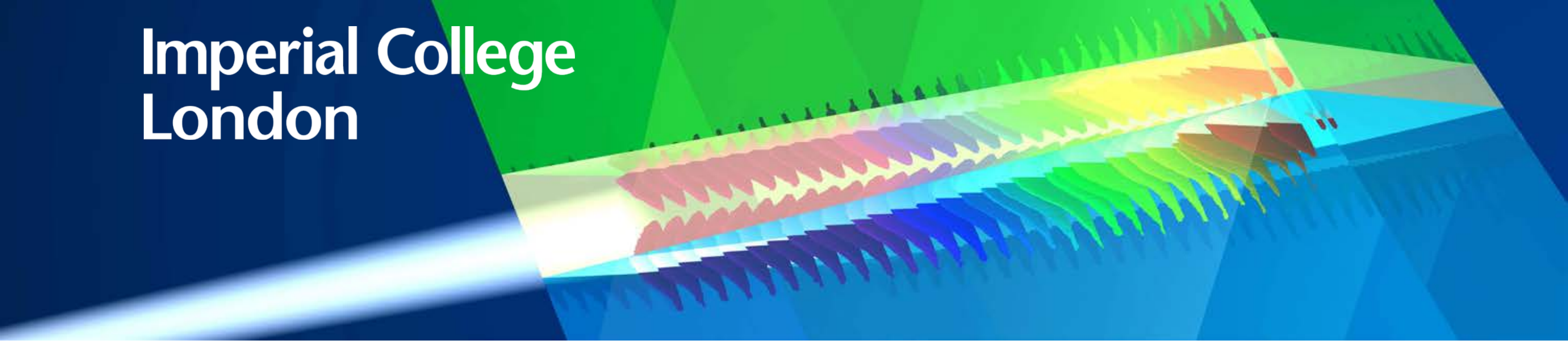


# Metamaterials

## Extreme Control of Light

**Ortwin Hess**

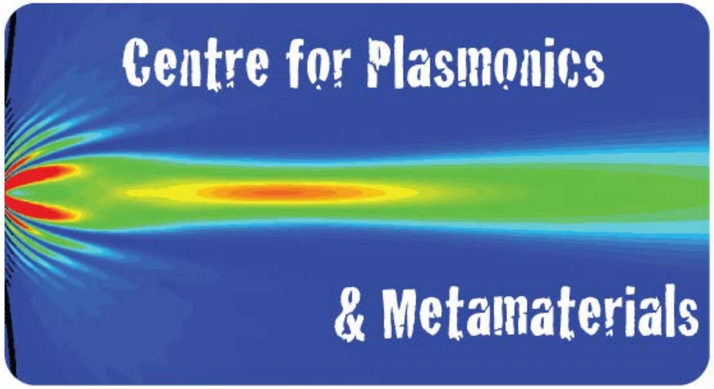
*The Blackett Laboratory*

*Department of Physics and Centre for Plasmonics & Metamaterials*

*Imperial College London*
*London SW7 2AZ, UK*

http://www.imperial.ac.uk/people/o.hess

# Centre for Plasmonics and Metamaterials



**Co-Directors**
Prof Ortwin Hess
Prof Stefan Maier
Prof Sir John Pendry

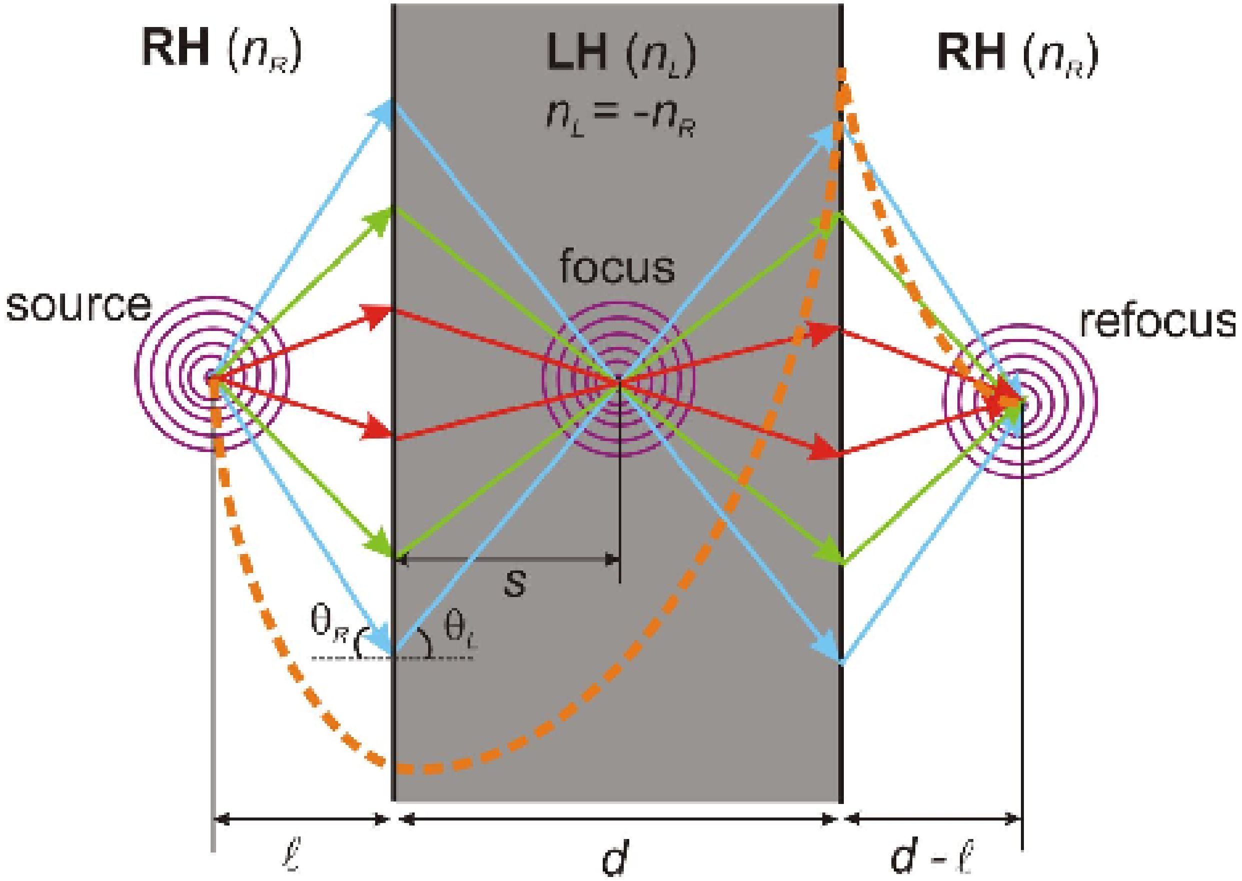
cross-faculty centre involving:
Dept of Physics
Dept of Materials
Dept of Electrical & Electronic Engineering

> M£ 10 (Leverhulme, EPSRC, dstl, etc)

# A Team Effort

Imperial College
London

# Metamaterials – Imaging



[Pendry, *Physical Review Letters* **85**, 3966 (2000)]

# Imaging – Optical Experiment

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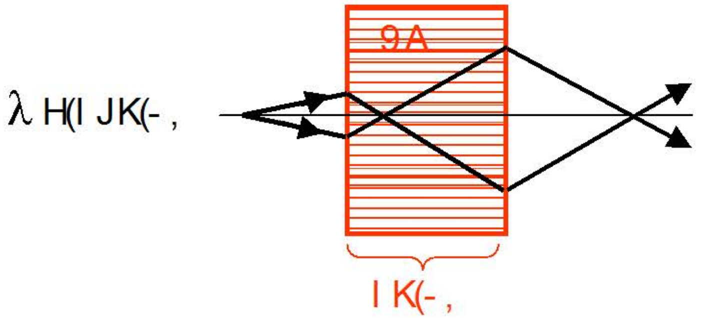
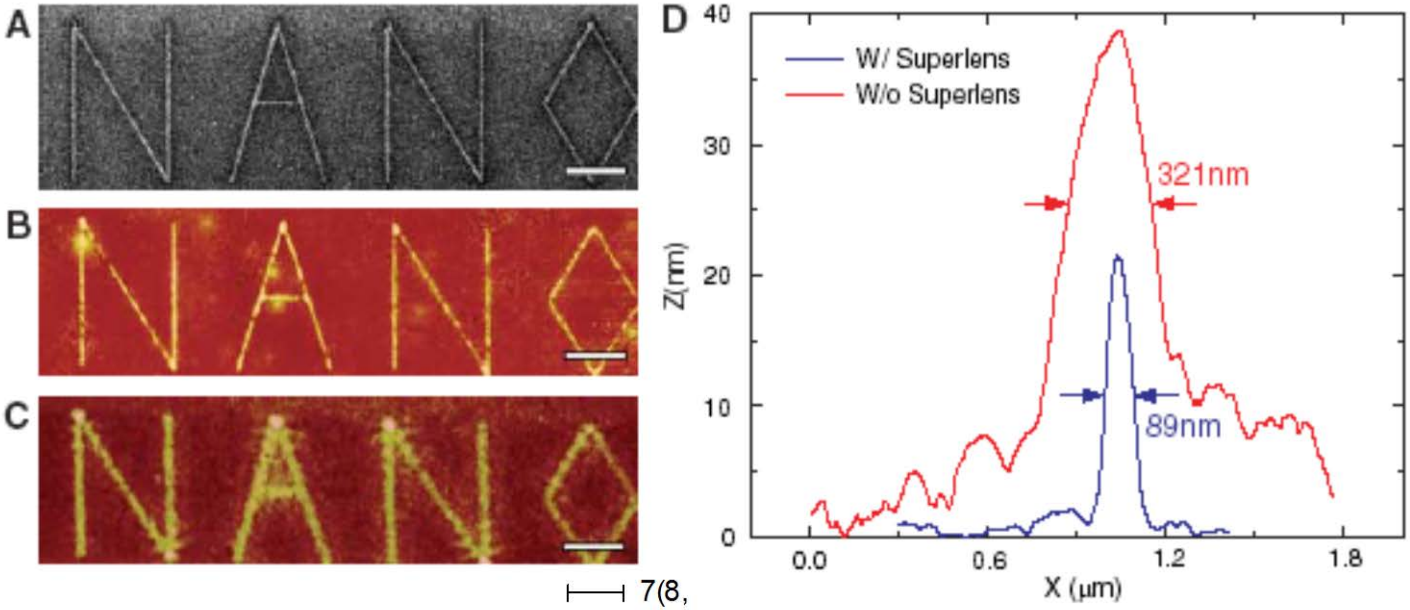
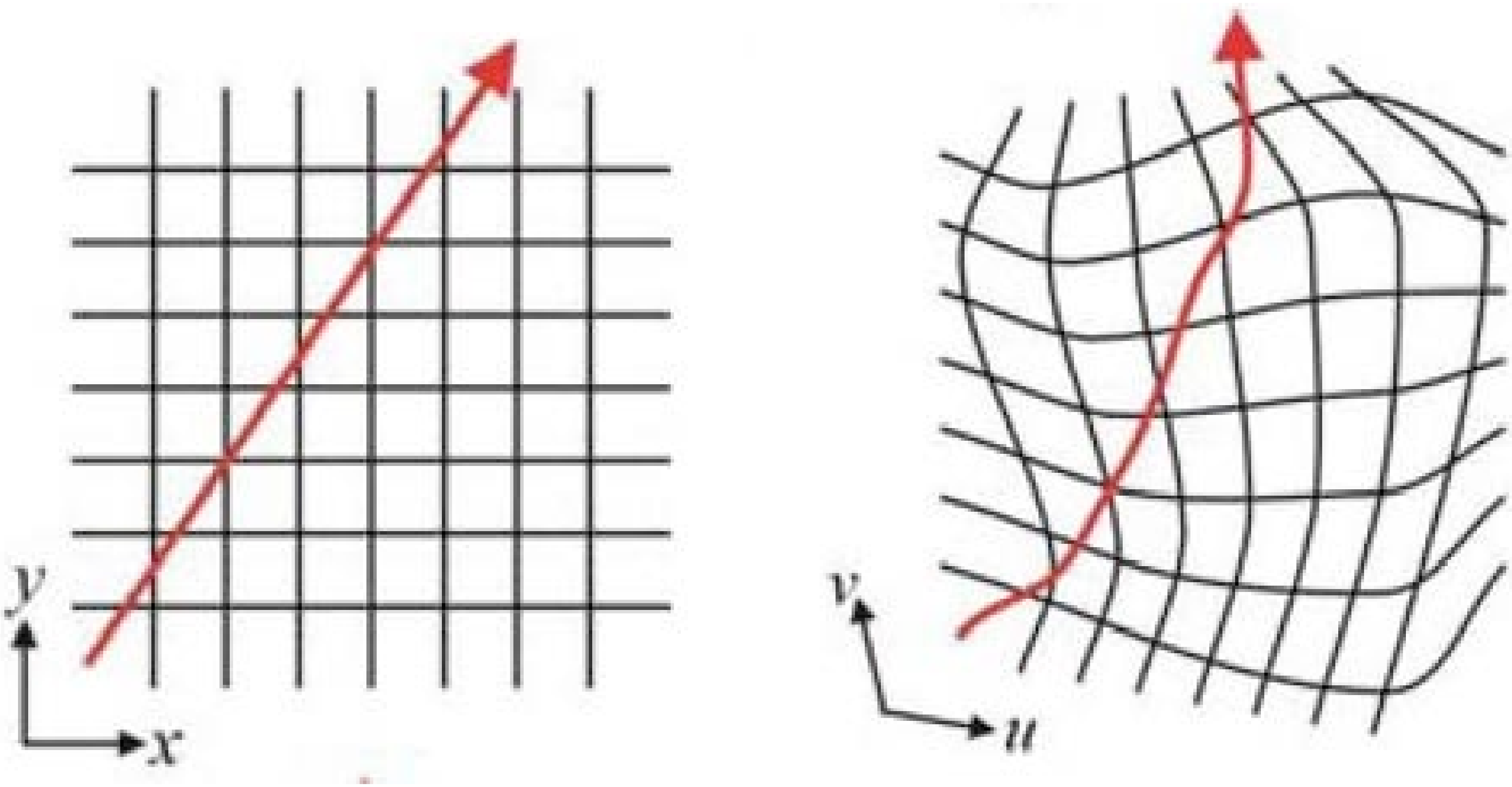




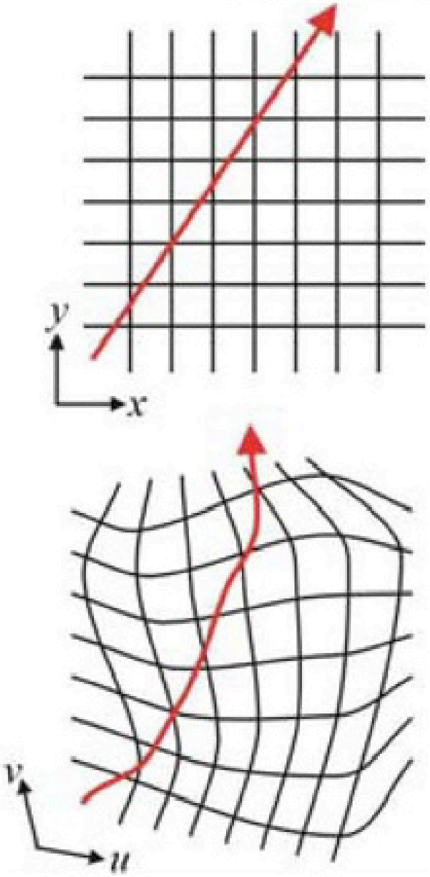
# Metamaterials – Transformation Optics



# Metamaterials – Transformation Optics

*San Diego, California (Summer 2009)*

# Metamaterials – Transformation Optics



New coordinates in terms of the old

$$u(x,y,z),\ v(x,y,z),\ w(x,y,z)$$

In the new coordinate system we must use renormalized values of the permittivity and permeability

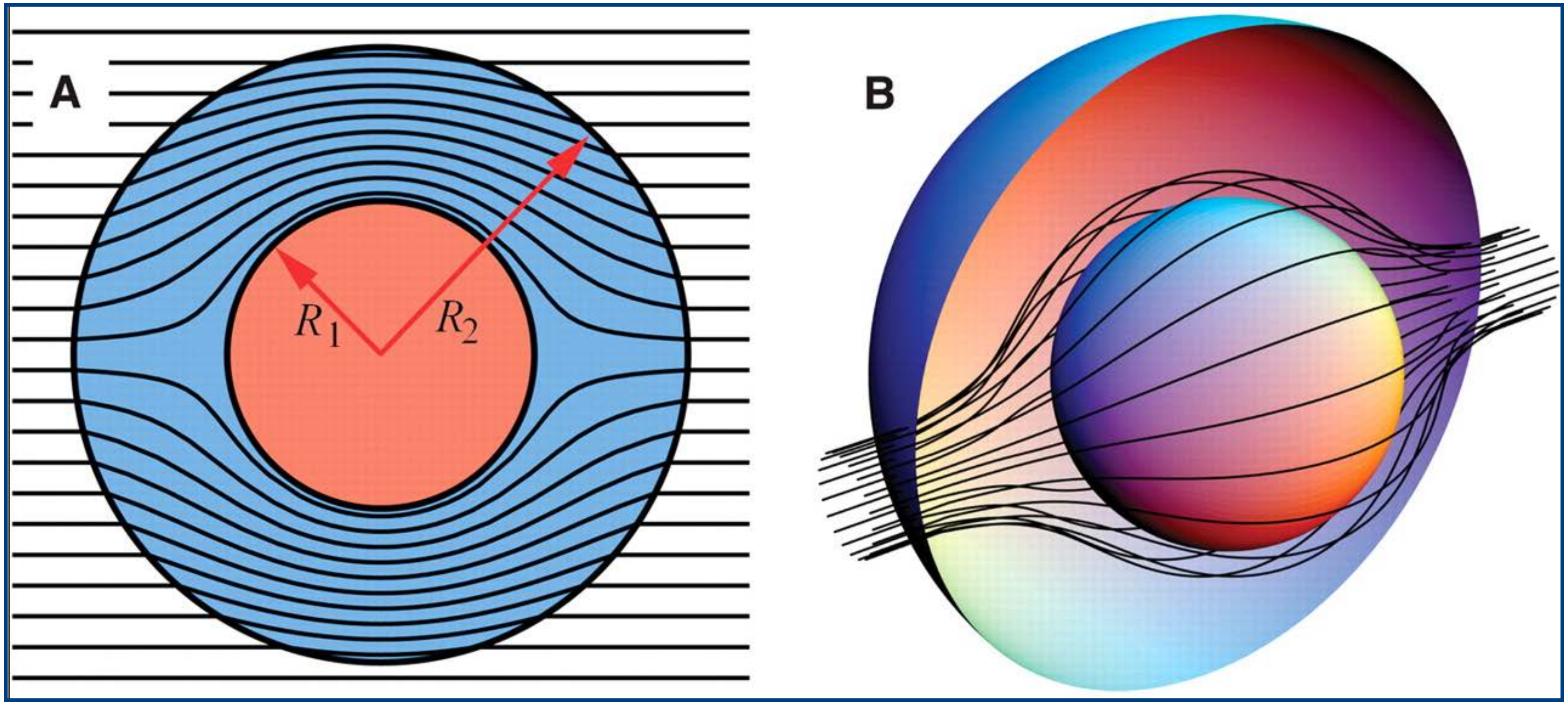
$$\tilde{\varepsilon}_u = \varepsilon_u \frac{Q_u Q_v Q_w}{Q_u^2}, \qquad \tilde{\mu}_u = \mu_u \frac{Q_u Q_v Q_w}{Q_u^2}, \qquad \text{etcetera}$$

where,

$$Q_u^2 = \left(\frac{\partial x}{\partial u}\right)^2 + \left(\frac{\partial y}{\partial u}\right)^2 + \left(\frac{\partial z}{\partial u}\right)^2, \text{ etcetera}$$

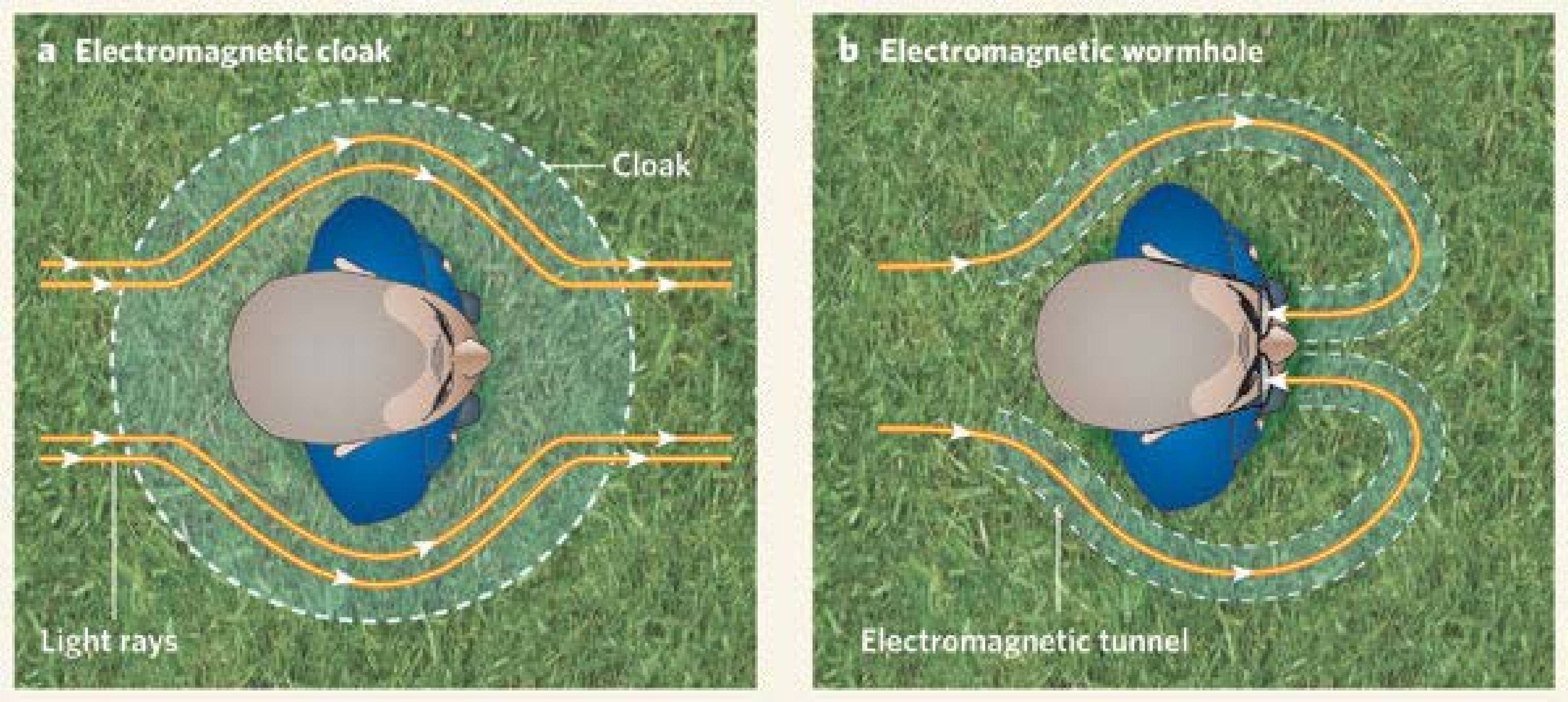
Imperial College
London

# Metamaterials – Cloaking



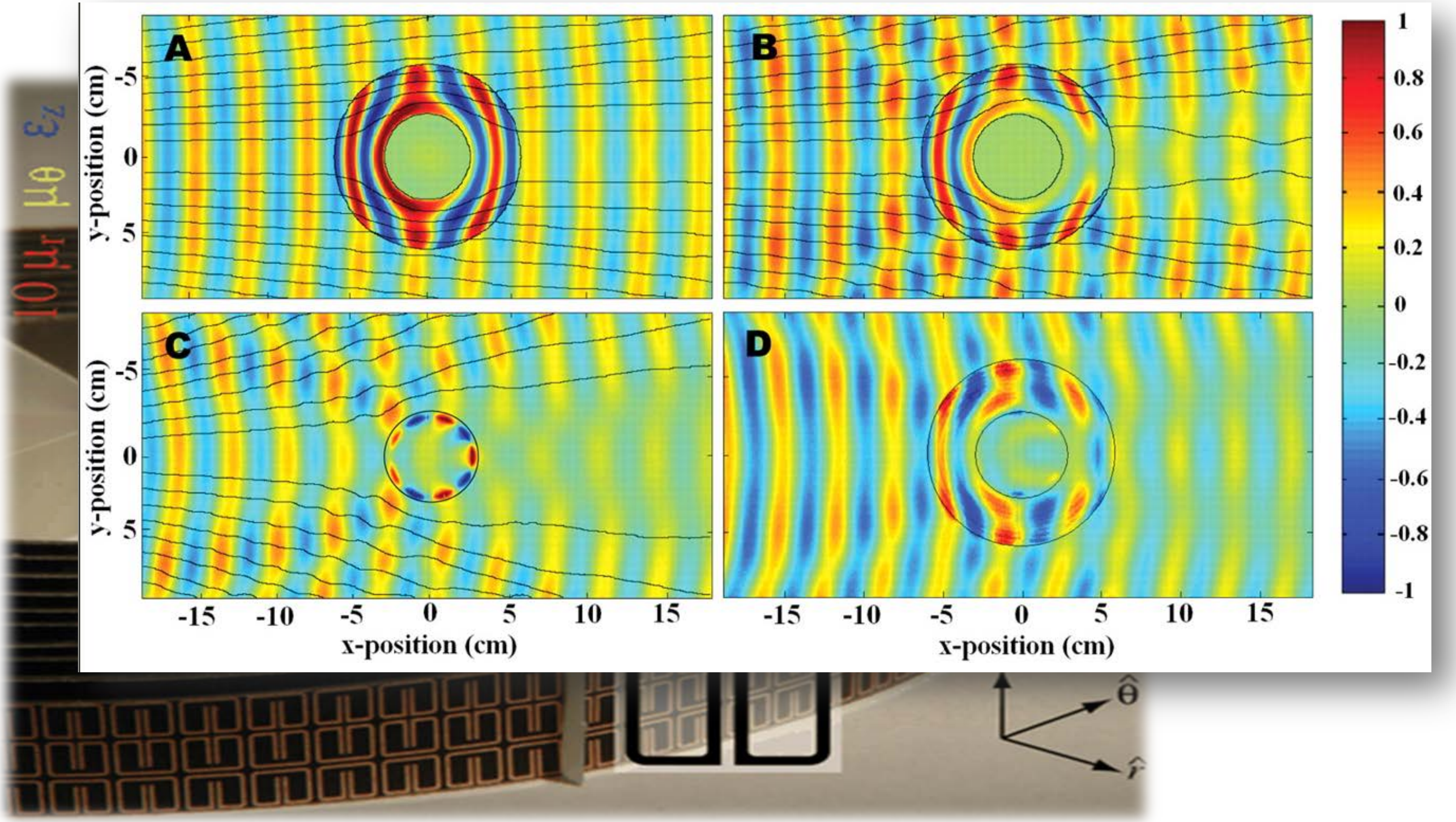
*[Pendry, et al., Science* ***312****, 1780 (2006)]*

# Metamaterials – Optical Wormholes



*[K Tsakmakidis and O Hess, Nature* ***451****, 27 (2008)]*

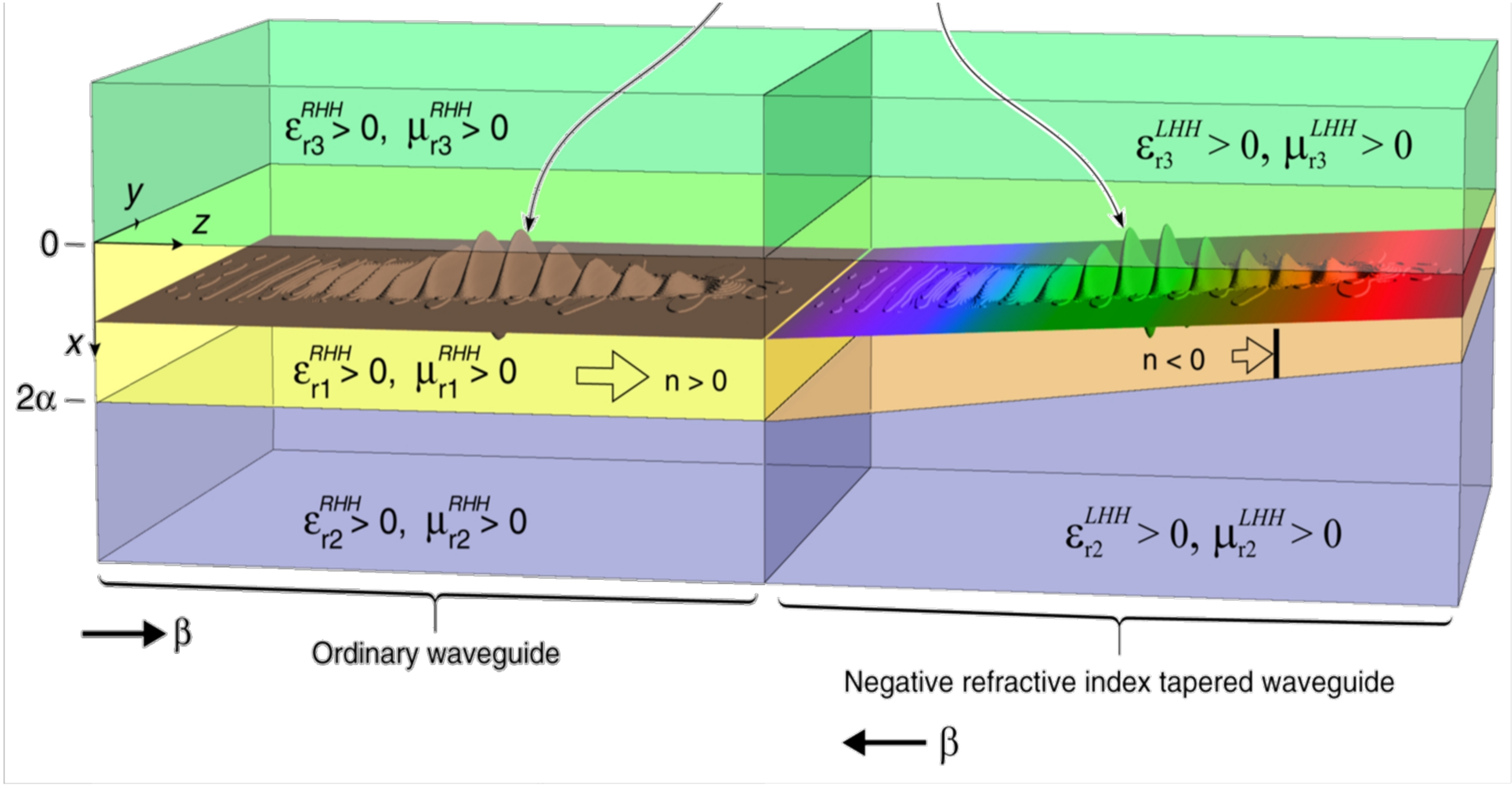
# Metamaterials - Cloaking



*[Schurig, et al., Science **314**, 977 (2006)]*

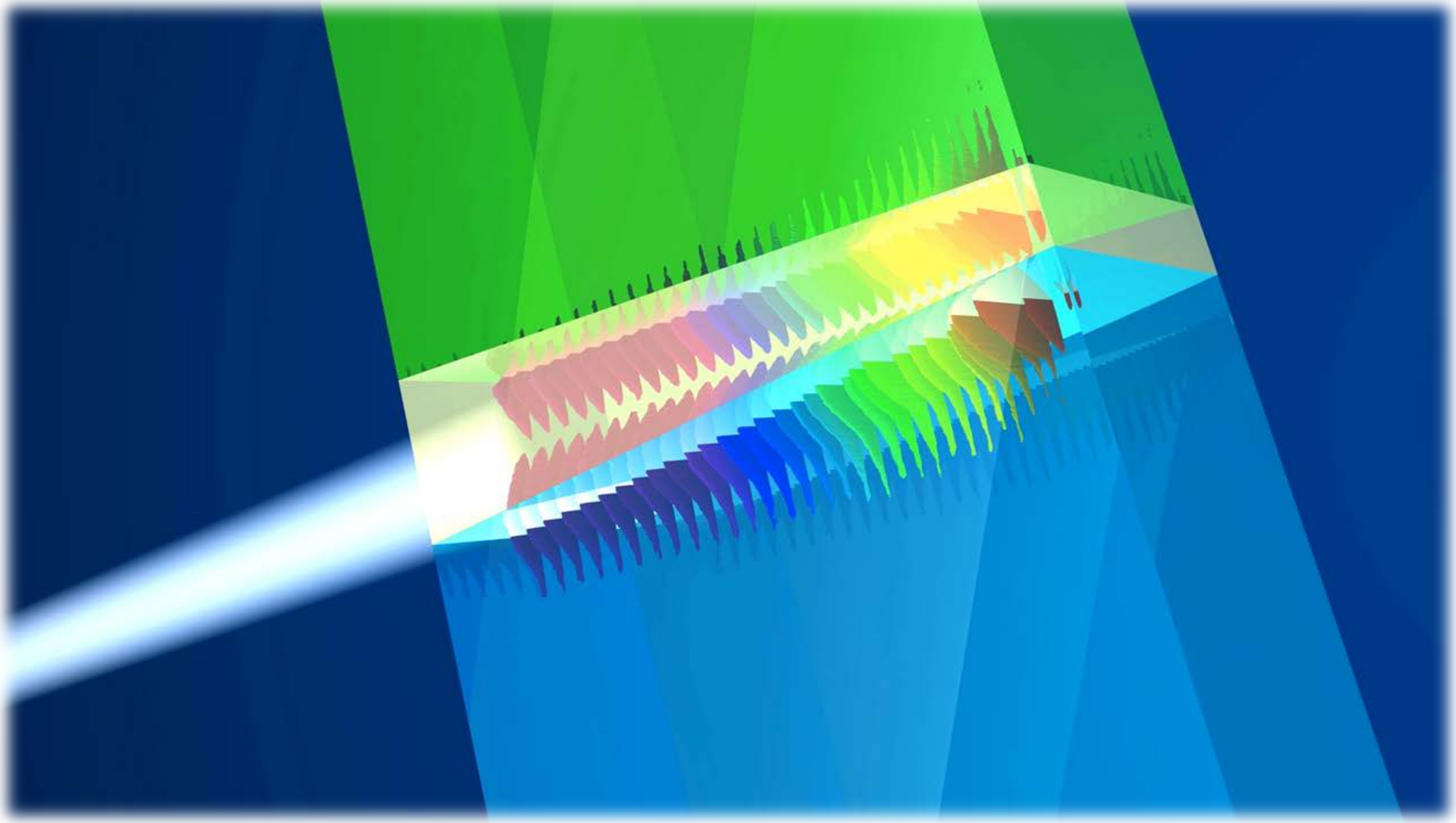
# Speed Control ?

# Metamaterials – ‘Trapped Rainbow’



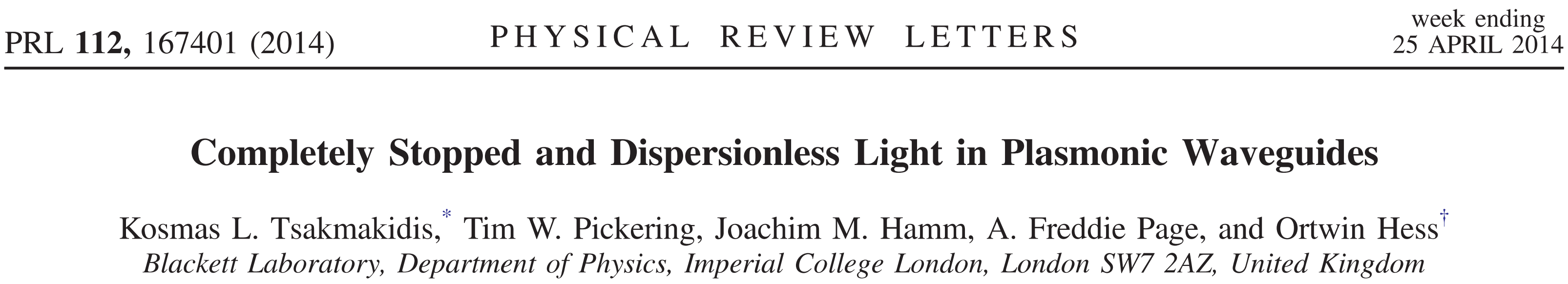
*K L Tsakmakidis, A D Boardman, and O Hess,*
*‘Trapped Rainbow’ Storage of Light in Metamaterials, Nature* ***450****, 397-401 (2007) .*

# Metamaterials – 'Trapped Rainbow'



K L Tsakmakidis, A D Boardman, and O Hess,
'Trapped Rainbow' Storage of Light in Metamaterials, Nature **450**, 397-401 (2007) .

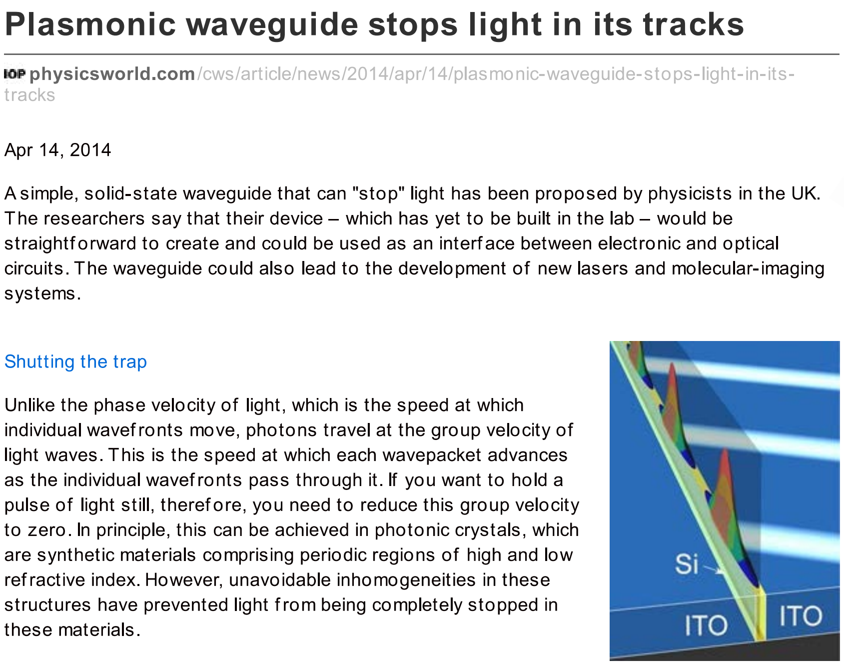
# Stopped Light in Nano-Plasmonic Waveguides



PRL **112,** 167401 (2014) PHYSICAL REVIEW LETTERS week ending 25 APRIL 2014

## Completely Stopped and Dispersionless Light in Plasmonic Waveguides

Kosmas L. Tsakmakidis,[*] Tim W. Pickering, Joachim M. Hamm, A. Freddie Page, and Ortwin Hess[†]
*Blackett Laboratory, Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom*



## Plasmonic waveguide stops light in its tracks

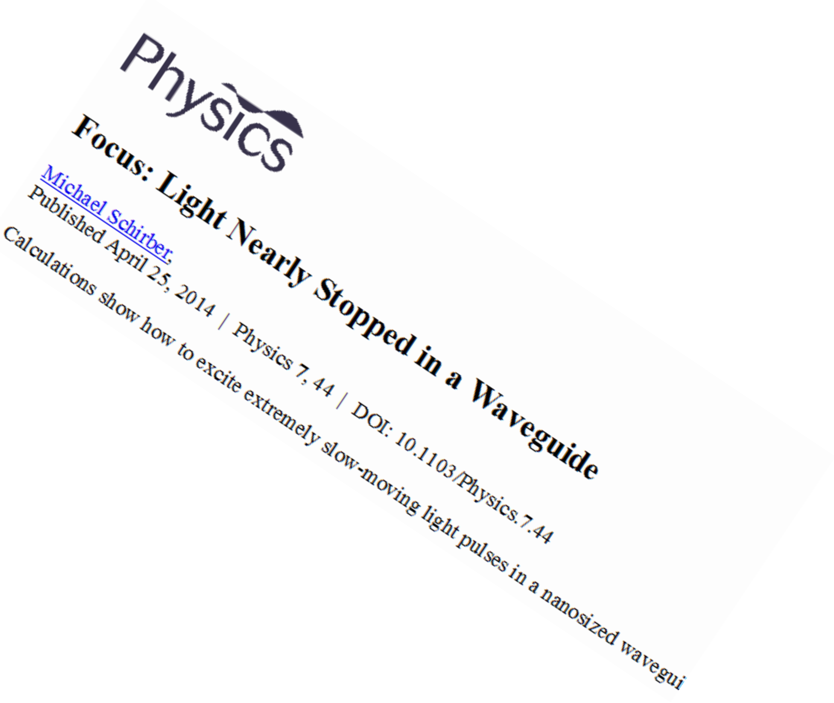
IOP physicsworld.com/cws/article/news/2014/apr/14/plasmonic-waveguide-stops-light-in-its-tracks

Apr 14, 2014

A simple, solid-state waveguide that can "stop" light has been proposed by physicists in the UK. The researchers say that their device – which has yet to be built in the lab – would be straightforward to create and could be used as an interface between electronic and optical circuits. The waveguide could also lead to the development of new lasers and molecular-imaging systems.

### Shutting the trap

Unlike the phase velocity of light, which is the speed at which individual wavefronts move, photons travel at the group velocity of light waves. This is the speed at which each wavepacket advances as the individual wavefronts pass through it. If you want to hold a pulse of light still, therefore, you need to reduce this group velocity to zero. In principle, this can be achieved in photonic crystals, which are synthetic materials comprising periodic regions of high and low refractive index. However, unavoidable inhomogeneities in these structures have prevented light from being completely stopped in these materials.



Physics

## Focus: Light Nearly Stopped in a Waveguide

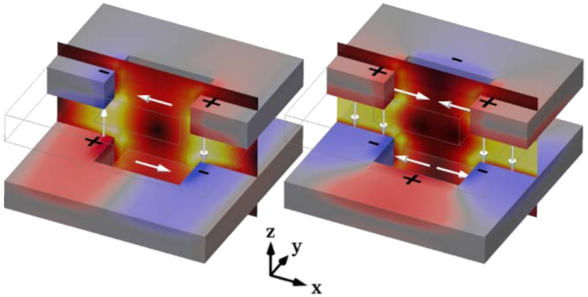
Michael Schirber
Published April 25, 2014 | Physics 7, 44 | DOI: 10.1103/Physics.7.44

Calculations show how to excite extremely slow-moving light pulses in a nanosized wavegui

# Outline

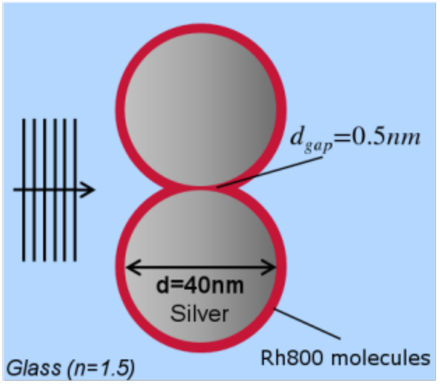
## “Materials with New Properties”

- *negative refractive index*
- *active ‘dark light’*



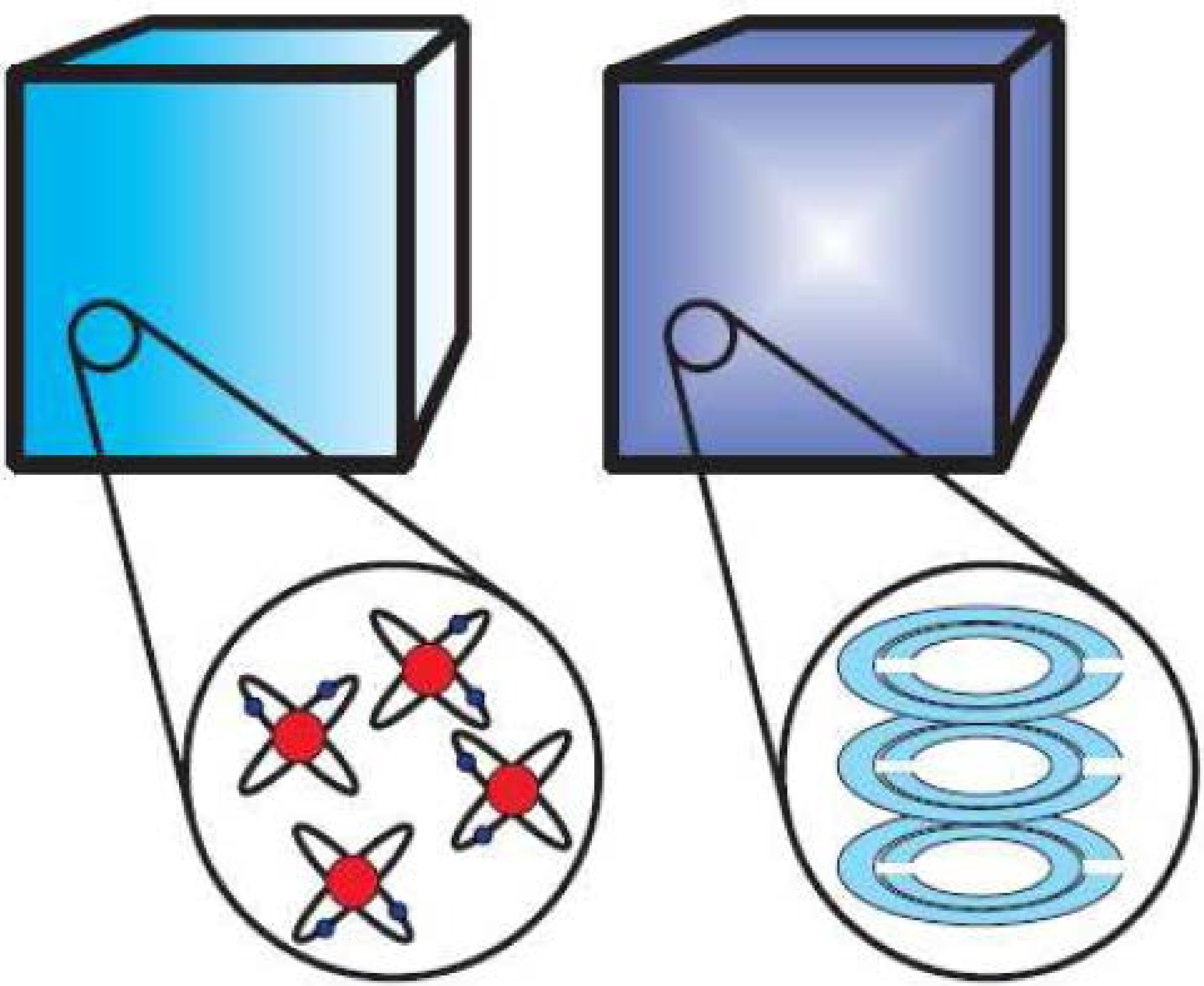
## Extreme Sensing

- *stopped light*
- *extreme light-matter interaction*
- *ultra-sensitive sensing (factor $10^4$)*

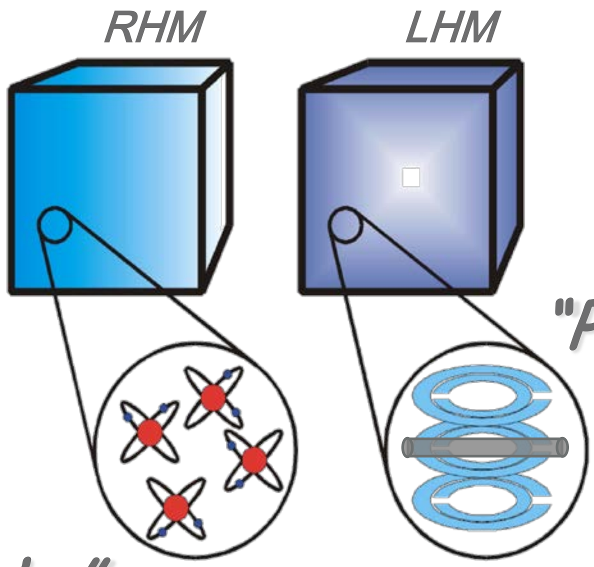


# Materials – Metamaterials

## Function from Structure

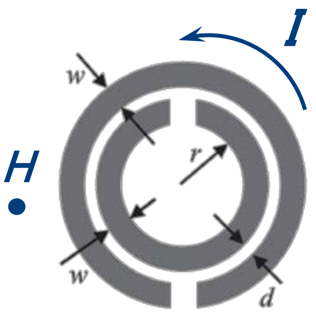


# Metamaterials – Negative Refractive Index

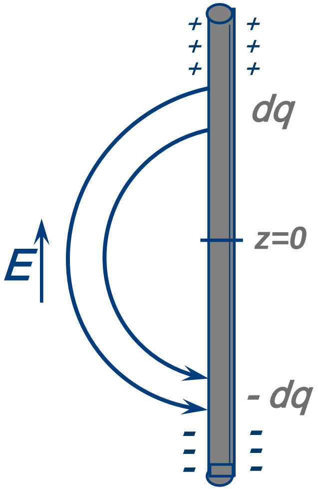


Circulating currents → magnetic dipoles

Displaced charges → electric dipoles



"Split-Ring Resonator"



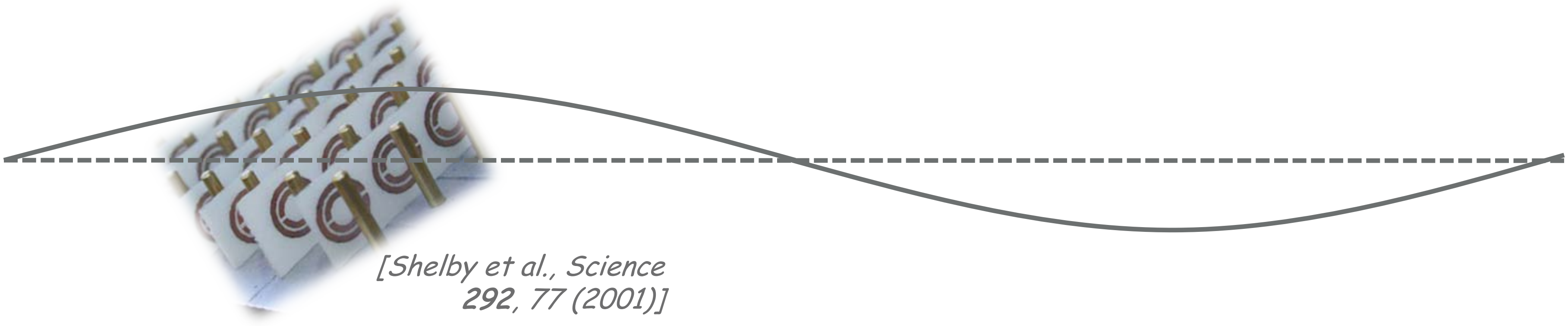
Metallic Rod

[Shelby et al., Science 292, 77 (2001)]

# Metamaterials – Negative Refractive Index

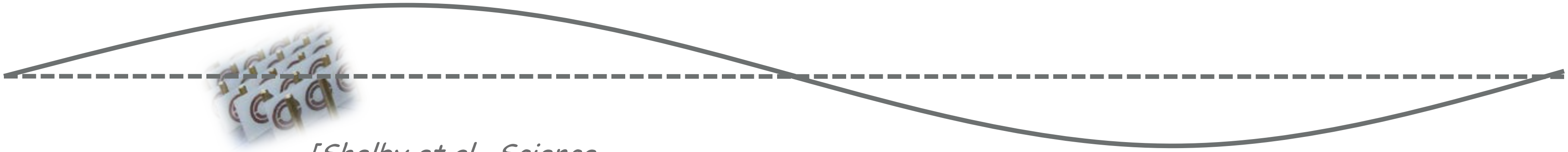
*[Shelby et al., Science* ***292****, 77 (2001)]*

# Metamaterials – Negative Refractive Index



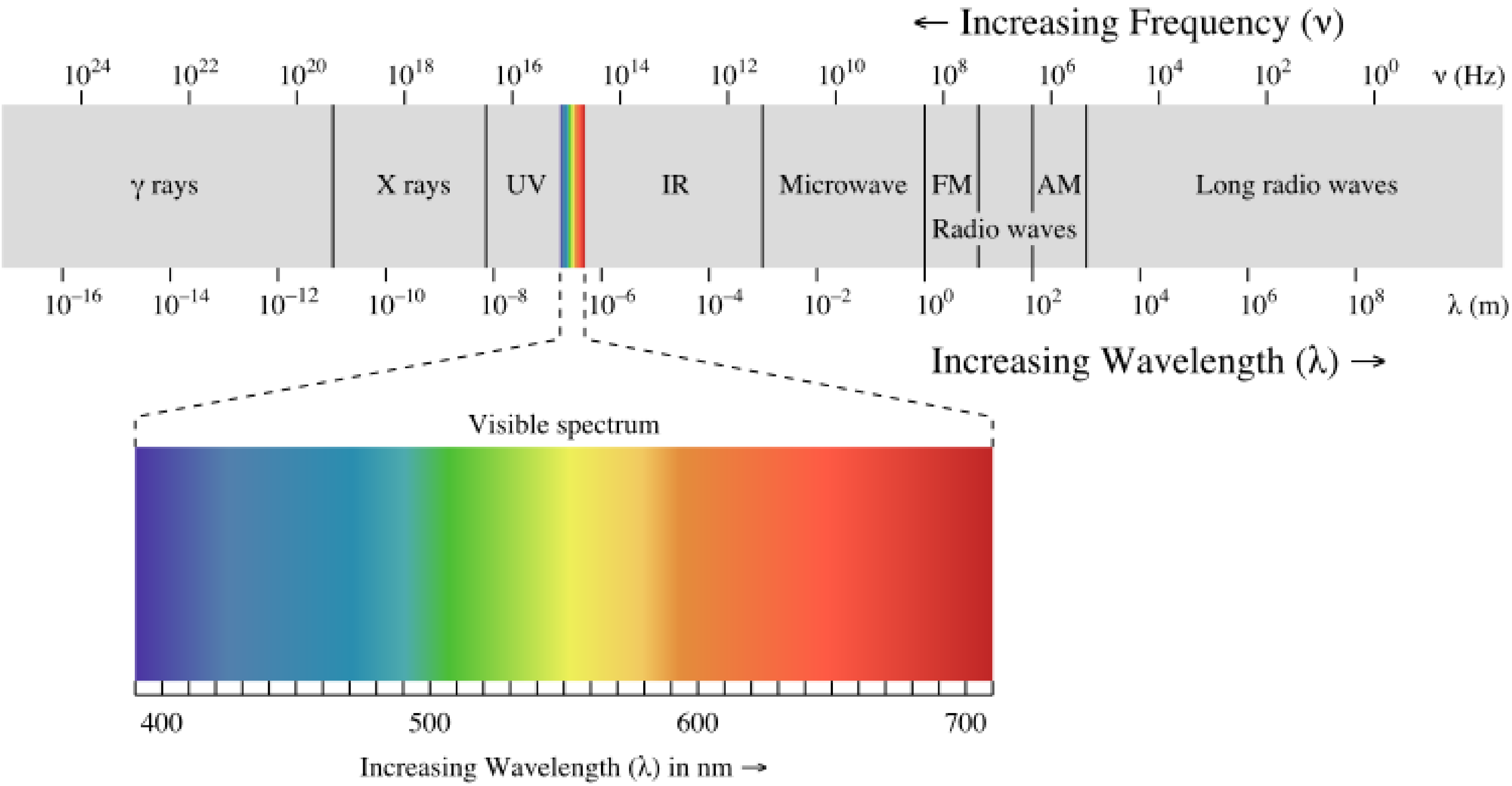
*[Shelby et al., Science*
***292**, 77 (2001)]*

# Metamaterials – Negative Refractive Index

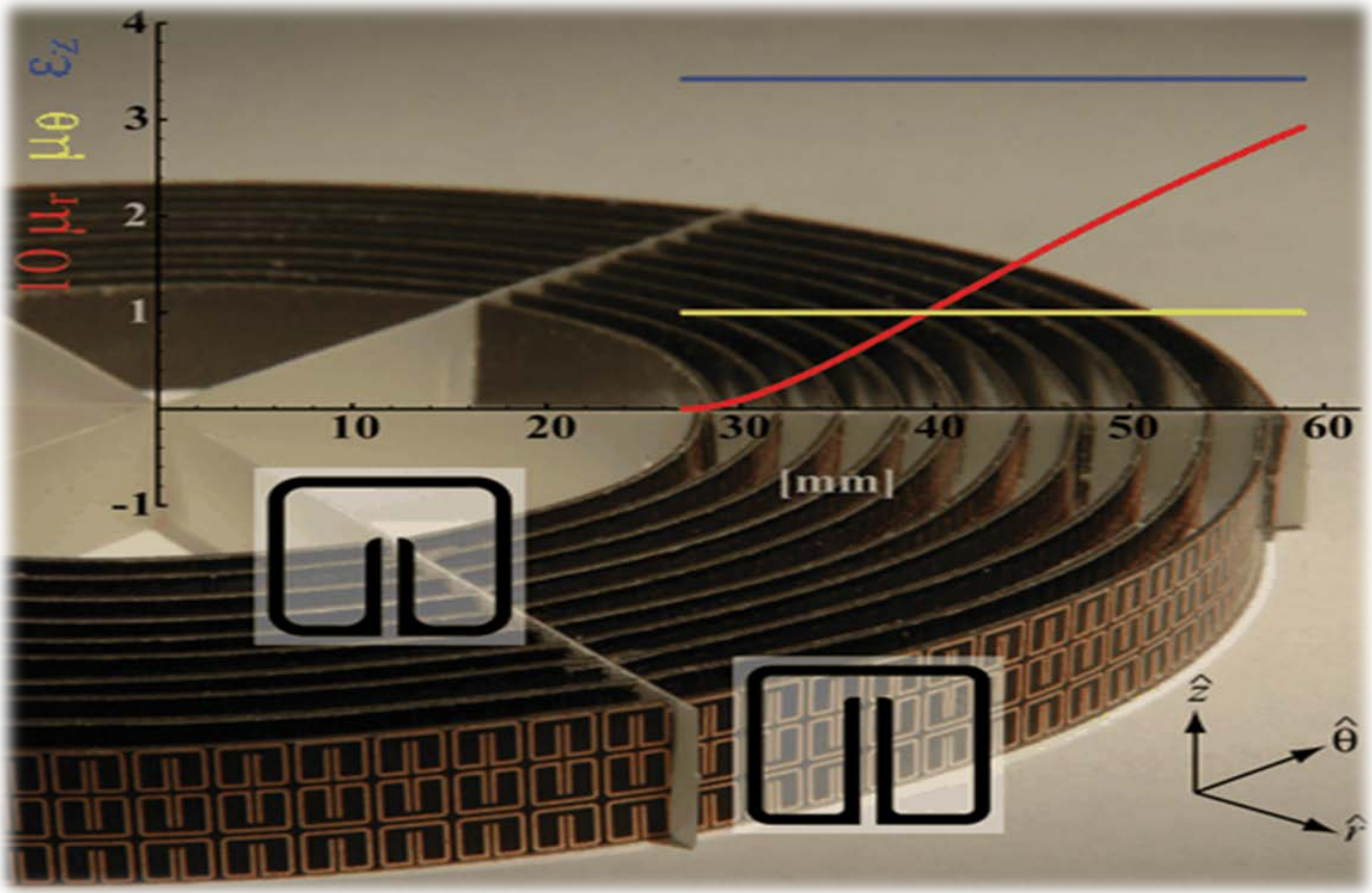


*[Shelby et al., Science* ***292****, 77 (2001)]*

# Metamaterials – Electromagnetic Spectrum

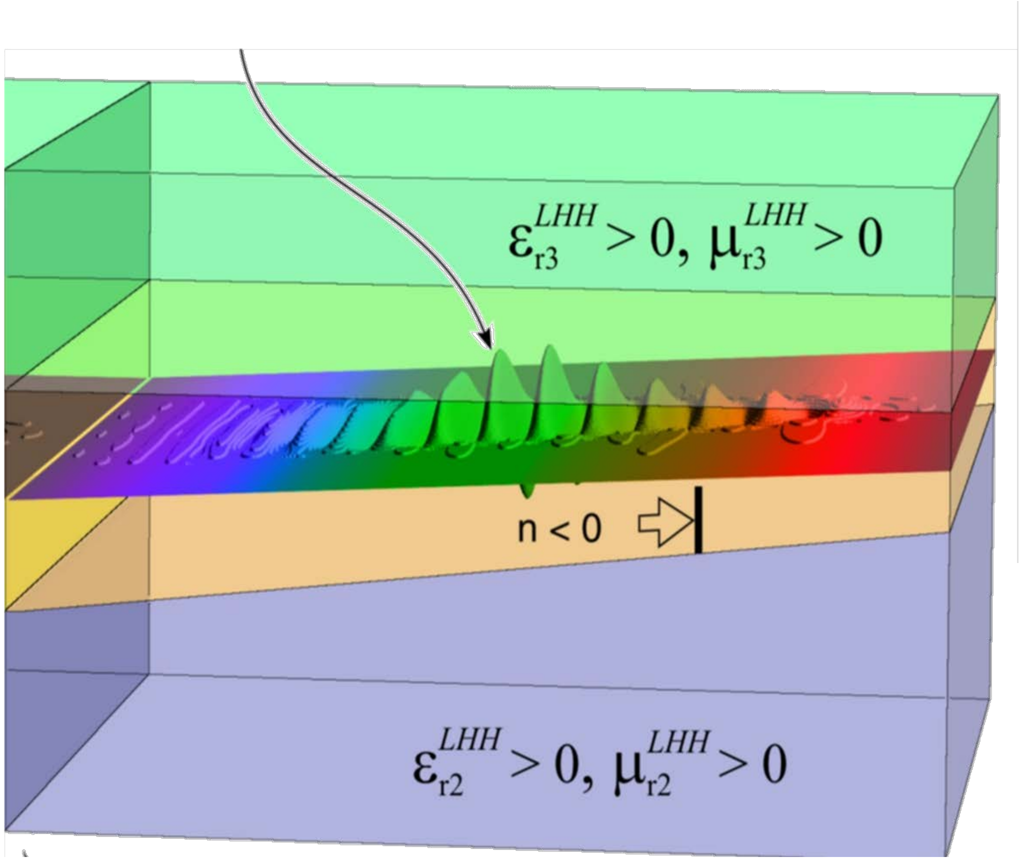


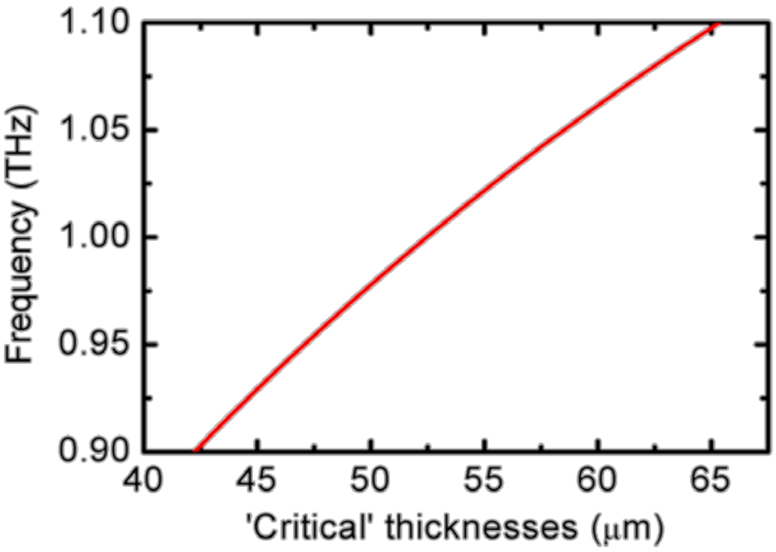
# Metamaterials - Cloaking



*[Schurig, et al., Science **314**, 977 (2006)]*

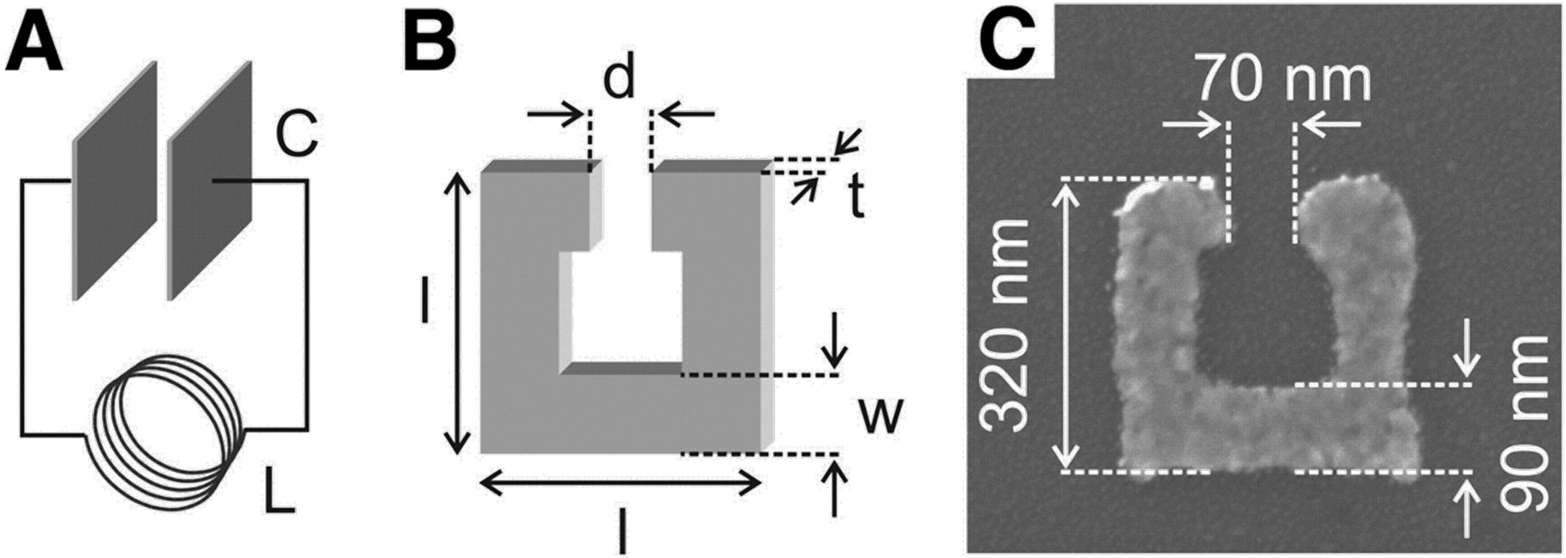
# Metamaterials – ‘Trapped Rainbow’





*[K L Tsakmakidis, A D Boardman, and O Hess, ‘Trapped Rainbow’ Storage of Light in Metamaterials, Nature* ***450****, 397-401 (2007)]*

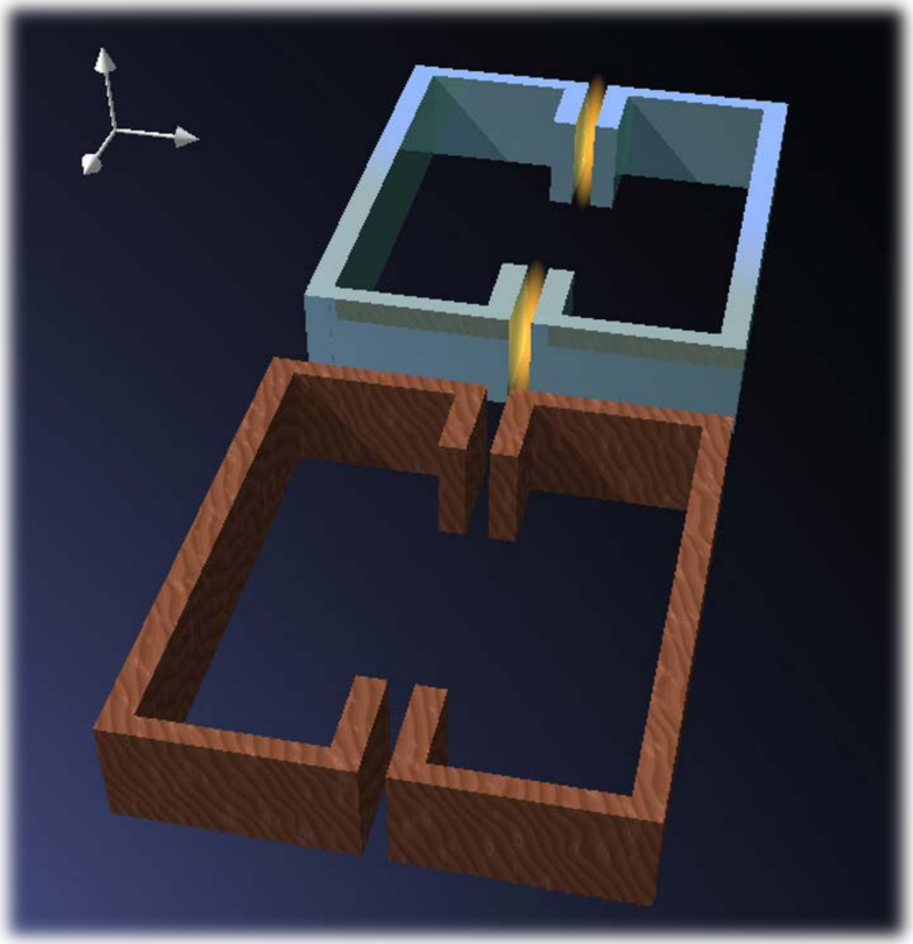
# Metamaterials – Plasmonic Nanostructures

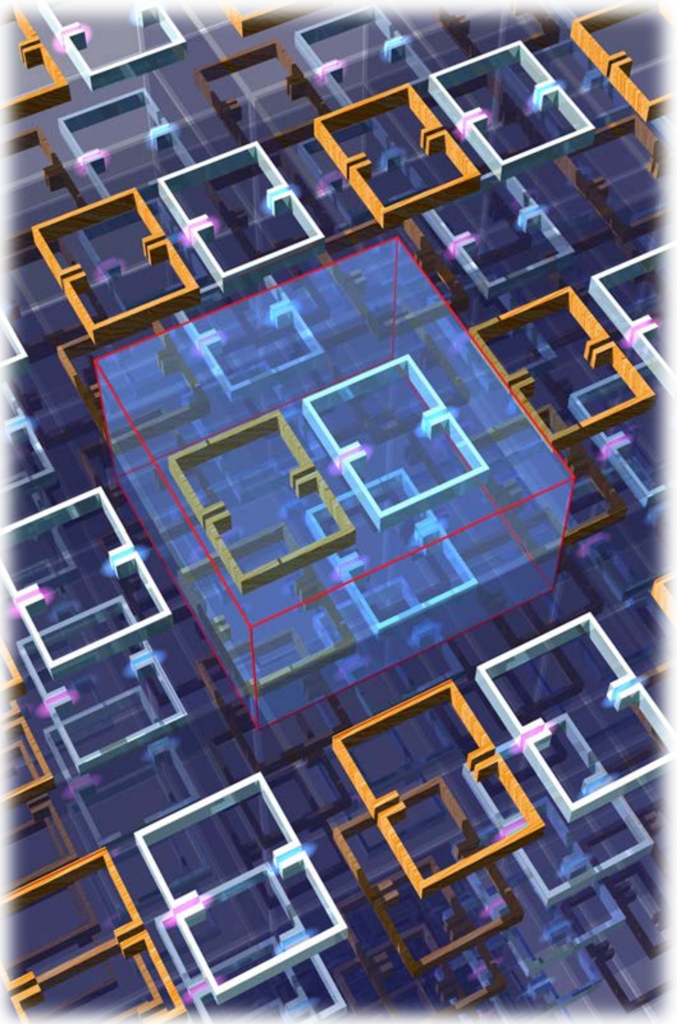


*S. Linden et al., Science 306, 1351 -1353 (2004)*

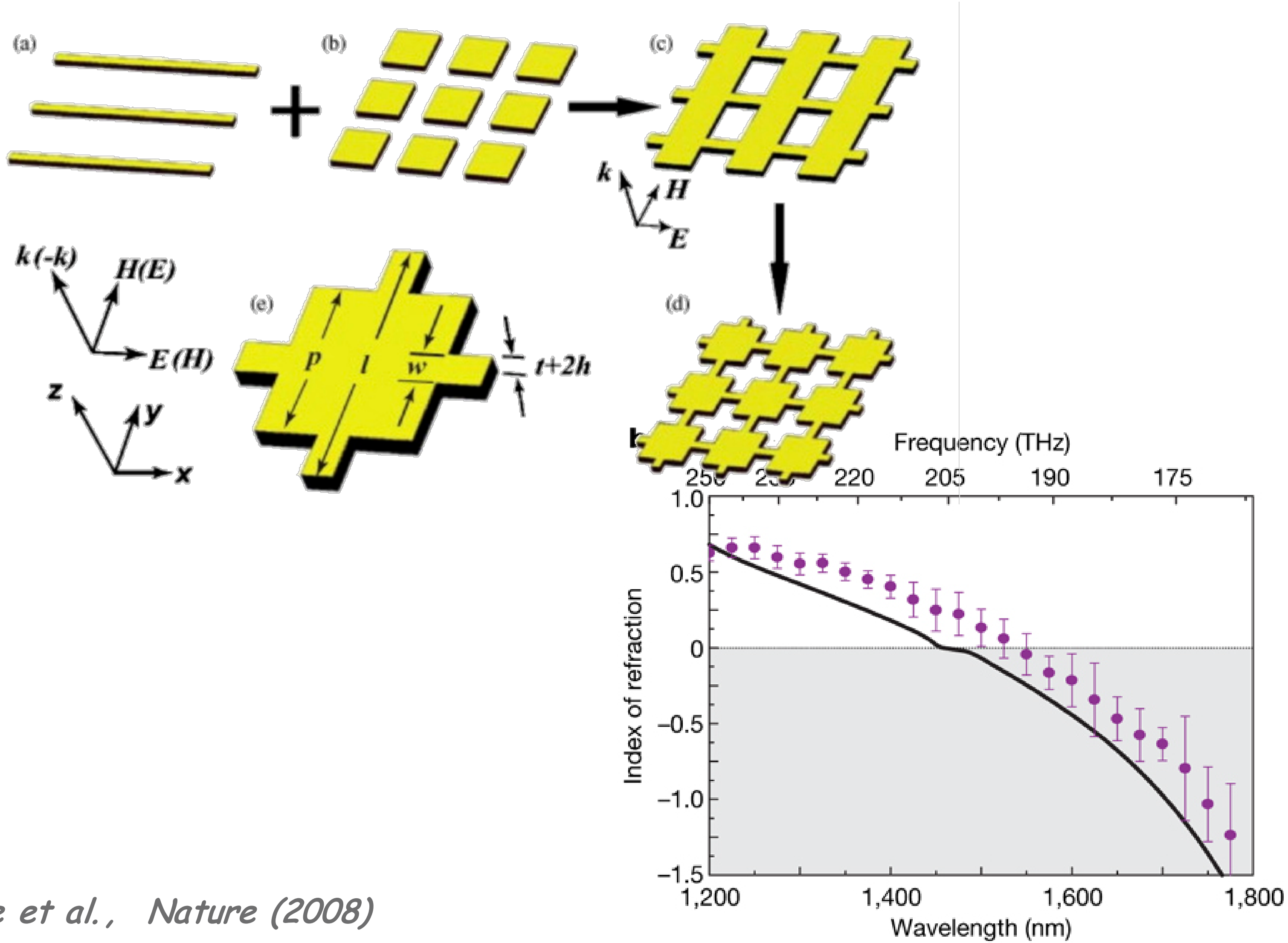
***Fig. 1. Illustration of the analogy between a conventional LC circuit (A), consisting of an inductance L, a capacitance C, and the single SRRs used here (B). l, length; w, width; d, gap width; t, thickness***

# From Meta-Molecules to Metamaterials





# Metamaterials – Fishnet Structure



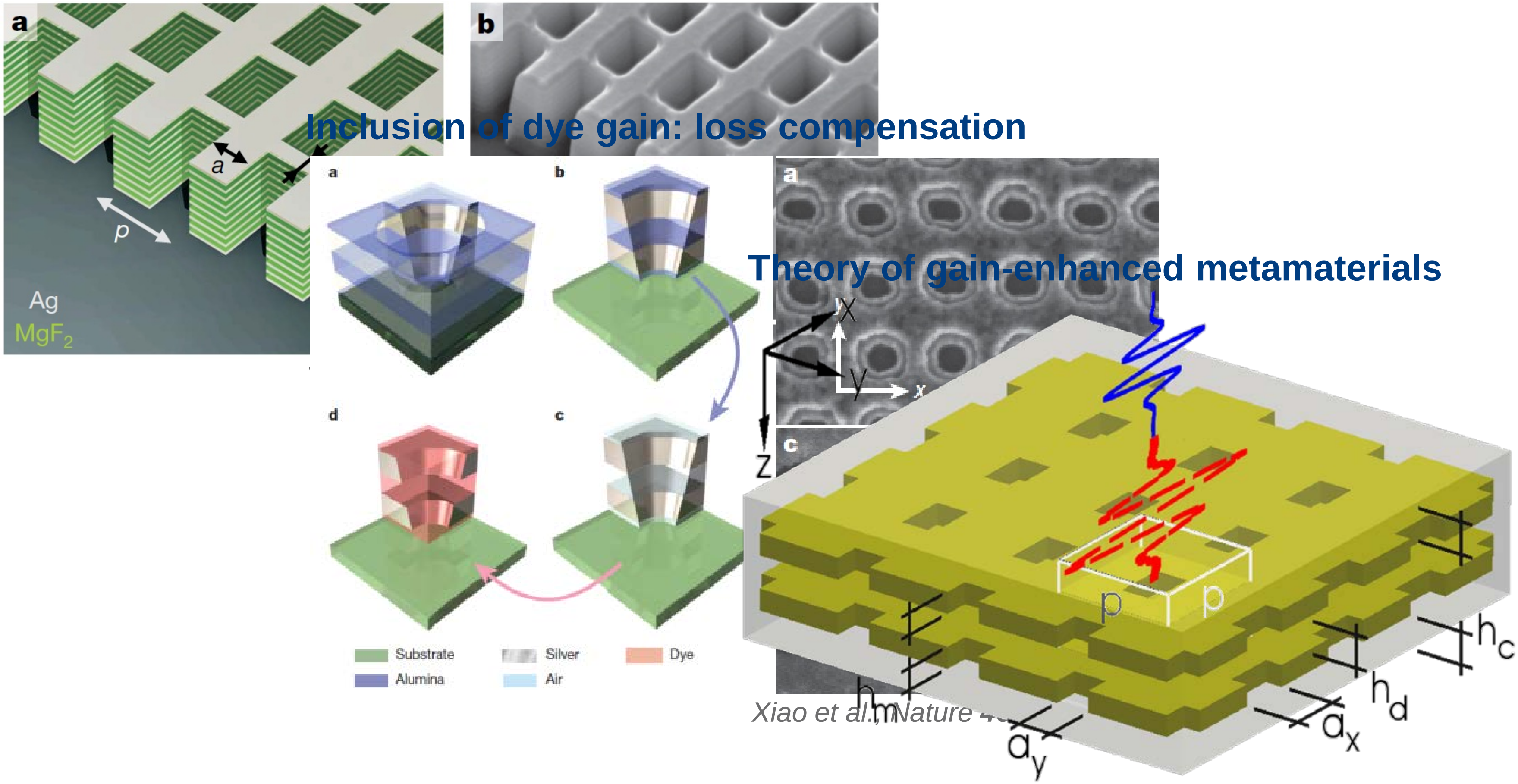
*Valentine et al., Nature (2008)*

# Gain-Enhanced Nanoplasmonic Metamaterials

## Fishnet negative-index metamaterial

## Inclusion of dye gain: loss compensation

## Theory of gain-enhanced metamaterials

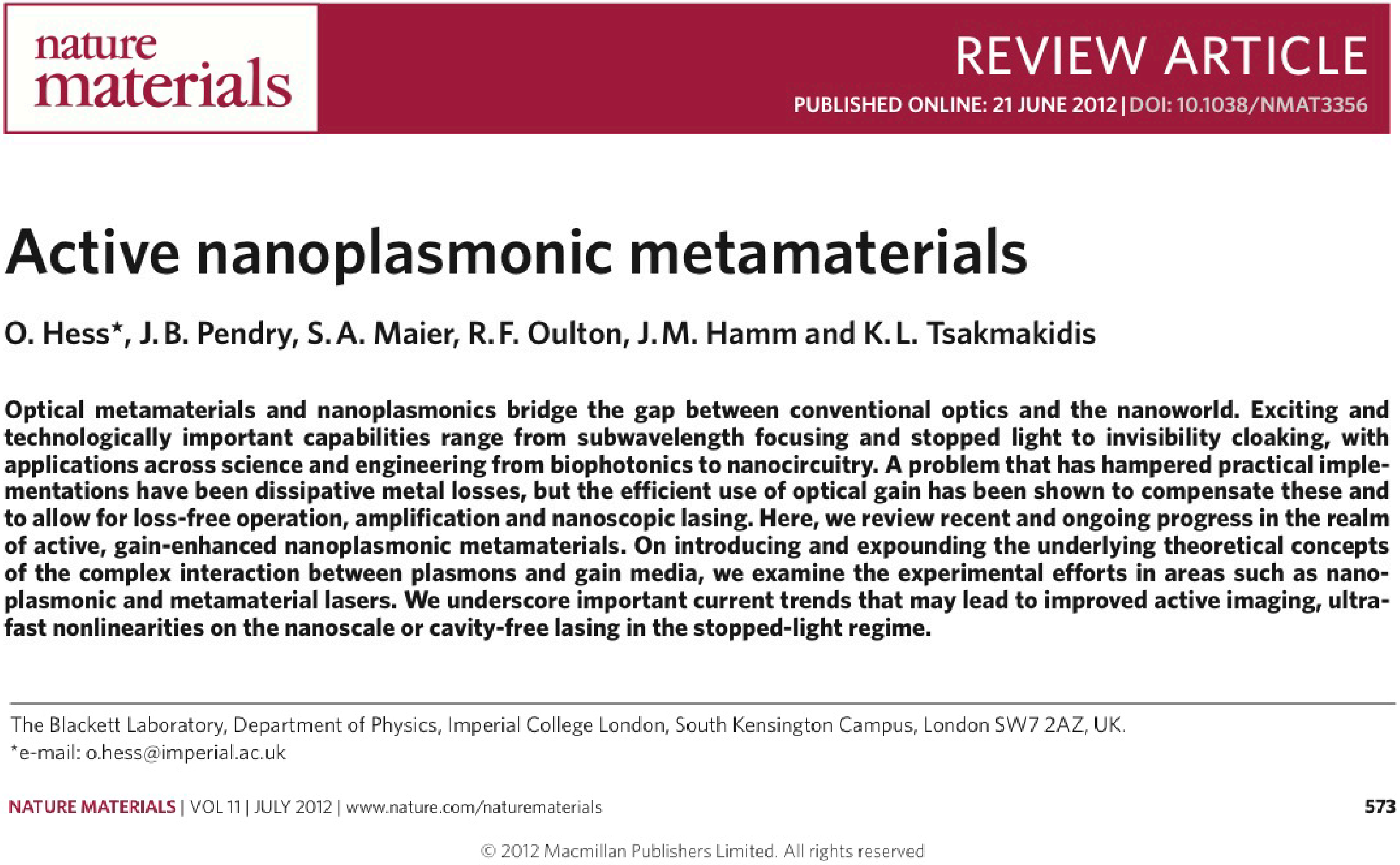


Xiao et al., Nature 4

S Wuestner, A Pusch, KL Tsakmakidis, JM Hamm and O Hess,
**"Overcoming Losses with Gain in a Negative Refractive Index Metamaterial"**
*Phys Rev Lett* ***105****, 127401 (2010)*

# Active Nanoplasmonic Metamaterials

## Nanoplasmonic Systems with Gain



nature materials

REVIEW ARTICLE

PUBLISHED ONLINE: 21 JUNE 2012 | DOI: 10.1038/NMAT3356

# Active nanoplasmonic metamaterials

O. Hess*, J. B. Pendry, S. A. Maier, R. F. Oulton, J. M. Hamm and K. L. Tsakmakidis

**Optical metamaterials and nanoplasmonics bridge the gap between conventional optics and the nanoworld. Exciting and technologically important capabilities range from subwavelength focusing and stopped light to invisibility cloaking, with applications across science and engineering from biophotonics to nanocircuitry. A problem that has hampered practical implementations have been dissipative metal losses, but the efficient use of optical gain has been shown to compensate these and to allow for loss-free operation, amplification and nanoscopic lasing. Here, we review recent and ongoing progress in the realm of active, gain-enhanced nanoplasmonic metamaterials. On introducing and expounding the underlying theoretical concepts of the complex interaction between plasmons and gain media, we examine the experimental efforts in areas such as nanoplasmonic and metamaterial lasers. We underscore important current trends that may lead to improved active imaging, ultrafast nonlinearities on the nanoscale or cavity-free lasing in the stopped-light regime.**

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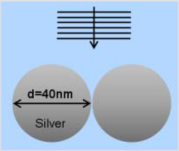
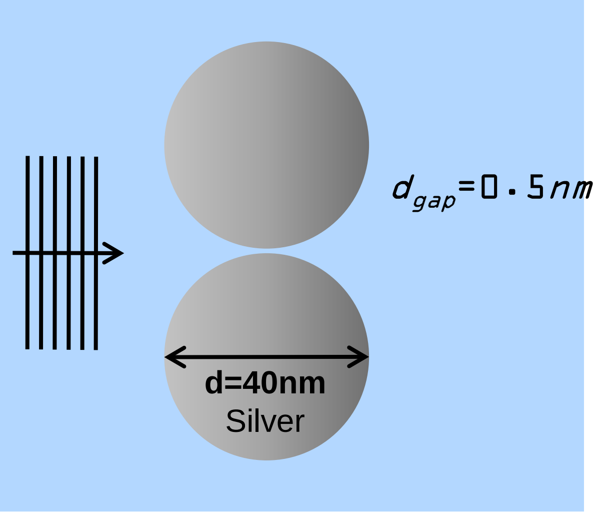
The Blackett Laboratory, Department of Physics, Imperial College London, South Kensington Campus, London SW7 2AZ, UK.
*e-mail: o.hess@imperial.ac.uk



# NANO-PLASMONIC SYSTEM



- Nearly touching cylinders with 40nm diameter
- Embedded in glass (n=1.5)
- Varying gap sizes

# Plasmonic System

## Spatio-Temoral Nano-Plasmonics

$$\mathbf{D}(\mathbf{r},t)=\varepsilon_0\varepsilon(\mathbf{r})\mathbf{E}(\mathbf{r},t)+\mathbf{P}(\mathbf{r},t)$$

$$\varepsilon_0\varepsilon\frac{\partial\mathbf{E}}{\partial t}=\nabla\times\mathbf{H}-\partial_t\mathbf{P}-\mathbf{J}$$

$$\mu_0\mu\frac{\partial\mathbf{H}}{\partial t}=-\nabla\times\mathbf{E}$$

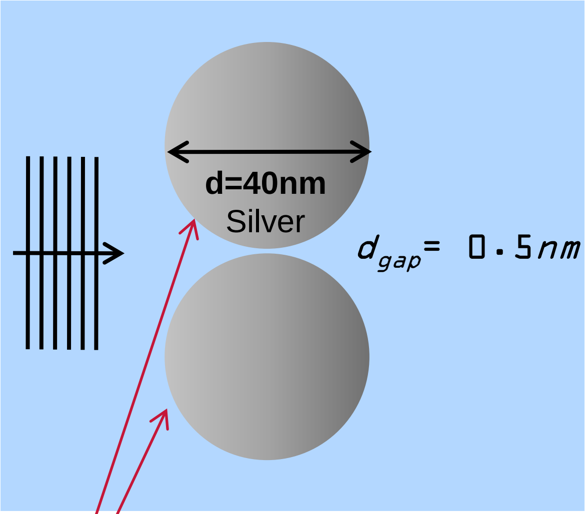
Maxwell’s equations ($\rho=0$)

$$\varepsilon(r)=\sum_{i=1}^{j}\varepsilon_i(\mathbf{r})$$

$$\mathbf{P}(\mathbf{r},t)=\sum_{i=1}^{k}\mathbf{P}_i(\mathbf{r},t)$$

$$\mathbf{J}(\mathbf{r},t)=\sum_{i=1}^{l}\mathbf{J}_i(\mathbf{r},t)$$

Material equations



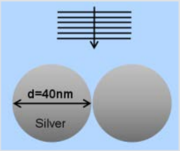
spatio-temporal dynamics

Lorentz: $$\frac{\partial^2\mathbf{P}_i}{\partial t^2}+2\gamma_{L,i}\frac{\partial\mathbf{P}_i}{\partial t}+\omega_{L,i}^2\mathbf{P}_i=\Delta\varepsilon_{L,i}\omega_{L,i}^2\mathbf{E}$$

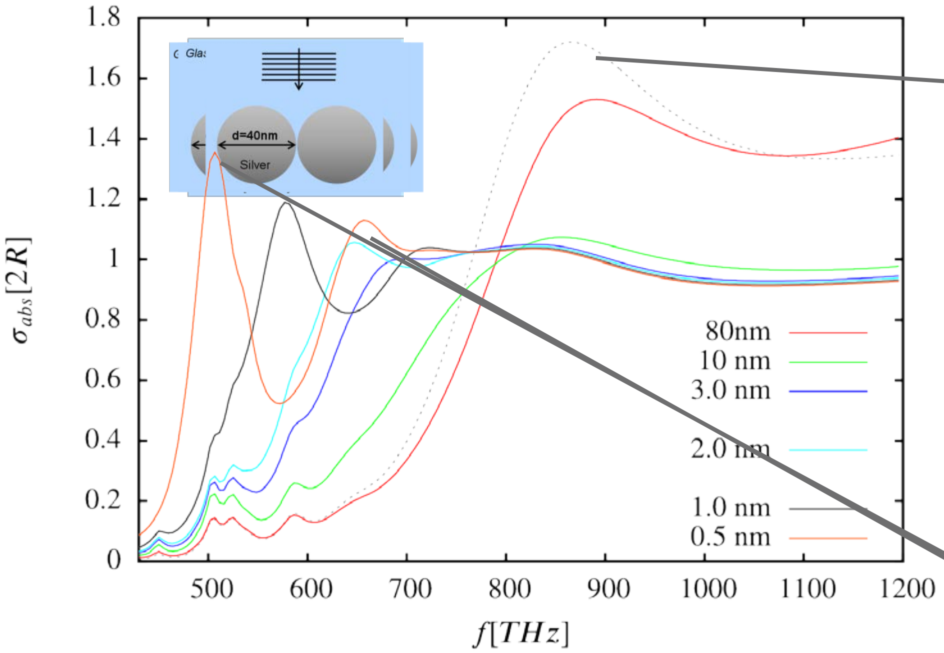
Drude: $$\frac{\partial\mathbf{J}_i}{\partial t}+\gamma_{D,i}\mathbf{J}=\omega_{D,i}^2\mathbf{E}$$

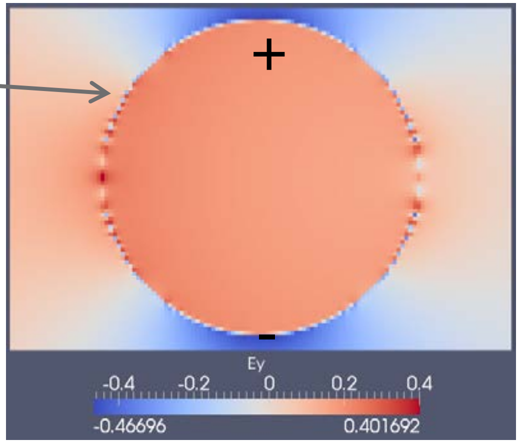
**classical non-locality *dynamically* included**

Imperial College
London

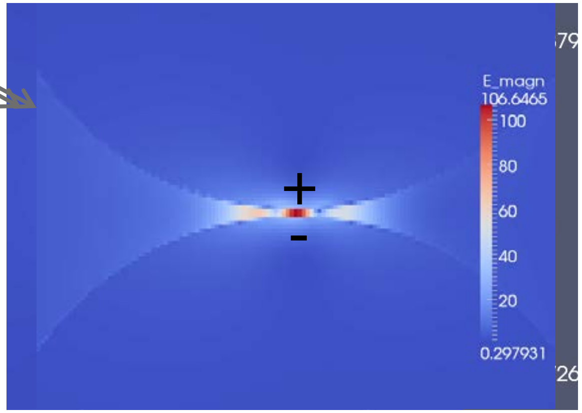


# Plasmonic System





Dipole



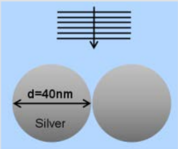
“Dipole”

Monomer

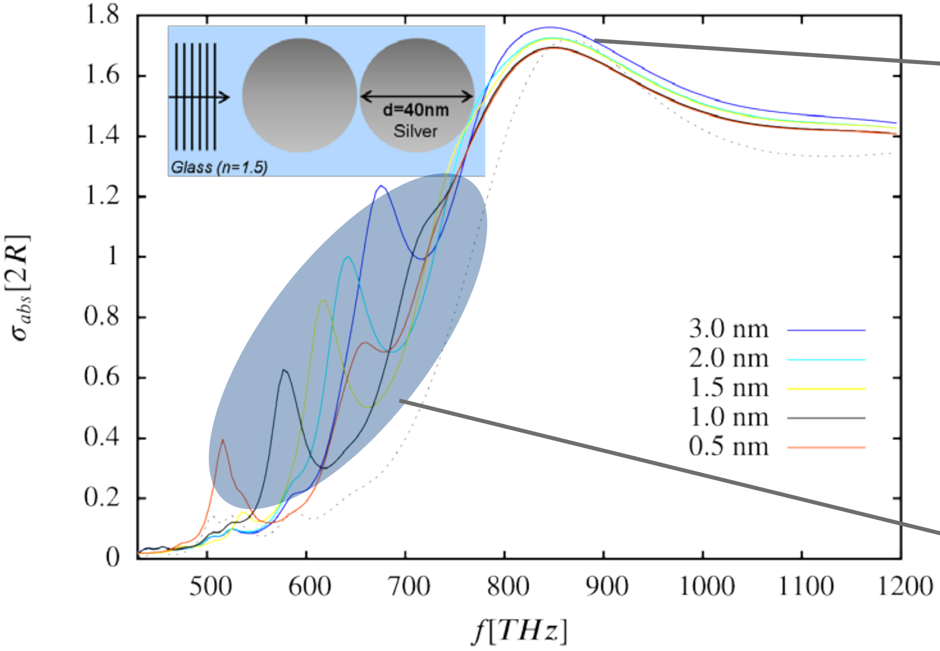
- Lowest resonance is dipole centred at centre of cylinder

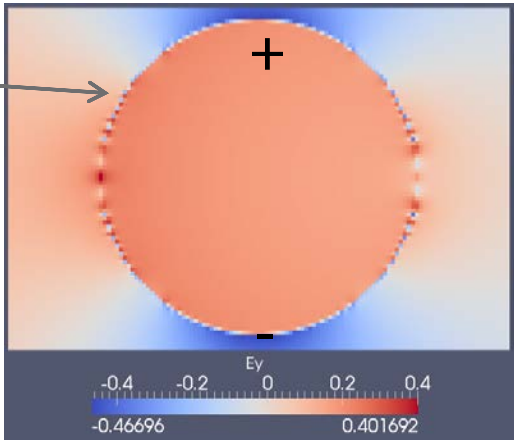
Dimer

- Resonant modes are dipolar in nature
- Dipole is centred at touching point
- Nodes in field profile along the gap increase with increasing resonance energy

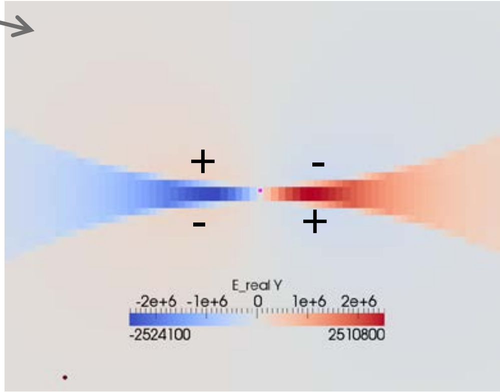


# Plasmonic System





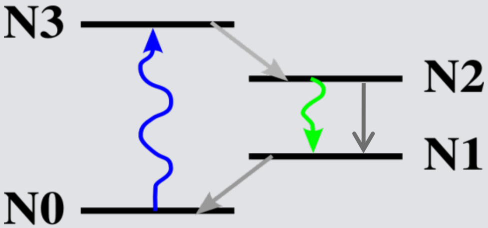
Dipole



“Quadrupolar”

Dimer

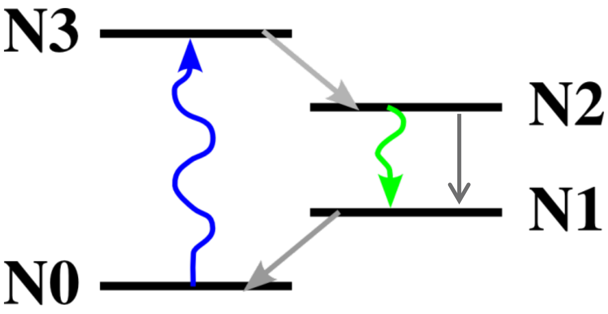
- Lowest energy mode is quadrupolar in nature
- Higher energy modes correspond to the modes of single monomer



# NONLINEAR / QUANTUM SYSTEM

## “Rh800” dye molecules

- Model decribes important radiative dipole transitions
- Both dipoles are coupled by “fast” non-radiative decay



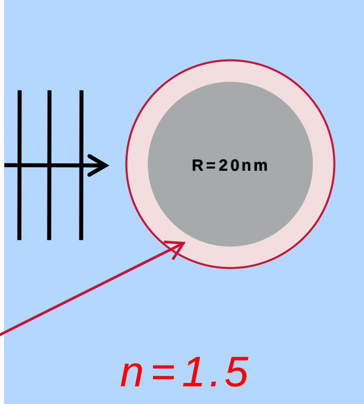
# Spontaneous Emission in Nanoplasmonic Systems with Gain

## Maxwell-Bloch Langevin equations

Polarisation

$$\frac{\partial^2 \mathbf{P}_\mathrm{e}}{\partial t^2} = -2\Gamma_\mathrm{e}\frac{\partial \mathbf{P}_\mathrm{e}}{\partial t} - \omega_{0,\,\mathrm{e}}^2 \mathbf{P}_\mathrm{e} - \sigma_\mathrm{e}(N_2 - N_1)\mathbf{E}$$

$$\frac{\partial^2 \mathbf{P}_\mathrm{a}}{\partial t^2} = -2\Gamma_\mathrm{a}\frac{\partial \mathbf{P}_\mathrm{a}}{\partial t} - \omega_{0,\,\mathrm{a}}^2 \mathbf{P}_\mathrm{a} - \sigma_\mathrm{a}(N_3 - N_0)\mathbf{E}$$



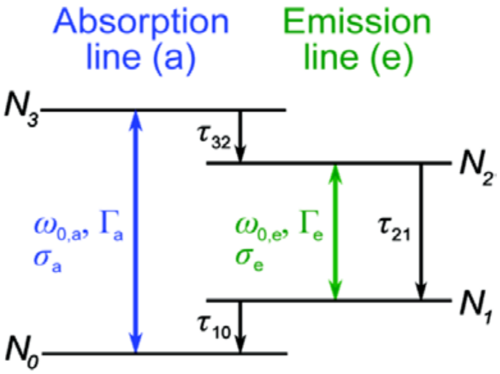
Occupation density

$$\frac{\partial N_3}{\partial t} = \frac{1}{\hbar\omega_{\mathrm{r,a}}}\left(\frac{\partial \mathbf{P}_\mathrm{a}}{\partial t} + \Gamma_\mathrm{a}\mathbf{P}_\mathrm{a}\right)\cdot\mathbf{E} - (\gamma_{32}^\mathrm{r} + \gamma_{30}^\mathrm{r})N_3$$

$$\frac{\partial N_2}{\partial t} = \frac{1}{\hbar\omega_{\mathrm{r,e}}}\left(\frac{\partial \mathbf{P}_\mathrm{e}}{\partial t} + \Gamma_\mathrm{e}\mathbf{P}_\mathrm{e}\right)\cdot\mathbf{E} + \gamma_{32}^\mathrm{r}N_3 - \gamma_{21}^\mathrm{r}N_2$$

$$\frac{\partial N_1}{\partial t} = -\frac{1}{\hbar\omega_{\mathrm{r,e}}}\left(\frac{\partial \mathbf{P}_\mathrm{e}}{\partial t} + \Gamma_\mathrm{e}\mathbf{P}_\mathrm{e}\right)\cdot\mathbf{E} + \gamma_{21}^\mathrm{r}N_2 - \gamma_{10}^\mathrm{r}N_1$$

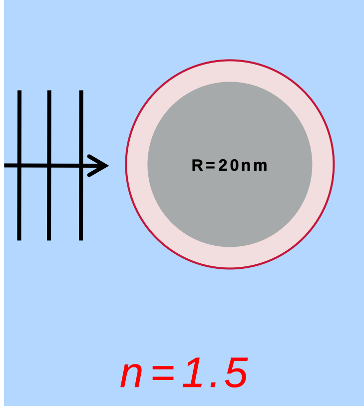
$$\frac{\partial N_0}{\partial t} = -\frac{1}{\hbar\omega_{\mathrm{r,a}}}\left(\frac{\partial \mathbf{P}_\mathrm{a}}{\partial t} + \Gamma_\mathrm{a}\mathbf{P}_\mathrm{a}\right)\cdot\mathbf{E} + \gamma_{30}^\mathrm{r}N_3 + \gamma_{10}^\mathrm{r}N_1$$

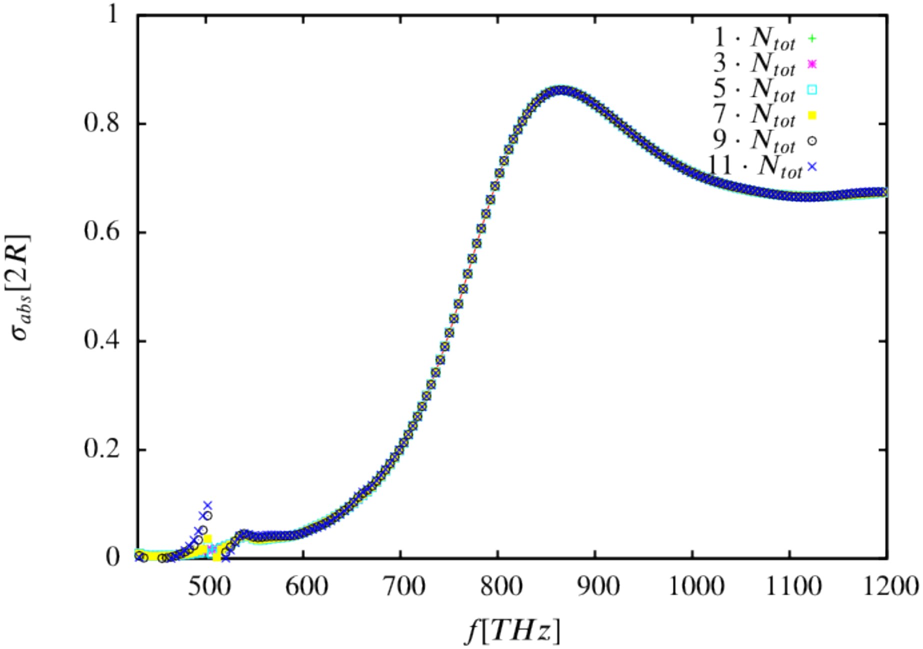


A Pusch, S Wuestner, JM Hamm, KL Tsakmakidis, O Hess, *ACS* Nano **6**, 2420-2431 (2012)

# Comparison: single cylinder (with gain)

Impact of gain in **single** cylinder geometry (**no** field enhancement!):





Negligible impact on cross sections for realistic gain densities

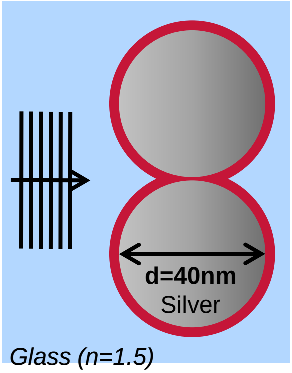
**Gain Parameters:** Rh800 molecules

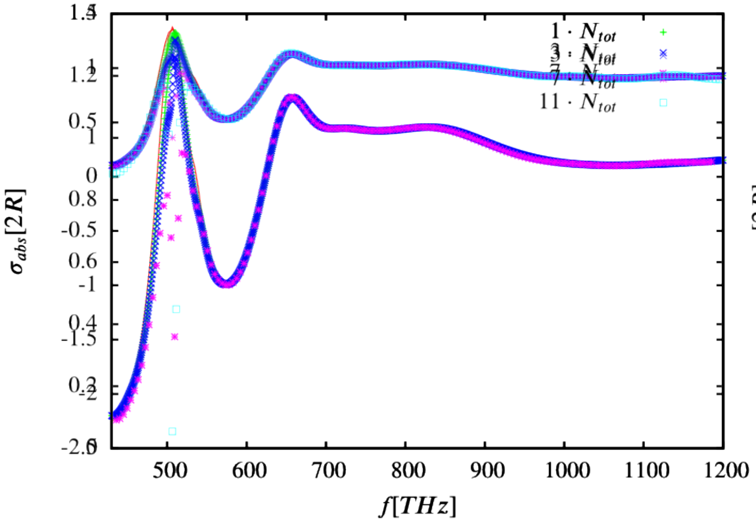
$f_{ems}$=506 THz, $f_{abs}$=659 THz, $\tau_{ems}$=20fs, $\tau_{abs}$=20fs, $\tau_{21}$=2ps

$\sigma_{ems}=0.024nm^2$, $\sigma_{abs}=0.030nm^2$, $N_{tot}=0.006nm^{-3}$

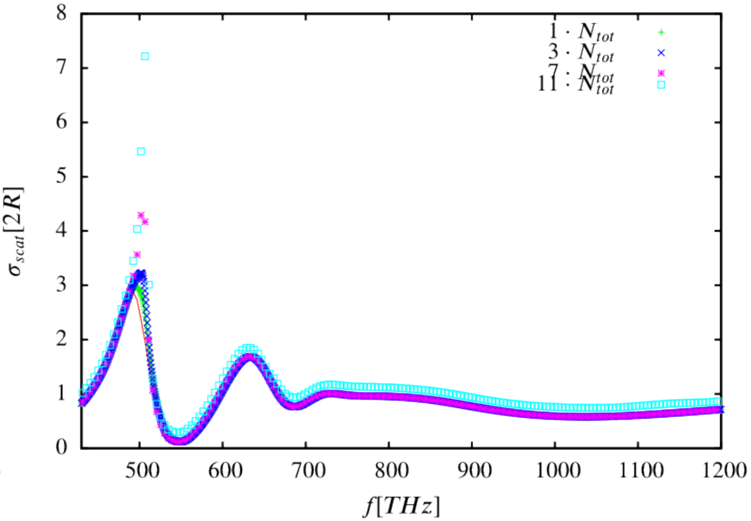
# Nanoscale cylinders with gain in gap

Impact of gain in **dimer** cylinder geometry (**large** field enhancement!):





**Absorption**



**Scattering**

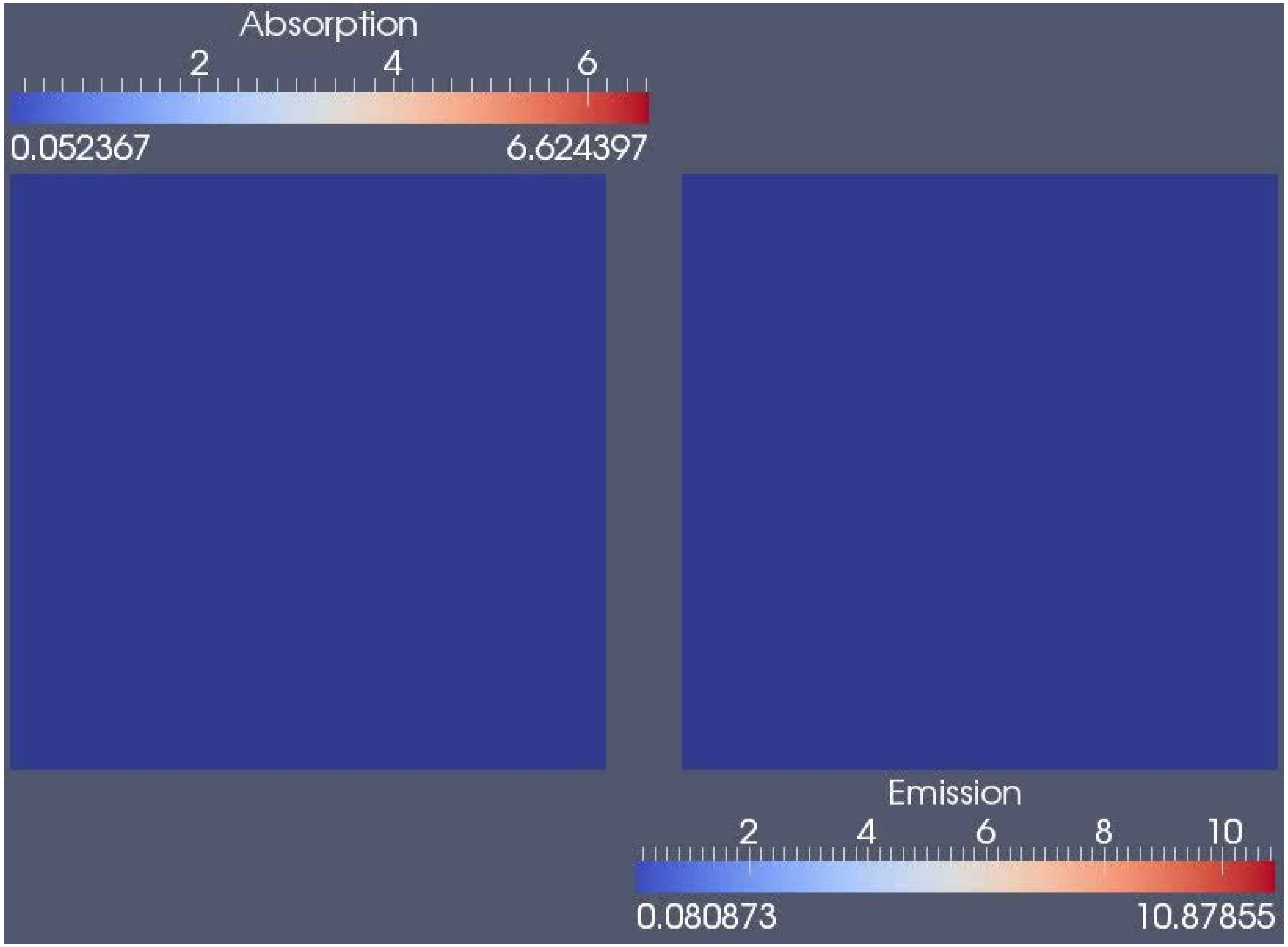
**Gain Parameters:** Rh800 molecules

$f_{ems}$=506 THz, $f_{abs}$=659 THz, $\tau_{ems}$=20fs, $\tau_{abs}$=20fs, $\tau_{21}$=2ps

$\sigma_{ems}=0.024\text{nm}^2$, $\sigma_{abs}=0.030\text{nm}^2$, $N_{tot}=0.006\text{nm}^{-3}$

Imperial College
London

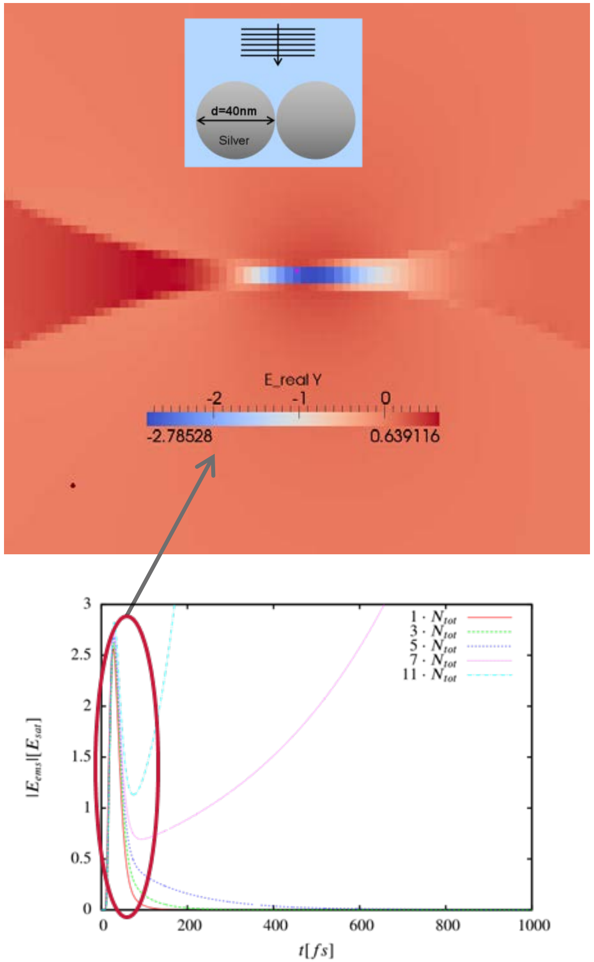
# Spatio-Temporal Dynamics

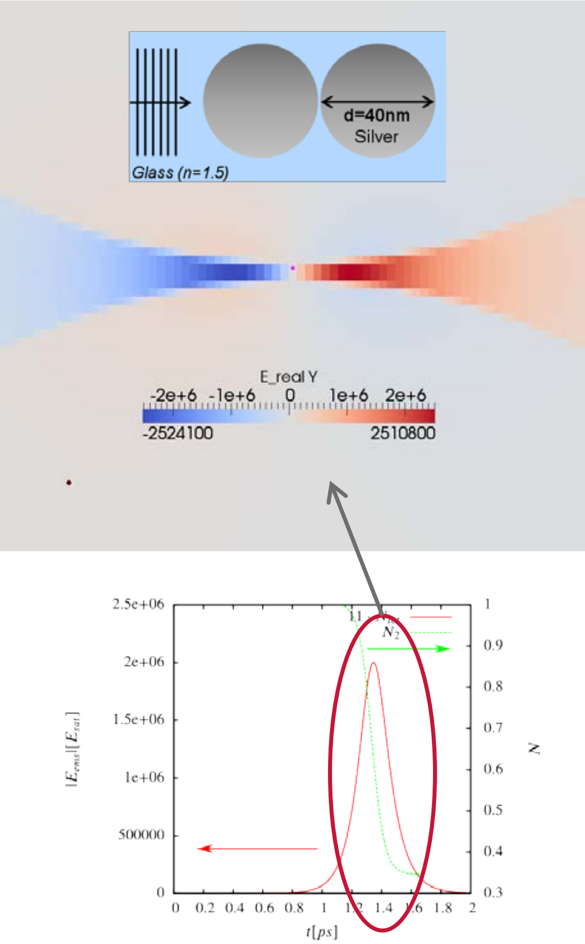


# Temporal evolution of dimers

Two different modes can be found at the emission frequency:

Probe Pulse
- Dipolar
- Radiative
- Low Q

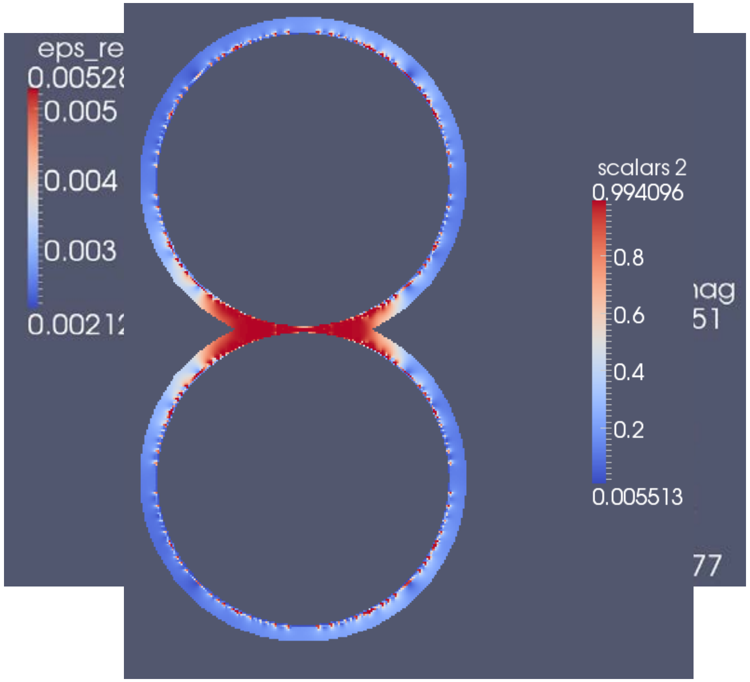


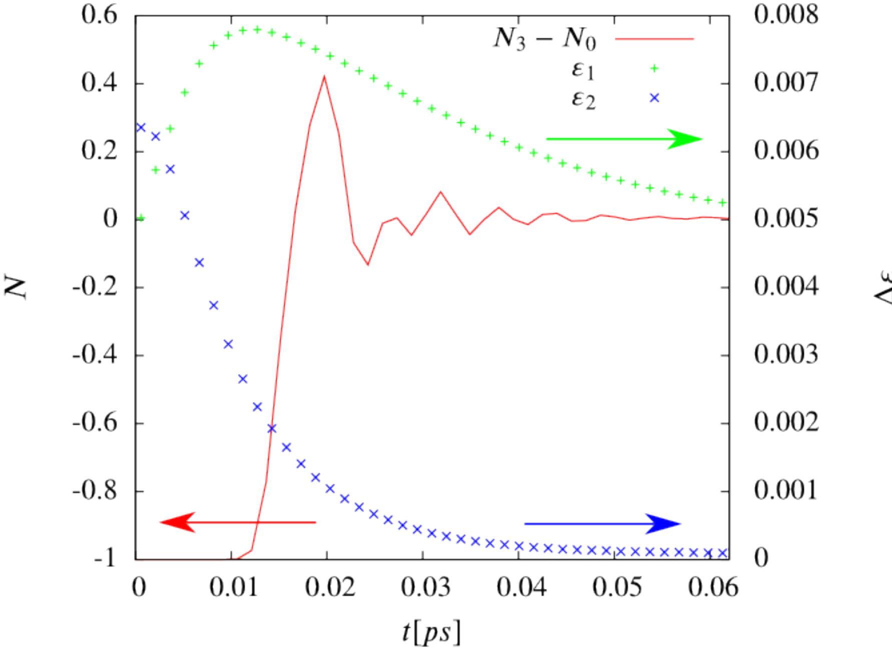


Burst
- Quadrupolar
- “Dark”
- High Q

# Refractive Index dynamics

- Pumping is more effective and very fast



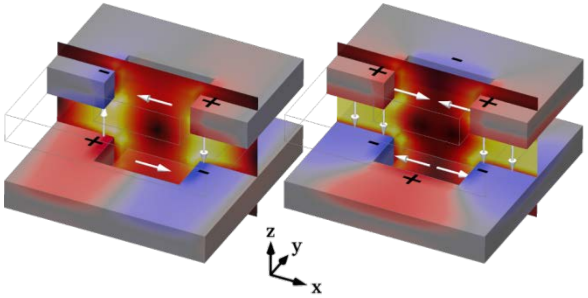


- Inversion will change effective refractive index in gap (Δn≈0.005 )
- Gap is highly sensitive to refractive index change
- Δn=0.005 corresponds to a peak shift of dipole resonance of about 15 THz
- Peak shift will cause less effective pumping resulting in interesting temporal dynamics

# Conclusion

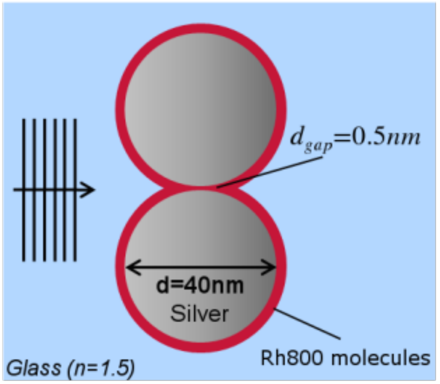
## *Active Nanoplasmonic Metasurfaces*

- *Extreme control of light*
- *Lasing emission from active metasurfaces – bright and dark lasing states*



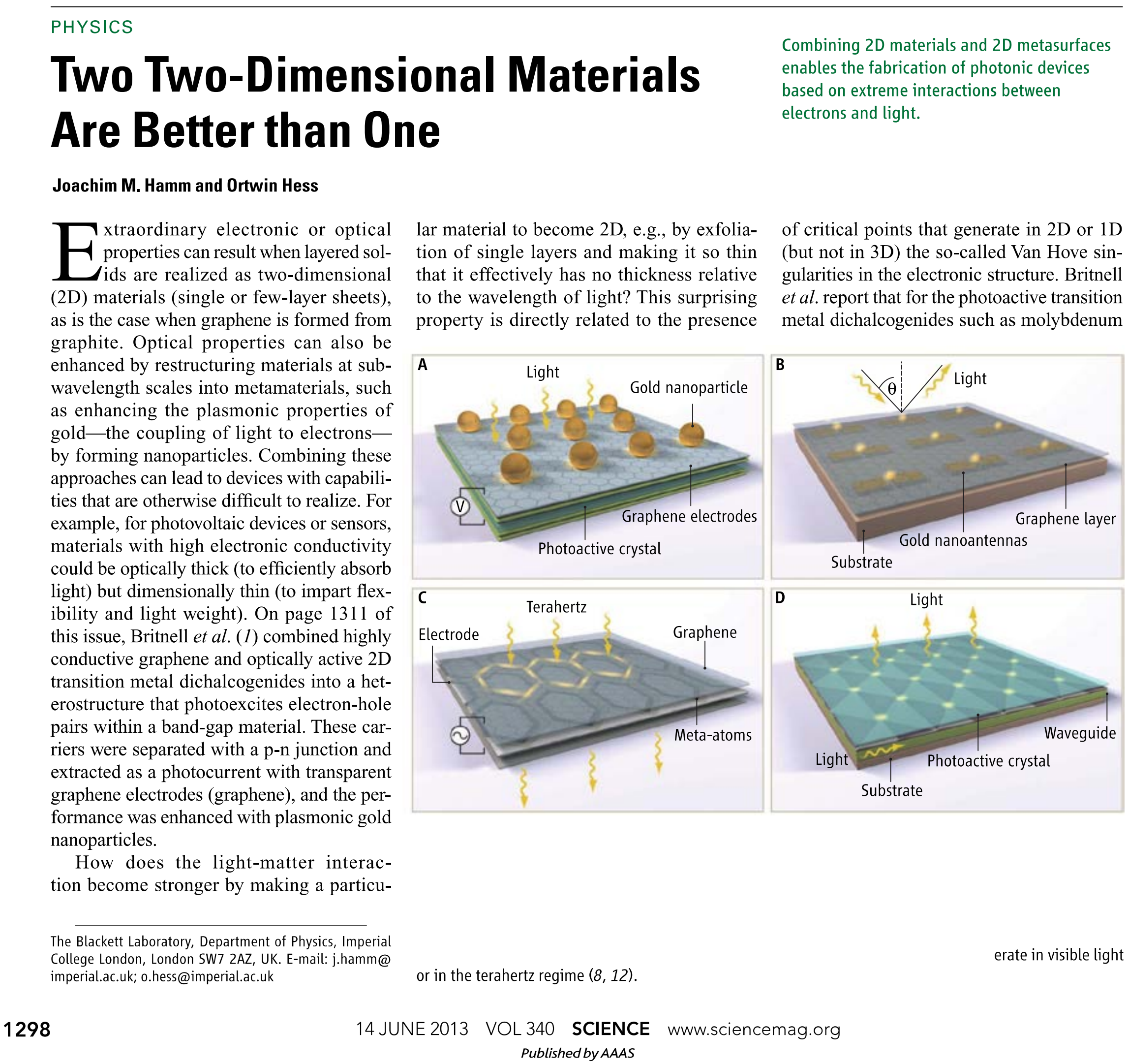
## *Active Nanoplasmonic Sensing*

- *nanofocusing enhances light-matter interaction*
- *ultra-sensitive sensing (factor $10^4$)*
- *self-sustained oscillation due to high-Q factor of dark quadrupolar mode*



# Singularities in the Electronic and Photonic Density of States

## Dark States for Electrons and Photons



PHYSICS

### Two Two-Dimensional Materials Are Better than One

Combining 2D materials and 2D metasurfaces enables the fabrication of photonic devices based on extreme interactions between electrons and light.

**Joachim M. Hamm and Ortwin Hess**

Extraordinary electronic or optical properties can result when layered solids are realized as two-dimensional (2D) materials (single or few-layer sheets), as is the case when graphene is formed from graphite. Optical properties can also be enhanced by restructuring materials at subwavelength scales into metamaterials, such as enhancing the plasmonic properties of gold—the coupling of light to electrons—by forming nanoparticles. Combining these approaches can lead to devices with capabilities that are otherwise difficult to realize. For example, for photovoltaic devices or sensors, materials with high electronic conductivity could be optically thick (to efficiently absorb light) but dimensionally thin (to impart flexibility and light weight). On page 1311 of this issue, Britnell *et al*. (*1*) combined highly conductive graphene and optically active 2D transition metal dichalcogenides into a heterostructure that photoexcites electron-hole pairs within a band-gap material. These carriers were separated with a p-n junction and extracted as a photocurrent with transparent graphene electrodes (graphene), and the performance was enhanced with plasmonic gold nanoparticles.

How does the light-matter interaction become stronger by making a particular material to become 2D, e.g., by exfoliation of single layers and making it so thin that it effectively has no thickness relative to the wavelength of light? This surprising property is directly related to the presence of critical points that generate in 2D or 1D (but not in 3D) the so-called Van Hove singularities in the electronic structure. Britnell *et al*. report that for the photoactive transition metal dichalcogenides such as molybdenum

or in the terahertz regime (*8*, *12*).

erate in visible light

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# Thanks for Your Attention