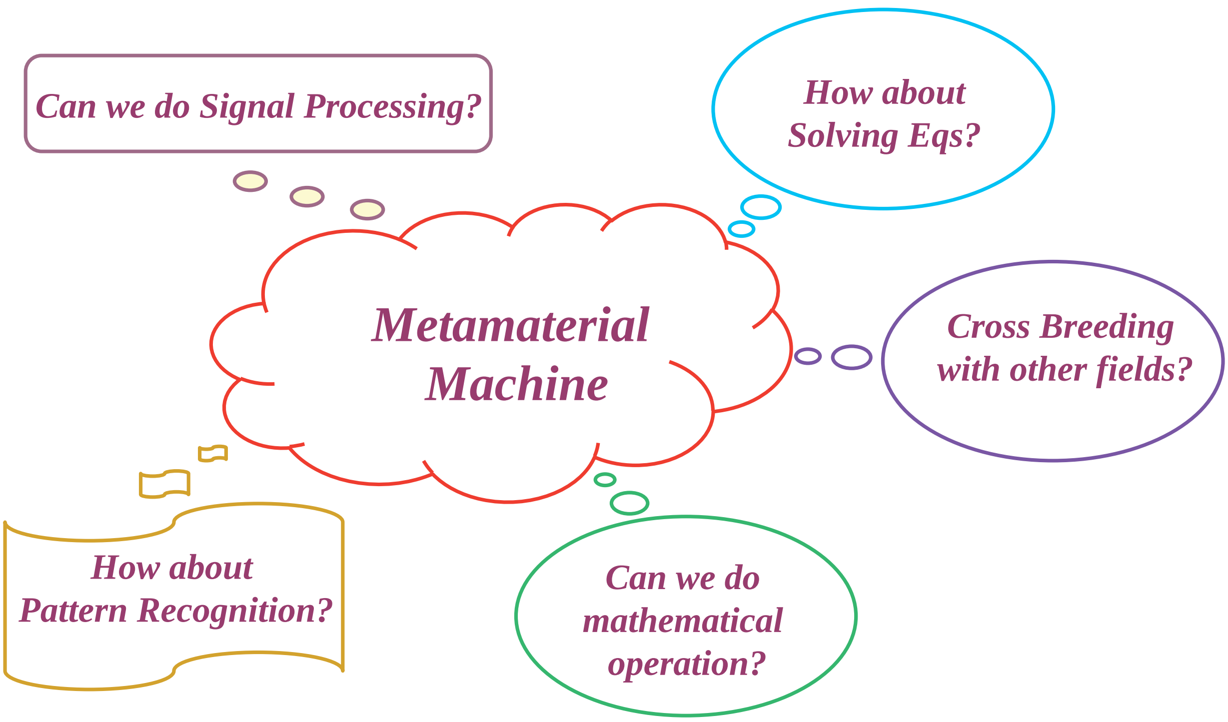
$\chi^{(2)}$

ξ

M

????

Metamaterial "Machines"?



Cross Breeding: Photonics vs Electronics

Photonics/ Microwaves → **Concept of Metamaterials** ← Electronics

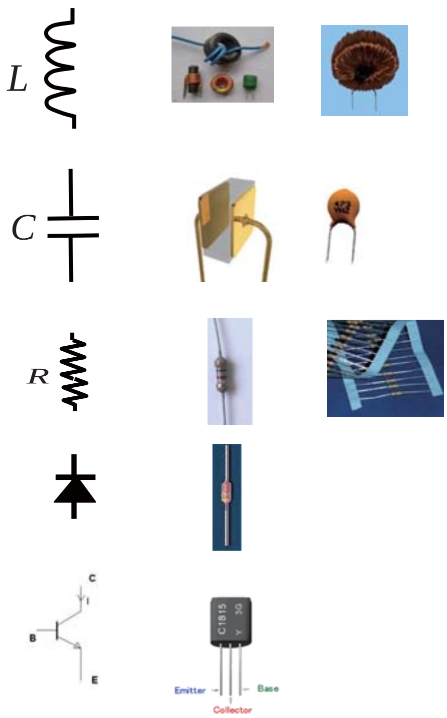
↓

"Metatronics"

↓

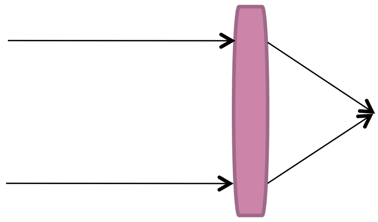
Building Blocks for Metamaterials

"Modular Blocks" in electronics



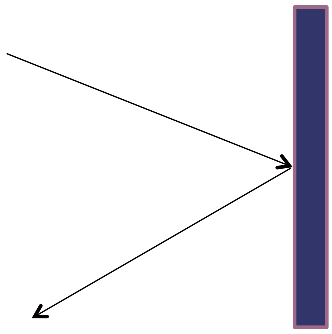
"Building Blocks" in Optics?

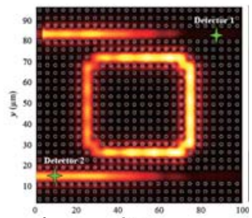
Waveguide



Lens

Optics

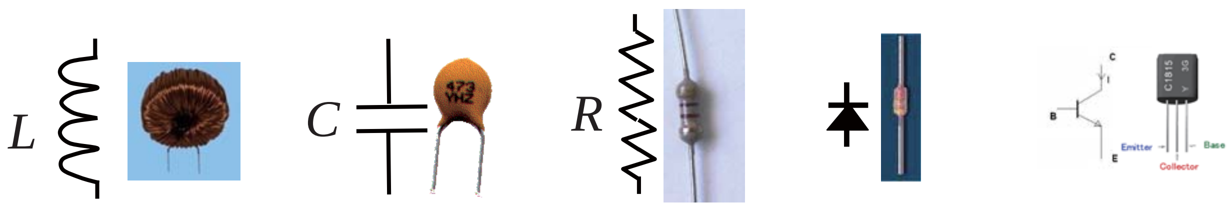




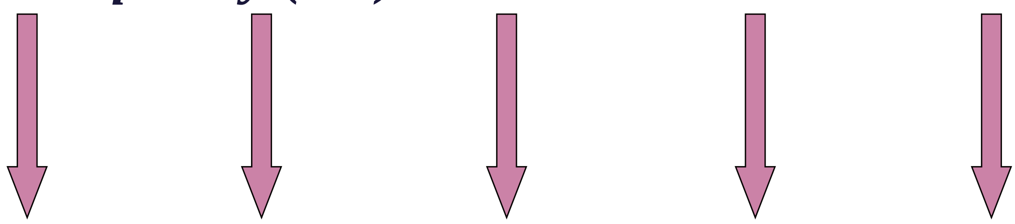
from: D. Prather's group

Mirror

"Lumped" Circuit Elements in Nanophotonics?



Radio Frequency (RF) electronics



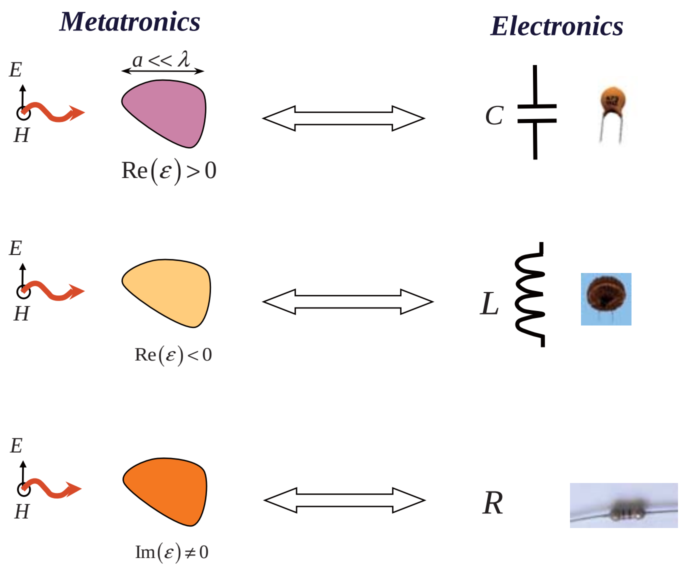
? ? ? ? ?

Nano-Optics

Optical Lumped Circuit Elements: Modular Blocks

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

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



Engheta, Science, 317, 1698 (2007)

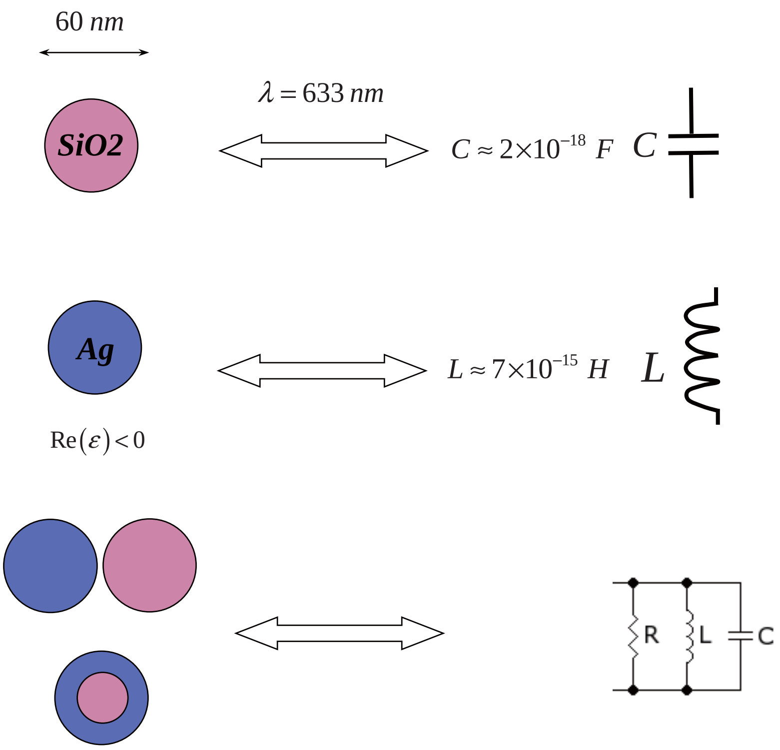
Caglayan, Hong, Edwards, Kagan, Engheta, Phys. Rev. Lett. (2013)

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

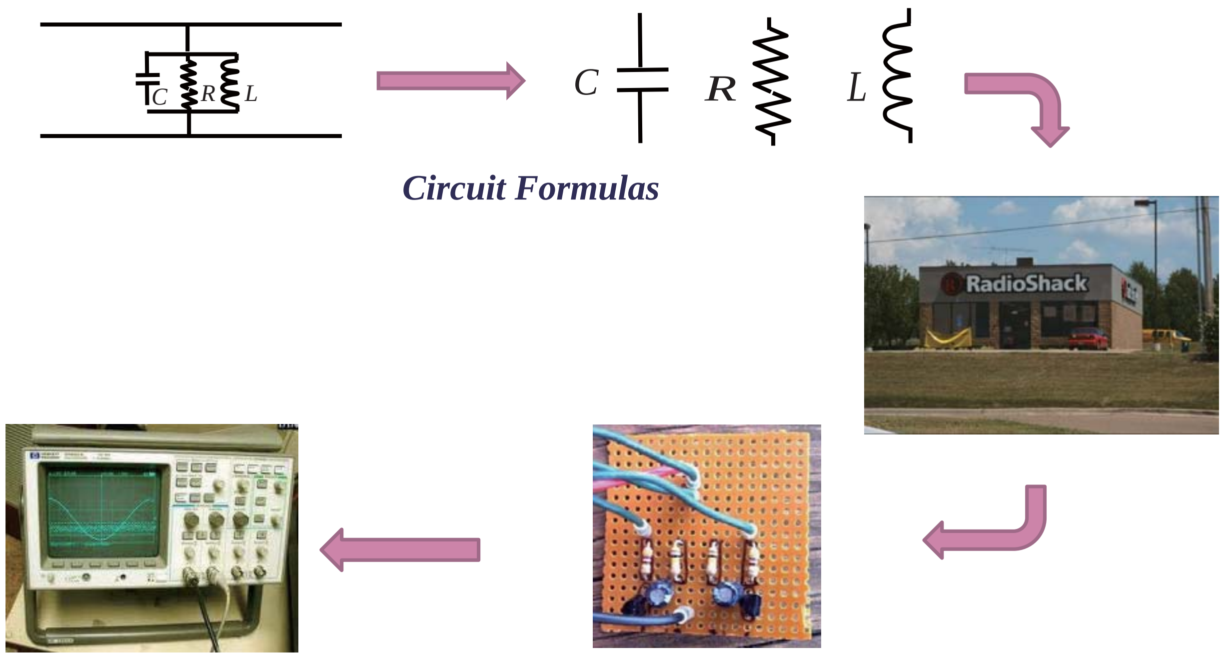
Sun, Edwards, Alu, Engheta, Nature Material, March 2012

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

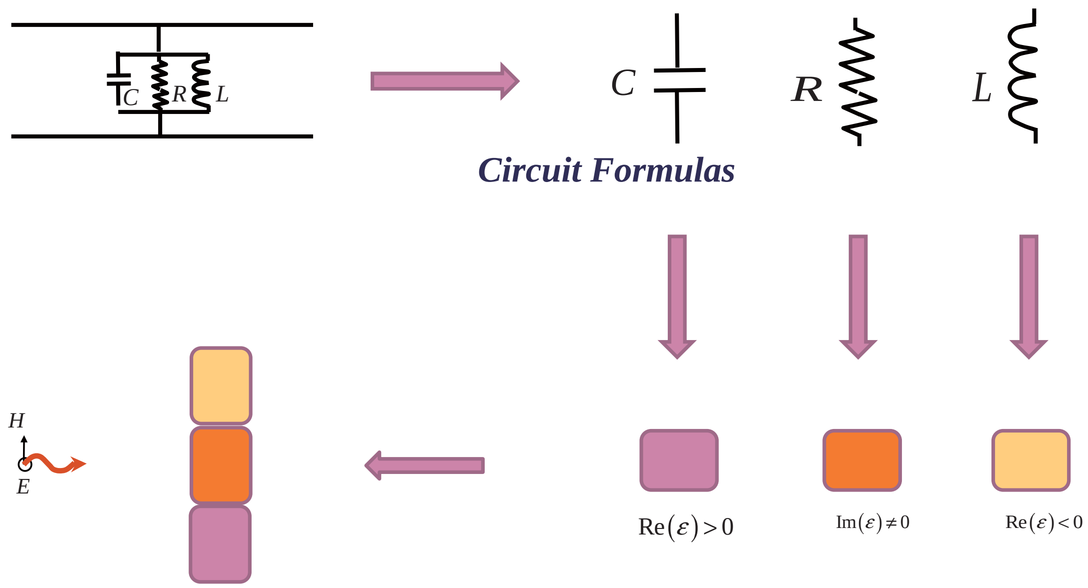
Examples



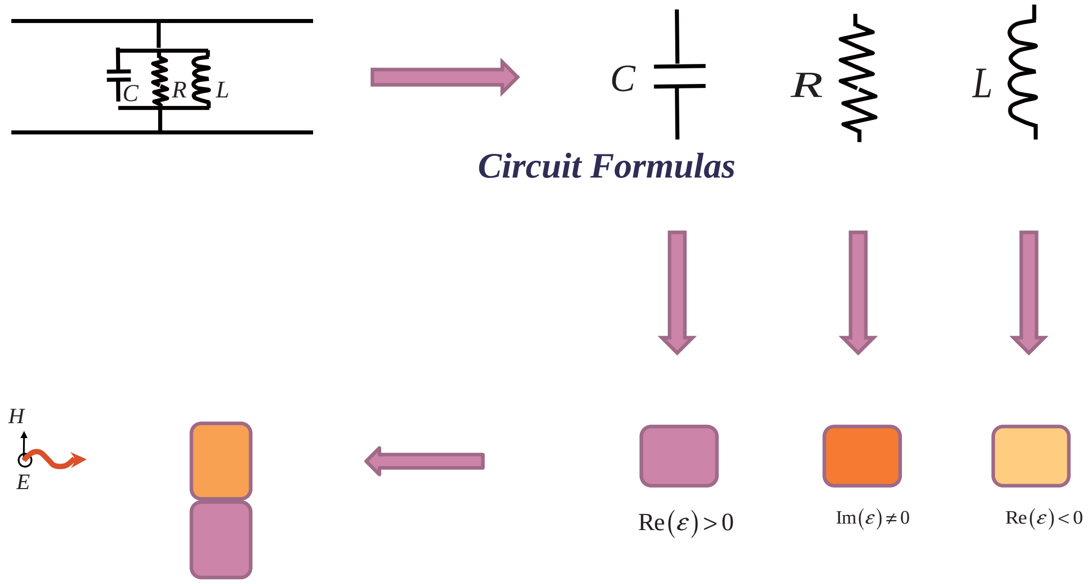
Electronic Circuit Design?



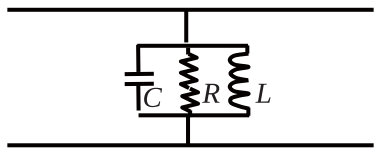
Can we do this in Nano-Optics?

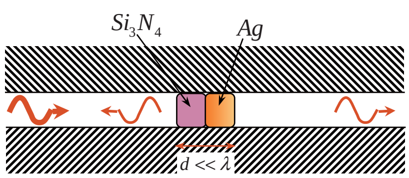


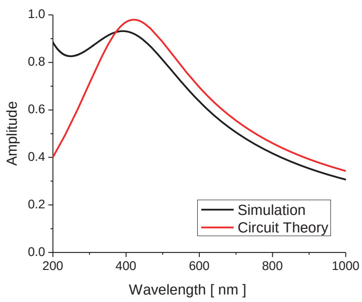
Can we do this in Nano-Optics?

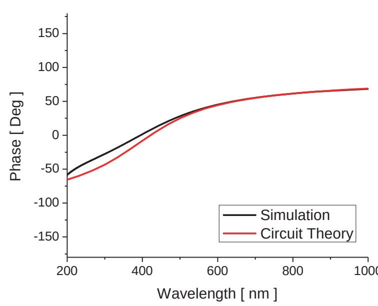


Optical Filter with Nanorods





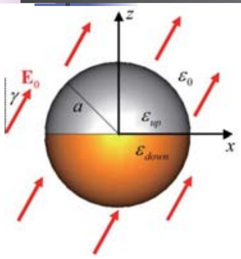


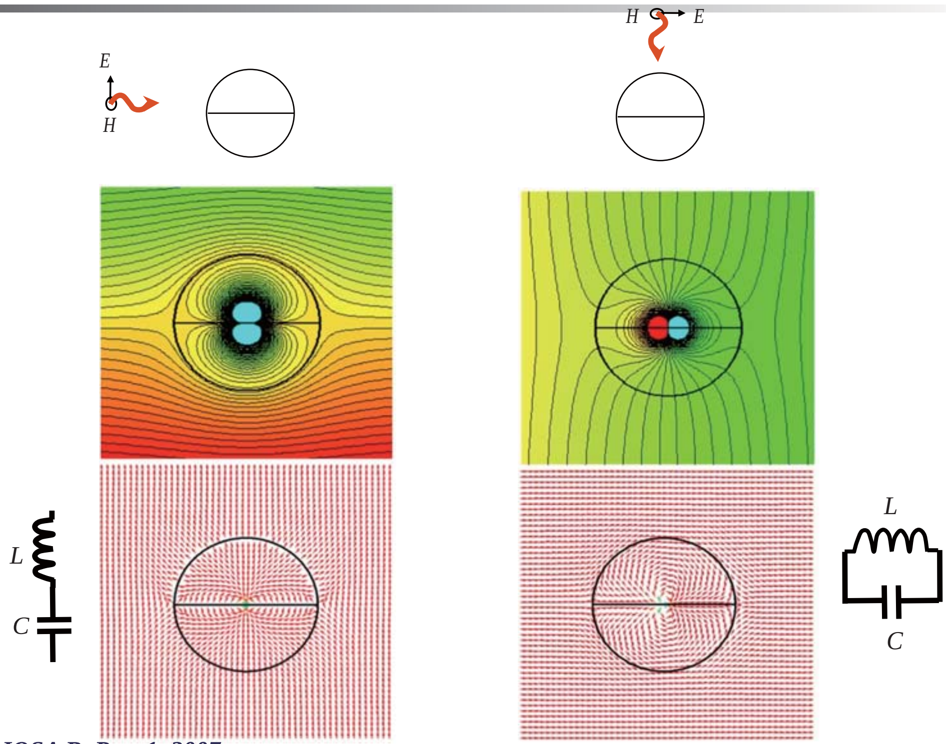


Engheta, Science, 317, 1698 (2007)

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

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

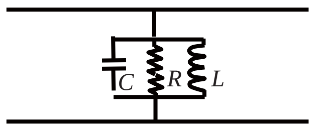


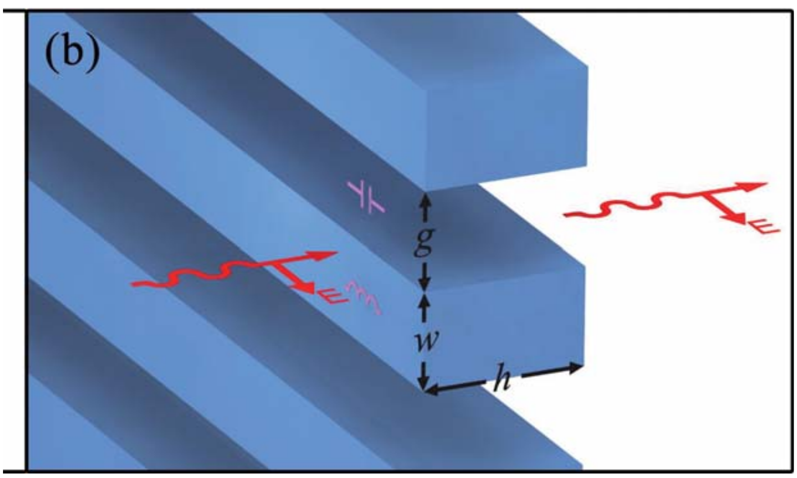


Salandrino, Alu, Engheta, JOSA B, Part 1, 2007
Alu, Salandrino, Engheta, JOSA B, Part 2, 2007

Alu and Engheta, New Journal of Physics, 2009

Experimental Verification at IR





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

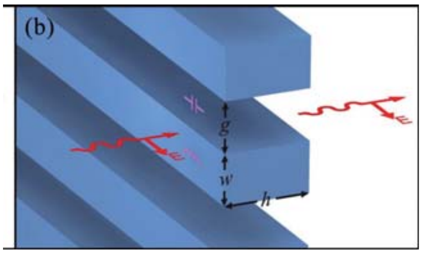
$g = 75nm$

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

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

Experimental Verification at IR

Circuit Theory Model



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

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

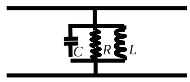
$$Z_{equivalent}^{par} \equiv \frac{Z_{wire}^{par} \cdot Z_{air\text{-}gap}^{par}}{Z_{wire}^{par} + Z_{air\text{-}gap}^{par}}$$

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

$g = 75nm$

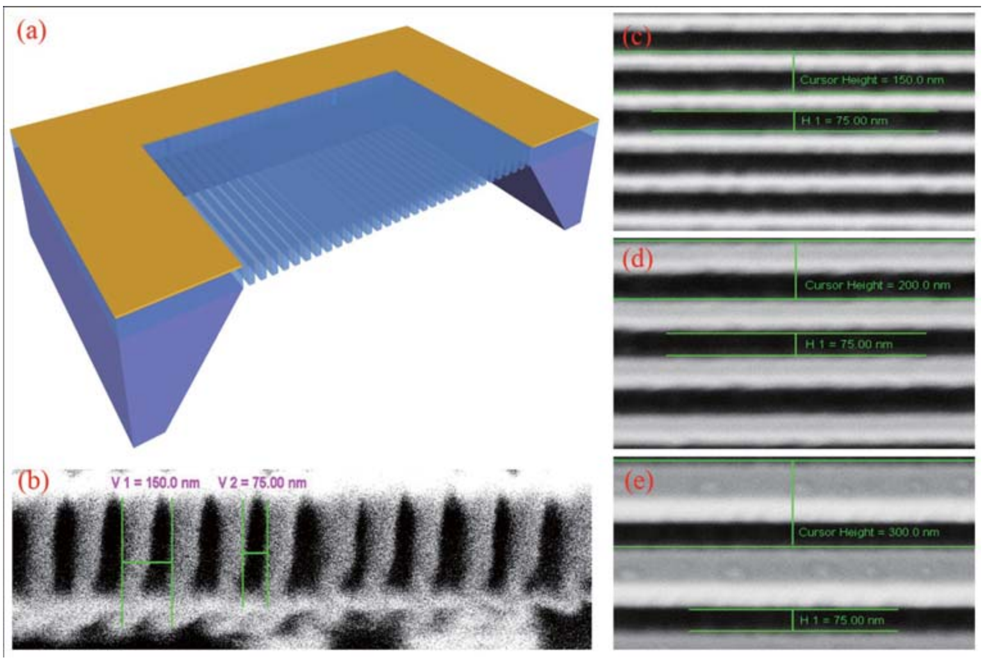
$h = 175nm, 250nm, 325nm$

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



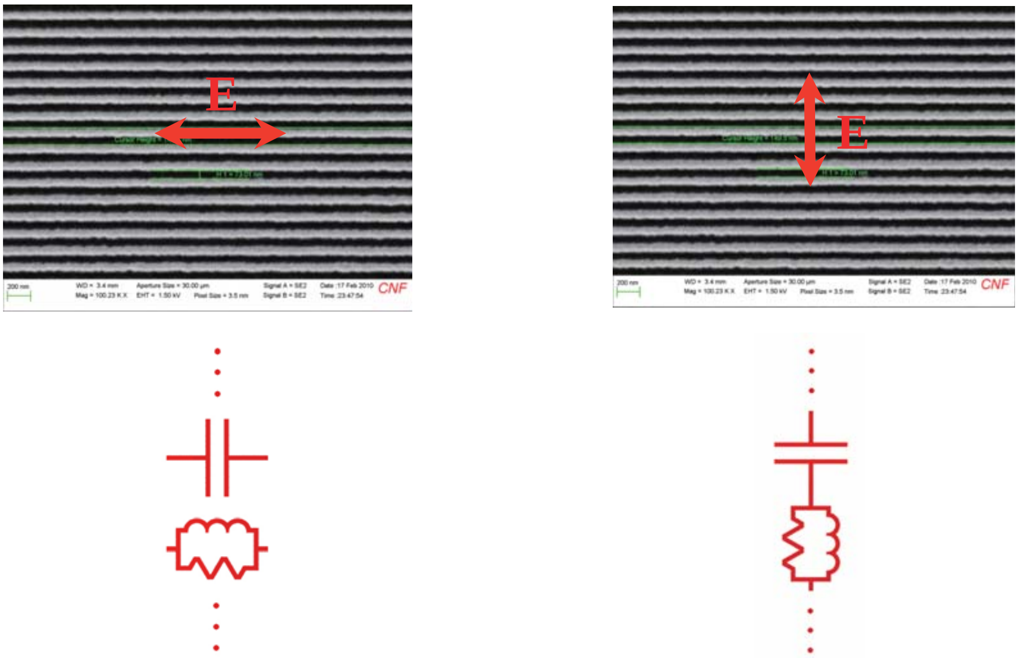
Y. Sun, B. Edwards, A. Alu, and N. Engheta, <u>Nature Materials,</u> March 2012

Our Samples



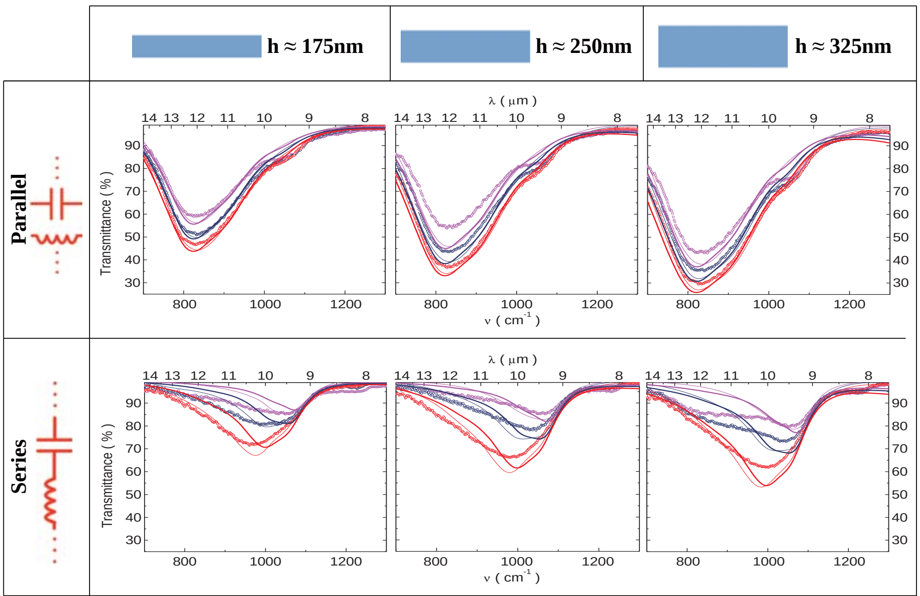
Y. Sun, B. Edwards, A. Alu, and N. Engheta, <u>Nature Materials,</u> March 2012

"Parallel" and "Series" Optical Circuits



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

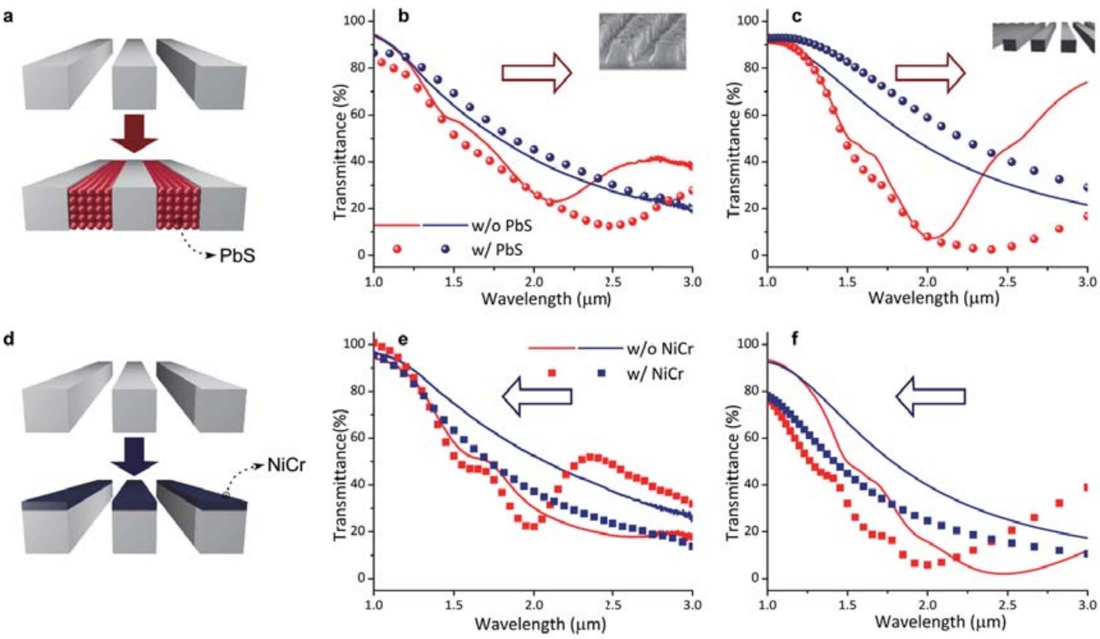
Collective Results



"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, March 2012

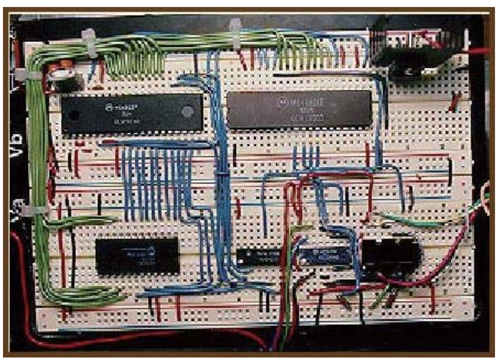
TCO NIR Metatronic Circuits Fabrication and Experimental Results



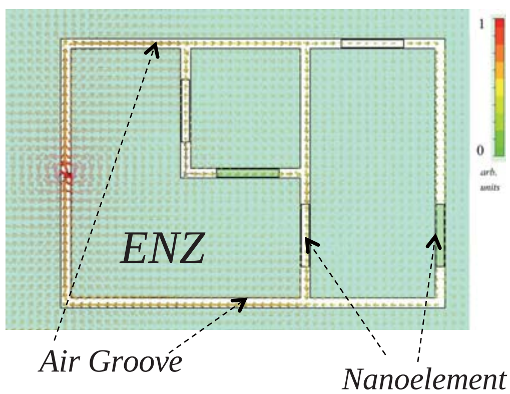
Caglayan, Hong, Edwards, Kagan, Engheta, Phys. Rev. Lett. 111, 073904 (2013)

Nano-Optics Circuit Boards

Electronic Circuit Board

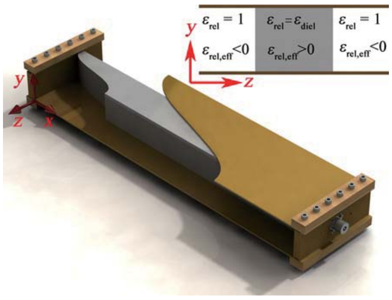


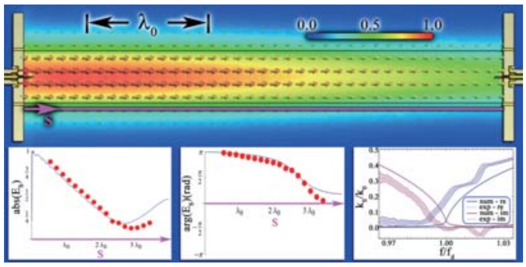
Metatronic Circuit Board

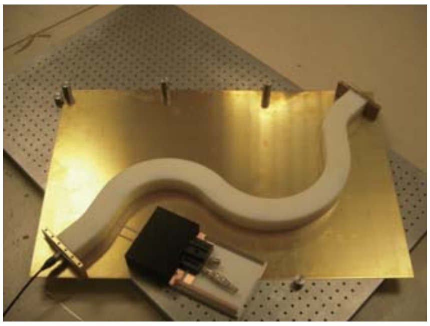
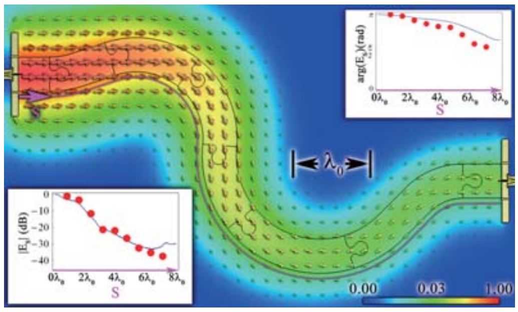


Alu and Engheta, Phys. Rev. Lett., 2009

Experimental Verification of Displacement-Current Wire

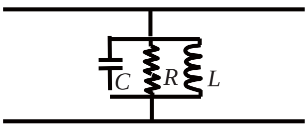


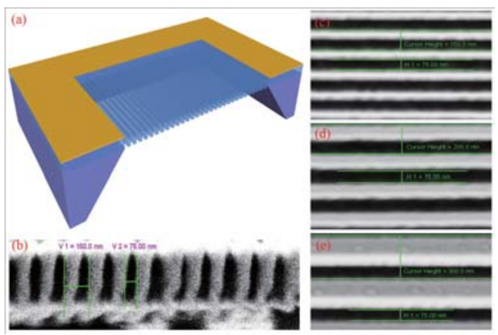


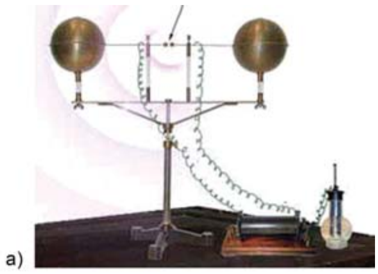
B. Edwards and N. Engheta, Physical Review Letters, May 7, 2012

From a "Filter" to a "Filter"

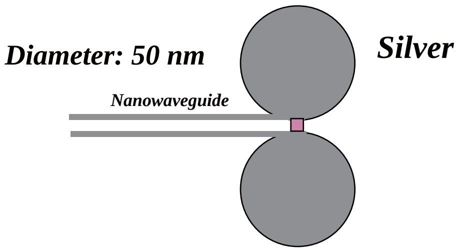


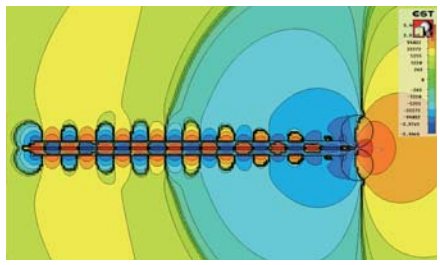


From an "Antenna" to an "Nanoantenna"



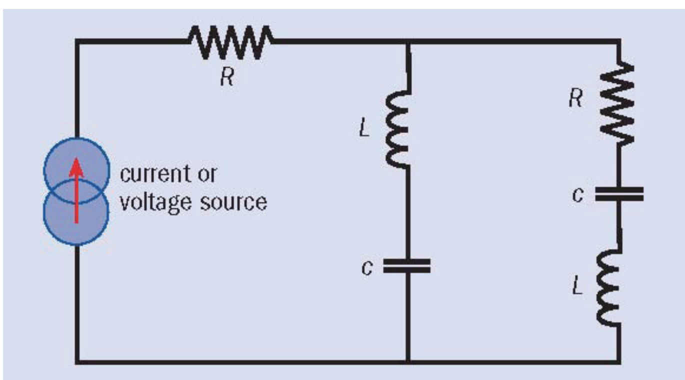
From: http://www.sparkmuseum.com

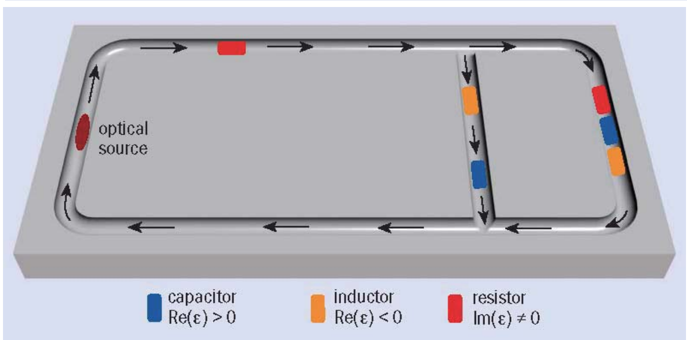




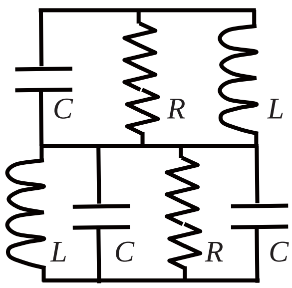
A. Alu and N. Engheta, Phys. Rev. B. 2008

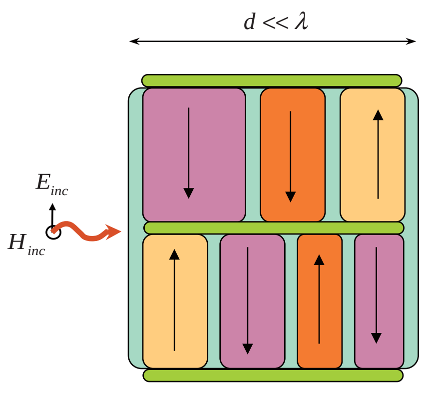
Optical Metatronics





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

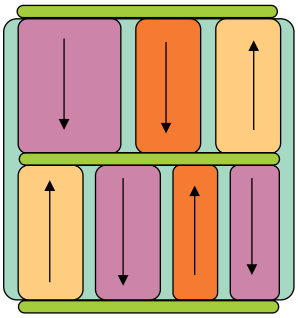


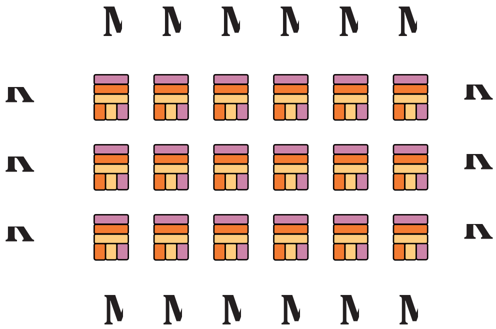


Engheta, Science, 317, 1698 (2007)

Metatronics vs Metamaterials

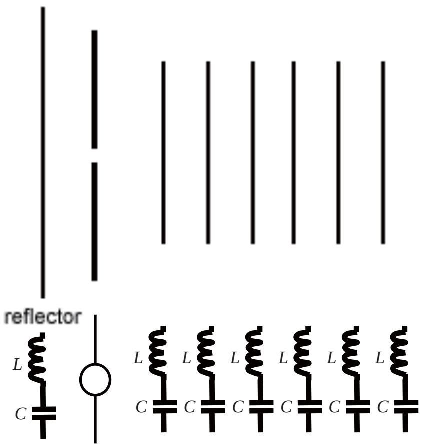
Metatronics ⟷ Building Blocks for Metamaterials





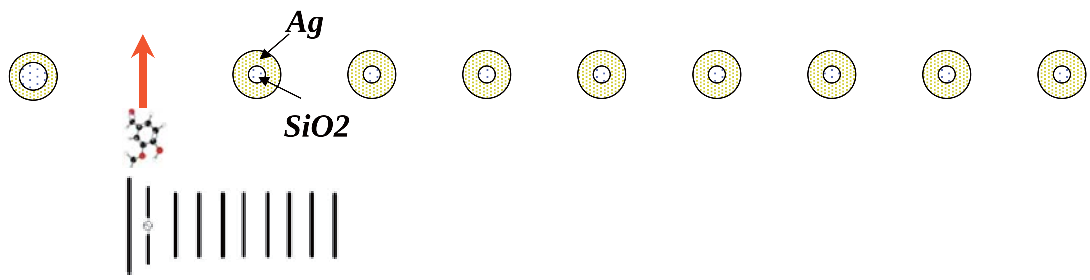
Yagi-Uda Antennas

Picasaweb.google.com/.../YOKis5Vf7nhDG5dGAoSD0w



Li, Salandrino, and Engheta, Phys. Rev. B , 76, 245403 (2007)

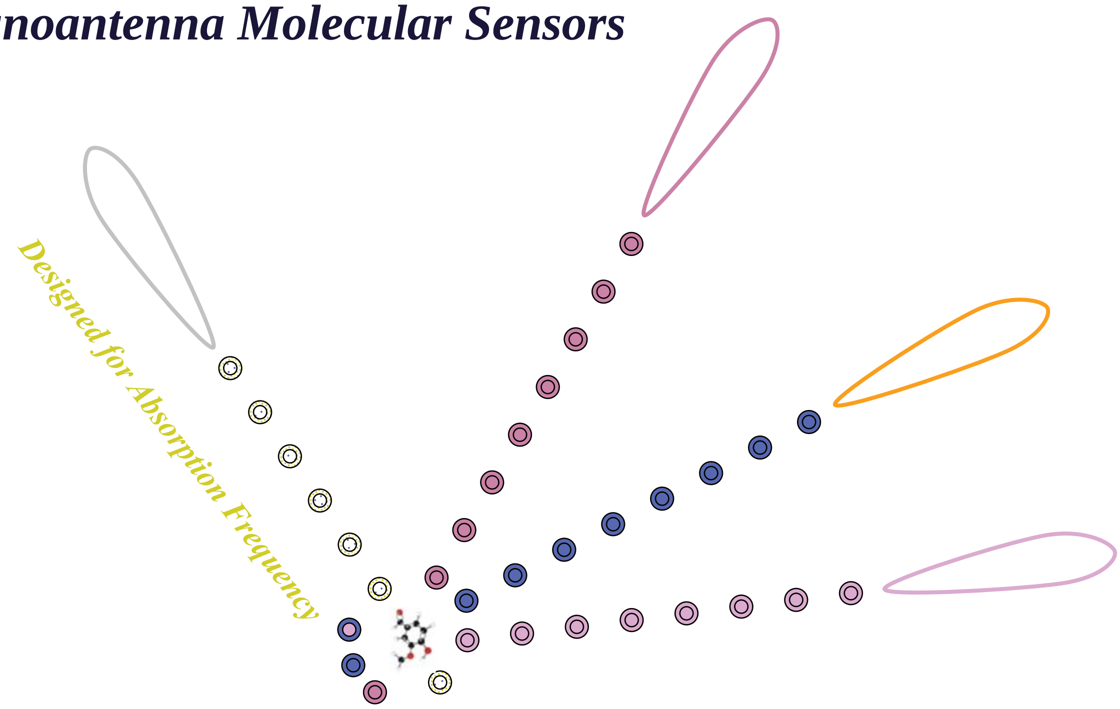
Optical "Yagi-Uda" Nanoantenna



Li, Salandrino, and Engheta, Phys. Rev. B , 76, 245403 **(2007)**

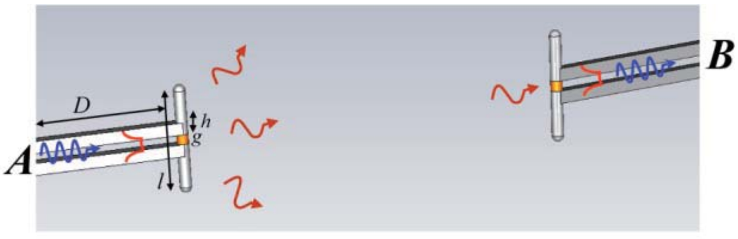
Nanoscale "Spectrometer" in Molecular Spectroscopy

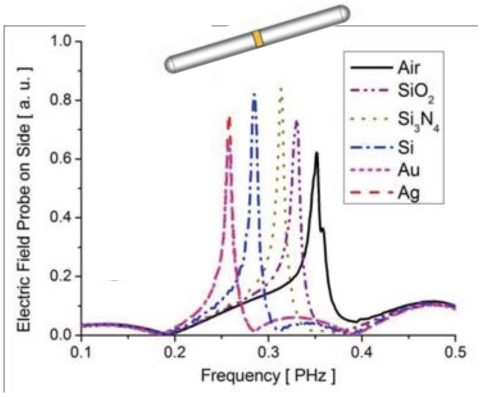
Nanoantenna Molecular Sensors



Li, Salandrino, and Engheta, Phys. Rev. B, 2009

Optical Wireless Link at Nanoscales





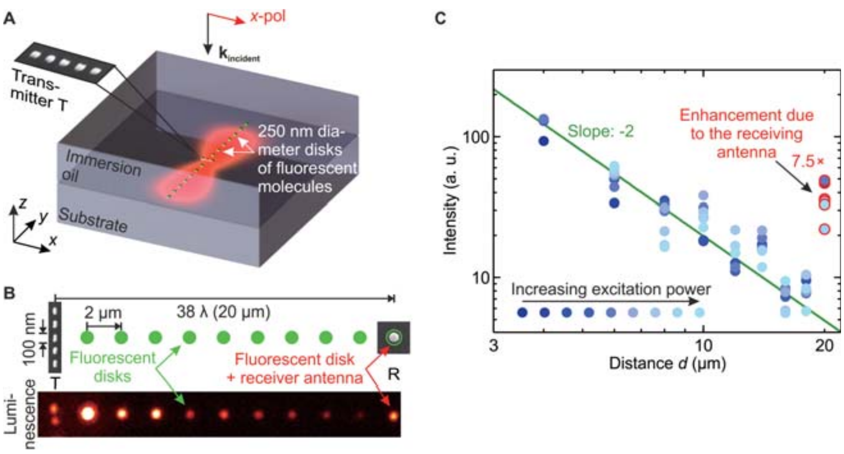
Antennas, local oscillators, filters, switches, mixers, modulators, demodulators, etc. etc.

Alu and Engheta, Phys. Rev. Lett, May 2010

Alu and Engheta, Nature Photonics, Vol. 2, May 2008

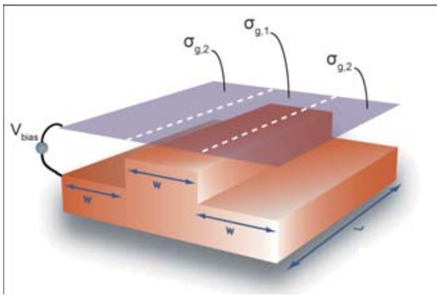
Experimental Verification

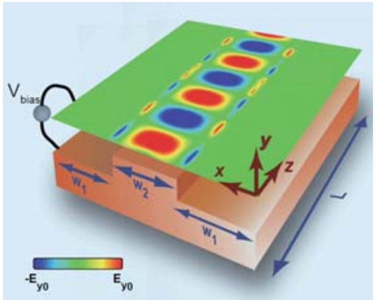
Harald Giessen's group in collaboration with my group

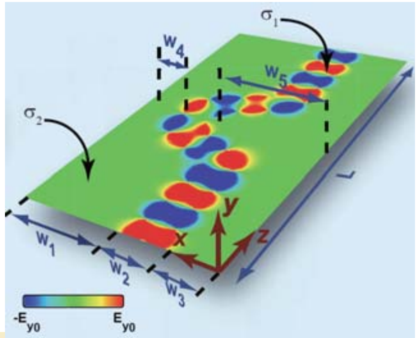


D. Dregely, K. Lindfors, M. Lippitz, N. Engheta, M. Totzeck, H. Giessen, Nature Communications, 2014

One-Atom-Thick Optical Devices





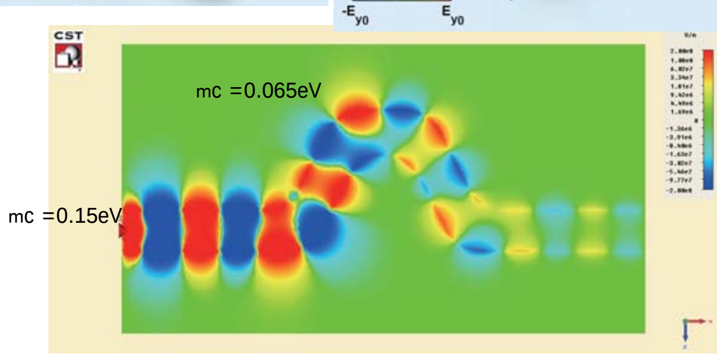


Region 1: $\sigma_{g,i} > 0$

$\mu_c = 150\, meV$

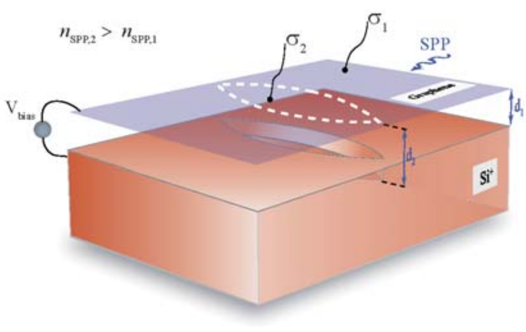
Region 2: $\sigma_{g,i} < 0$

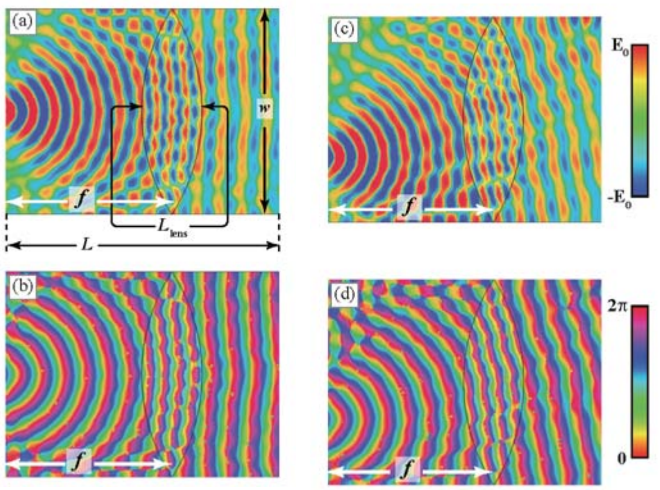
$\mu_c = 65\, meV$



A. Vakil and N. Engheta, Science, 2011

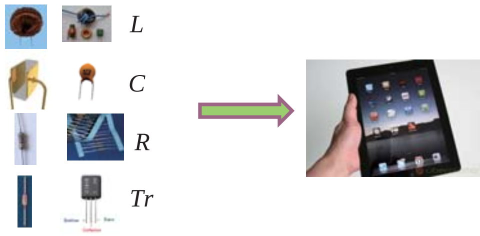
One-Atom-Thick Signal Processing: Fourier Transform





Vakil, Engheta, Phys. Rev. B, (2012)

Metasystems



Signal-Processing Metamaterials?

Metamaterial Computing

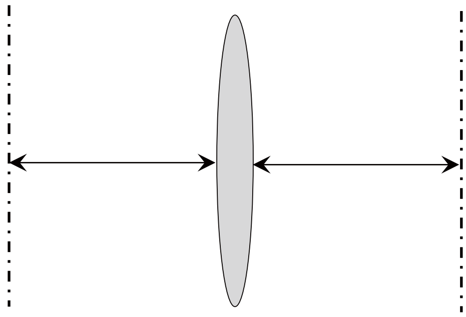
$f(x_1, x_2, \cdots) \longrightarrow$

$\longrightarrow g(x_1, x_2, \cdots)$

$$g(x_1, x_2, \cdots) = \iiint f(u_1, u_2, \cdots) k(x_1, x_2, \cdots; u_1, u_2, \cdots) du_1 du_2 \cdots$$

Metamaterial Analog Computer?

Fourier-Transform

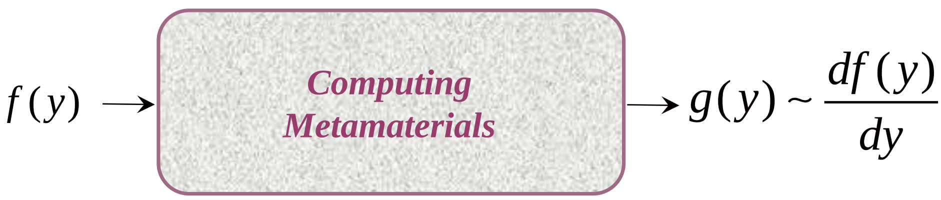


$f(x,y)$ $\qquad\qquad$ $F(\bar{x},\bar{y})$

$$F(\bar{x},\bar{y}):\ \textit{Fourier Transform}\left[f(x,y)\right]$$

J. Goodman, Fourier Optics, 1994

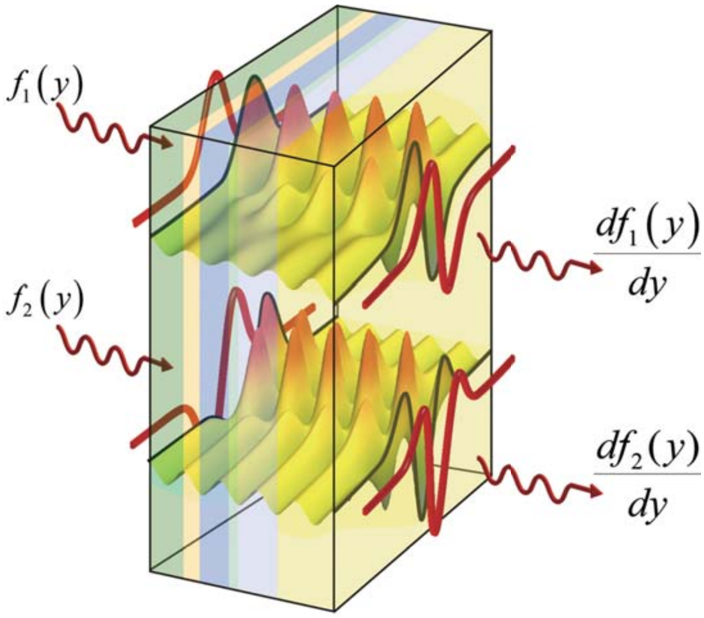
Metamaterial Computing



$$f(y) \rightarrow \boxed{\text{Computing Metamaterials}} \rightarrow g(y) \sim \frac{df(y)}{dy}$$

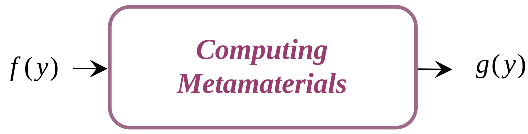
"Differentiator" Metamaterial

Computing Metamaterial



"Differentiator" Metamaterial

$$g(y) \sim \frac{df(y)}{dy}$$

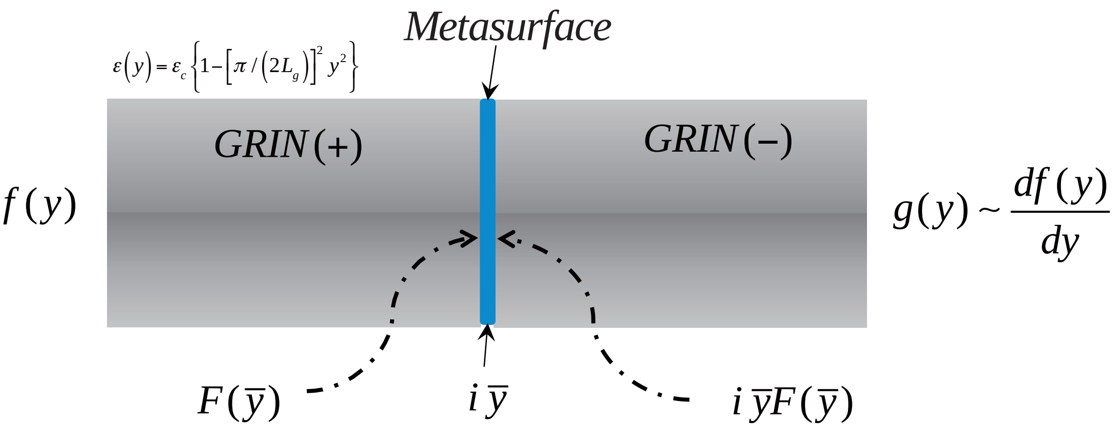


$$f(y) \xrightarrow{\text{Fourier}} F(\bar{y})$$

$$g(y) \xrightarrow{\text{Fourier}} G(\bar{y})$$

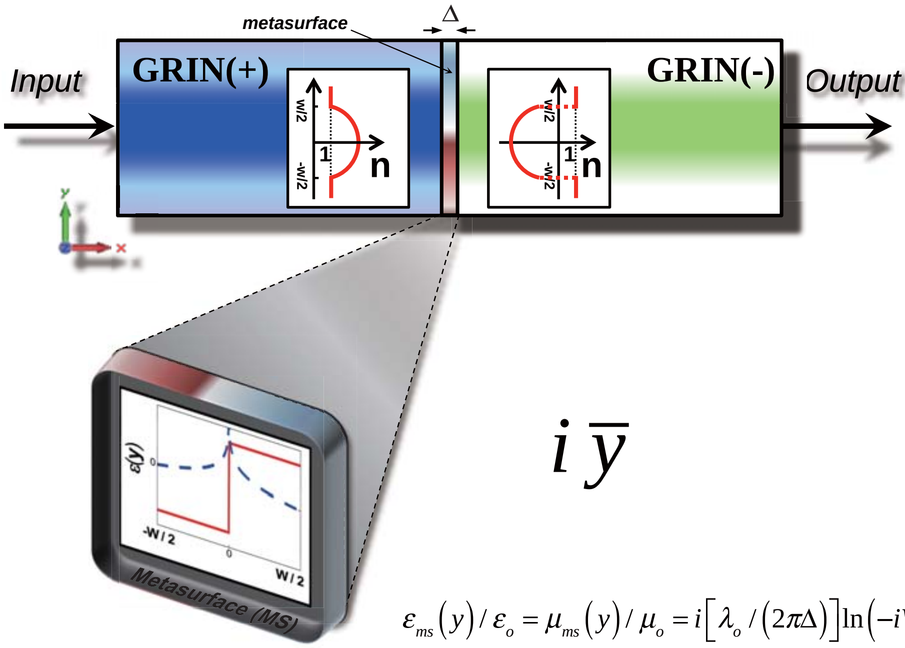
$$G(\bar{y}) \propto (i\bar{y}) F(\bar{y})$$

“Differentiator” Metamaterial



A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, <u>Science, Jan 2014</u>

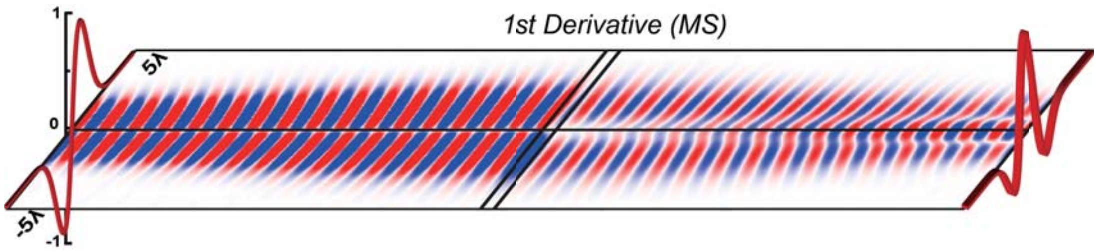
GRIN(+) - MS - GRIN (-)

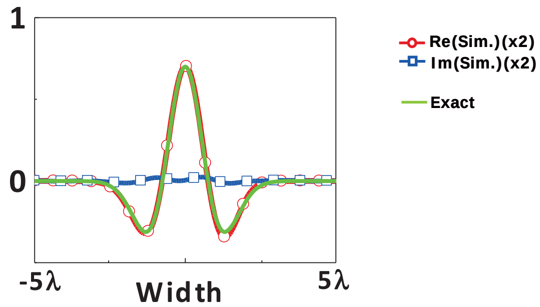


$$\varepsilon_{ms}(y)/\varepsilon_o = \mu_{ms}(y)/\mu_o = i\left[\lambda_o/(2\pi\Delta)\right]\ln\left(-iW/(2y)\right)$$

A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, <u>Science, Jan 2014</u>

Metamaterial as Differentiator

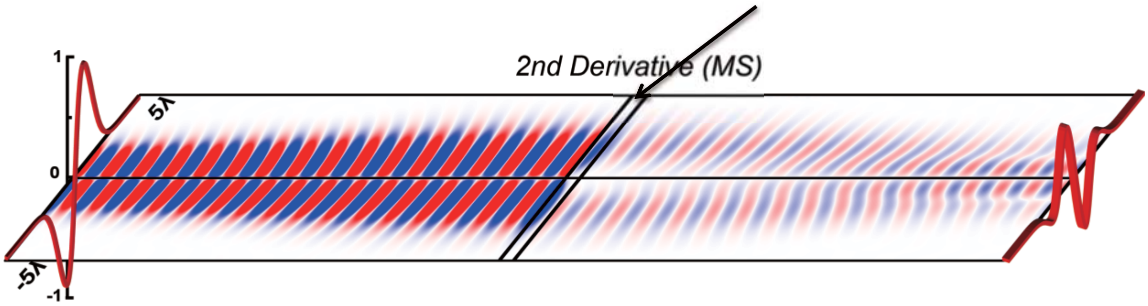


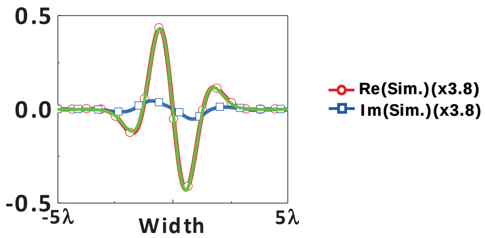


A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, Science, Jan 2014

Metamaterial as 2nd Differentiator

$$\varepsilon_{ms}(y)/\varepsilon_o = \mu_{ms}(y)/\mu_o = i2\left[\lambda_o/(2\pi\Delta)\right]\ln\left(-iW/(2y)\right)$$



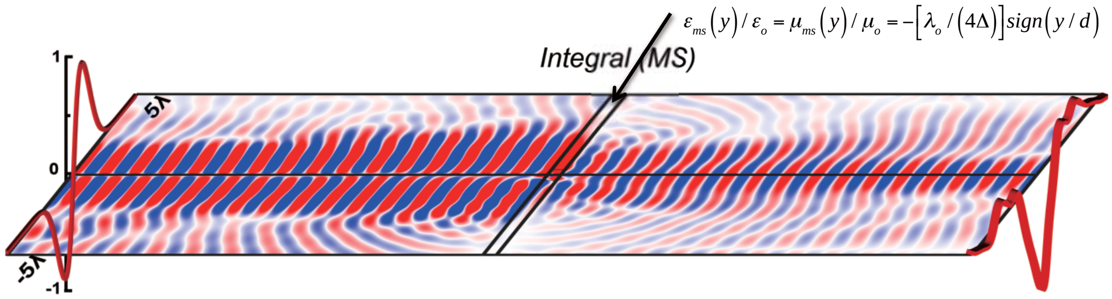


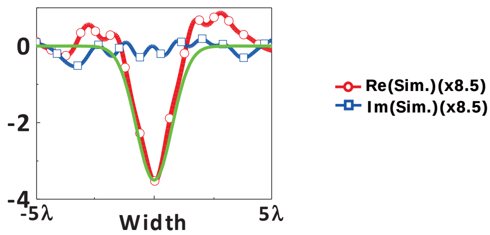
A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, Science, Jan 2014

Metamaterial as Integrator

$\varepsilon_{ms}(y)/\varepsilon_o = \mu_{ms}(y)/\mu_o = i\left[\lambda_o/(2\pi\Delta)\right]\ln(iy/d)$

$\varepsilon_{ms}(y)/\varepsilon_o = \mu_{ms}(y)/\mu_o = -\left[\lambda_o/(4\Delta)\right]sign(y/d)$

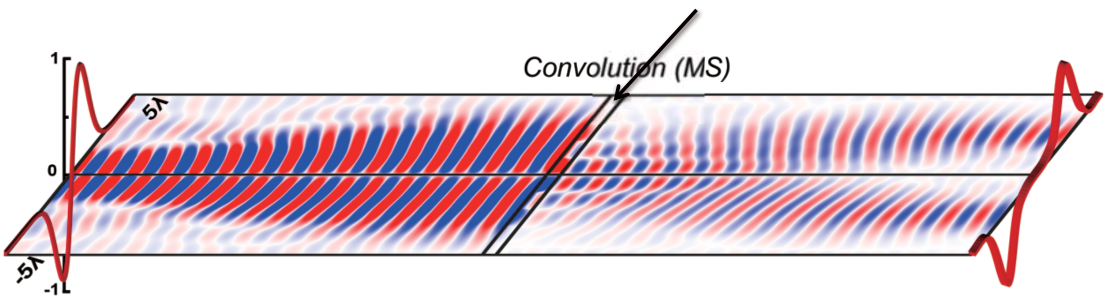


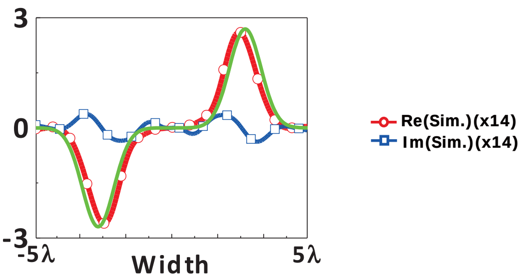


A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, Science, Jan 2014

Metamaterial as Convolver

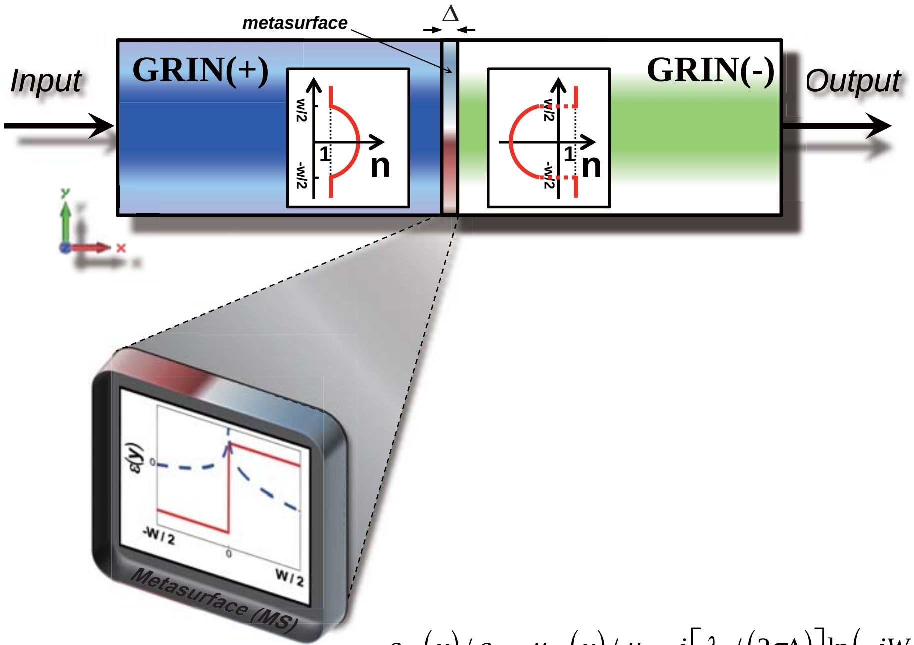
$\varepsilon_{ms}(y)/\varepsilon_o = \mu_{ms}(y)/\mu_o = i\left[\lambda_o/(2\pi\Delta)\right]\ln\left[i/sinc\left(W_k y/(2s^2)\right)\right]$





A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, Science, Jan 2014

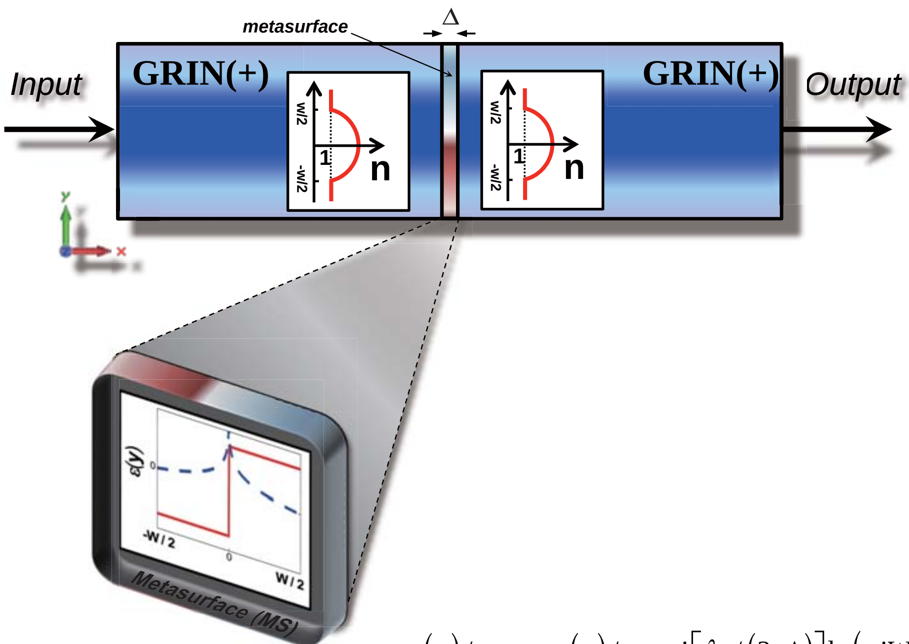
Realistic Materials for Structures



$$\varepsilon_{ms}(y)/\varepsilon_o = \mu_{ms}(y)/\mu_o = i\left[\lambda_o/(2\pi\Delta)\right]\ln\left(-iW/(2y)\right)$$

A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, Science, Jan 2014

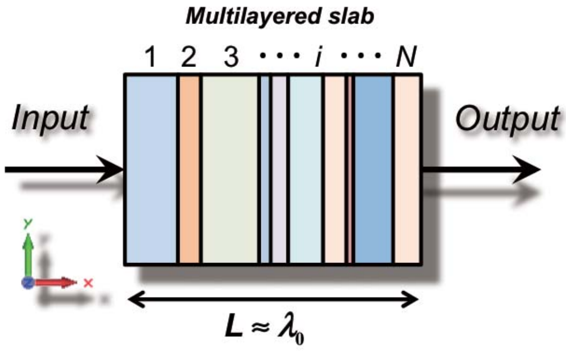
Realistic Materials for Structures



$$\varepsilon_{ms}(y)/\varepsilon_o = \mu_{ms}(y)/\mu_o = i\left[\lambda_o/(2\pi\Delta)\right]\ln\left(-iW/(2y)\right)$$

A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, Science, Jan 2014

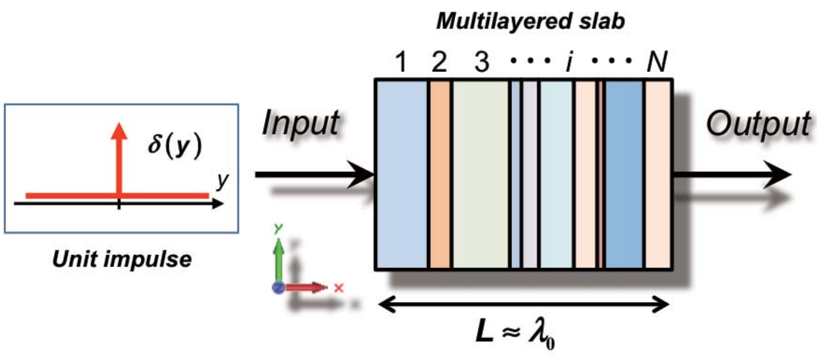
Green's Function Approach



$$g(y) = \int f(y')G(y - y')\,dy'$$

A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, Science, Jan 2014

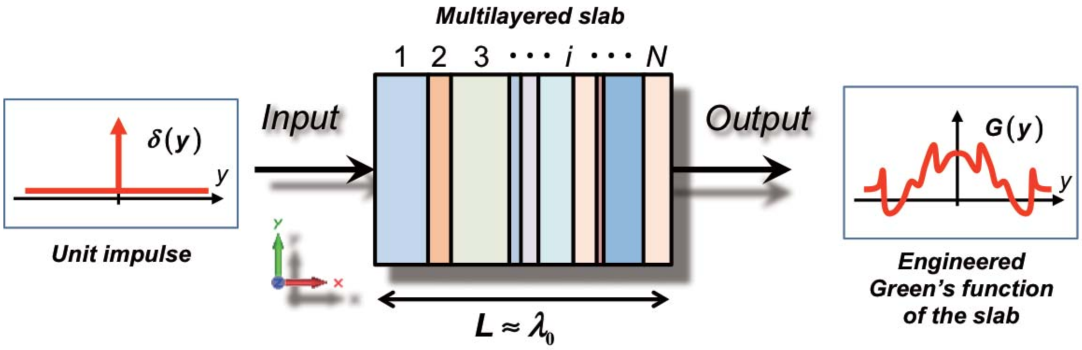
Green's Function Approach



$$g(y) = \int f(y')G(y - y')\,dy'$$

A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, Science, Jan 2014

Green's Function Approach

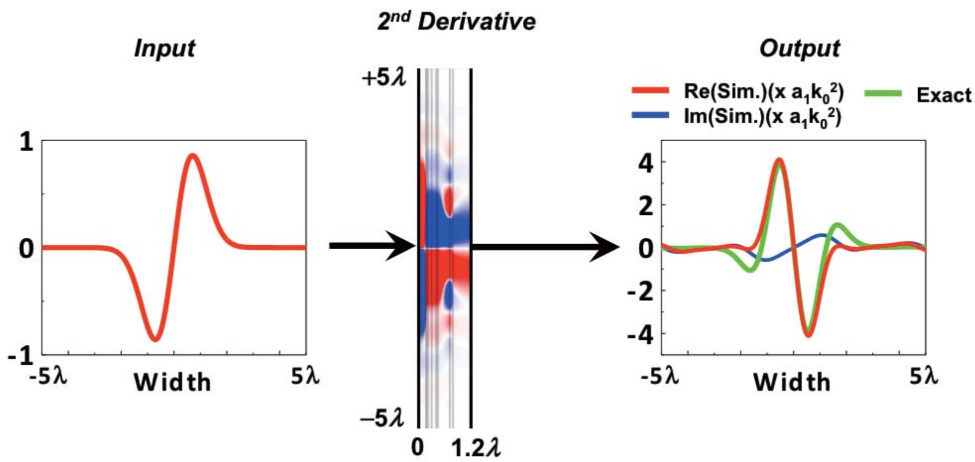


$$g(y) = \int f(y')G(y-y')\,dy'$$

$$\frac{d^2 f(y)}{dy^2} \propto \int f(y')\delta^{(2)}(y-y')\,dy'$$

A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, Science, Jan 2014

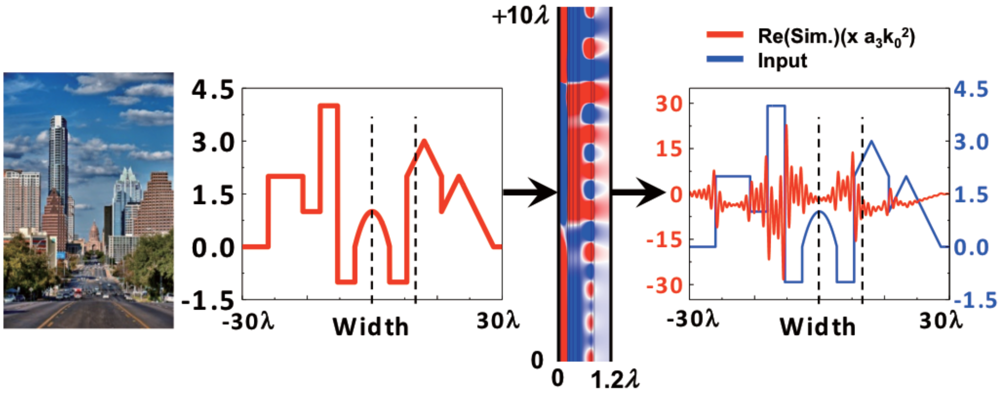
2nd Differentiation: Green's Function Approach



	1	2	3	4	5	6	7	8	9	10
ε_r	13.85	5.98	4.44	0.06	0.03	0.01	-0.003	-2.12	2.30	0.08
d	$\lambda_0/293.4$	$\lambda_0/6.0$	$\lambda_0/212.9$	$\lambda_0/24.2$	$\lambda_0/12.1$	$\lambda_0/9.8$	$\lambda_0/25.0$	$\lambda_0/3.6$	$\lambda_0/14.5$	$\lambda_0/2.4$

A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, Science, Jan 2014

2^{nd} Differentiation: Green's Function Approach



A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alu, N. Engheta, Science, Jan 2014

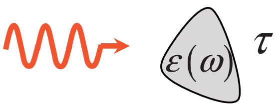
Fields and Waves in Metamaterials Part 2

Nader Engheta

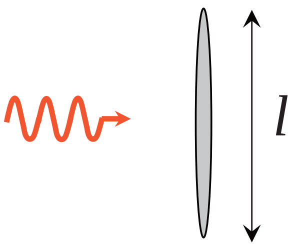
University of Pennsylvania
Philadelphia, PA 19104, USA

August 16-17, 2014

Light-Matter Interaction



$$\omega \leftrightarrow 2\pi / T$$



$$k \leftrightarrow 2\pi / \lambda$$

$$k \equiv \frac{2\pi}{\lambda} = \omega\sqrt{\varepsilon\mu}$$

Metamaterials

N. Engheta, Science, 340, 286 (2013)

What will happen, if epsilon is near zero?

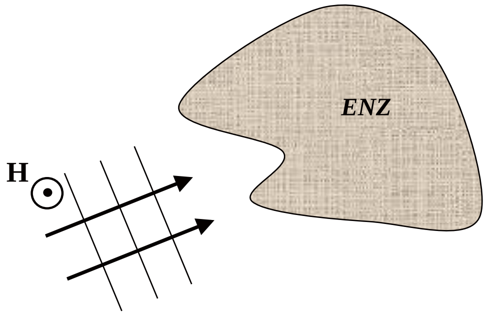
- *Maxwell Equations* $\nabla\times\boldsymbol{H} = -i\omega\varepsilon\boldsymbol{E} \;\longrightarrow\; \nabla\times\boldsymbol{H} = 0$

  $\nabla\times\boldsymbol{E} = i\omega\mu\boldsymbol{H}$

- *2-D Scenario with TM polarization*

$$\mathbf{H} = H(x,y)\ \hat{\mathbf{u}}_z$$

$$\mathbf{E} = \frac{1}{-i\omega\varepsilon}\nabla H(x,y)\times\hat{\mathbf{u}}_z$$



$H = const.$ ***inside ENZ material.*** $n = \sqrt{\varepsilon\mu} \to 0$

M. Silveirinha & N. Engheta, Phys. Rev. Lett. 97, 157403, Oct 2006

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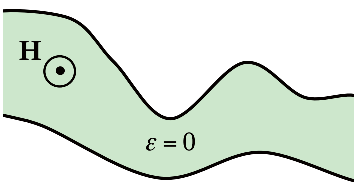
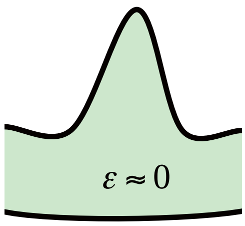




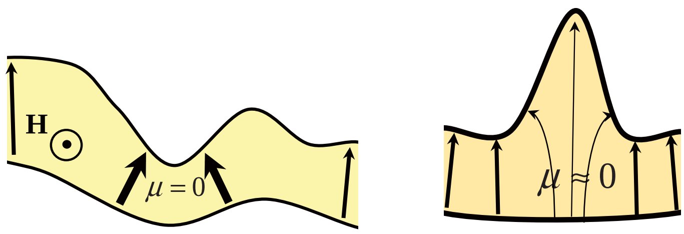
$H = const.$ ***inside ENZ material.*** $n = \sqrt{\varepsilon\mu} \to 0$

What will happen, if mu is near zero?

- *Maxwell Equations* $\nabla \times \boldsymbol{H} = -i\omega\varepsilon \boldsymbol{E}$

  $\nabla \times \boldsymbol{E} = i\omega\mu \boldsymbol{H} \;\longrightarrow\; \nabla \times \boldsymbol{E} = 0$

- *2-D Scenario with TM polarization*



"ENZ Supercoupling"

M. Silveirinha & N. Engheta, Phys. Rev. Lett. 97, 157403, Oct 2006

M. Silveirinha & N. Engheta, Phys. Rev. B., 76, 245109 (2007)

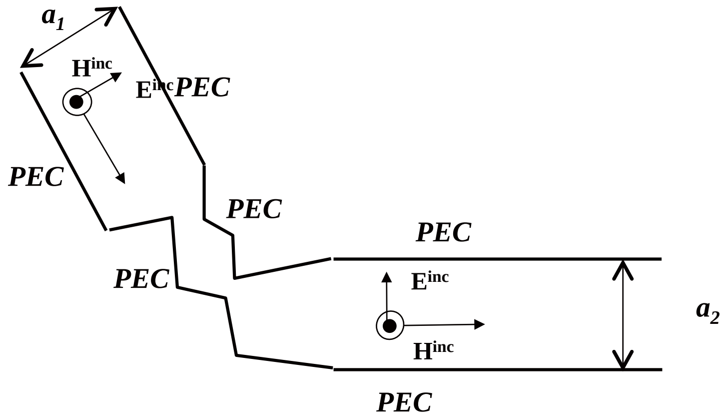
B. Edwards, A. Alu, M. Young, M. Silveirinha, N. Engheta, Phys. Rev. Lett., 100, 033903, 245109 (2008)

A. Alu, M. Silveirinha, N. Engheta, Phys. Rev. E., 78, 016604 (2008)

A. Alu, N. Engheta, Phys. Rev. B., 78, 045102 (2008)

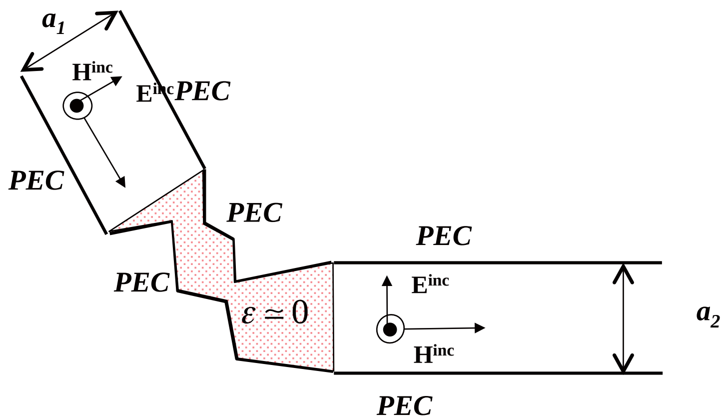
A. Alu, N. Engheta, Phys. Rev. B., 78, 035440 (2008)

"Supercoupling" in Sub-λ Channels



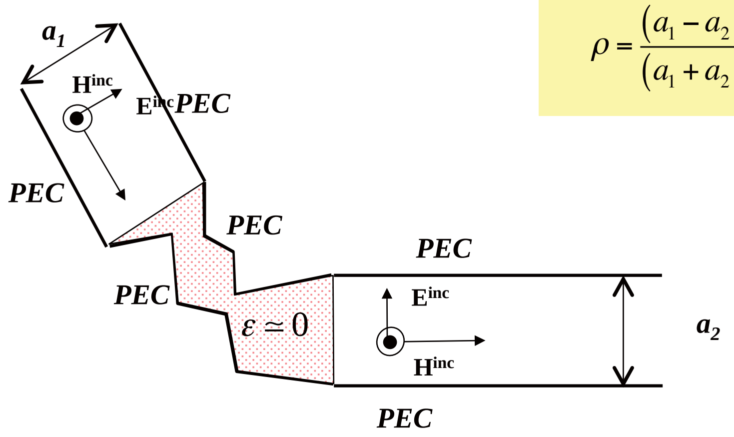
M. Silveirinha & N. Engheta, Phys. Rev. Lett. 97, 157403, Oct 2006

"Supercoupling" in Sub-/ Channels



M. Silveirinha & N. Engheta, Phys. Rev. Lett. 97, 157403, Oct 2006

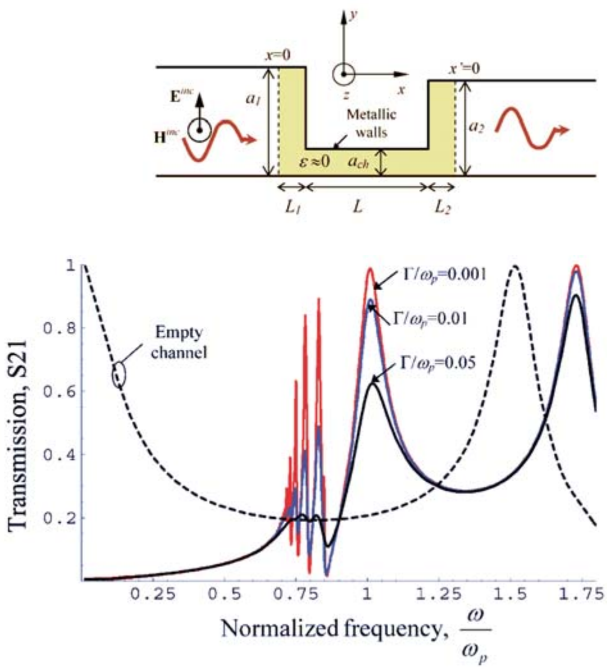
"Supercoupling" in Sub-/ Channels



$$\rho = \frac{(a_1 - a_2) + i k_0 \mu_r A_D}{(a_1 + a_2) - i k_0 \mu_r A_D}$$

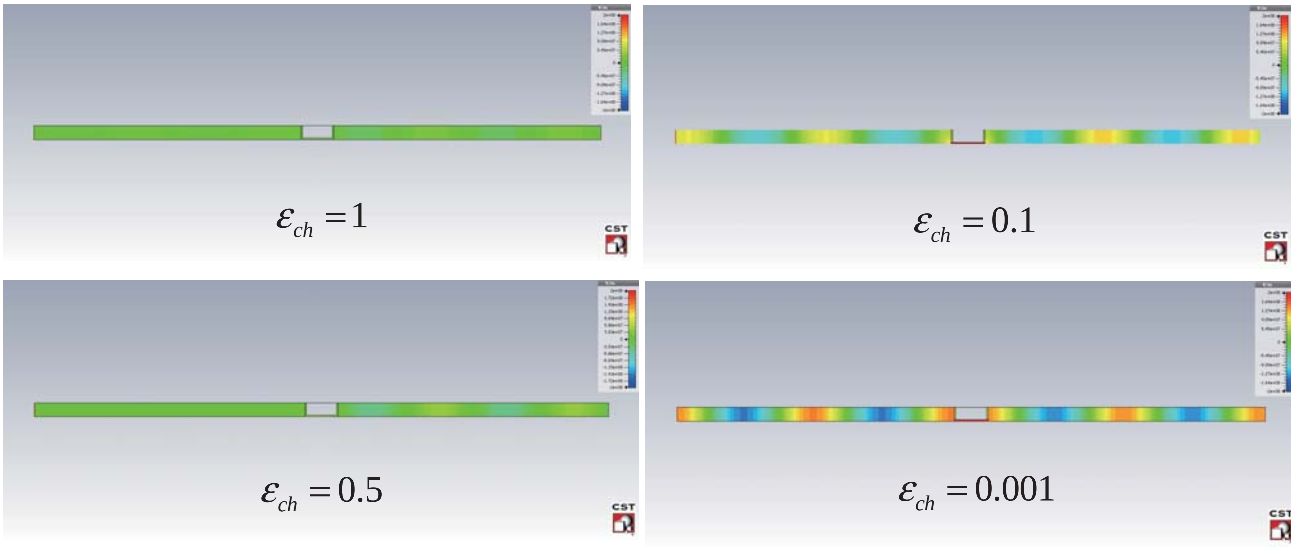
M. Silveirinha & N. Engheta,
Phys. Rev. Lett. 97, 157403, Oct 2006

U-shaped Waveguide Transition & Supercoupling (cont'd)

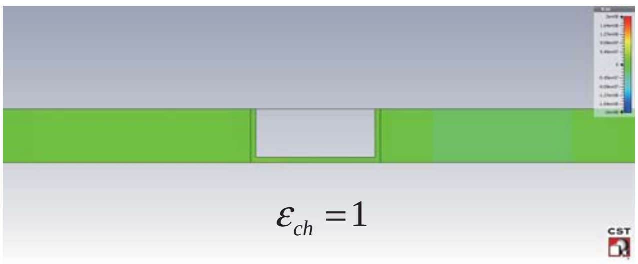


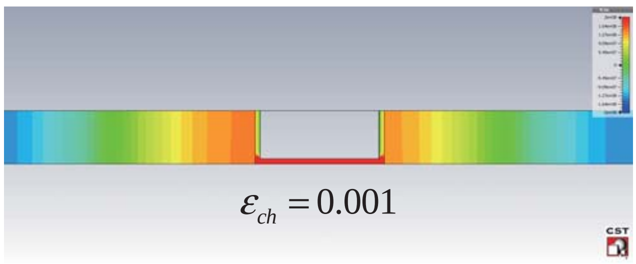
M. Silveirinha & N. Engheta, Phys. Rev. B., 76, 245109 (2007)

Simulation Results: 2D scenario

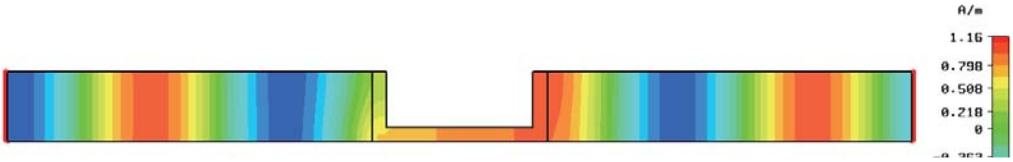


Simulation Results: 2D scenario





Intuitive Explanation



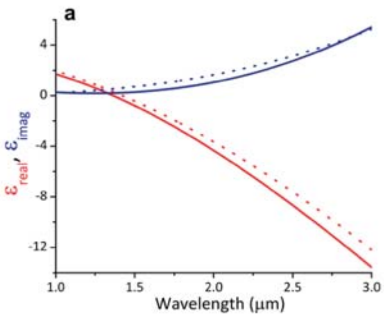
$$Z_{wg} = \frac{V}{I} = \frac{E \cdot h}{H \cdot W} = \frac{E}{H}\frac{h}{W} = \sqrt{\frac{\mu}{\varepsilon}}\frac{h}{W}$$

$$Z_{wg1} = Z_{wg2}$$

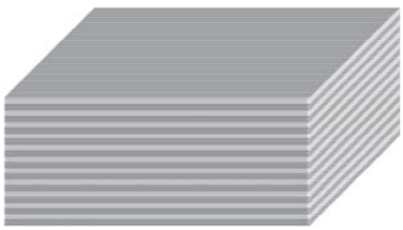
$$\sqrt{\frac{\mu_1}{\varepsilon_1}}\frac{h_1}{W_1} = \sqrt{\frac{\mu_2}{\varepsilon_2}}\frac{h_2}{W_2}$$

B. Edwards, A. Alu, M. Young, M. Silveirinha, N. Engheta, Phys. Rev. Lett., 100, 033903, 245109 (2008)

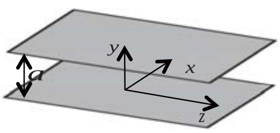
ENZ Structures



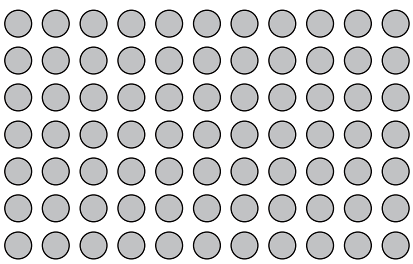
ITO



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



$$k_z = \omega\sqrt{\mu_0\varepsilon_0}\sqrt{\varepsilon_r - \frac{1}{\omega^2\mu_o\varepsilon_o}\left(\frac{\pi}{a}\right)^2}$$



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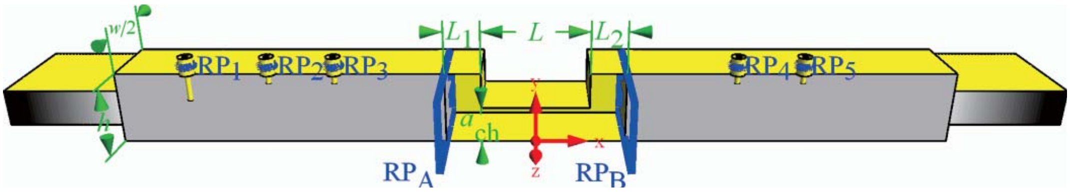
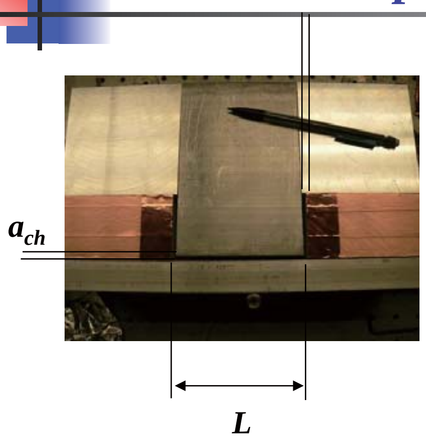
Experimental Verification

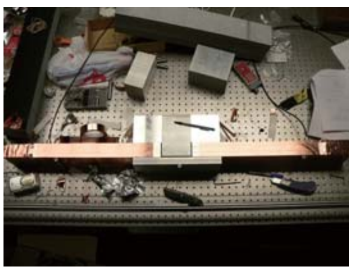


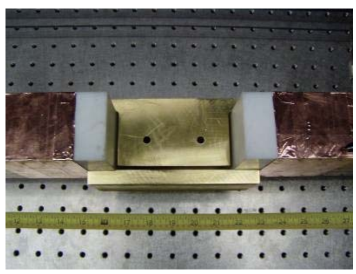
$$\beta_z = \omega\sqrt{\mu_o \varepsilon_o}\sqrt{\varepsilon_r - c^2/\left(4 f^2 w^2\right)} \longrightarrow \varepsilon_{eff}/\varepsilon_0 = \varepsilon_r - c^2/\left(4 f^2 w^2\right)$$

B. Edwards, A. Alu, M. Young, M. Silveirinha, N. Engheta, Phys. Rev. Lett., 100, 033903, 245109 (2008)

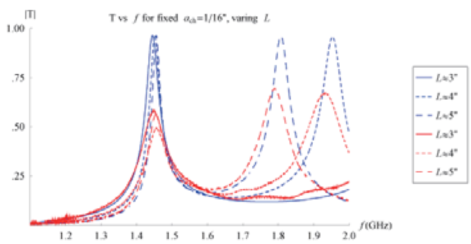
Experimental Verification

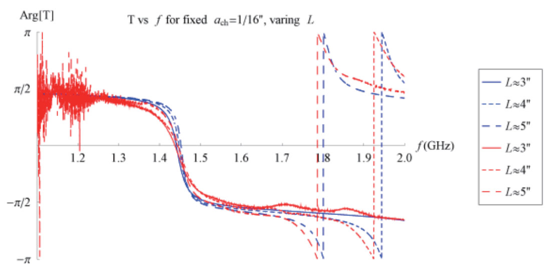




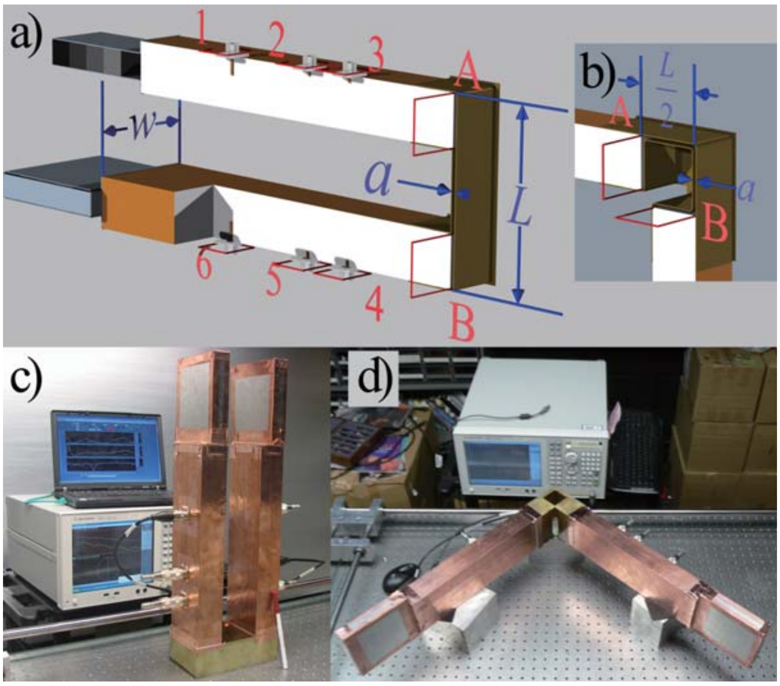


B. Edwards, A. Alù, M. Young, M. Silveirinha, N. Engheta
Phys. Rev. Lett. 100, 033103 (2008)

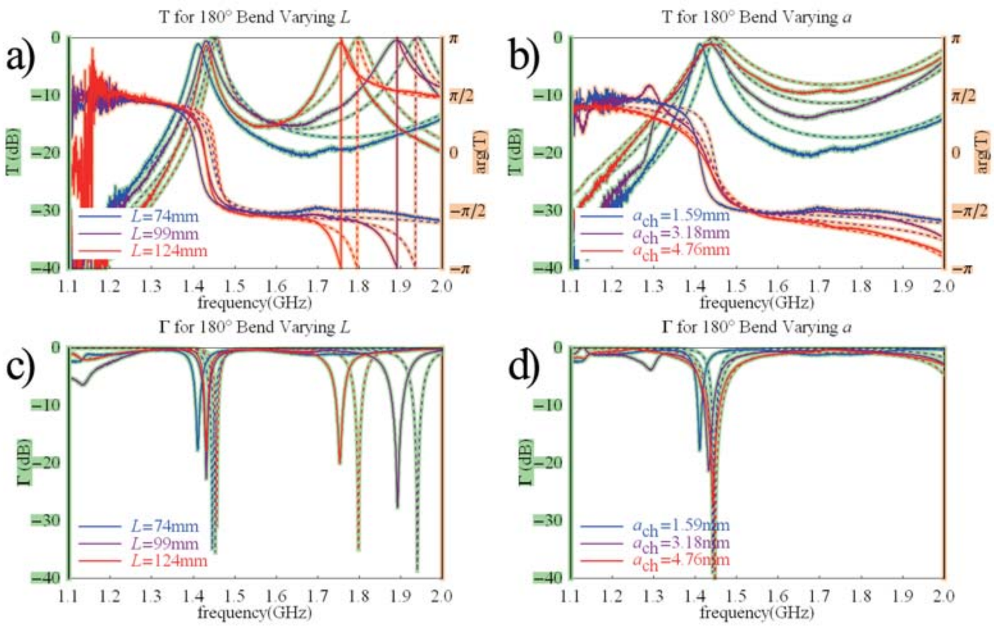




Waveguide Bends with Narrow Channels

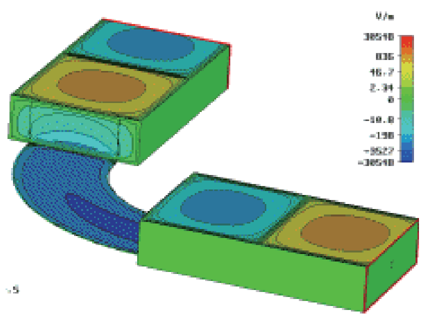


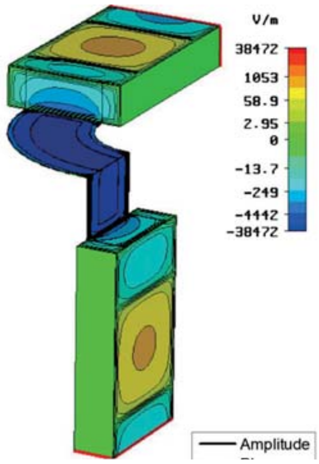
180-degree Waveguide Bends



B. Edwards, A. Alù, M. Silveirinha, N. Engheta
Journal of Applied Physics, 2009

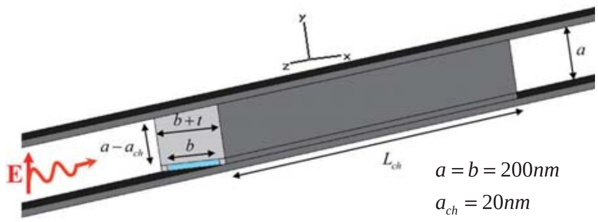
Waveguide Bends with Narrow Channels





A. Alu, M. Silveirinha, N. Engheta, Phys. Rev. E., 78, 016604 (2008)

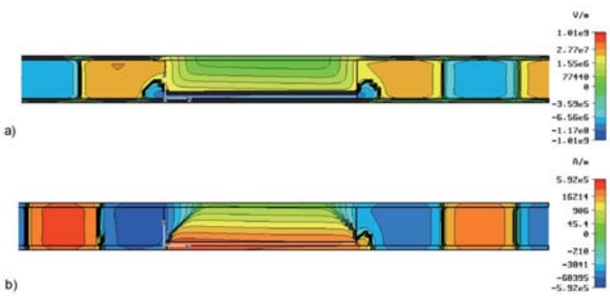
Plasmonic Channels and ENZ Tunneling

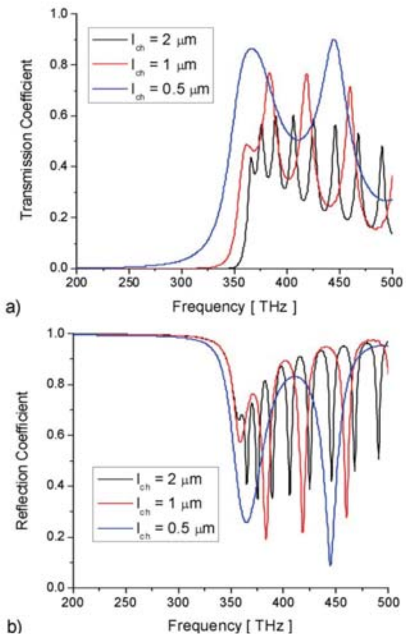


$a = b = 200nm$

$a_{ch} = 20nm$

$t = 50nm$





A. Alù and N. Engheta
Phys. Rev. B, 78, 2008

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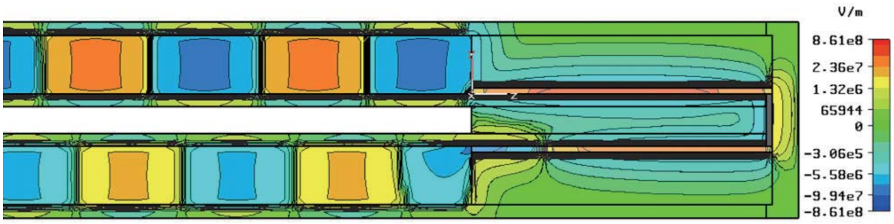
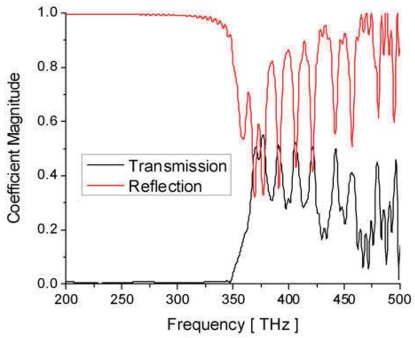




$a = b = 200nm$

$a_{ch} = 20nm$

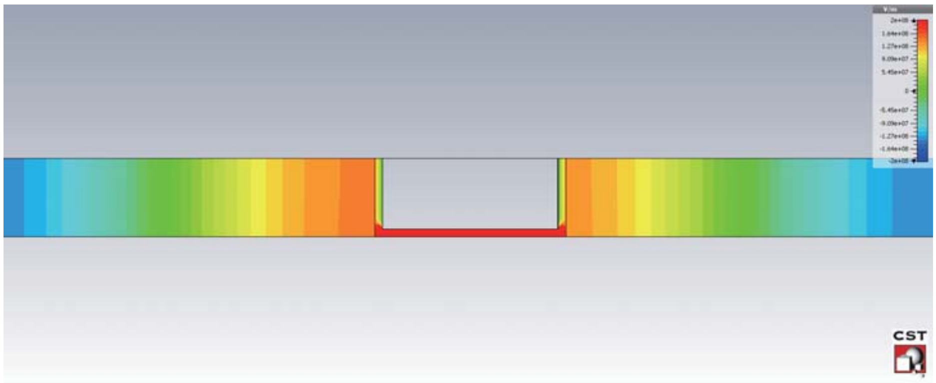
$t = 50nm$

A. Alù and N. Engheta
Phys. Rev. B. 78, 2008

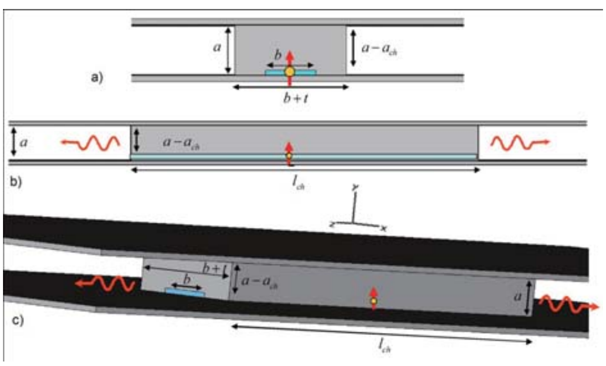
ENZ and Spontaneous Emission Rate of Optical Emitters

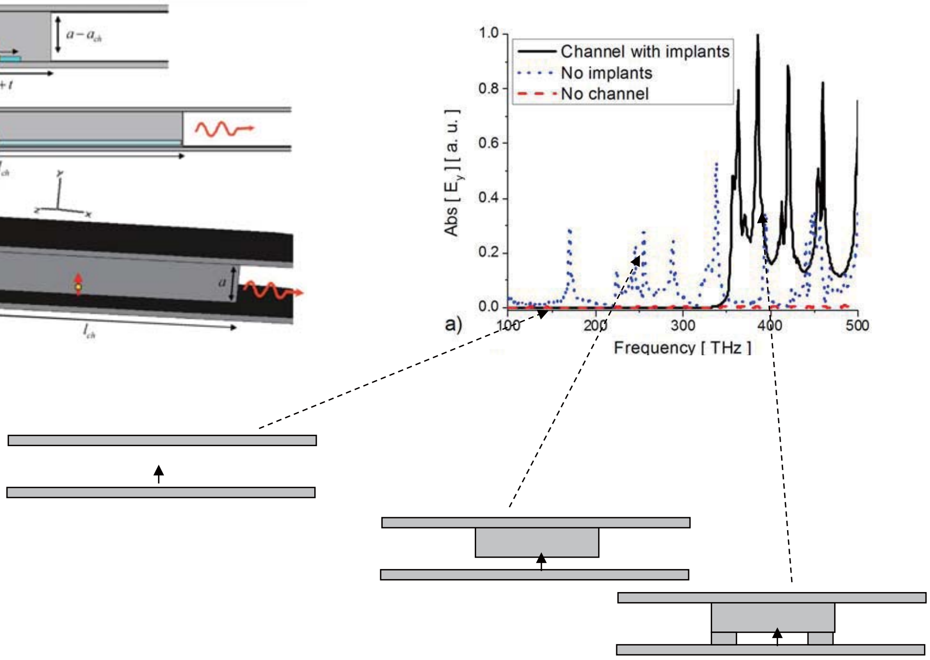
A. Alu and N. Engheta, Phys. Rev. Lett. 103, 043902 (2009)

Field Enhancement Using ENZ



Enhancement of Optical Emitters





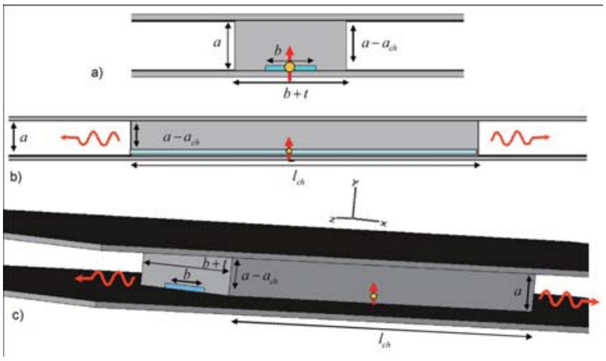
$a = b = 200nm$

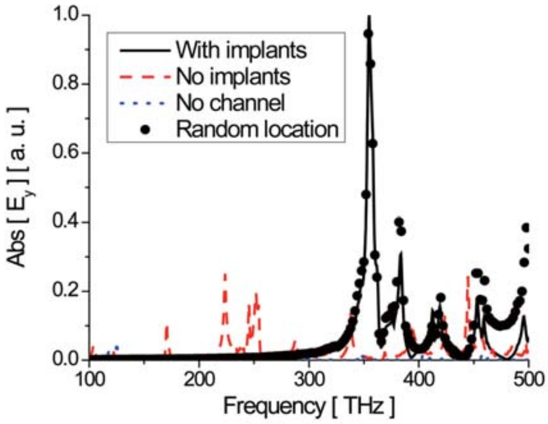
$a_{ch} = 20nm$

$t = 300nm$

A. Alù and N. Engheta
Phys. Rev. Lett. 2009

Enhancement of Optical Emitters

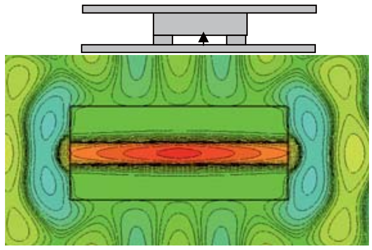




$a = b = 200nm$

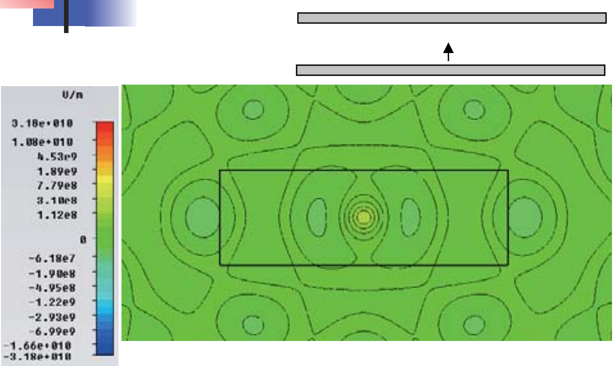
$a_{ch} = 20nm$

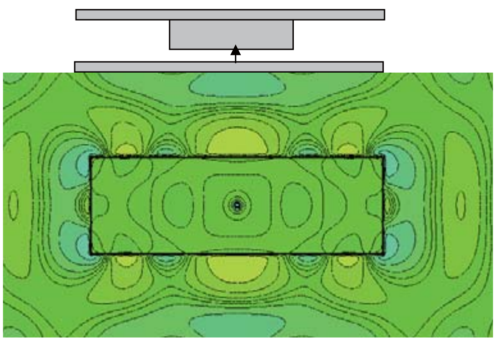
$t = 50nm$

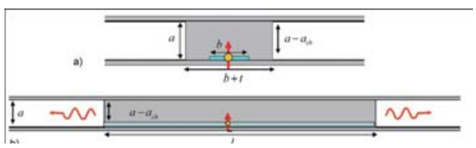


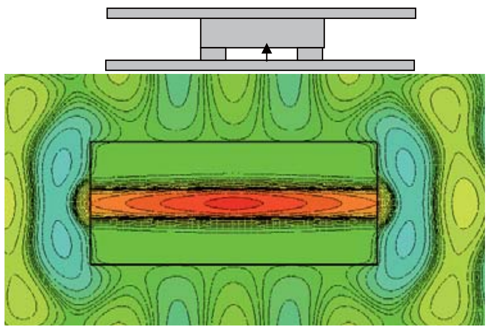
A. Alù and N. Engheta
Phys. Rev. Lett. 103, 043902 (2009)

ENZ and Purcell Effects



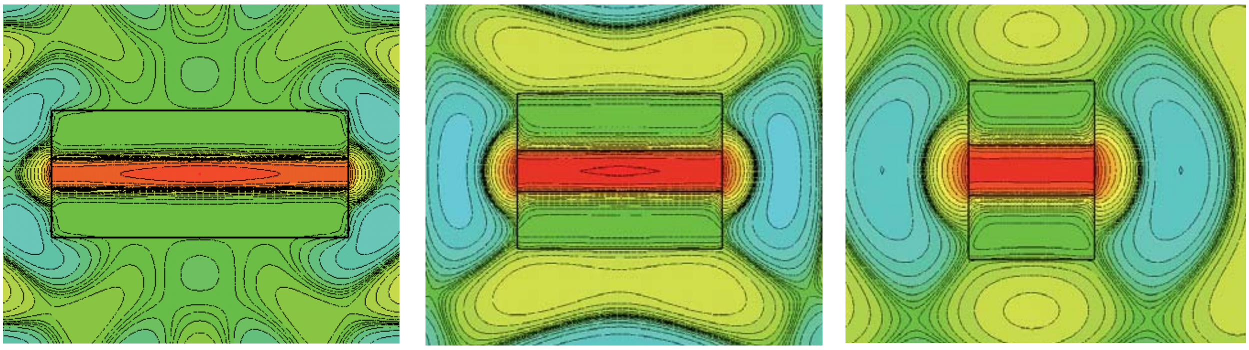






A. Alù and N. Engheta
Phys. Rev. Lett. 2009

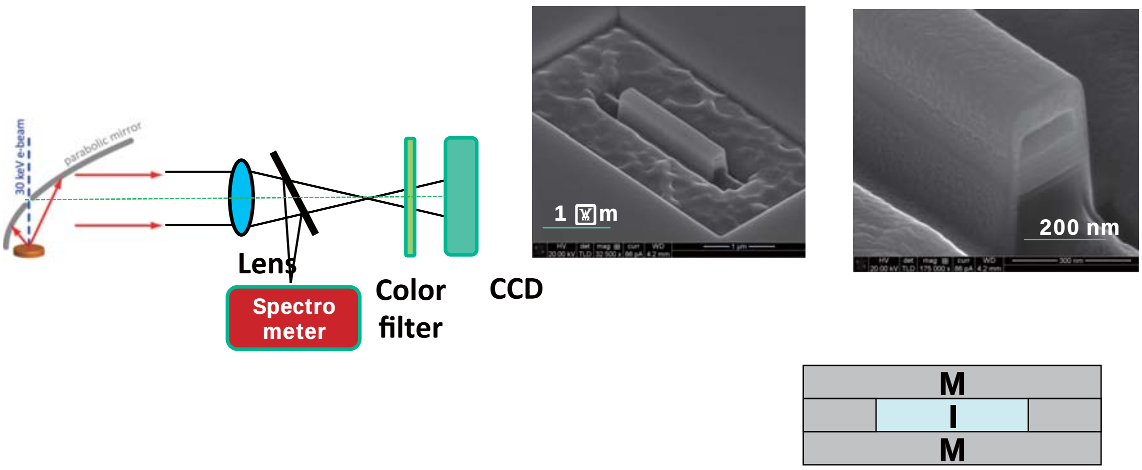
ENZ and Purcell Effects



A. Alù and N. Engheta
Phys. Rev. Lett. 2009

Experimental Verification Using CL Spectroscopy

Collaboration with Albert Polman's Group in AMOLF



E. J. Vesseur, T. Coenen, H. Caglayan, N. Engheta, A. Polman Phys. Rev. Lett., 110, 013902 (2013)

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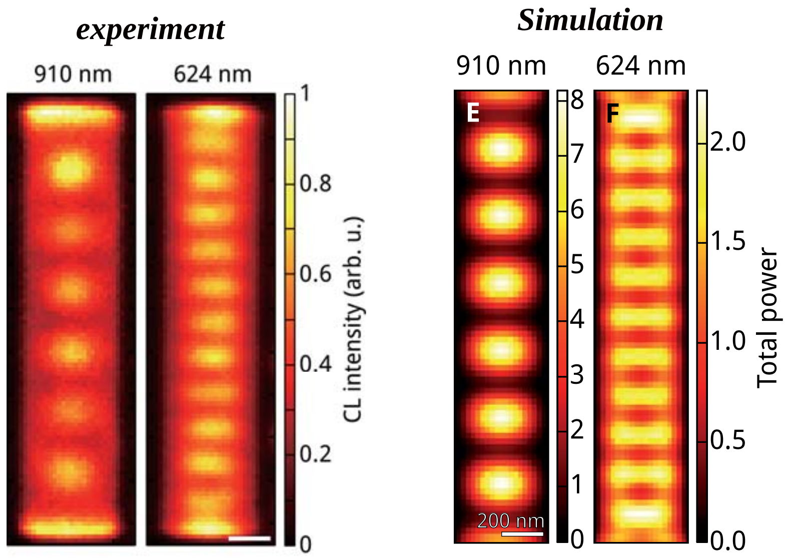

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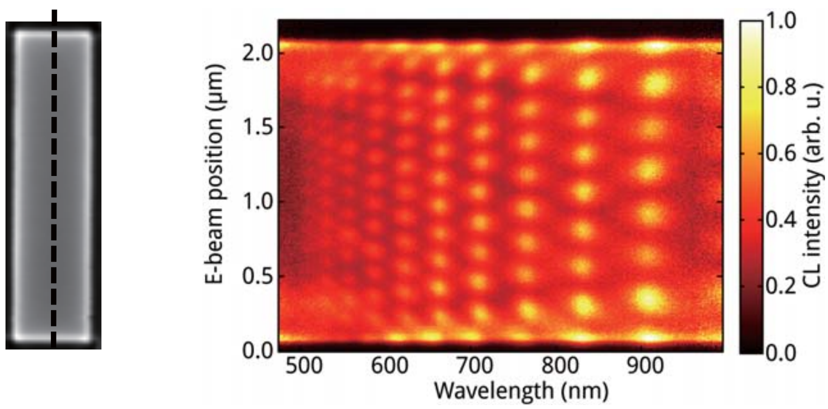
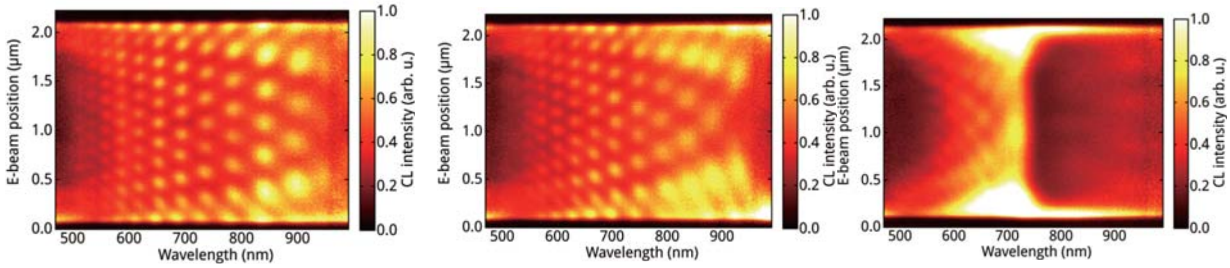


E. J. Vesseur, T. Coenen, H. Caglayan, N. Engheta, A. Polman Phys. Rev. Lett., (2013)

Experimental Verification Using CL Spectroscopy

Collaboration with Albert Polman's Group in AMOLF

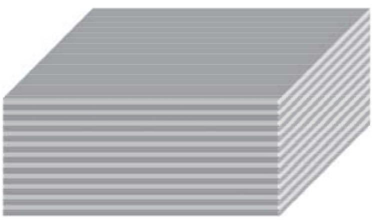
Waveguide Width = 250 nm **Waveguide Width = 240 nm** **Waveguide Width = 180 nm**



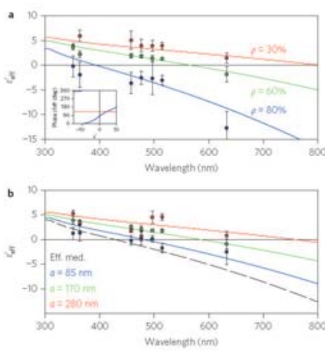
E. J. Vesseur, T. Coenen, H. Caglayan, N. Engheta, A. Polman *Phys. Rev. Lett., 110, 013902 (2013)*

Experimental Verification ENZ Stack

Collaboration with Albert Polman's Group in AMOLF

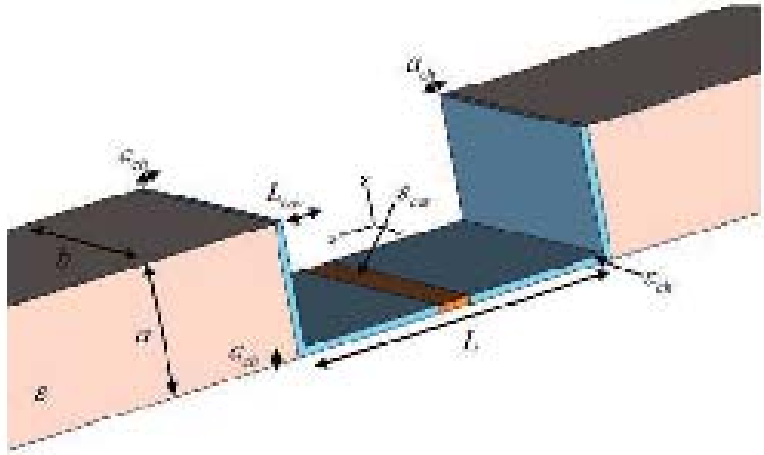


$\mathrm{Re}(\varepsilon) \cong 0$



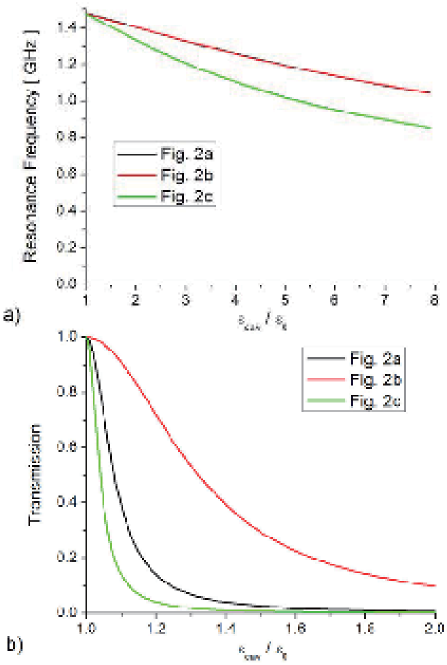
R. Maas, J. Parsons, N. Engheta, A. Polman *Nature Photonics, 7(11), 907-912 (2013)*

Dielectric Sensing



A. Alù and N. Engheta, Phys. Rev. B., 78, July 2008

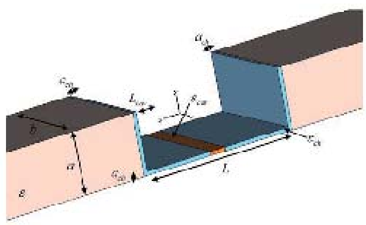
Dielectric Sensing



$L_{cav} = L/10$
$a_{ch} = a/64$

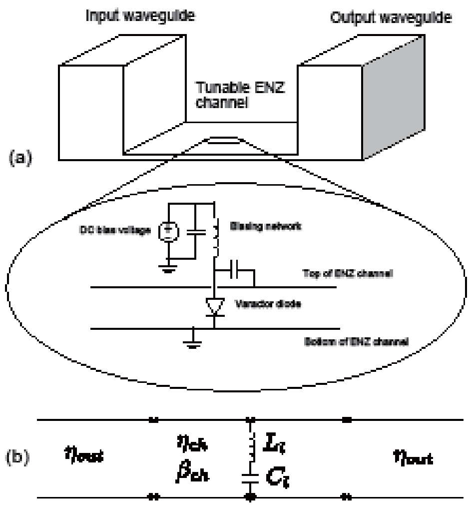
$L_{cav} = L/10$
$a_{ch} = a/16$

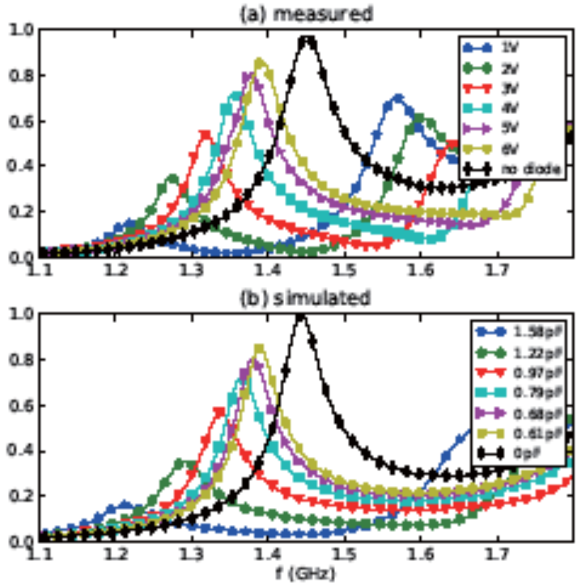
$L_{cav} = L/5$
$a_{ch} = a/64$



A. Alù and N. Engheta, Phys. Rev. B., 78, July 2008

Nonlinearity in ENZ Channels





D. Powell, A. Alù, B. Edwards, A. Vakil, Y. Kivshar, and N. Engheta,
Phys. Rev. B. 2009.

Fields and Waves in Metamaterials Part 3

Nader Engheta

University of Pennsylvania
Philadelphia, PA 19104, USA

August 16-17, 2014

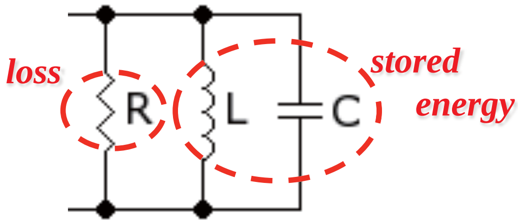
Graphene

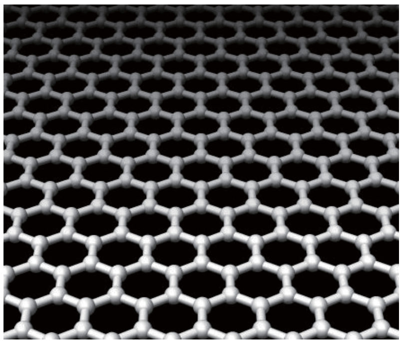
$$J_s = \sigma_g E$$

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

$$\underbrace{\sigma_g}_{} = \underbrace{\sigma_{g,r}}_{>0} + i\underbrace{\sigma_{g,i}}_{>0 \text{ or } <0}$$

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





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

Graphene Conductivity

$$\sigma_g(\omega,\mu_c,\Gamma,T) =$$
$$= \frac{-ie^2(\omega+i2\Gamma)}{\pi\hbar^2}\left[\frac{1}{(\omega+i2\Gamma)^2}\int_0^\infty \Omega\left(\frac{\partial f_d(\Omega)}{\partial\Omega} - \frac{\partial f_d(-\Omega)}{\partial\Omega}\right)d\Omega - \int_0^\infty \frac{f_d(-\Omega)-f_d(\Omega)}{(\omega+i2\Gamma)^2 - 4(\Omega/\hbar)^2}\Omega\right]$$

$$\sigma_g = \sigma_{\text{interband}} + \sigma_{\text{intraband}}$$

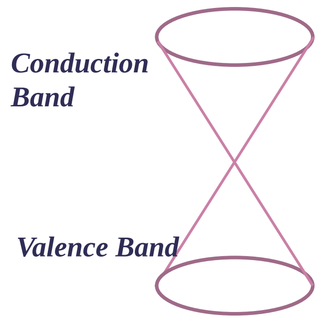
$$f_d(\Omega) \equiv \left[e^{(\Omega-\mu_c)/k_BT} + 1\right]^{-1}$$

$$\sigma_{\text{interband}} \approx \frac{ie^2}{4\pi\hbar}\ln\left[\frac{2|\mu_c| - (\omega+i2\Gamma)\hbar}{2|\mu_c| + (\omega+i2\Gamma)\hbar}\right] \qquad k_BT \ll |\mu_c|$$

$$\mathrm{Im}(\sigma_{\text{interband}}) < 0$$

$$\sigma_{\text{intraband}} = \frac{ie^2 k_BT}{\pi\hbar^2(\omega+i2\Gamma)}\left[\frac{\mu_c}{k_BT} + 2\ln\left(e^{-\mu_c/k_BT} + 1\right)\right]$$

$$\mathrm{Im}(\sigma_{\text{intraband}}) > 0$$



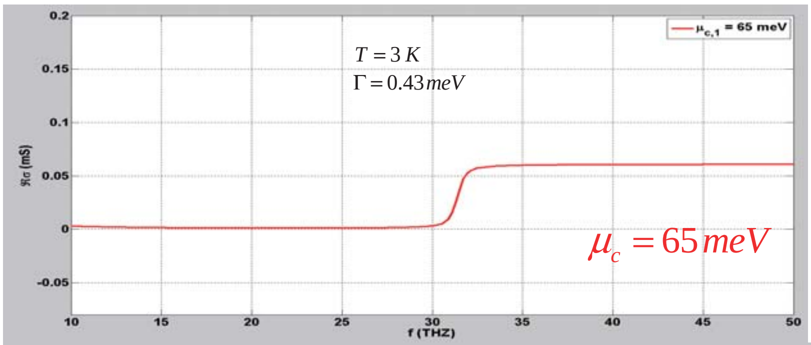
P. Gusynin et al., J. Phys: Condens. Matter, 19 (2007)

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

Graphene Conductivity

$$\sigma_g = \sigma_{\text{interband}} + \sigma_{\text{intraband}}$$

$\mathrm{Re}(\sigma_g)$



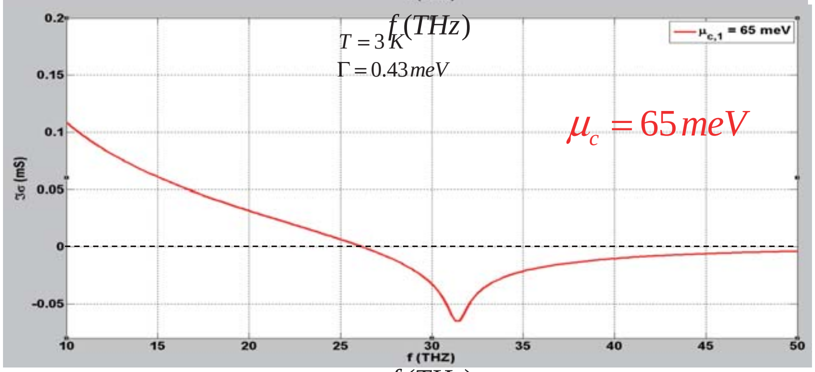
$f\,(THz)$

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

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

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

$\mathrm{Im}(\sigma_g)$

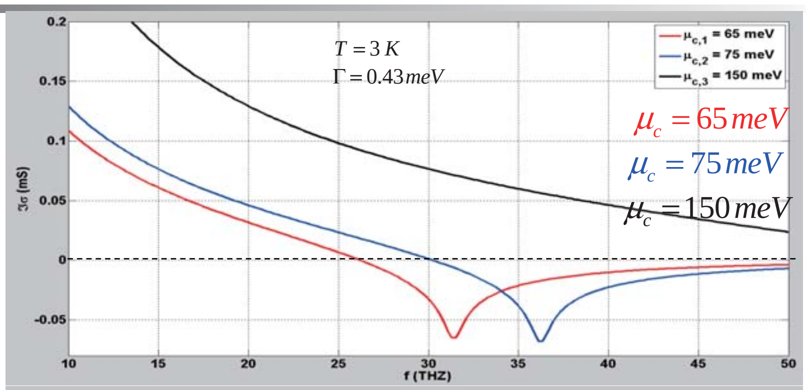


$f\,(THz)$

P. Gusynin et al., J. Phys: Condens. Matter, 19 (2007) ***G. Hanson, J. Appl. Phys. 103, 064302 (2008)***

Graphene Conductivity

$\mathrm{Im}(\sigma_g)$



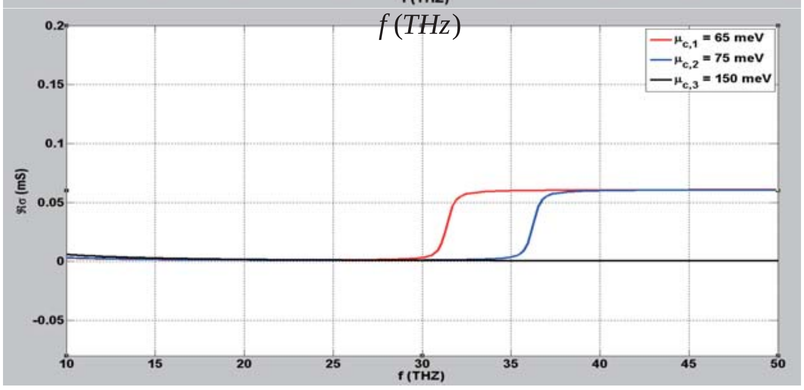
$f\,(THz)$

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

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

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

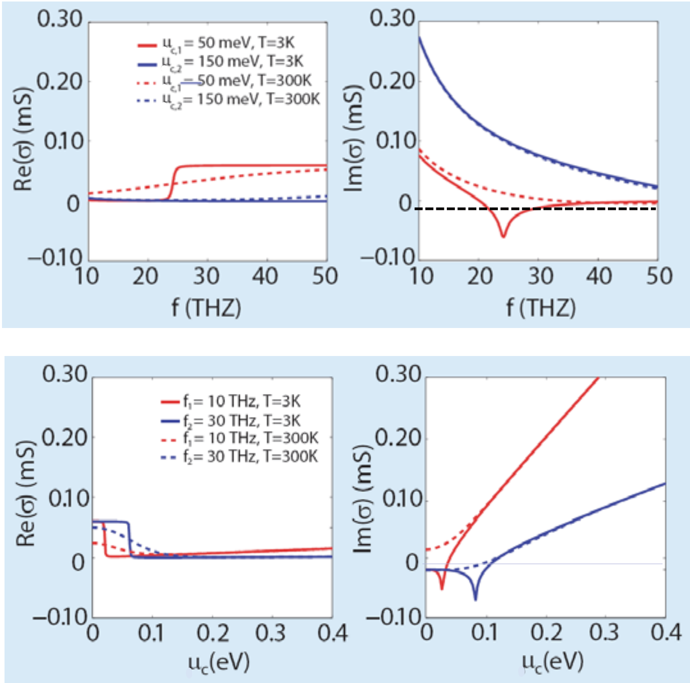
$\mathrm{Re}(\sigma_g)$



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

$f\,(THz)$

Graphene Conductivity



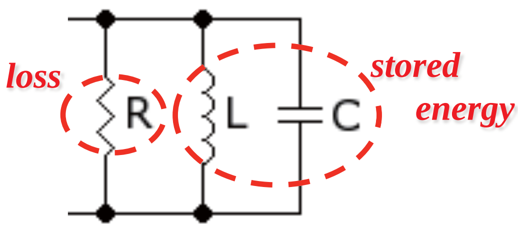
$\Gamma = 0.43$ meV

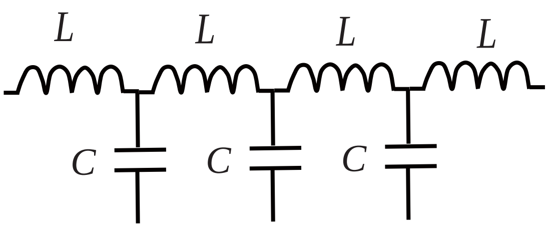
$$\sigma_g = \sigma_r + i\sigma_i$$

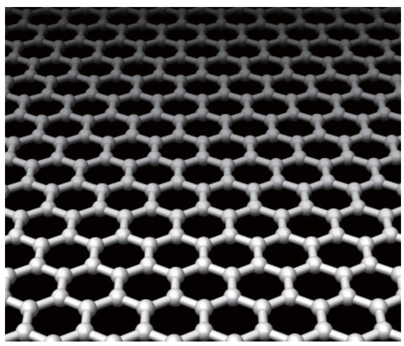
G. Hansen, J. Appl. Phys. 103, 064302 (2008)

From Transmission Line to Graphene

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





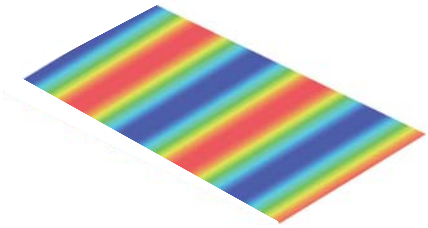


http://math.ucr.edu/home/baez/graphene.jpg

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, <u>Phys. Rev. Lett.</u> 99, 016803 (2007)

G. Hanson, <u>J. Appl. Phys.</u> 103, 064302 (2008)

M. Jablan, H. Buljan, M. Soljacic, <u>Phys. Rev. B.,</u> 80, 245435 (2010)

Tailoring Conductivity and SPP

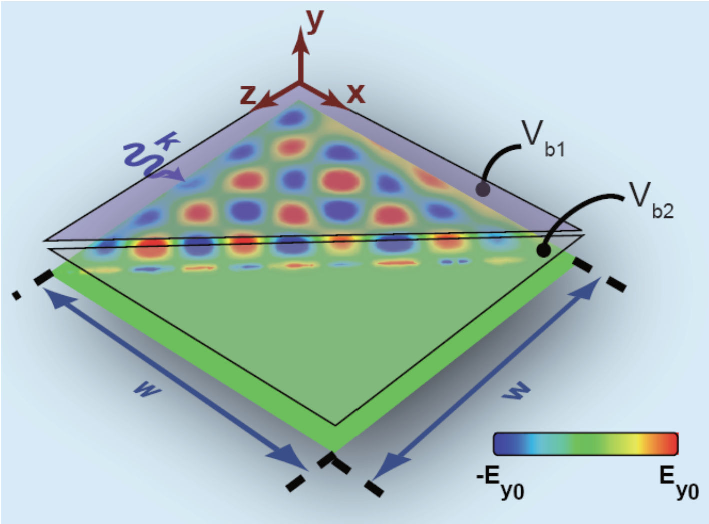
$$\sigma_{g,i} = f(\omega, \mu_c, \Gamma, T)$$

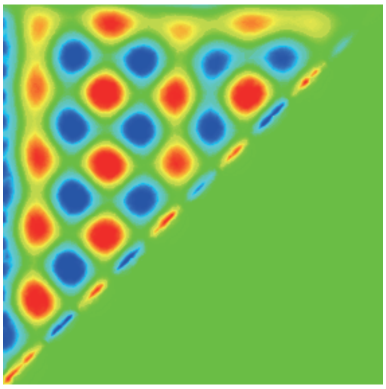
cnst cnst cnst

$$n_{SPP} = \frac{\beta_{SPP}}{k_0} \propto \frac{1}{\sigma_{g,i}}$$

$\sigma_{g,i}$? $\sigma_{g,r}$

Fresnel Reflection





w= 800 nm

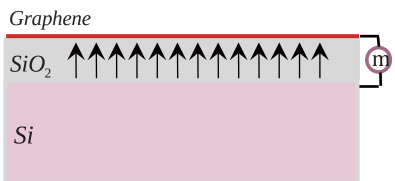
T = 3 K, Γ = 0.43 meV

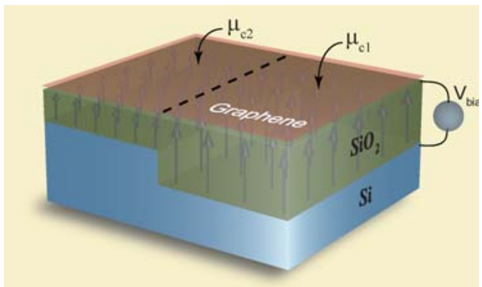
$m_{c,1}$ = 150 meV → σ_{g1} = 0.0009 + i 0.0765 mS

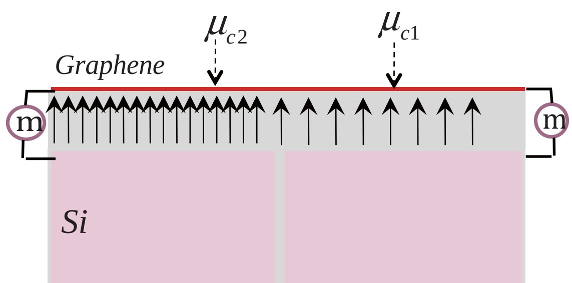
$m_{c,2}$ = 6.5 meV → σ_{g2} = 0.0039 − i 0.0324 mS

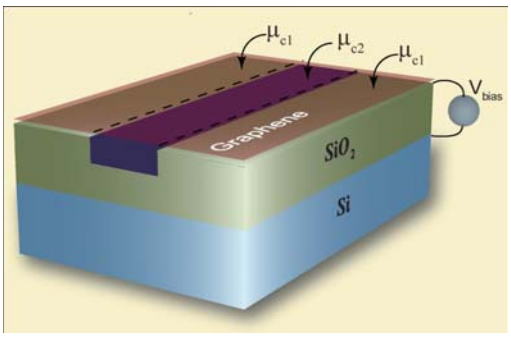
Vakil, Engheta, Science 332, 1291 (2011)

Inhomogeneous Conductivity across Graphene



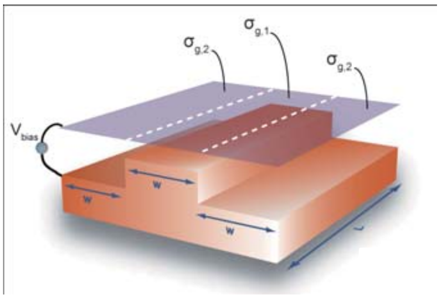


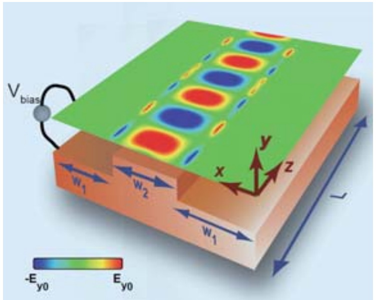


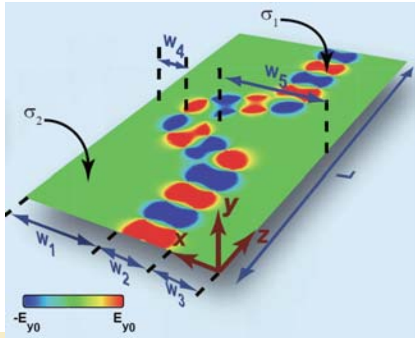


Vakil, Engheta, Science 332, 1291 (2011)

One-Atom-Thick Waveguides





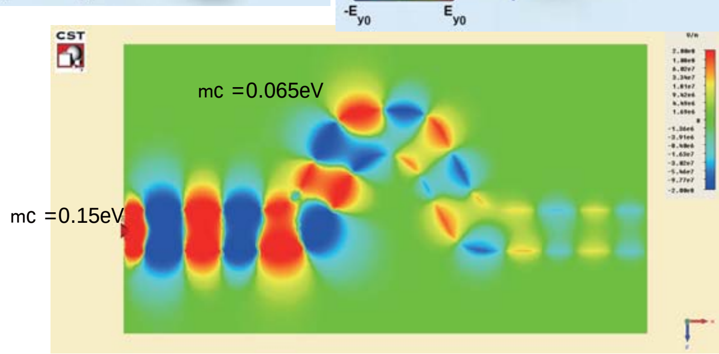


Region 1: $\sigma_{g,i} > 0$

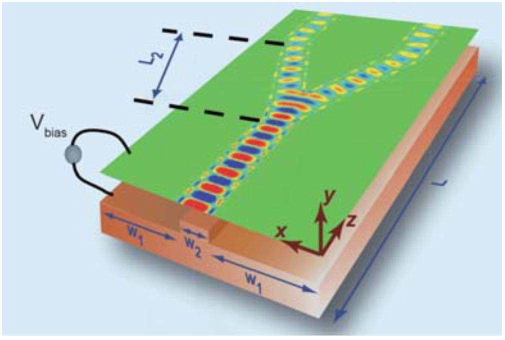
$\mu_c = 150\, meV$

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

$\mu_c = 65\, meV$



One-Atom-Thick IR Splitter

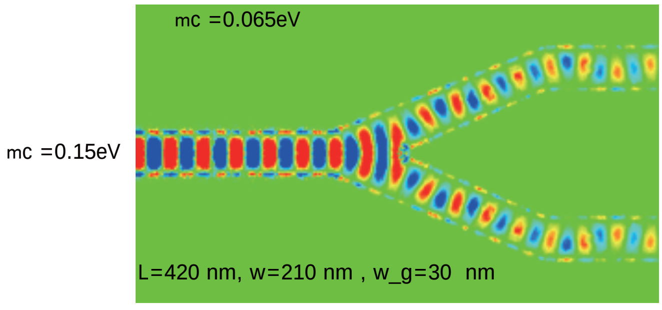


Region 1: $\sigma_{g,i} > 0$

$\mu_c = 0.15\, eV$

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

$\mu_c = 0.065\, eV$



One-Atom-Thick Optical "Fiber"

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

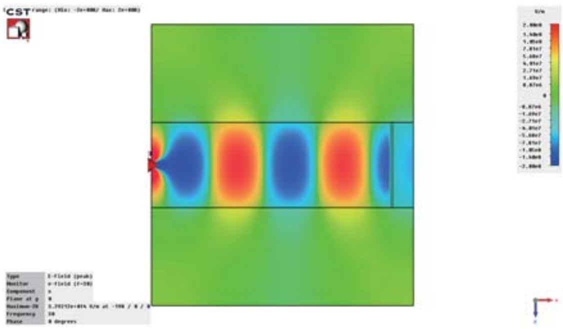
$\mu_c = 150\ meV$

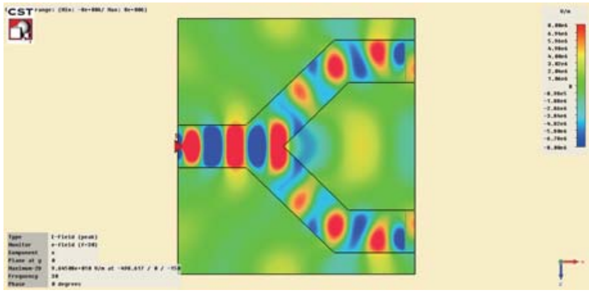
$\mathrm{Re}(\beta_{SPP})\ ;\ 70k_o$

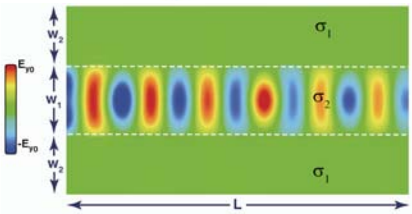
Region 2: $\sigma_{g,i} > 0$

$\mu_c = 300\ meV$

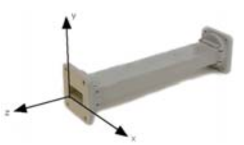
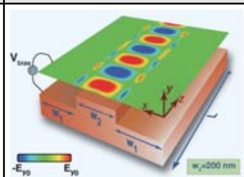
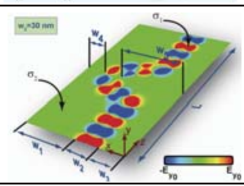
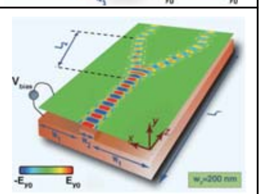
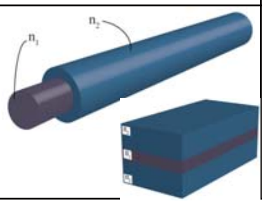
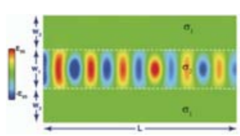
$\mathrm{Re}(\beta_{SPP})\ ;\ 30k_o$







Guiding Waves on one-atom-thick Platform

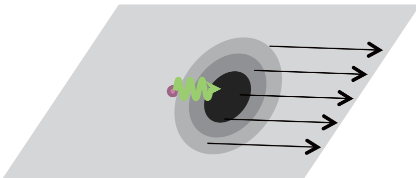
	3D component	One-Atom-Thick Version
Waveguide		
Bent Waveguide		
Splitter/Divider		
Optical Fiber/ Dielectric Slab waveguide		

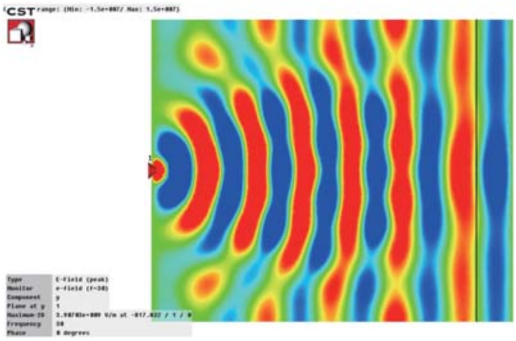
Graphene SPP Lens

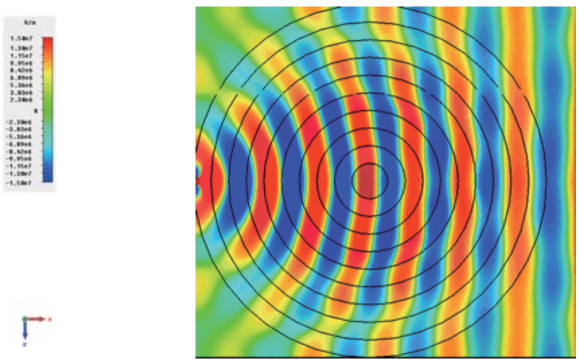
One-Atom-Thick TO: Lens

$$\beta_{SPP} \equiv n_{SPP} k_o >> k_o$$

$$\lambda_{SPP} << \lambda_{free-space}$$







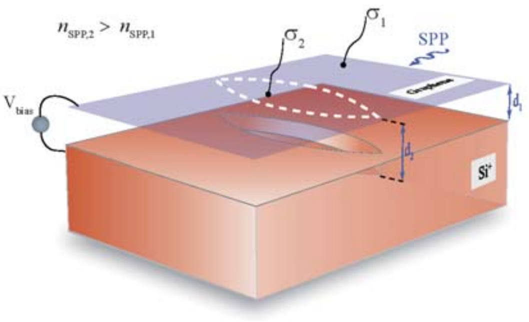
$D = 1.5\,\mu m$

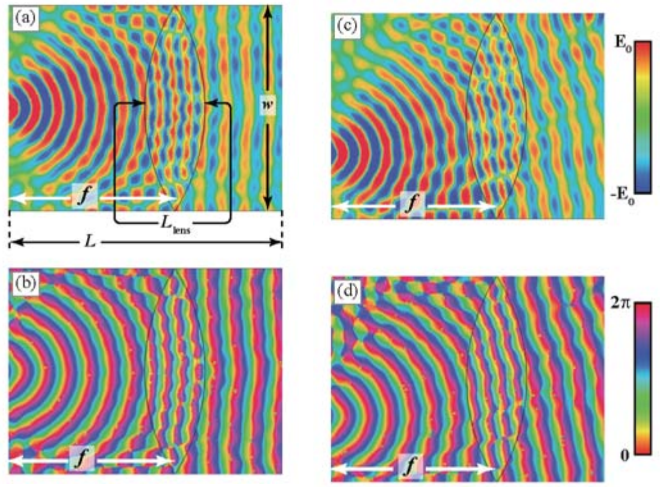
$L = 1.6\,\mu m$

$W = 75\,nm$

Vakil, Engheta, <u>Science</u> 332, 1291 (2011)

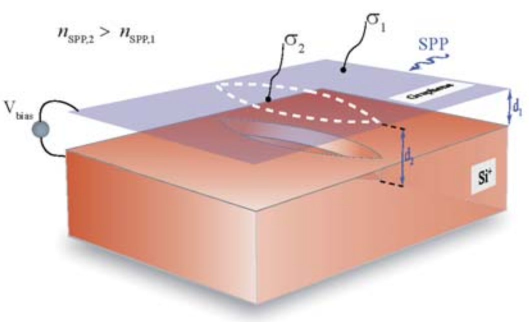
One-Atom-Thick Signal Processing: Fourier Transform

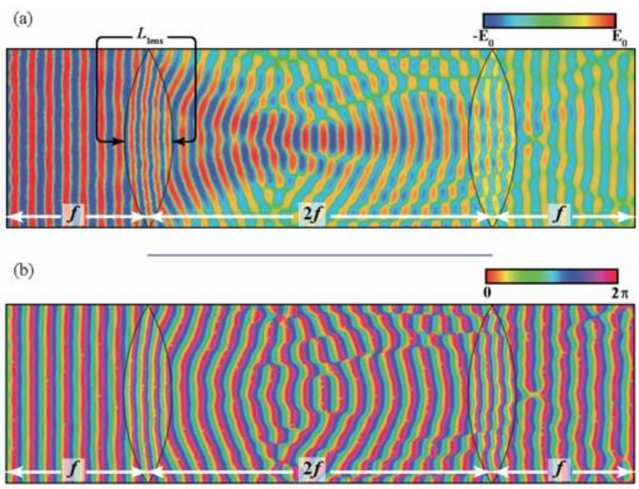




Vakil, Engheta, <u>Phys. Rev. B,</u> (2012)

Graphene Fourier Optics

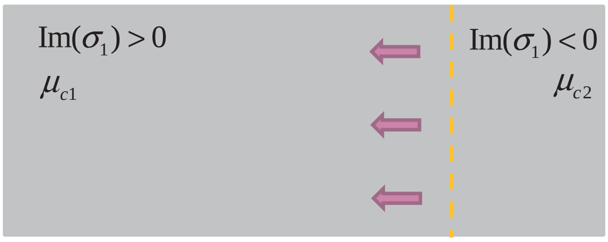


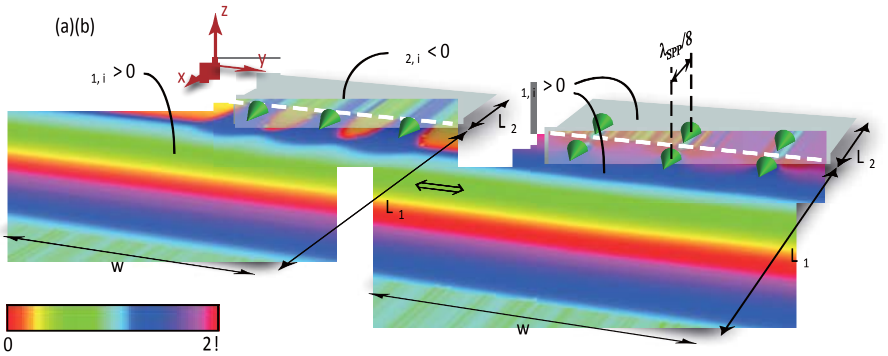


Vakil and Engheta, <u>Phys. Rev. B</u> (2012)

Graphene SPP Mirror

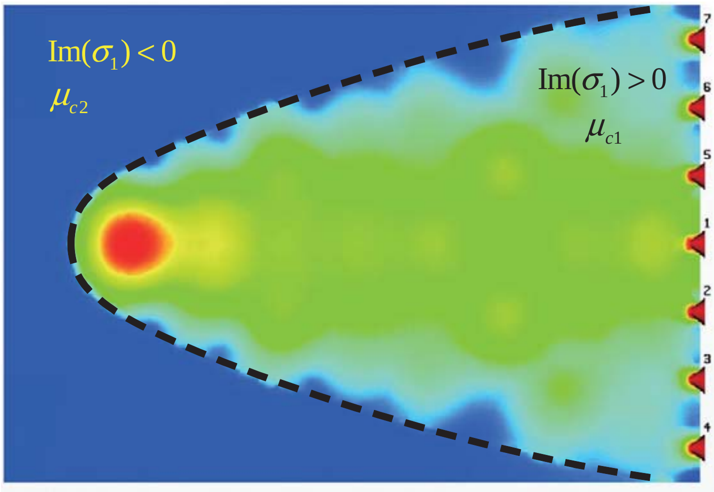
One-Atom-Thick SPP Reflector





Vakil and Engheta, <u>Optics Communications,</u> (2012)

One-Atom-Thick SPP Reflector



Vakil and Engheta, Optics Communications (2012)

Graphene Metamaterials

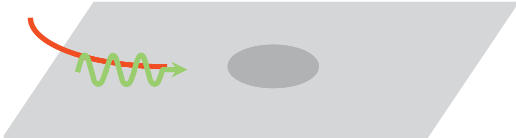
One-Atom-Thick Scatterer

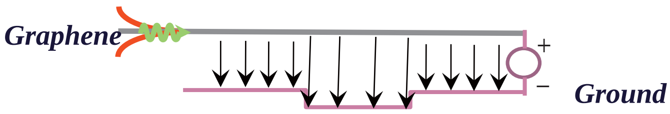
Region 1: $\sigma_{g,i} > 0$

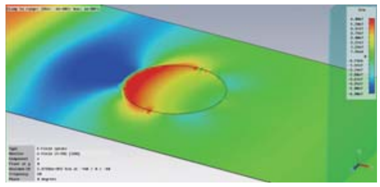
$\mu_c = 150\ meV$

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

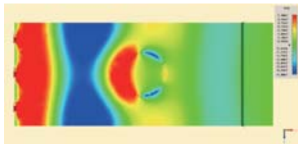
$\mu_c = 65\ meV$





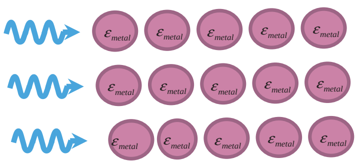


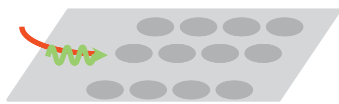
w=120nm
r=25nm



w=55 nm
D = 30 nm

One-Atom-Thick Metamaterials



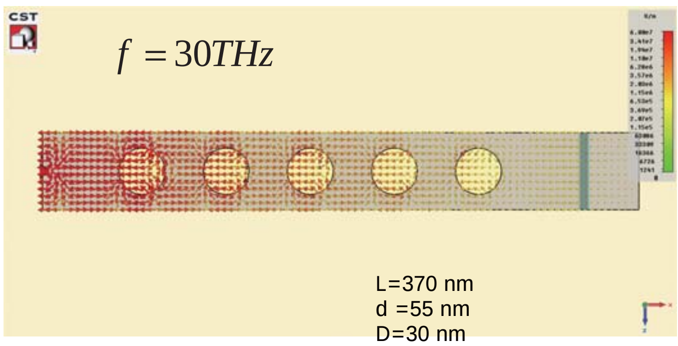


Region 1: $\sigma_{g,i} > 0$

$\mu_c = 150\ meV$

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

$\mu_c = 65\ meV$



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