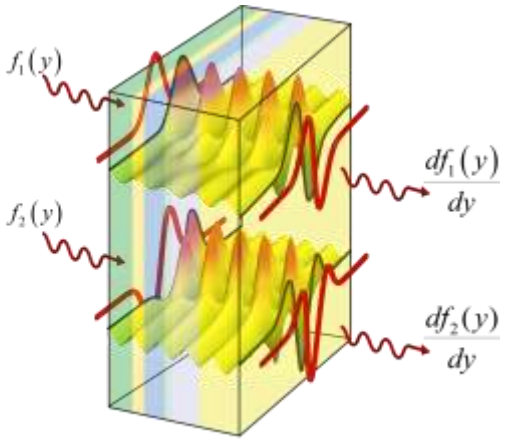
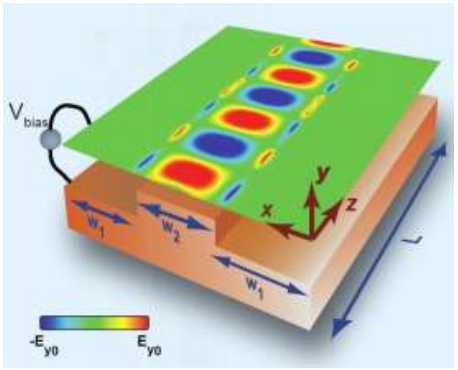
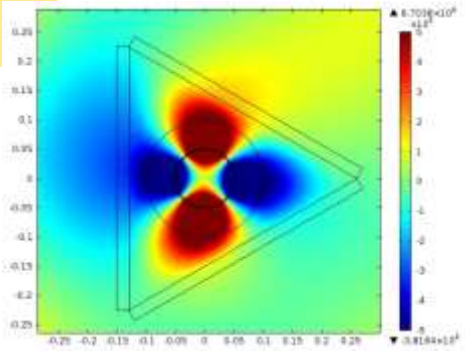
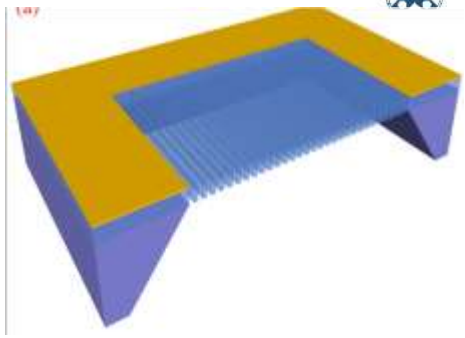
# *Tailoring Waves at the Extreme with Metamaterials*




*Nader Engheta*
*University of Pennsylvania*
*Philadelphia, PA, USA*



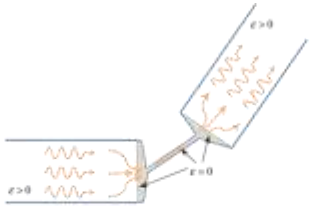


*November 2, 2017*

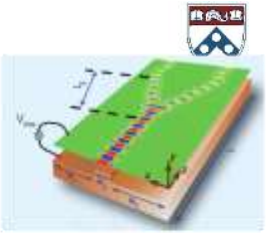
# *Previous Visits to Kharkov (1998, 2000)*

# *Current Research Programs*

Metamaterials Plasmonics

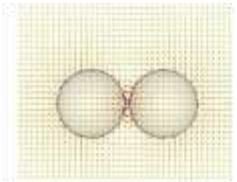


Graphene Metamaterials

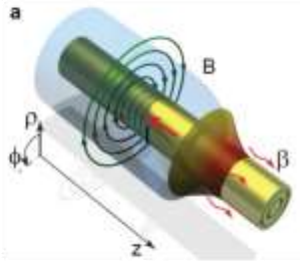


Extreme-Parameter Materials

Nanoscale Optics



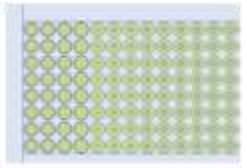
Nonreciprocal Photonics



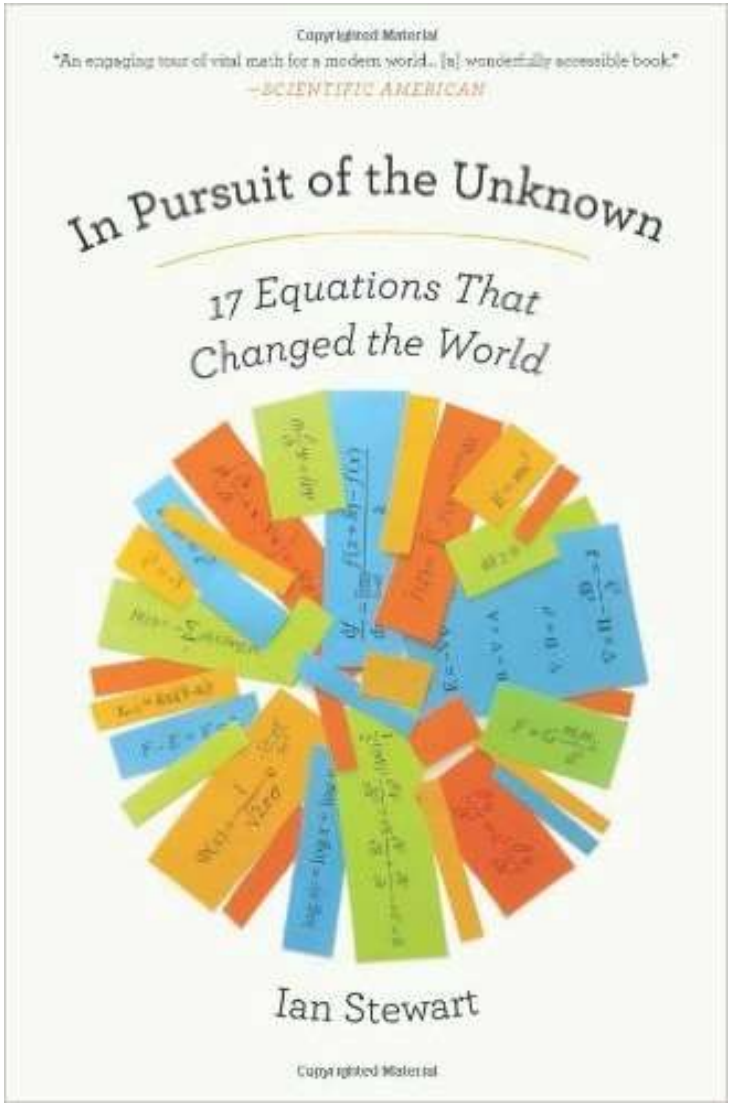

Bio-Inspired Imaging & Sensing

Optical Nanocircuitry

Digital/Quantum Photonics



# *17 Equations That Changed the World*



# 17 Equations That Changed the World

*Ian Stewart, "In Pursuit of the Unknown, 17 Equations that Changed the World", 2012*

***Pythagoras's Theorem*** $a^2 + b^2 = c^2$ ***Pythagoras 530 BC***

***Logarithms*** $\log(xy) = \log(x) + \log(y)$ ***Neper, 1610***

***Calculus*** $\frac{df}{dt} = \lim_{h} f(t+h) - f(t)\big|_{h \to 0}$ ***Newton, 1668***

*Ian Stewart, "In Pursuit of the Unknown, 17 Equations that Changed the World", 2012*

# 17 Equations That Changed the World

*Newton, 1687*

***Law of Gravity***

$$F = G\frac{m_1 m_2}{r^2}$$

*D'Alambert, 1746*

***Wave Equation***

$$\frac{\partial^2 u}{\partial t^2} = v^2 \frac{\partial^2 u}{\partial x^2}$$

*Ian Stewart, "In Pursuit of the Unknown, 17 Equations that Changed the World", 2012*

# 17 Equations That Changed the World

***Square Root of -1*** $i^2 = -1$ ***Euler, 1750***

***Euler's Formula for Polyhedra*** $V - E + F = 2$ ***Euler 1751***

***Normal Distribution*** $\Phi(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$ ***Gauss 1810***

***Fourier Transform*** $F(\omega) = \int_{-\infty}^{+\infty} f(x) e^{-2\pi i x \omega} dx$ ***Fourier 1822***

$$\frac{v}{} + v \cdot \nabla v \Big| = -\nabla p + \nabla \cdot T +$$

$\partial$ $f$ ***Navier & Stokes, 1845***

*Ian Stewart, "In Pursuit of the Unknown, 17 Equations that Changed the World", 2012*

# *17 Equations That Changed the World*

***Navier-Stokes Eq*** ρ &

%∂*t* (

***Maxwell Equations*** $\nabla \cdot \boldsymbol{D} = \rho \quad \nabla \cdot \boldsymbol{B} = 0$ ***Maxwell 1865***

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \qquad \nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}$$

***2nd law of thermodynamic*** $dS \geq 0$ ***Boltzmann 1874***

*Ian Stewart, "In Pursuit of the Unknown, 17 Equations that Changed the World", 2012*

# *17 Equations That Changed the World*

| | | |
|---|---|---|
| ***Relativity*** | $E=mc_2$ | ***Einstein, 1905*** |
| ***Schrodinger Eq.*** | $i\hbar\frac{\partial\Psi}{\partial t}=H\Psi$ | ***Schrodinger 1927*** |
| ***Information Theory*** | $H=-\sum p(x)\log p(x)$ | ***Shannon, 1949*** |

*Ian Stewart, "In Pursuit of the Unknown, 17 Equations that Changed the World", 2012*

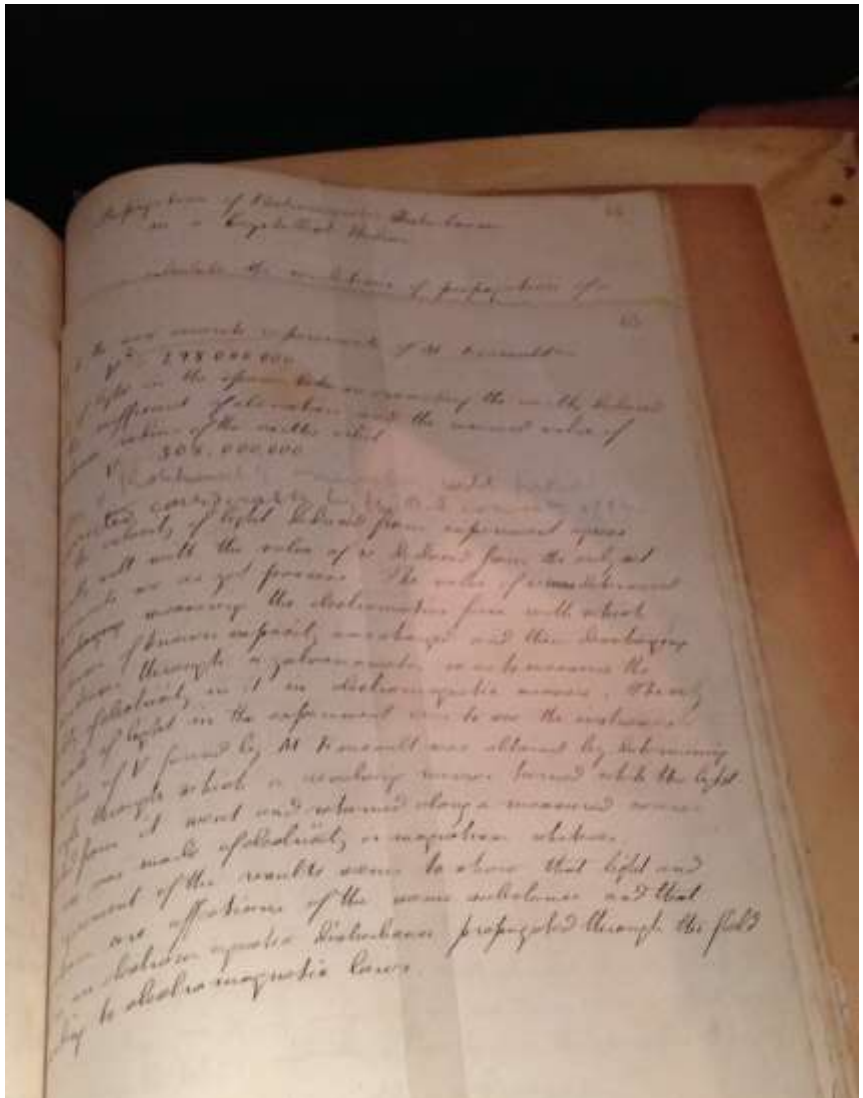
# *17 Equations That Changed the World*

***Chaos Theory*** $x_{t+1} = kx_t(1-x_t)$ ***R. May 1975***

***Black-Scholes Eq.*** $-\frac{1}{2}\sigma^2 S^2 \frac{\partial^2 V}{\partial S^2} + rS\frac{\partial V}{\partial S} + \frac{\partial V}{\partial t} - rV = 0$ ***Black + Scholes 1990***

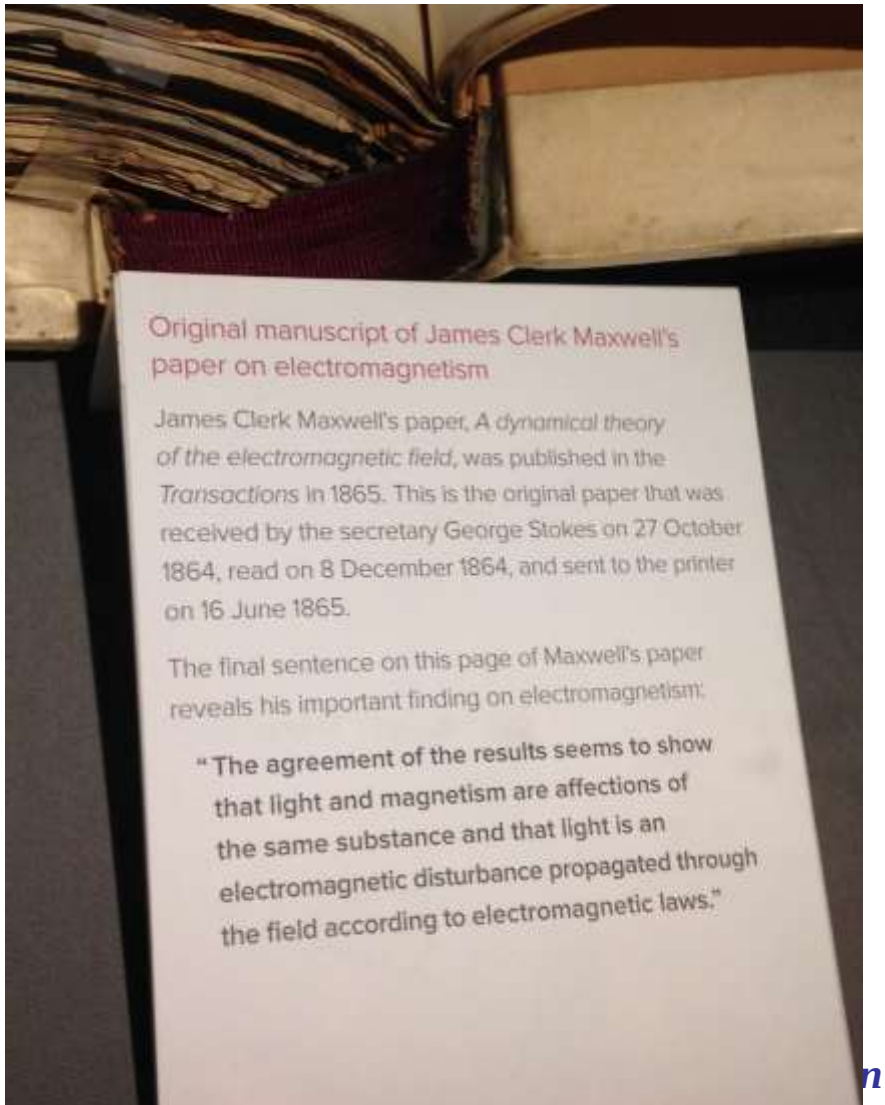
*Ian Stewart, "In Pursuit of the Unknown, 17 Equations that Changed the World", 2012*

# *James Clerk Maxwell's Manuscript*



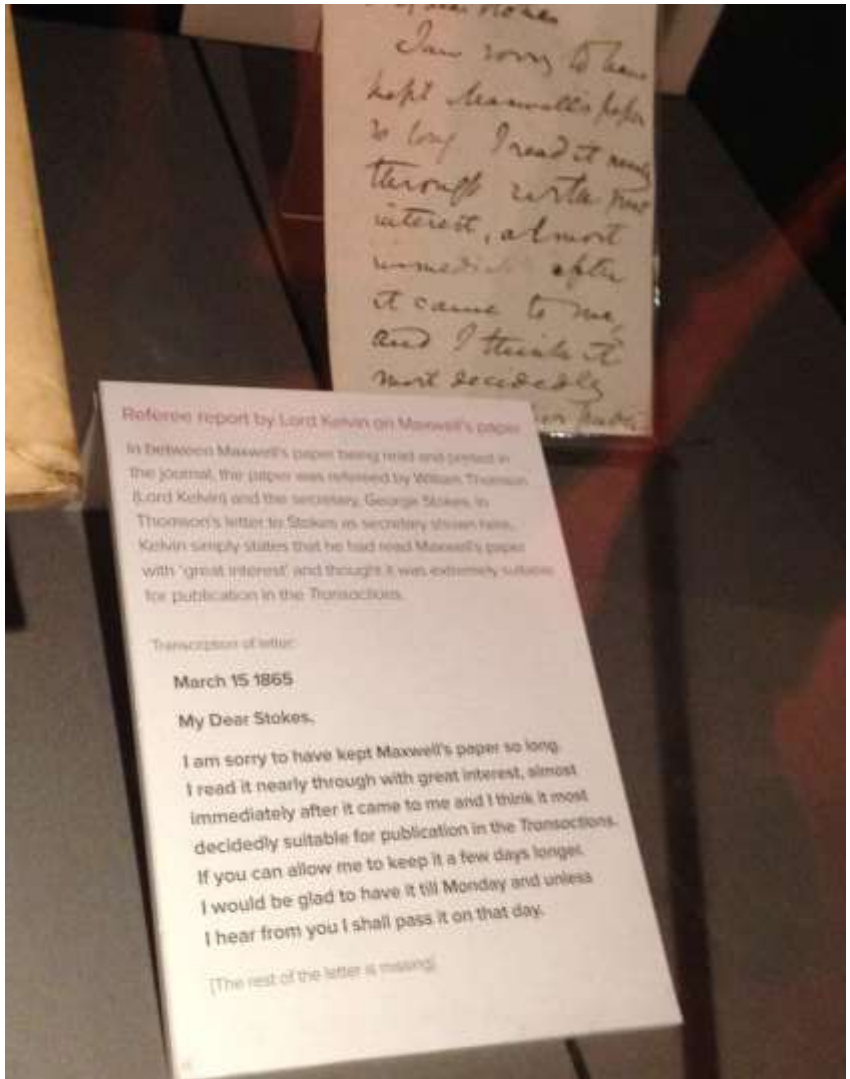
*Royal Society, London, UK*

# *James Clerk Maxwell's Manuscript*




*n Royal Society, London, UK*

# *James Clerk Maxwell's Manuscript*



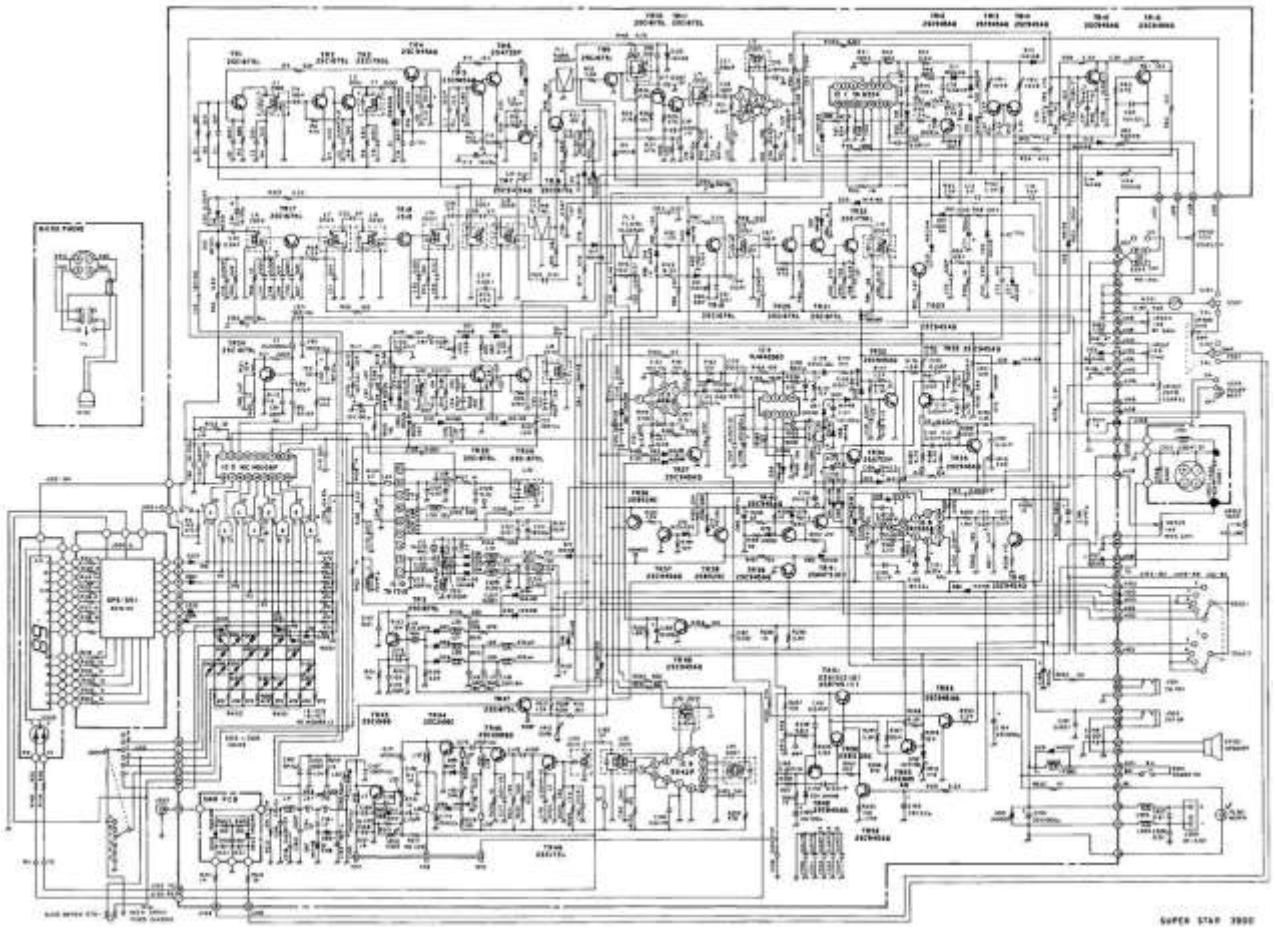

*Royal Society, London, UK*

# *Scientific & Technological Development*

## *Controlling Paths of Charged Carriers*

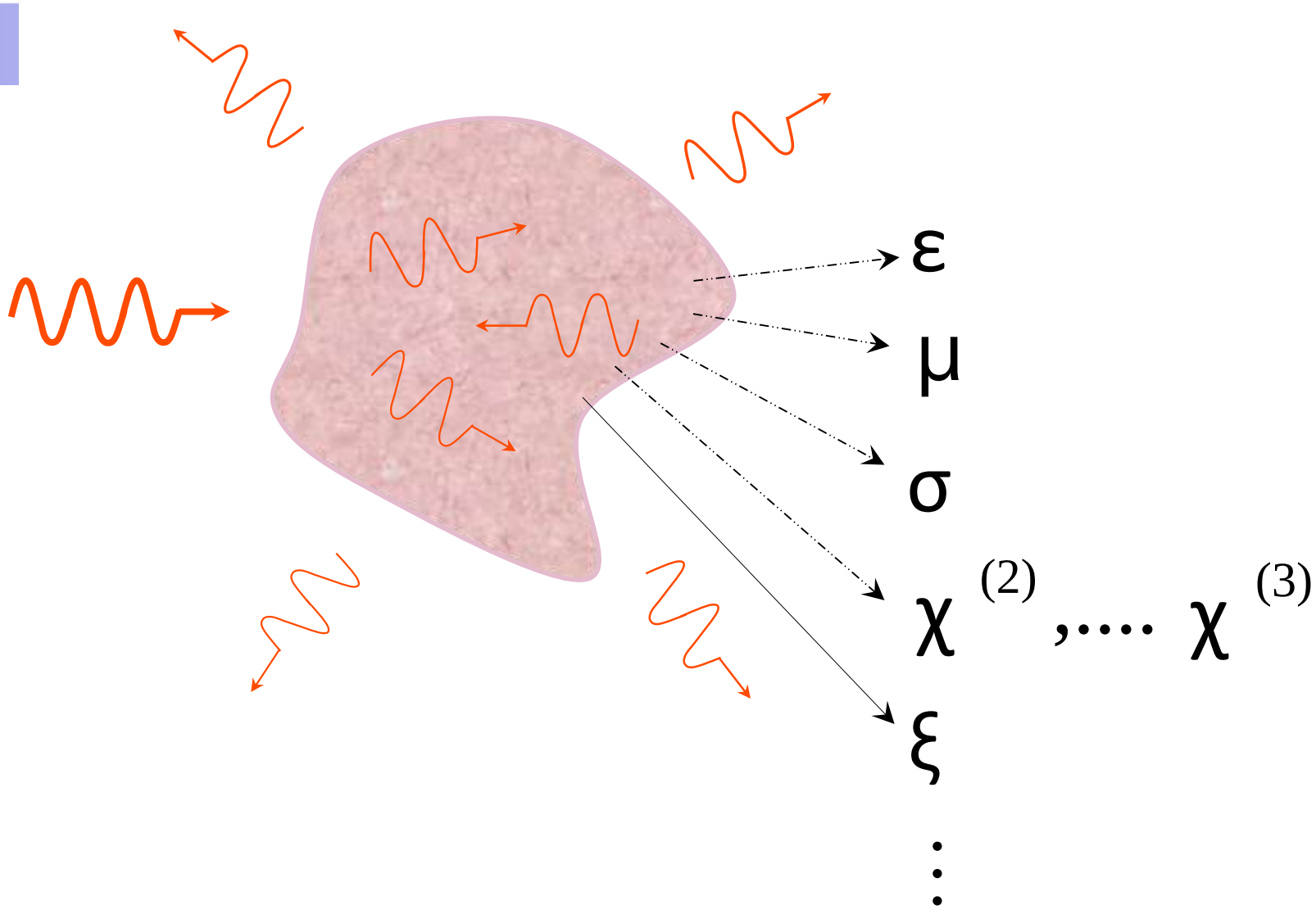
## *Manipulating and Tailoring EM Waves*

# *Circuit Diagram*

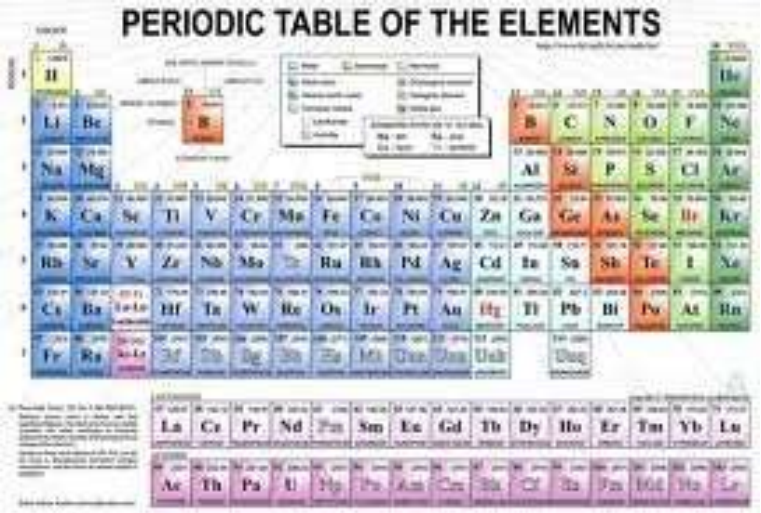


*http://www.schematic.me/radio-circuit-diagram/30/superstar-3900-circuit-schematicjpg*

# *Light-Matter Interaction*


ε
μ
σ
χ (2) ,.... χ (3)
ξ
⋮

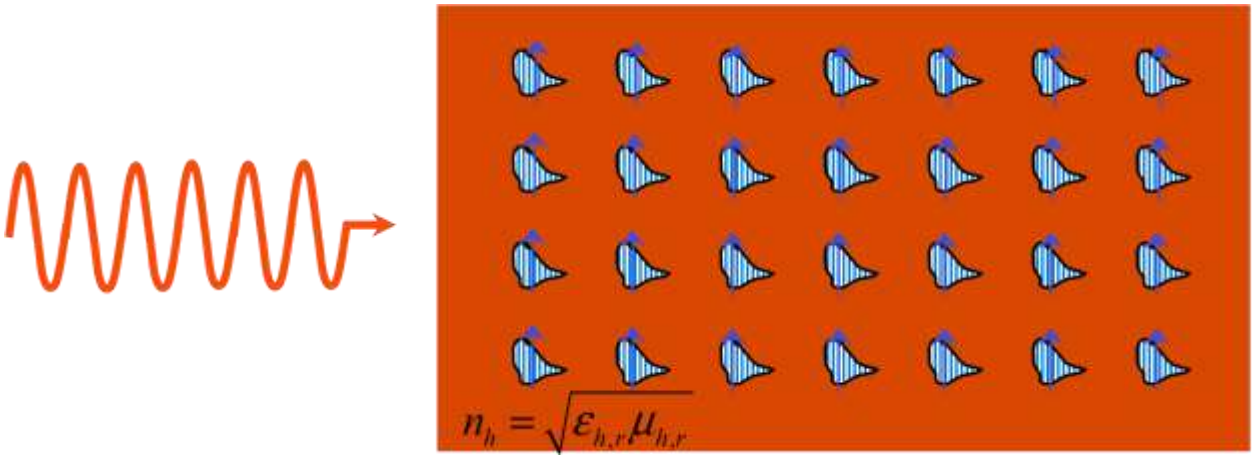
# *"Natural" Materials*





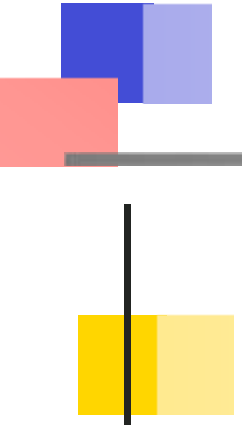
# *Metamaterials*

- *Particulate Composite Materials*
  - *Composition*




- *Alignment*
- *Arrangement*
- *Density*
- *Host Medium*

- *Geometry/Shape*



# *History*

# *Sir Jagadish Chunder Bose*

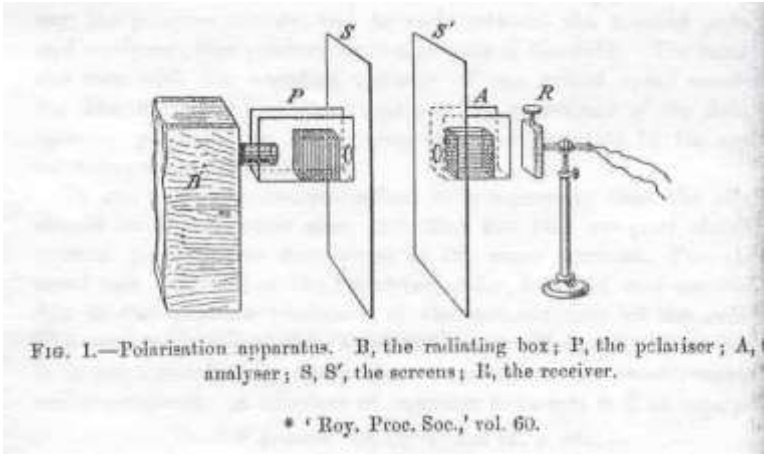



FIG. 1.—Polarisation apparatus. B, the radiating box; P, the polariser; A, analyser; S, S′, the screens; R, the receiver.

* 'Roy. Proc. Soc.,' vol. 60.

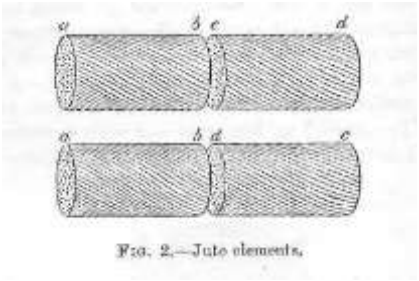



FIG. 2.—Jute elements.

***(1898)***

**From: T. K. Sarkar and D. L. Sengupta, "An appreciation of J. C. Bose's pioneering work in millimeter waves," *IEEE Antennas and Propagation Magazine*, Vol. 39, No. 5, pp. 55-63, 1997. Originally from P. Geddes, *The life and work of Sir Jadagish C. Bose*, New York, Longmans, Greens & Co, 1920.**

**From: J. C. Bose: "On the Rotation of Plane of Polarisation of Electric Waves by a Twisted Structure,"**

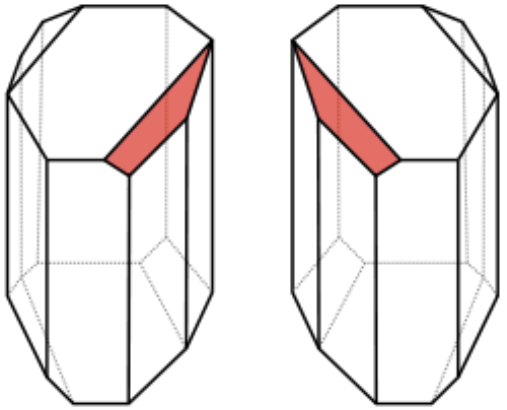
***Proceedings of the Royal Society*, Vol. 63, pp. 146-152, 1898.**

# *Handedness in Nature*

*From Tom Murphy VII wikipedia*

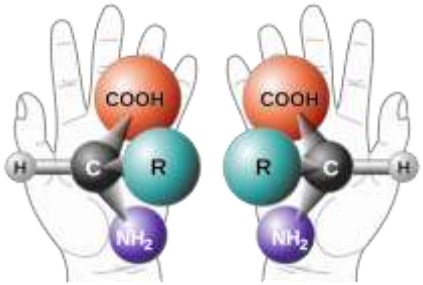
*Right-Handed and Left-Handed Structures*

*From Tom Murphy VII wikipedia*



## *Louis Pasteur (1822-1895)*

*Enantiomors of Amino Acids*

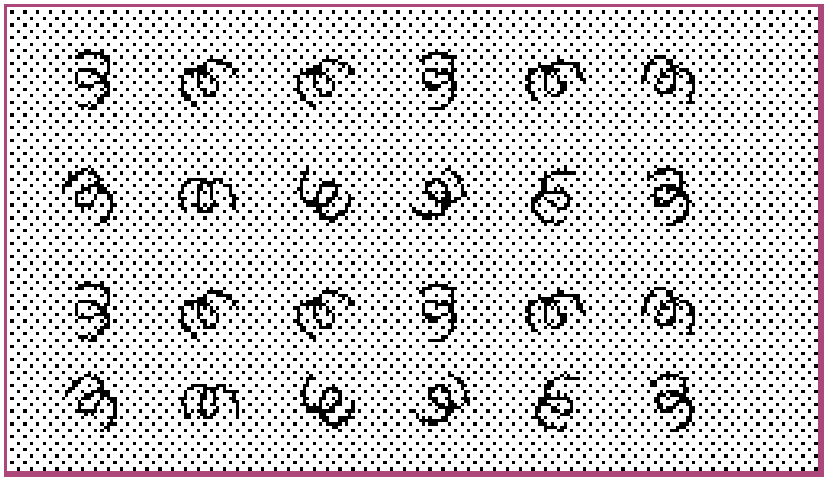



*From NASA wikipedia*

# *History (cont' d)*

## *Karl Ferdinand Lindman (1914)*

**"Under eine durch ein isotropes System von spiralformigen Resonatoren erseugte Rotationspolarisation der elektromagnetischen Wellen," *Annalen der Physik*, Vol. 63, No. 4, pp. 621-644, 1920.**



**From: I. V. Lindell, A. H. Sihvola, S. A. Treyakov, and A. J. Viitatenen, *Electromagnetic Waves in Chiral and Bi-Isotropic Media*, Artech House, 1994**

# *History (cont' d)*

- ***Winston E. Kock (1946)***

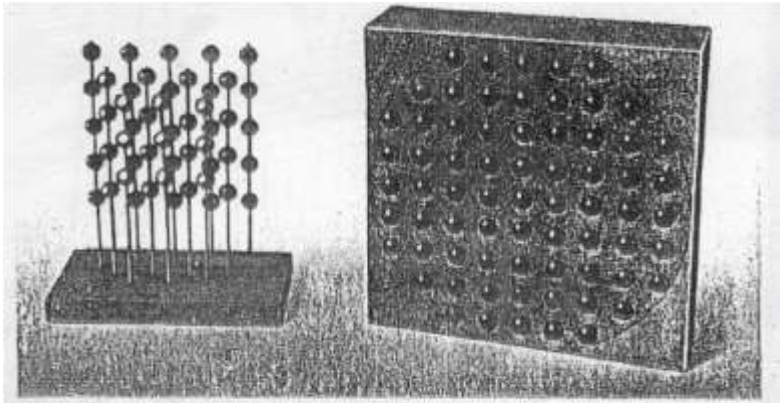
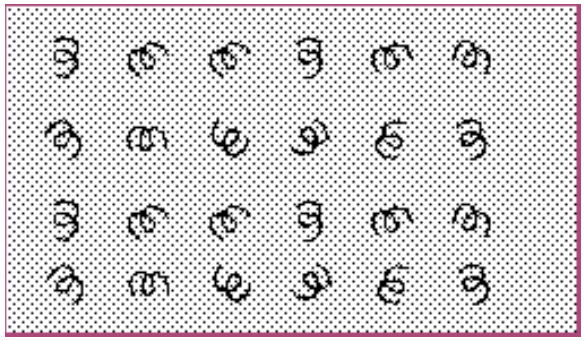


Fig. 3—Left: The sphere lens of Fig. 2. Right: Sphere lattice supported by foam sheets.

**From: W. E. Kock, "Metallic Delay Lenses" *Bell Systems Technical Journal*,**

**Vol. 27, pp. 58-82, 1948**

# *History (cont' d)*



- *Winkler (1956)*
- *Ticono and Freeman (1957)*
- *W. H. Pickering (1970's)*
- *Several Groups in 1980's and 1990's*

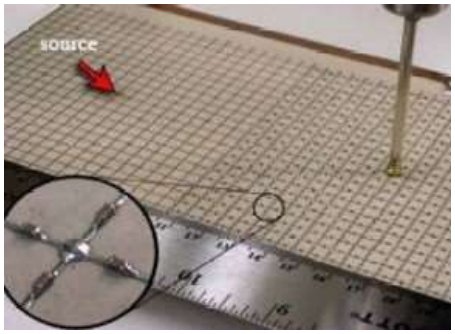
*(Lindell, Sihvola, Varadan, Engheta, Jaggard, Tretyakov,*

# *History (cont' d)*

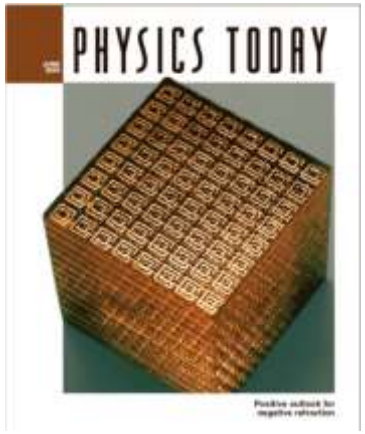
*Ziolkowski, Lakhtakia, Weiglhofer, Zouhdi, Mariotte, Olyslager, Silverman, Whites, many more…….)*

# *Metamaterials Samples (2000-2015)*

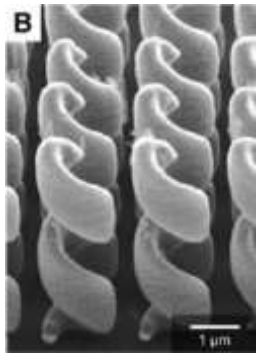
*Smith, Schultz group (2000)*



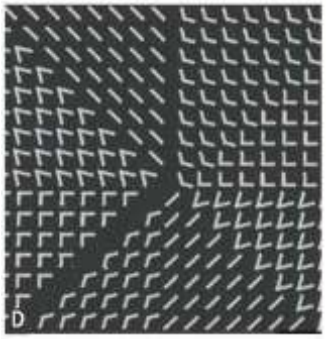

*Grbic & Eleftheriades (2004)*

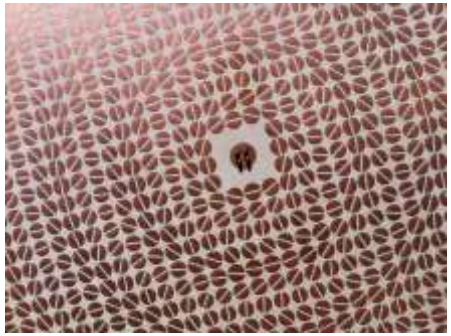


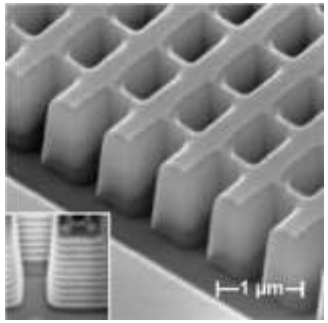

*Boeing group*

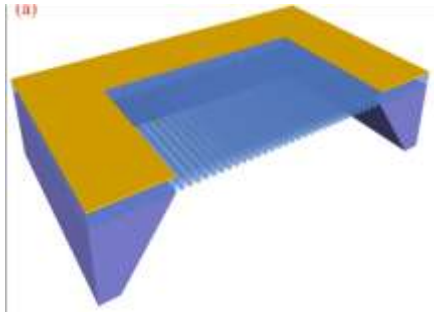



*Wegener group (2009)*



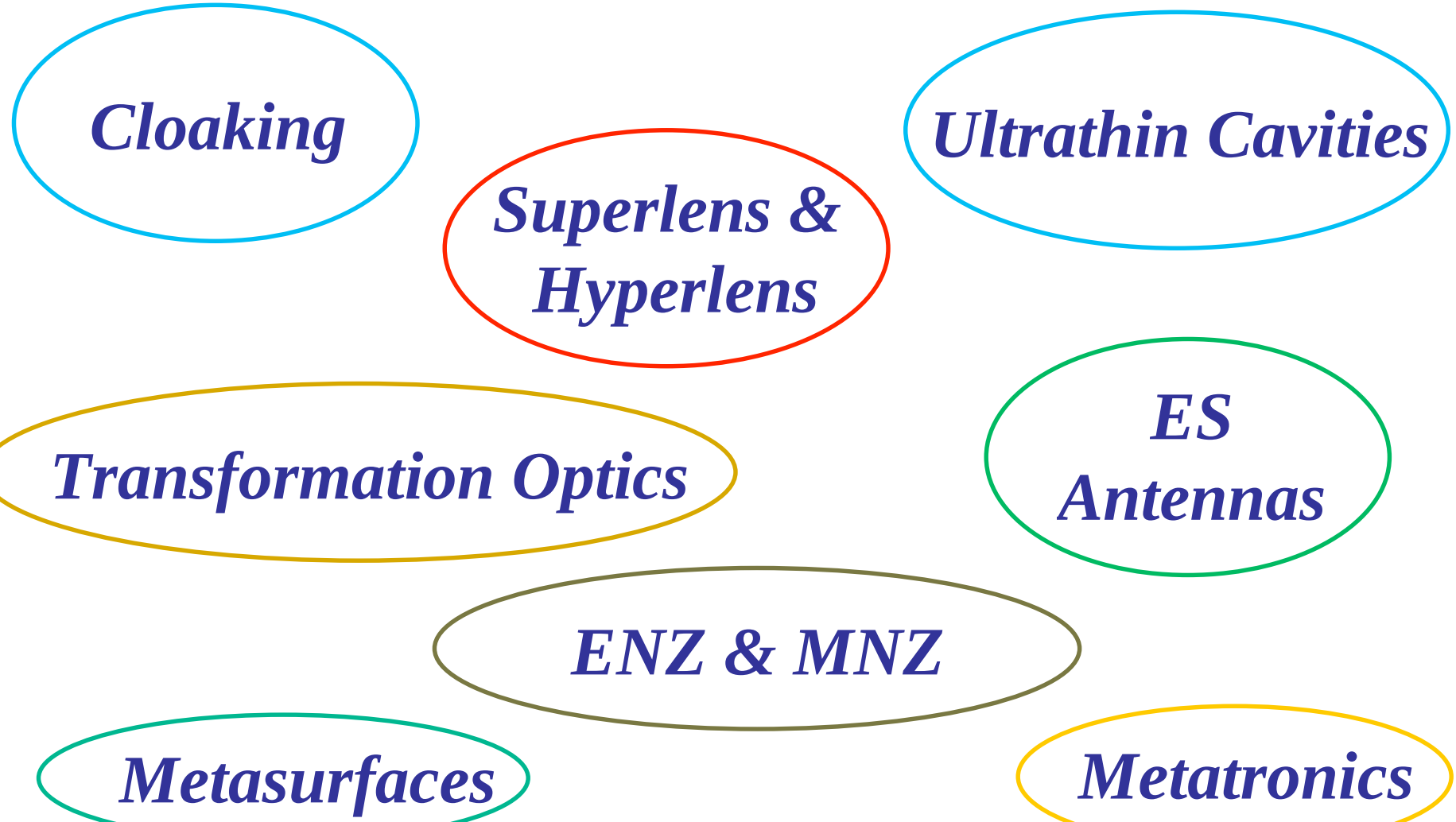



1 µm


(a)

*Capasso group (2011)* *Maci group (2014)* *Zhang group (2008)* *Engheta group (2012)*

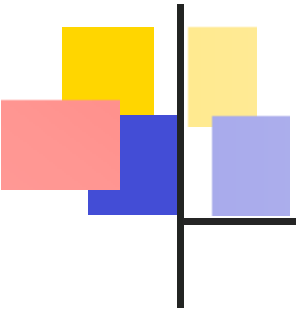
# *Metamaterial Applications (2000-2015)*



# *“There’s Plenty of Room at the Bottom”*

*Richard Feynman*

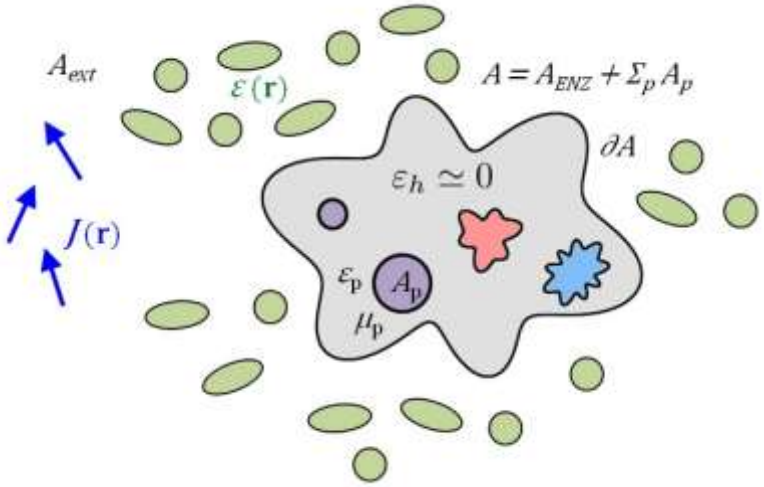
# *“There’s Plenty of Room at the ‘Extreme’”*



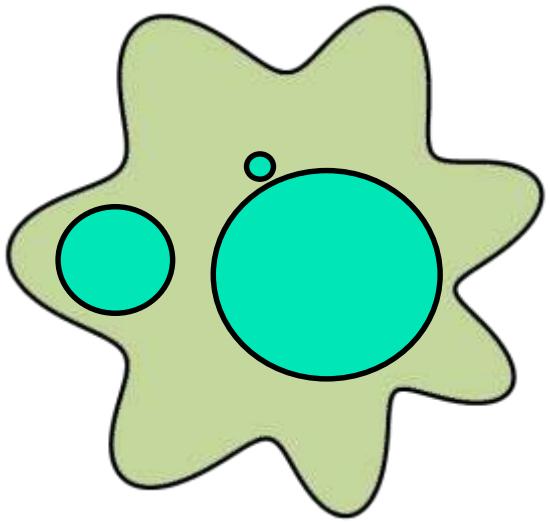
# Extreme Scenario - 1

## Metamaterials Go to the "Extreme"

### Photonic Doping




### Peculiar Effective Medium Properties

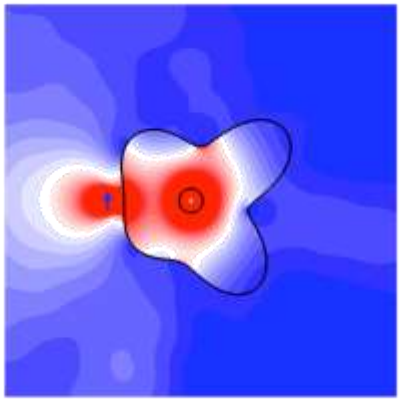


*Liberal, Mahmoud, Li, Edwards, Engheta, Science, 2017*

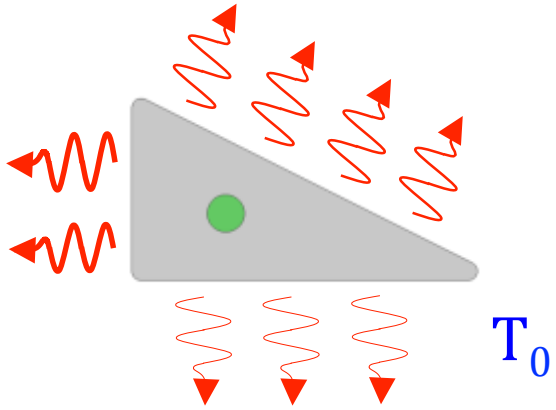
# *Extreme Scenario - 2*

## *Thermal Engineering with Zero-Index Media*

### *Photonic Doping*



### *Engineering Thermal Emission*



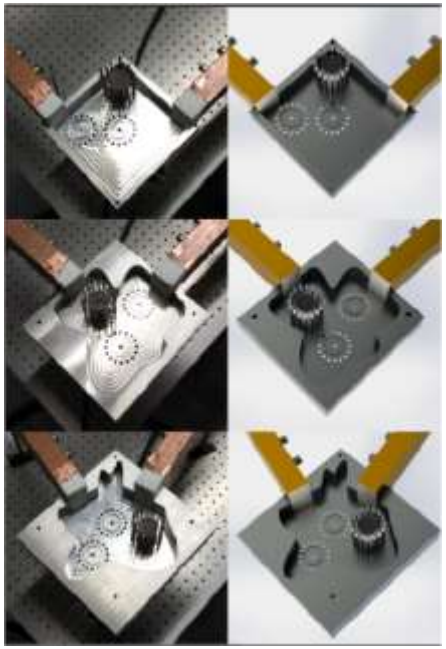

*Liberal & Engheta, CLEO Conference, May 2017*

*Liberal & Engheta, manuscript in preparation*

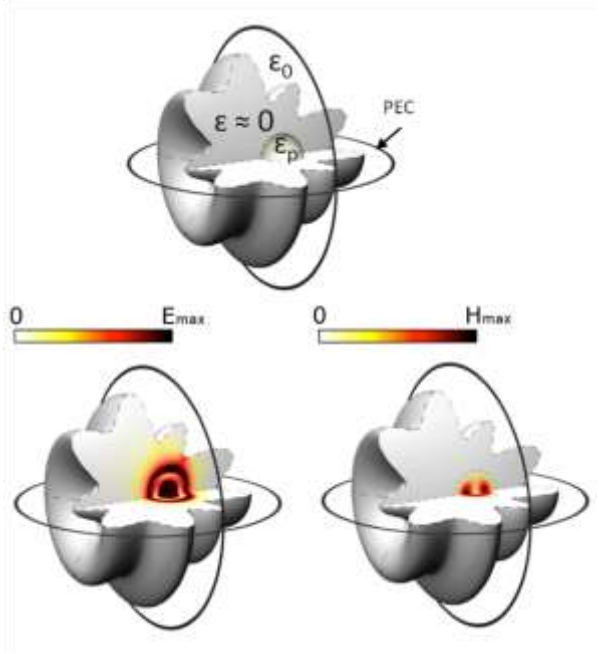
# *Extreme Scenario - 3*

## *Extreme Resonant Cavities*

### *Geometry-Independent Cavities*



### *Bound State in the Continuum*




*Liberal and Engheta, Nature Photonics, March 2017*

# *Extreme Scenario - 4*

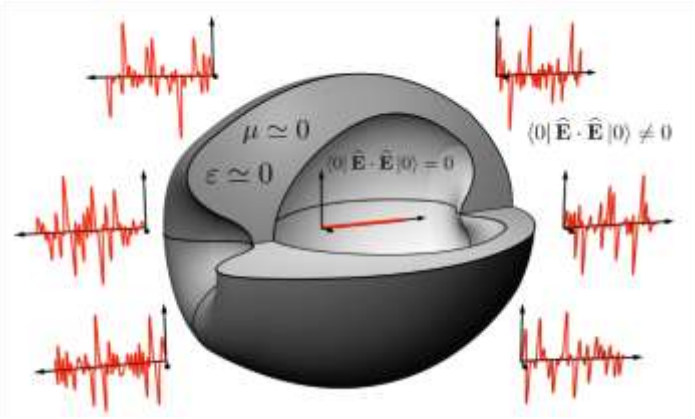
*Liberal, Mahmoud, Li, Edwards, Engheta, Science, 2017*

*Mahmoud, Liberal and Engheta, Nature Communications, 2016*

## *Quantum Optics of Zero-Index Structures*

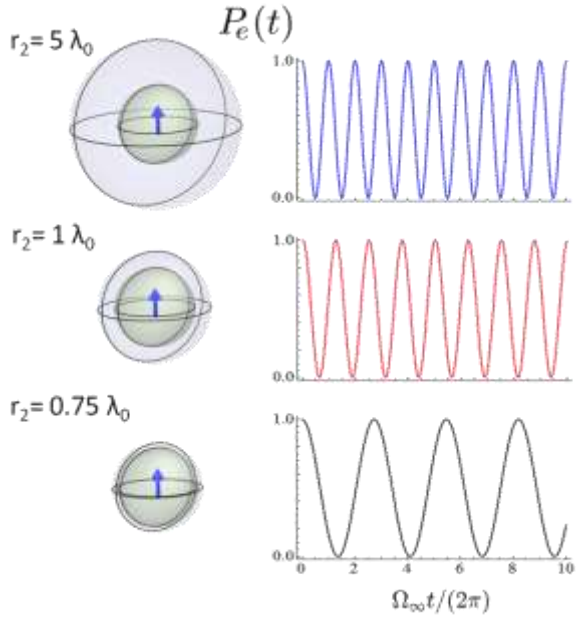
# *Extreme Scenario - 5*

## *Extreme Quantum Optics*




*Liberal and Engheta, Proc. Nat. Acad. Sci., 2017*

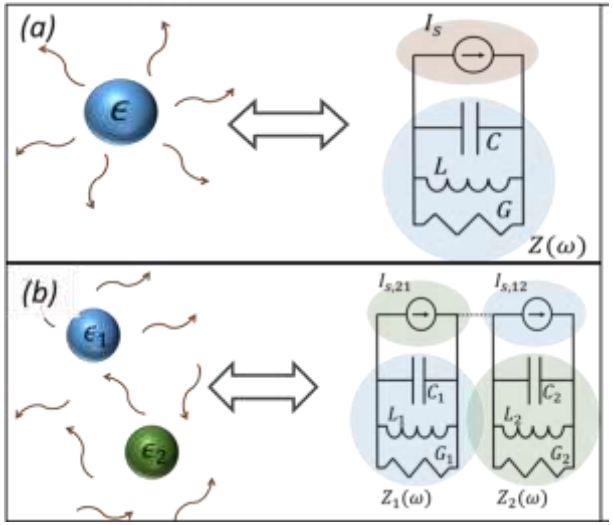
## *Engineering Rabii Frequencies without detuning*



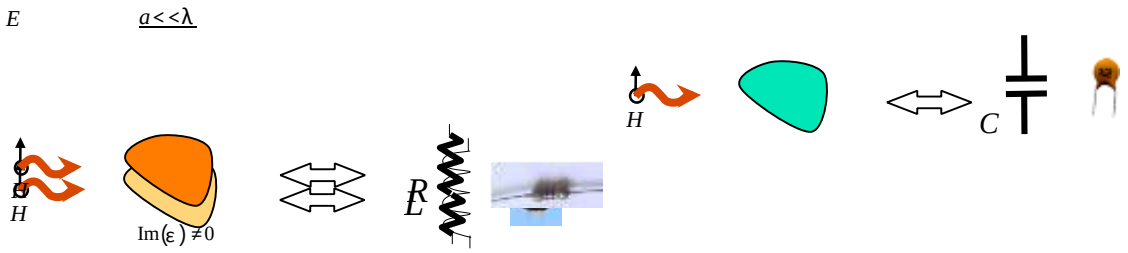

*Liberal and Engheta, Pro. Nat. Acad. Sci, 2017*

# Extreme Scenario - 6

## Optical Metatronics




**Optical Metatronics** **Quantum Metatronics**



# Extreme Scenario - 7

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

*E*

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

*E*

*N. Engheta, et al. PRL, 2005 N. Engheta, Science, 2007*

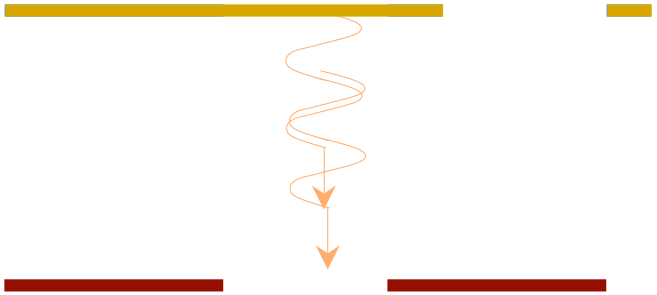
*Lumer, Liberal and Engheta, CLEO Conference, May 16, 2017*

## *Extreme Metasurfaces*

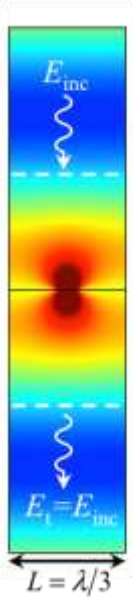
***Cascaded Metasurfaces***

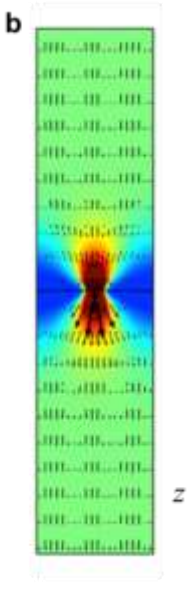
***Transparent Metasurfaces with Prescribed Aperture Fields***

# *Extreme Scenario - 8*



*Mohammadi Estakhri, Kastner, Engheta, IEEE AP-S Symposium, San Diego, July 2017*

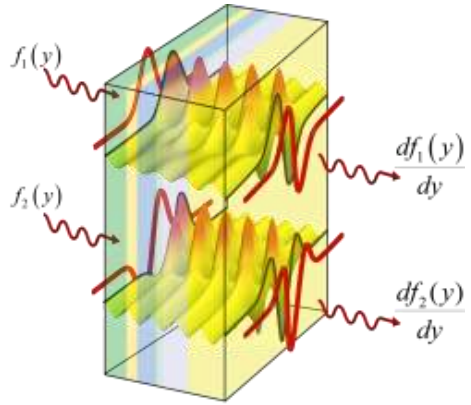


# Extreme Scenario - 9

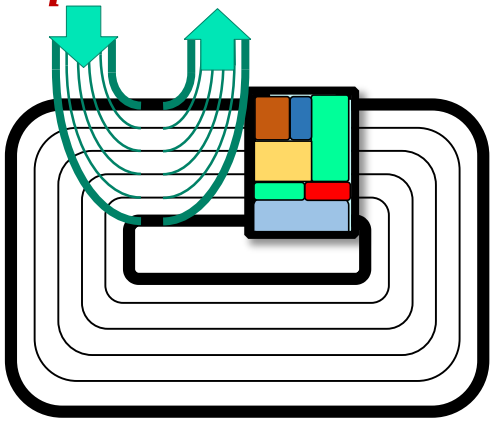
## Extreme Platforms for Mathematical Operations

### Informatic Metastructures




*Silva, Monticone, Castaldi, Galdi, Alu, Engheta, Science, 2014*

### Metastructures to Solve Integral Equations with Waves

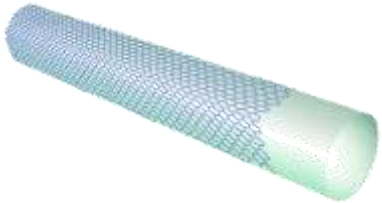


*N. Mohammadi Estakhri, B. Edwards, N. Engheta*
*CLEO Conference, May 18, 2017*

# *Extreme Scenario - 1*

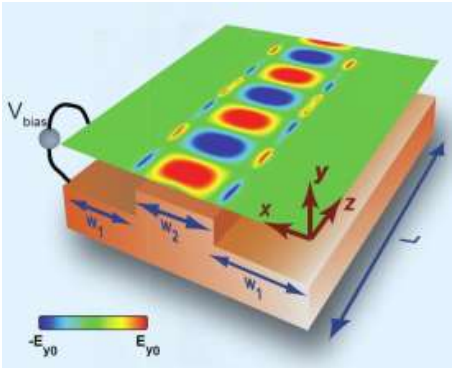
*B. Edwards, N. Mohammadi Estakhri, N. Engheta*
*MRS Spring Meeting, April 11, 2017*

## *"Meta-Tube"*



*A. Davoyan and N. Engheta, ACS Photonics (2016)*

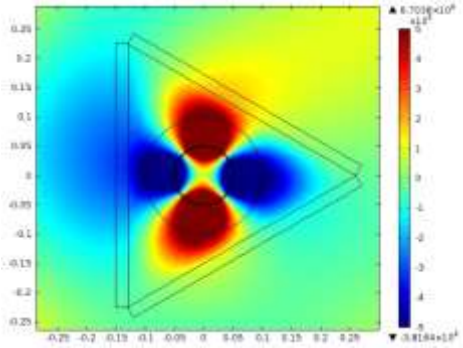
## *Thinnest Metamaterials*




*A. Vakil and N. Engheta, Science, 2011*

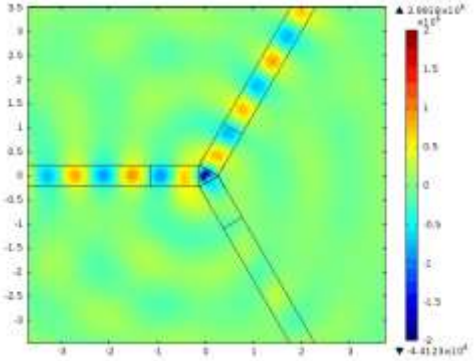
# *Extreme Scenario - 1*

## *"Extreme Near-Field"*



*A. Davoyan and N. Engheta, PRL, 2013*

## *"Plasmonic Circulator"*

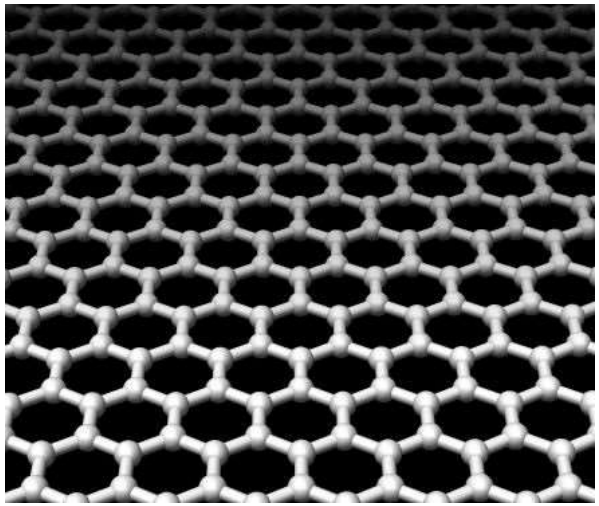


*A. Davoyan and N. Engheta, NJP, 2013*

# *Ultimate Metasurface*

## *"Extreme" in Dimensionality*

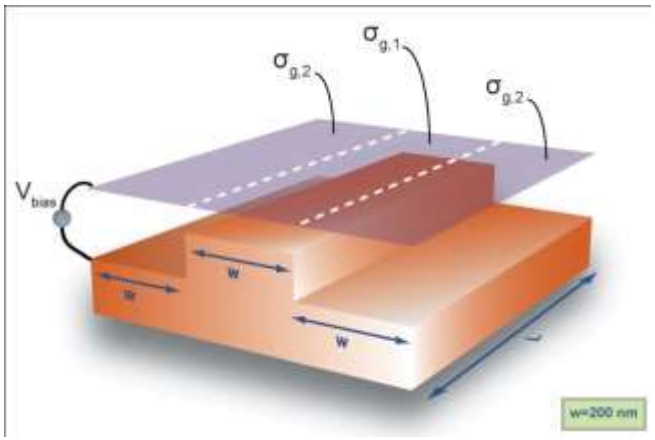
### *Thinnest Metamaterials*

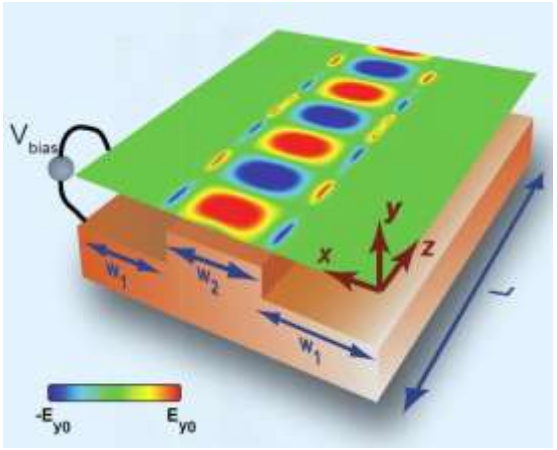


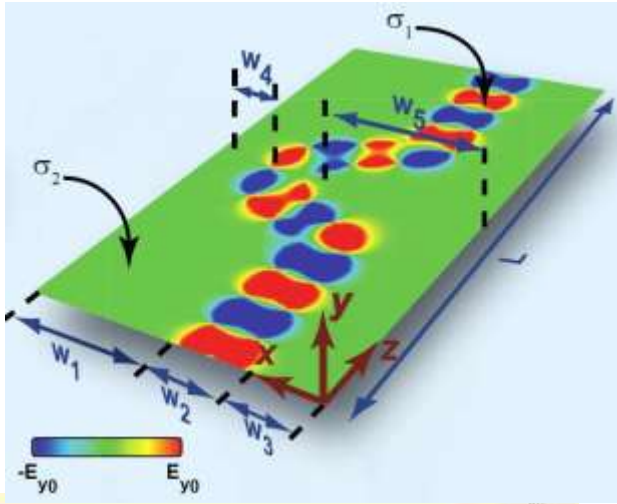
http://math.ucr.edu/home/baez/graphene.jpg

*A. Vakil and N. Engheta, Science, 2011*

# One-Atom-Thick Optical Devices



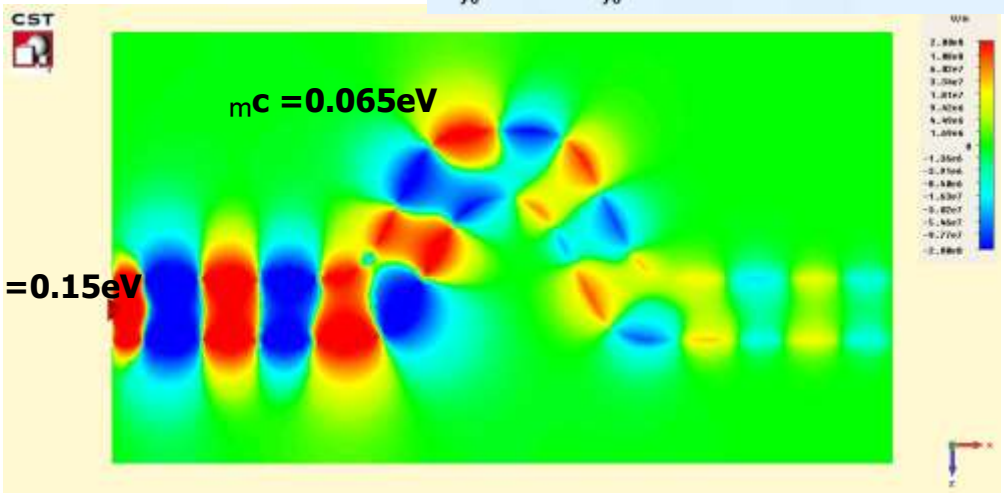




Region 1: $\sigma_{gi} > 0$

$\mu_c = 150\, meV$

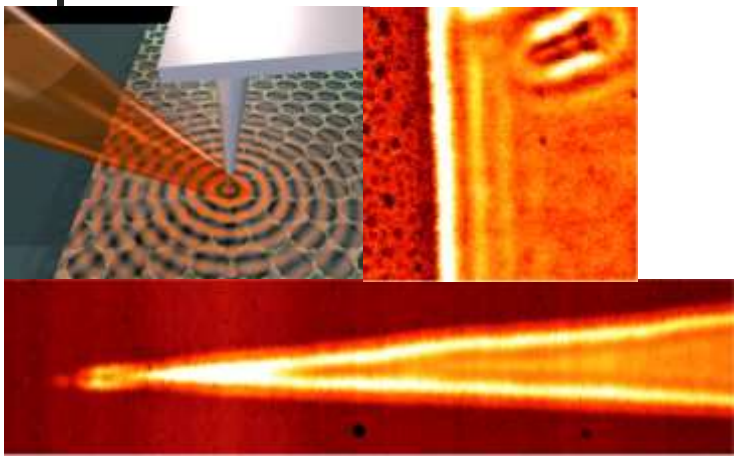
Region 2: $\sigma_{gi} < 0$

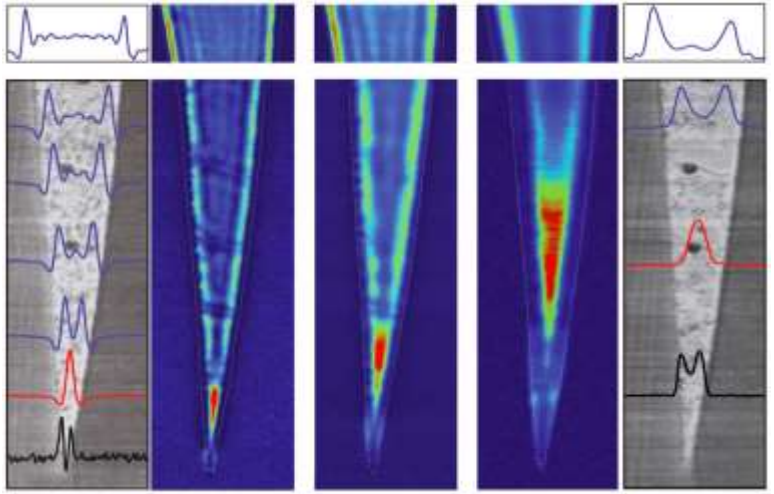
$\mu_c = 65\, meV$




*A. Vakil and N. Engheta, Science, 2011*

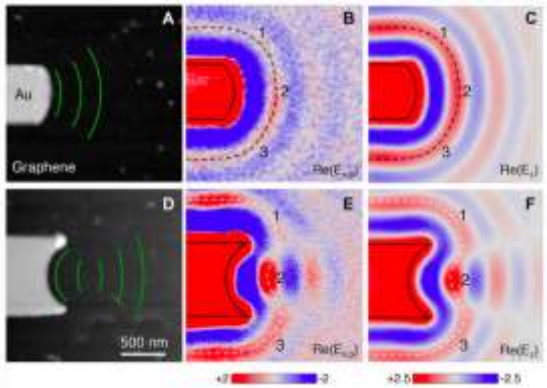
# *Graphene*





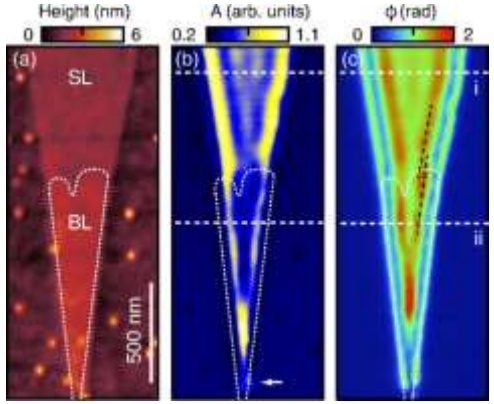
## *Experimental Verification of SPP on*

*Basov group, Nature (2012)*




*Hillenbrand and Koppens, Science (2014)*

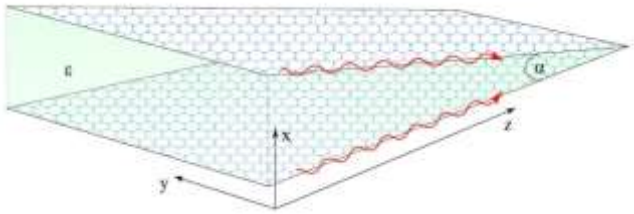
*Koppens, Hillenbrand and Garcia de Abajo, Nature (2012)*

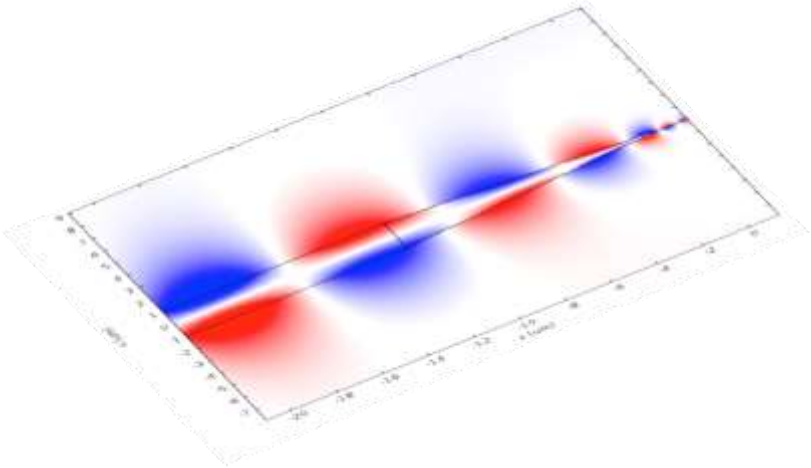


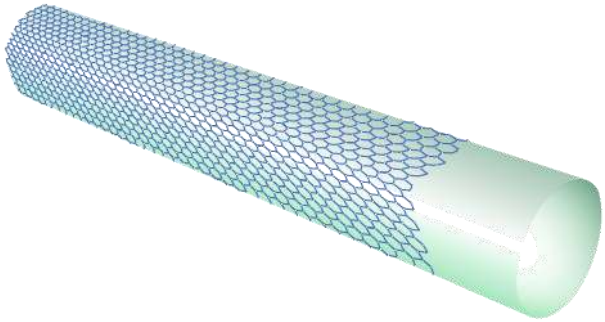

*Raschke, PRL (2014)*

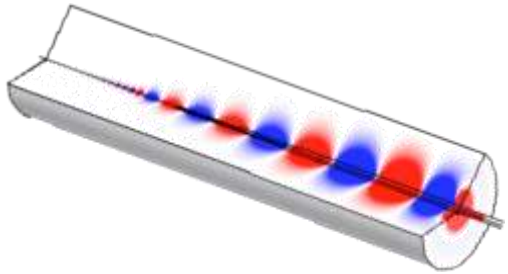
# *Graphene-coated dielectric waveguide: Hybrid Graphene-Dielectric Systems*

**2D**





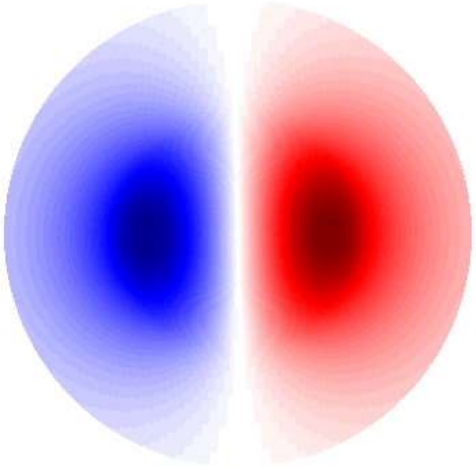


*"Meta-Tube"*

*A. Davoyan and N. Engheta, ACS Photonics (2016)*

*A. Davoyan and N. Engheta, ACS Photonics (2016)*

# *Graphene-coated dielectric waveguide: Hybrid Graphene-Dielectric Systems*



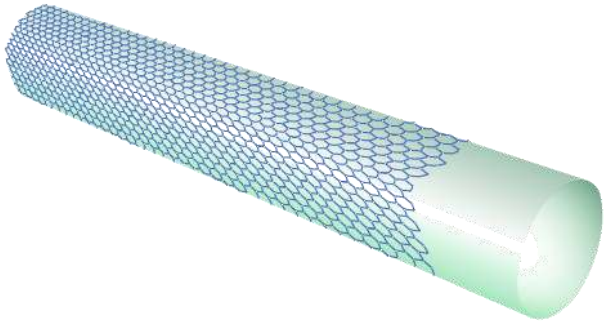
*Dielectric Fiber ($HE_{11}$)*

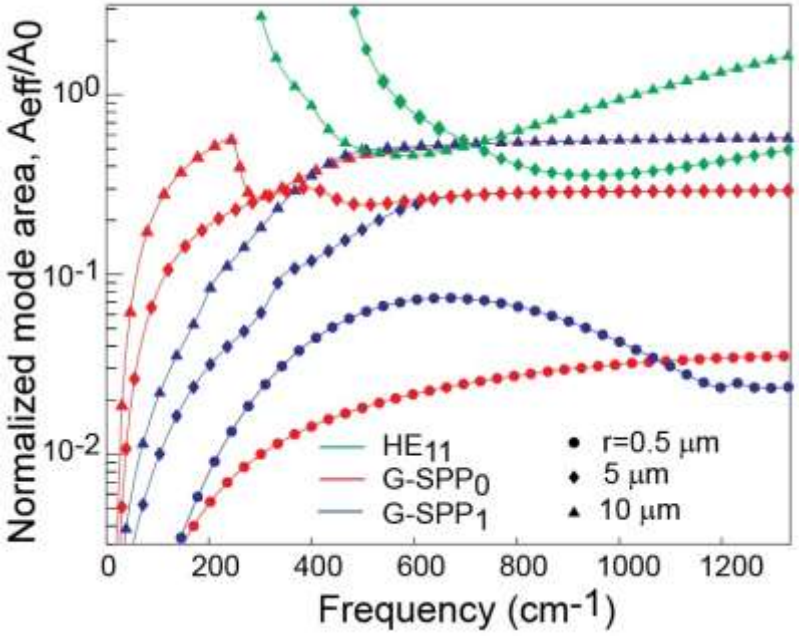
*Graphene-Fiber ($SPP_1$)*

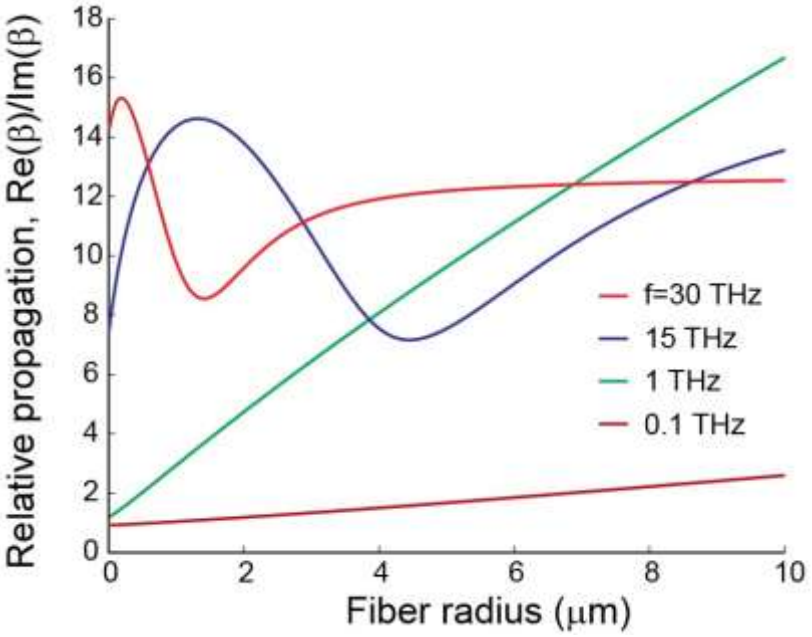
*Graphene-Fiber ($SPP_0$)*

*A. Davoyan and N. Engheta, ACS Photonics (2016)*

# *Wave Guided in Graphene-coated Fiber*

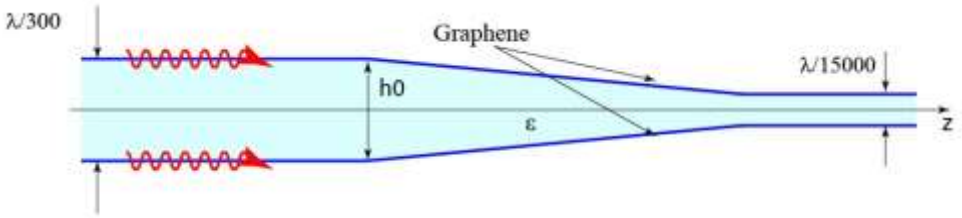




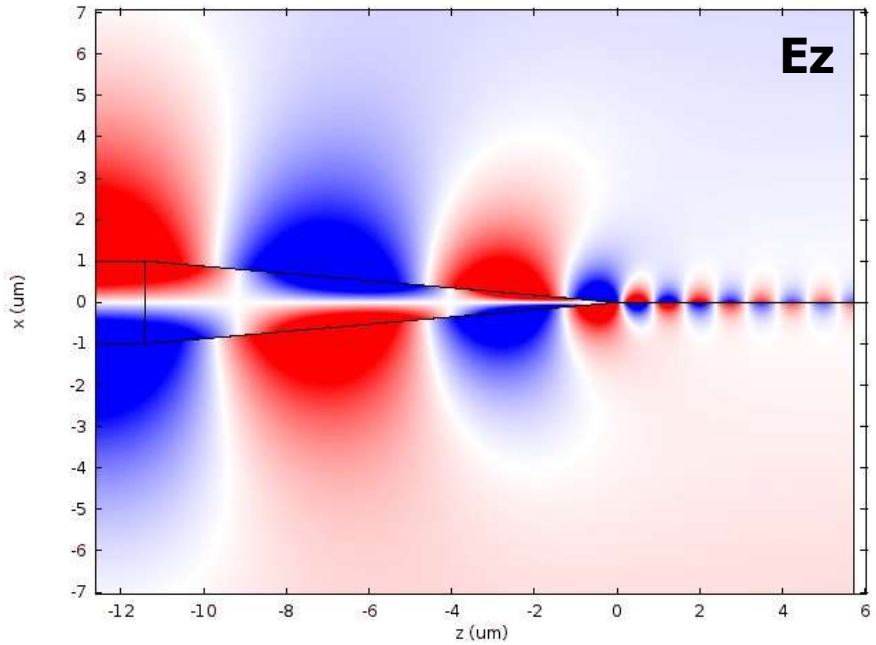




*A. Davoyan and N. Engheta, ACS Photonics (2016)*

# *Squeezing THz energy into Nanoscale WG*

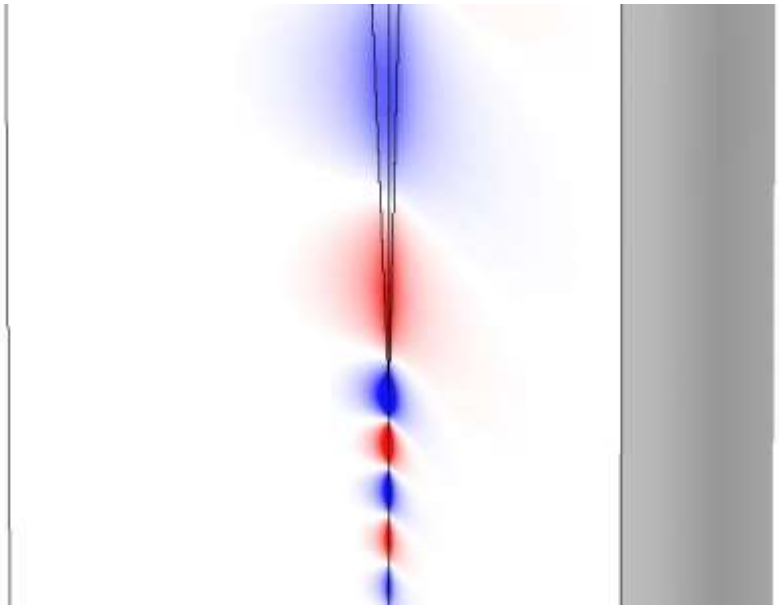



**2D taper**



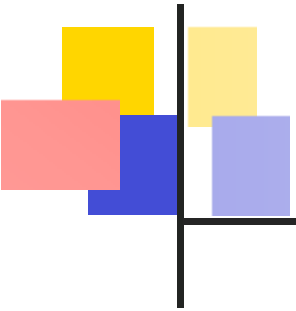

$\alpha=10°, f=1THz$

**3D taper**



$\alpha=4°, f=1THz$

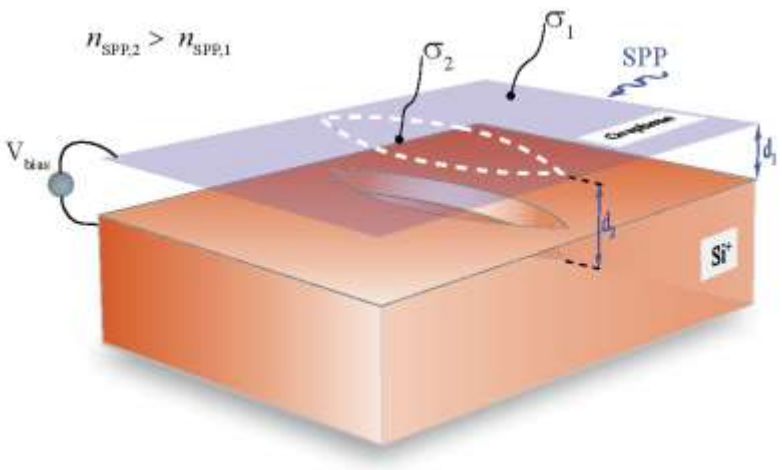
*A. Davoyan and N. Engheta, ACS Photonics (2016)*

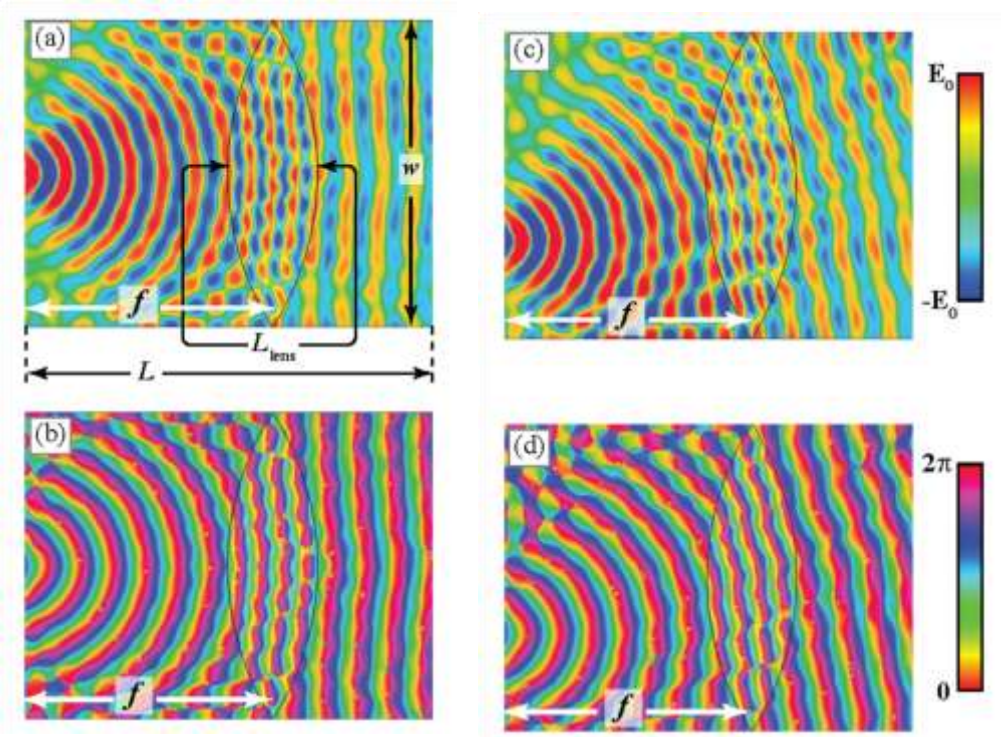


# *Processing at the Extreme*

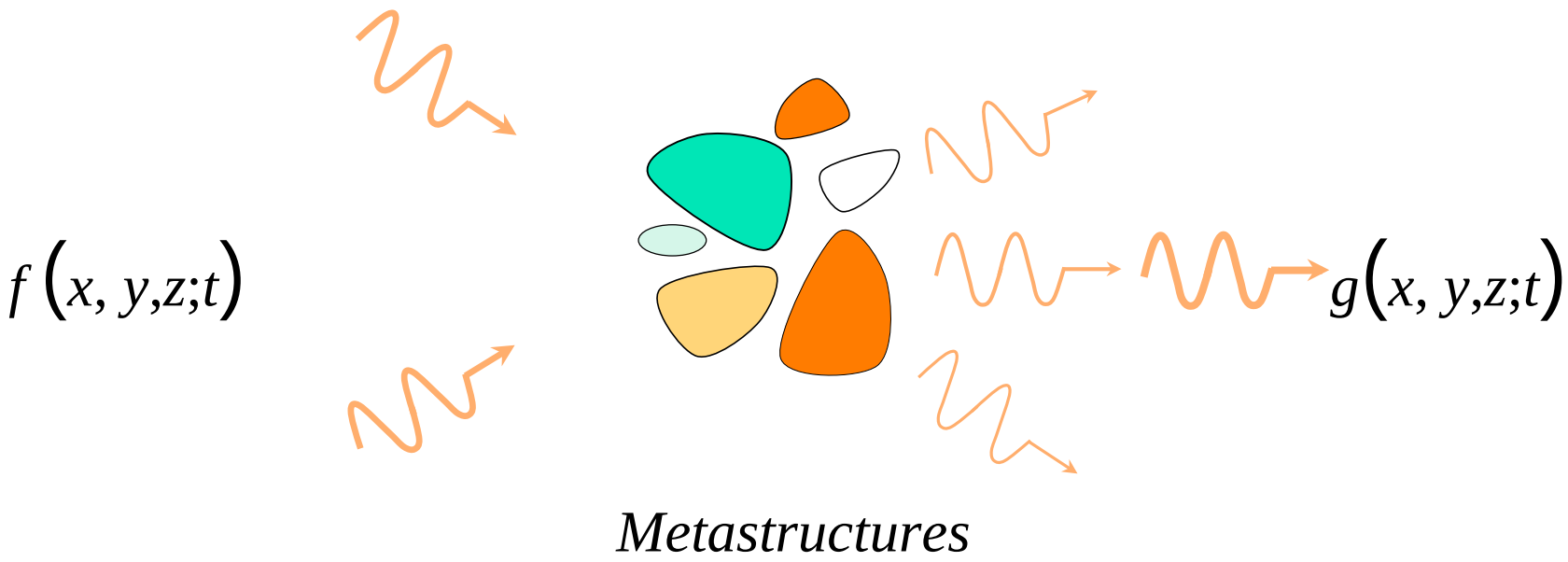
# *One-Atom-Thick Fourier Optics*

*A. Vakil and N. Engheta, Phys. Rev. B, 2012*

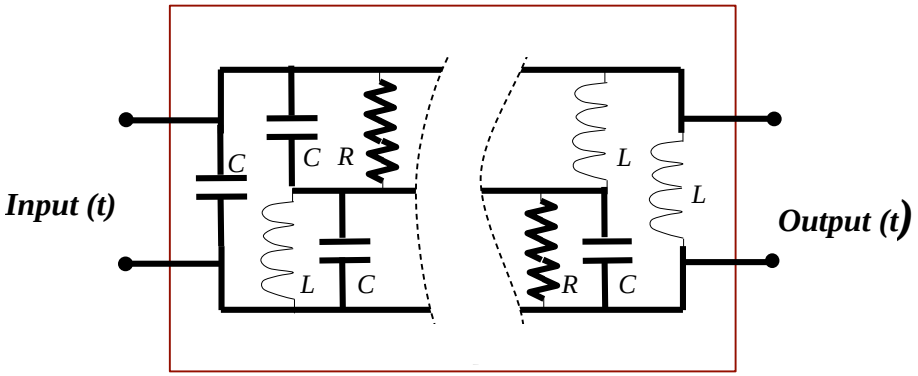


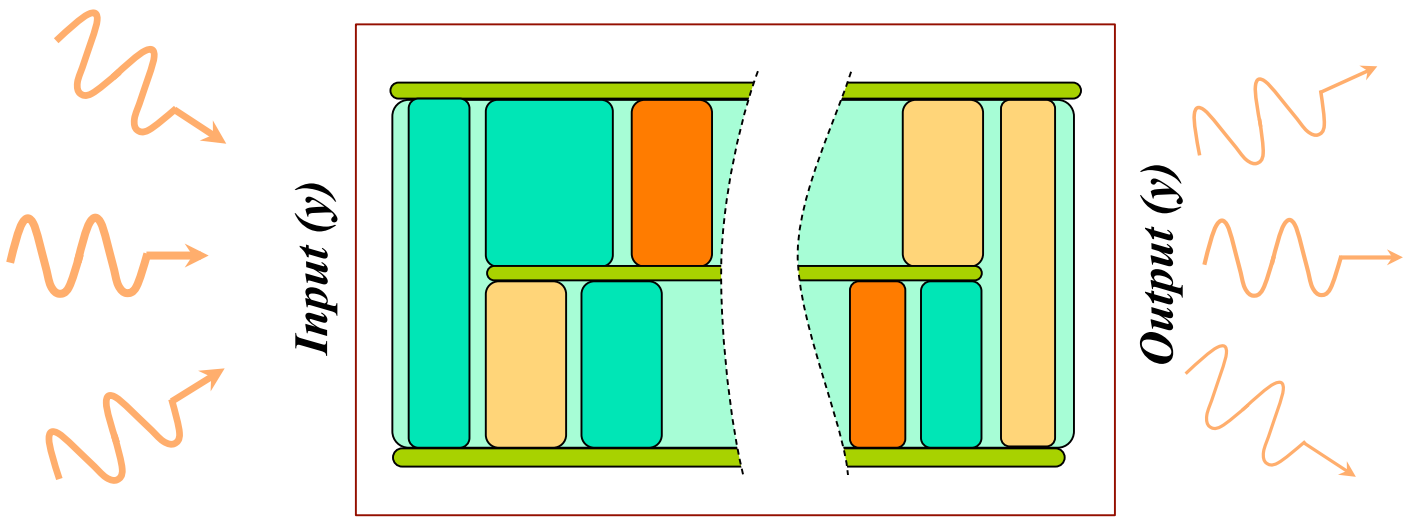



# *Can Metastructures Play a Role in Information Processing?*

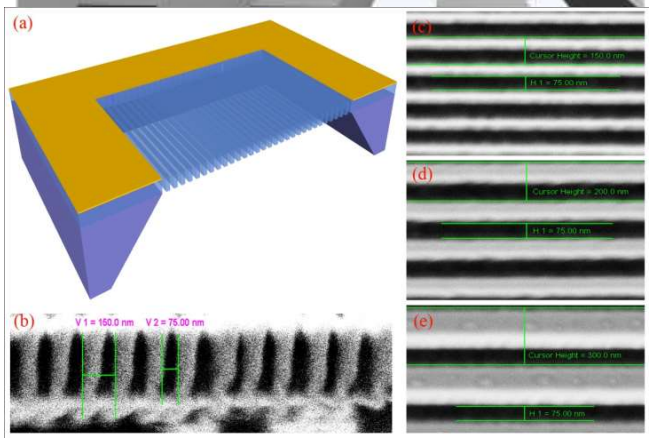


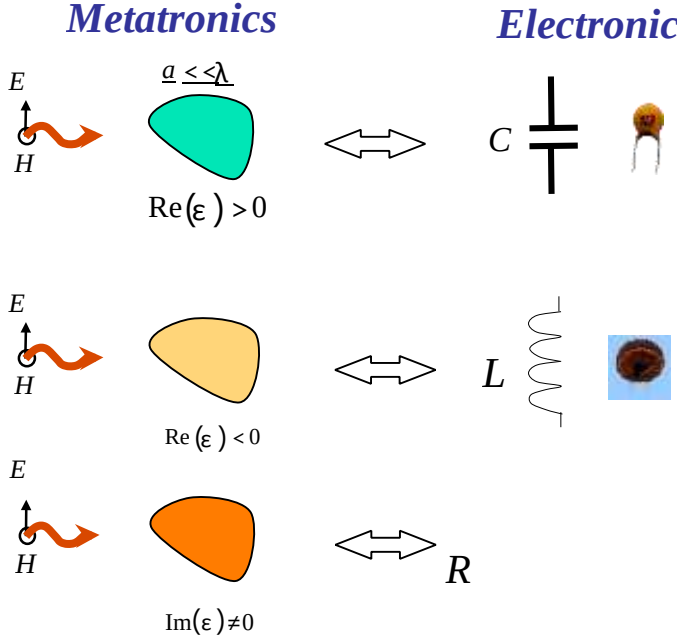
# Clear Analogy between Electronics and Photonics




Input (y)
Output (y)

# Optical Metatronics




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

*Engheta, Science, 317, 1698 (2007)*

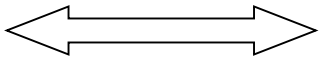
*Sun, Edwards, Alu, Engheta, Nature Materials (2012)*

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

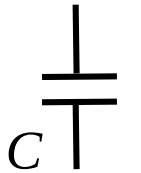
*Engheta, Salandrino, Alu, Phys. Rev. Lett, (2005)*

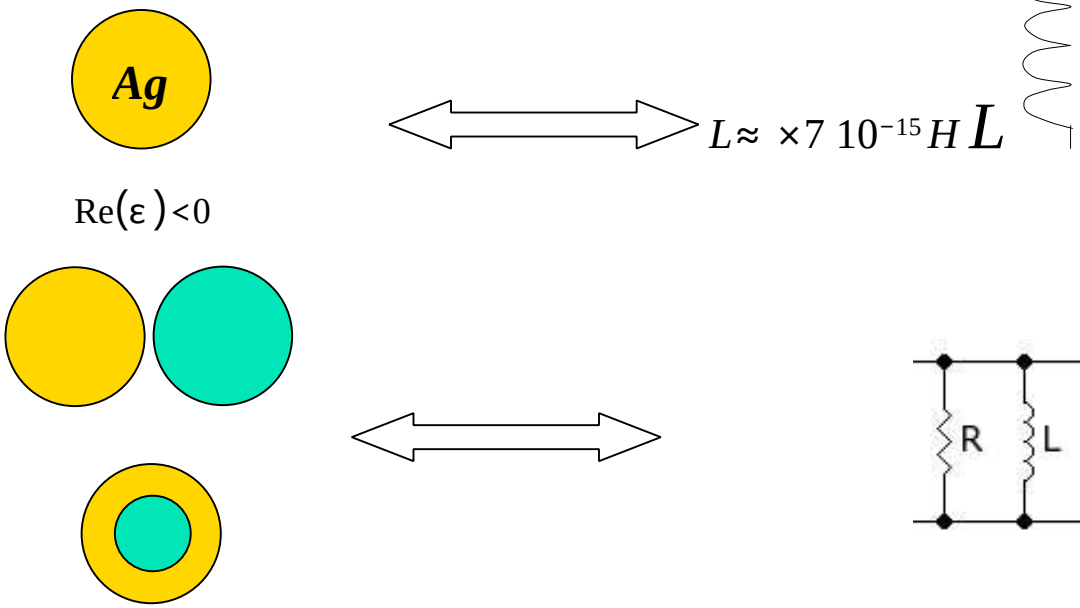
# *Examples*

$60nm\ \lambda = 633nm$

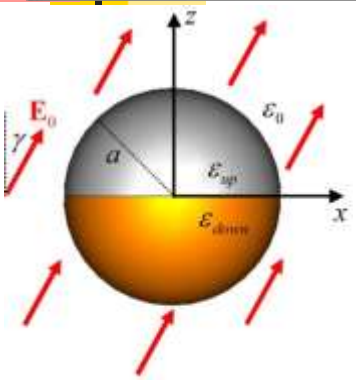



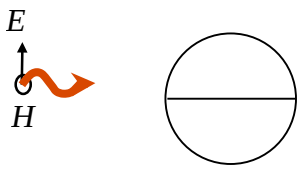
$C \approx \times 2\ 10^{-18} F$

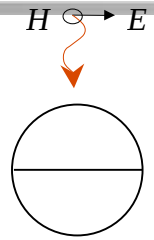


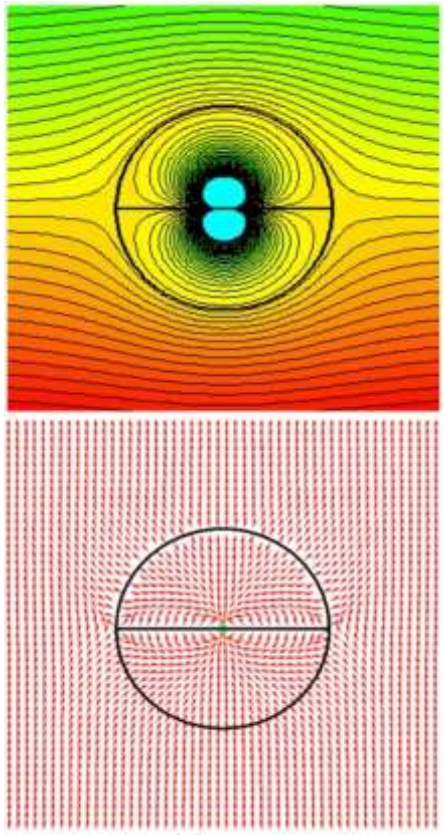

Ag
Re(ε)<0
L≈ ×7 10⁻¹⁵ H
L
R
L
C

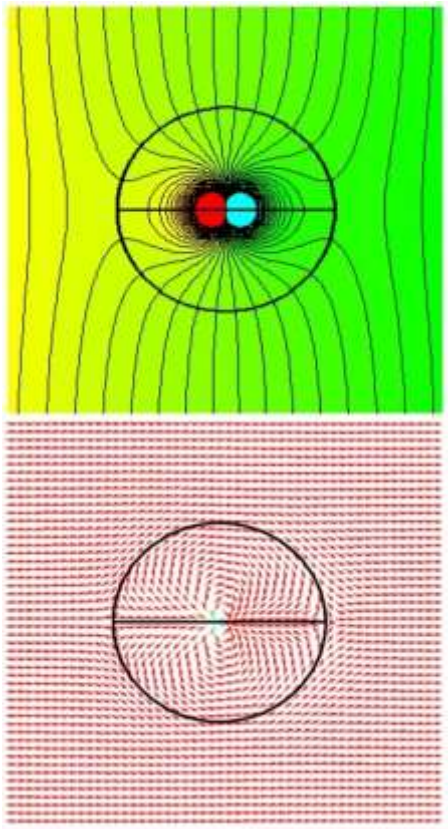
# "Stereo-Circuits"
# Different "Circuits" for Different "Views"

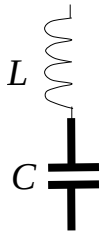


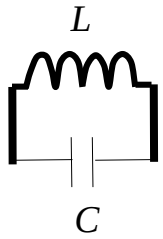





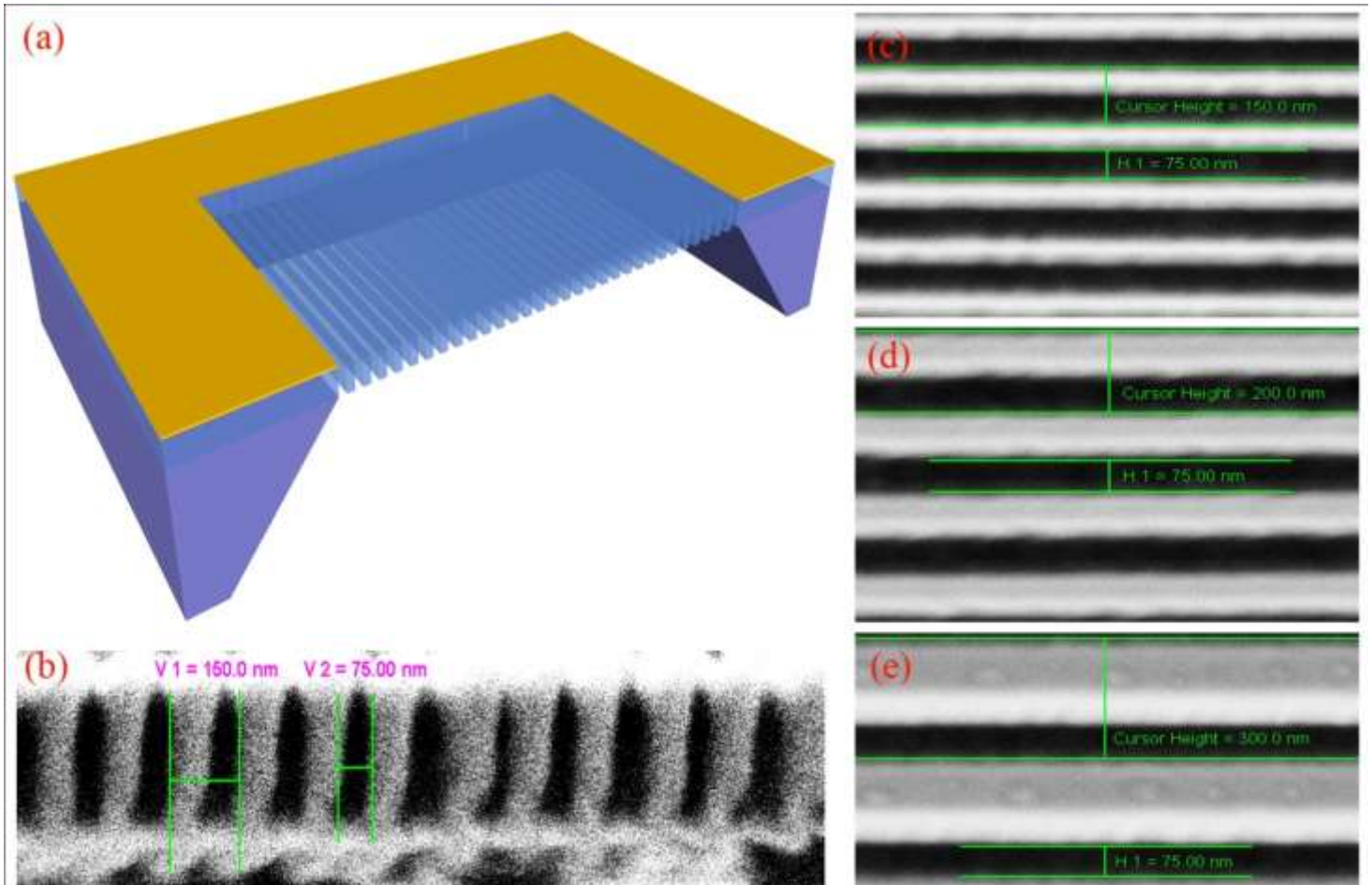



*Salandrino, Alu, Engheta, JOSA B, Part 1, 2007*
*Alu, Salandrino, Engheta, JOSA B, Part 2, 2007*

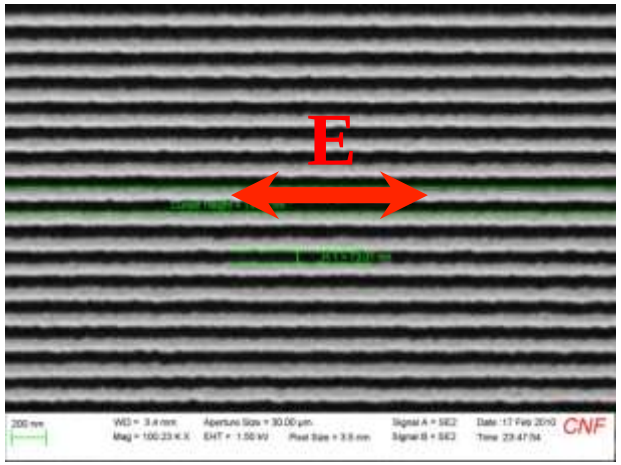
*Alu and Engheta, New Journal of Physics, 2009*

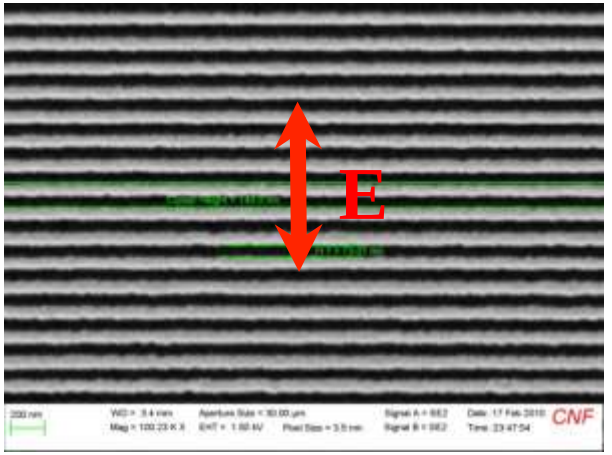
# *Our Samples*

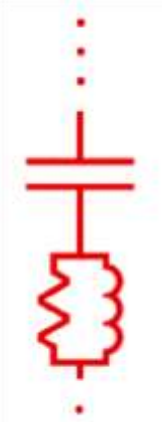

(a)
(b)
V 1 = 160.0 nm
V 2 = 75.00 nm
(c)
Cursor Height = 150.0 nm
H 1 = 75.00 nm
(d)
Cursor Height = 200.0 nm
H 1 = 75.00 nm
(e)
Cursor Height = 300.0 nm
H 1 = 75.00 nm

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

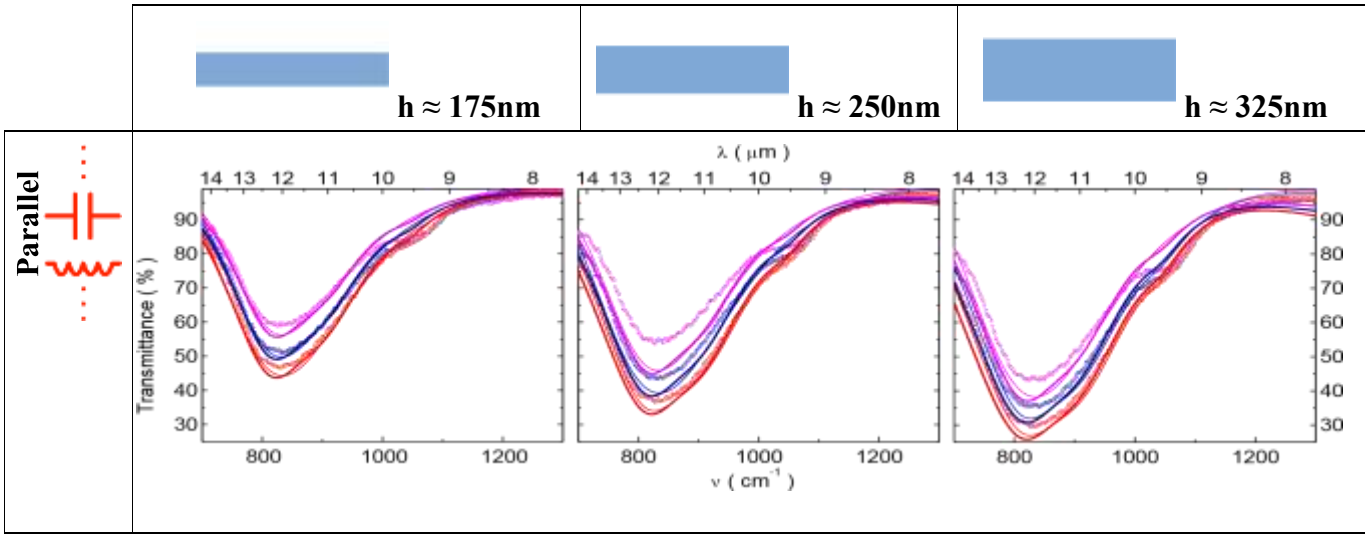
# *"Parallel" and "Series" Optical Circuits*



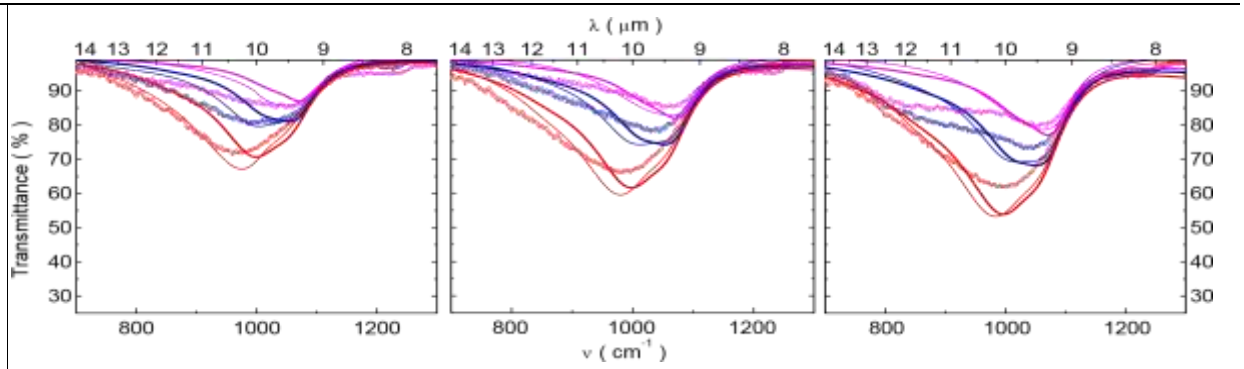



*Y. Sun, B. Edwards, A. Alu, and N. Engheta, Nature Materials, March 2012*

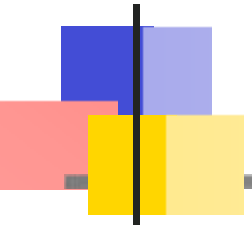


Series




| | |
|---|---|
| "empty circle": | Experimental data |
| "Thick line": | Circuit theory |
| "Thin line" : | Full wave |

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

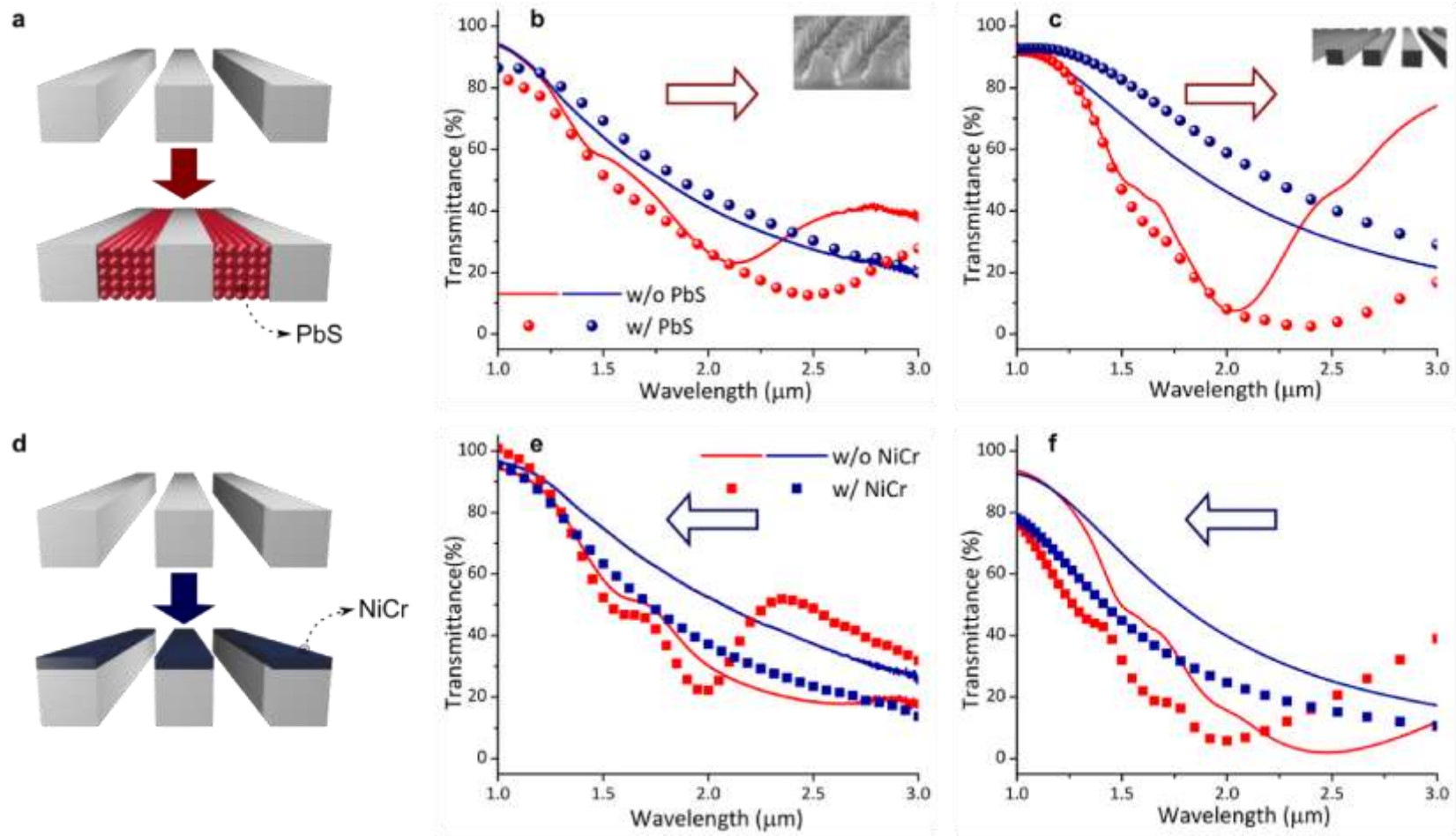


# *Collective Results*

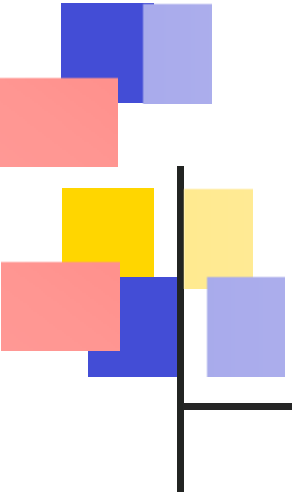
**simulation**

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

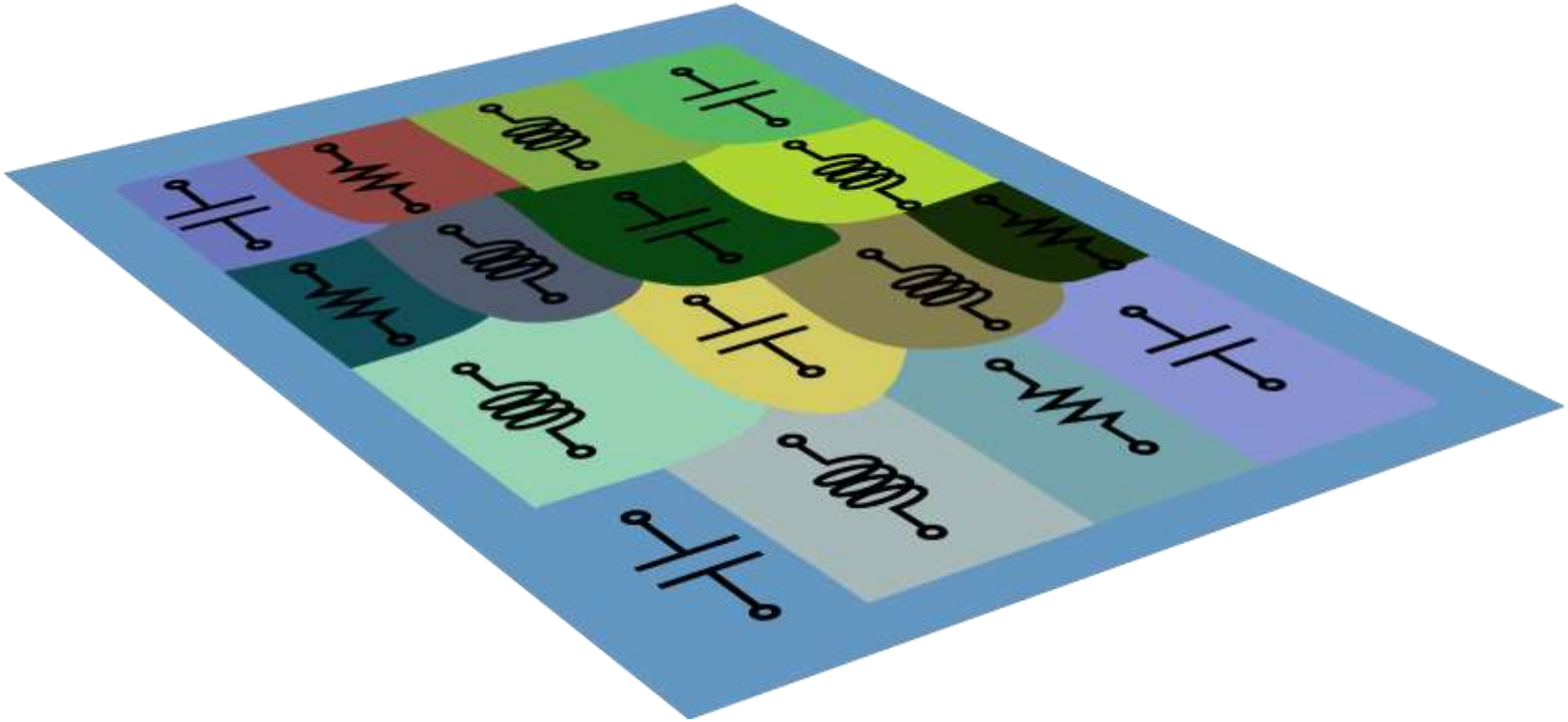
# *TCO NIR Metatronic Circuits Fabrication and Experimental Results*




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



# *Thinnest Possible Circuits?*



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

*Capacitor C*

*A. Vakil and N. Engheta, Science, 2011*