Exotic optical properties of metal-SC core-shell NWs: Low-loss NIMs & ZIMs, transparent contacts

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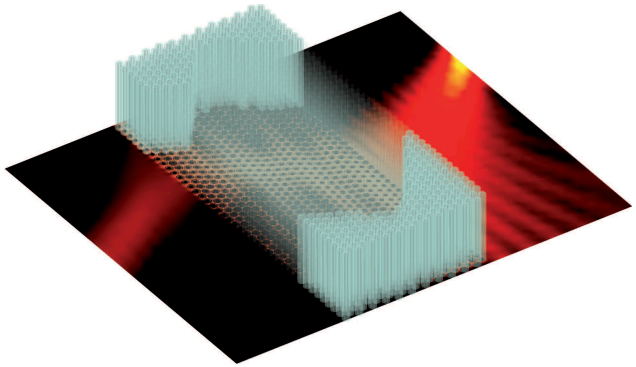
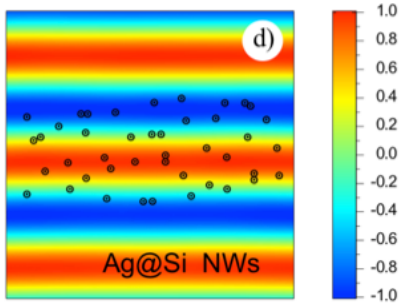




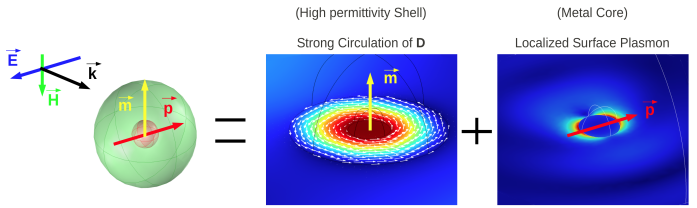
Physics

or

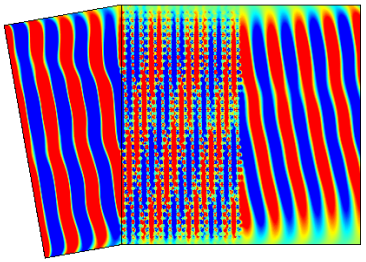
Physical?

Outline

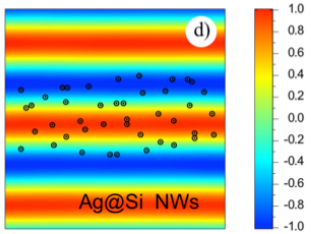
- **Motivation: Optical Negative-Index Metamaterials (NIMs)**
- **Metal-SC core-shell NSs & NWs:**
  3D/2D bulk Opt. NIMs & ZIMs?



- **Other light-scattering properties**
  Transparent Metallo-dielectric NWs



- **Making it VISIBLE**



- **Conclusions**

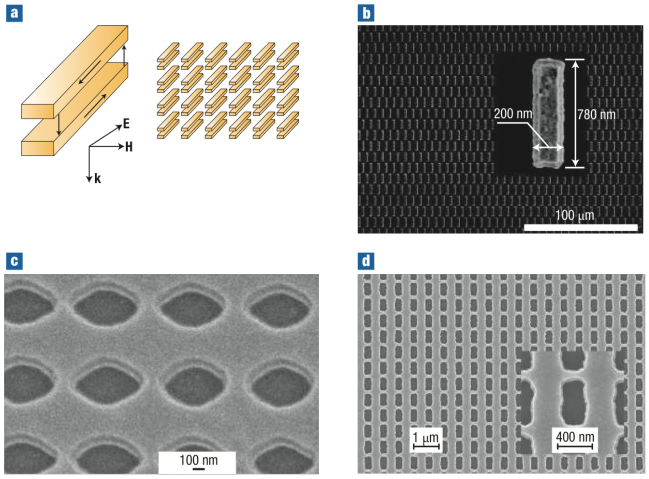
Optical Metamaterials

Optical Bulk Negative-index Metamaterials

- Negative Electric response: obvious (metal NPs)
- Negative Magnetic response ➔ Big challenge

Conventional approach: ~SRR
Complex Metal Nanostructures

NanoSRRs, paired nanorods, nano-fishnet…



Shalaev, Nat. Phot. 2010

BRINGING METAMATERIALS TO OPTICS:

-ANISOTROPY

-POLARIZATION DEPENDENCE

-THREE-DIMENSIONALITY

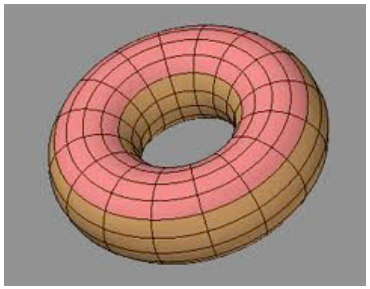
-METALS:
- -HIGH LOSSES
- -SATURATION OF MAGNETIC RESPONSE

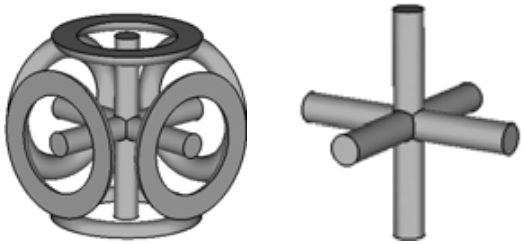
Other approaches: NWs, Metasurfaces,…

Optical Negative-index Metamaterials

New approach: Magnetic resonances of high-dielectric index semiconductors

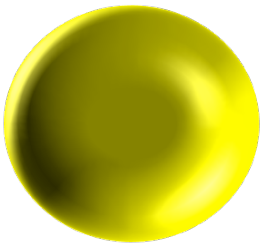
Si Rings, Rods: static model

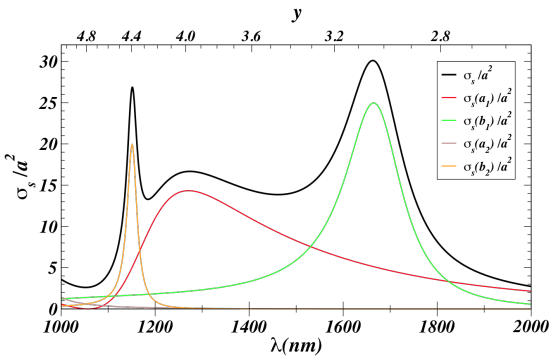




Jelinek & Marqués, JPCM 2009

Si Sphere r~200 nm: Mie





García-Etxarri et al, Opt. Express 2011

Magnetic Light: EXP✓

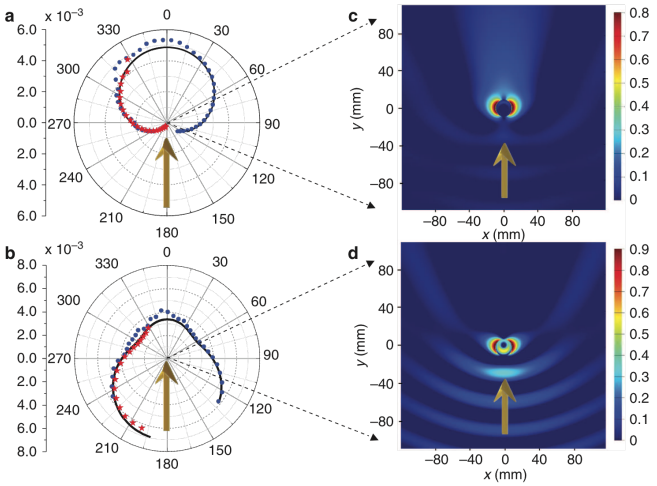
nature COMMUNICATIONS

ARTICLE

Received 13 Jul 2012 | Accepted 25 Sep 2012 | Published 30 Oct 2012 DOI: 10.1038/ncomms2167

Magnetic and electric coherence in forward- and back-scattered electromagnetic waves by a single dielectric subwavelength sphere

J.M. Geffrin[1], B. García-Cámara[2,3], R. Gómez-Medina[4], P. Albella[5], L.S. Froufe-Pérez[6], C. Eyraud[1], A. Litman[1], R. Vaillon[7], F. González[3], M. Nieto-Vesperinas[8], J.J. Sáenz[4,5] & F. Moreno[3]

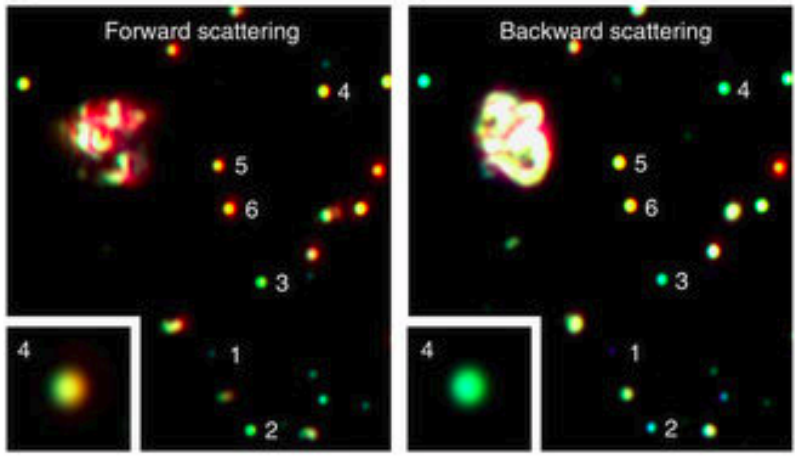


ARTICLE

Received 6 Dec 2012 | Accepted 22 Jan 2013 | Published 26 Feb 2013 DOI: 10.1038/ncomms2538

Directional visible light scattering by silicon nanoparticles

Yuan Hsing Fu[1], Arseniy I. Kuznetsov[1], Andrey E. Miroshnichenko[2], Ye Feng Yu[1] & Boris Luk'yanchuk[1]



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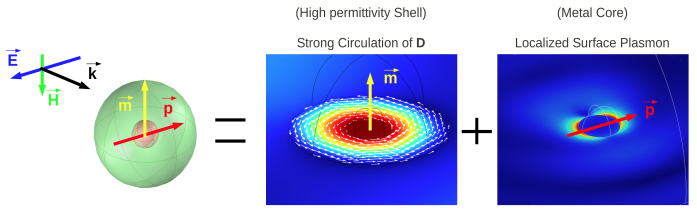
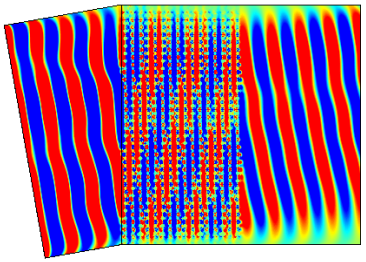
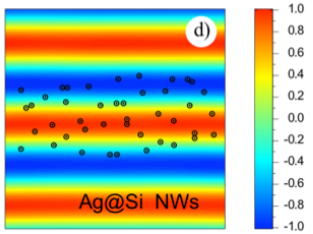
- **Metal-SC core-shell NSs & NWs: 3D/2D bulk Opt. NIMs & ZIMs?**







- Other light-scattering properties
  Transparent Metallo-dielectric NWs
- Making it VISIBLE
- Conclusions

Optical NIMs: Single core-shell NSs

Optical Negative-index Metamaterials

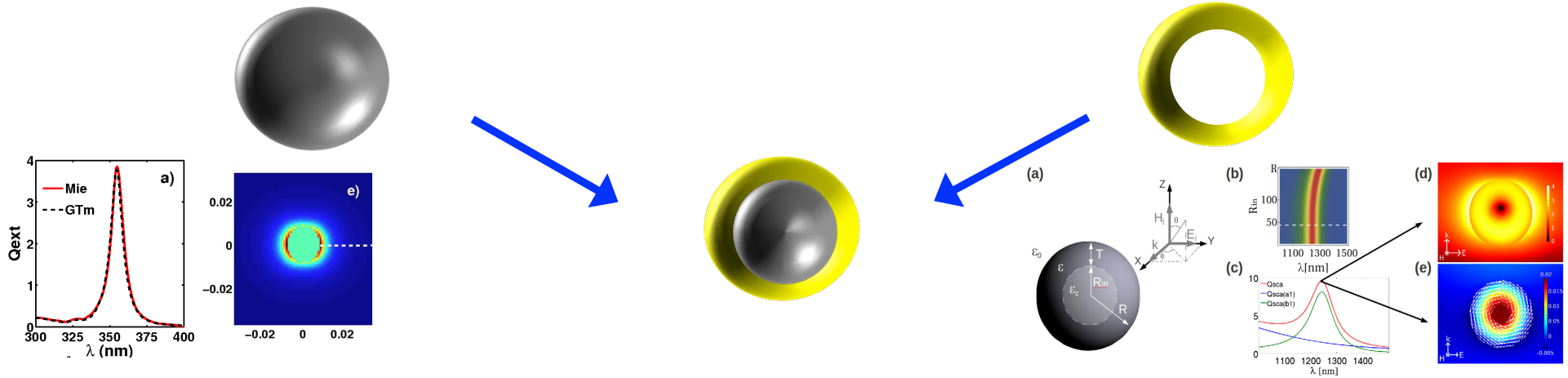
Negative electric

Negative Magnetic

Metal Core: LSP
Electric resonance

Semiconducting Shells:
Magnetic resonance

Si Sphere r~200 nm: Mie

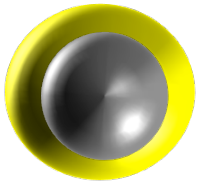


Ag/Si Core-Shell NSs

E,M resonances survive & overlap??

Paniagua-Domínguez, López-Tejeira, Marqués, JASG, NJP 2011

Optical NIMs: Single core-shell NSs

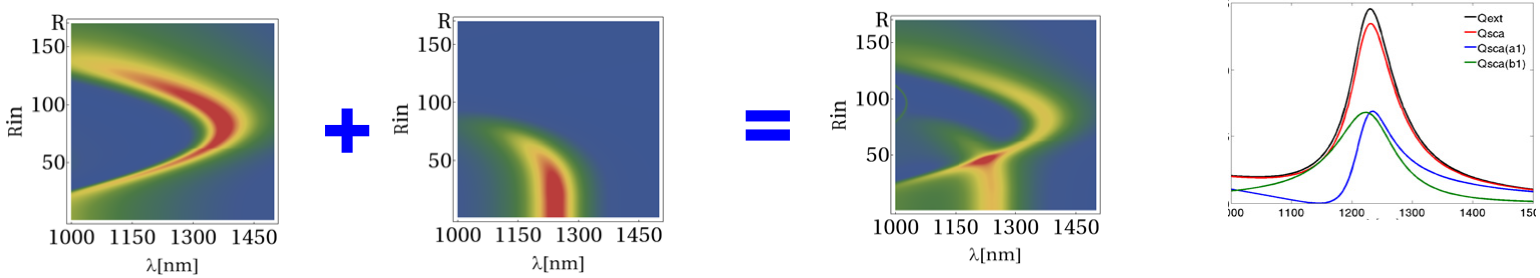


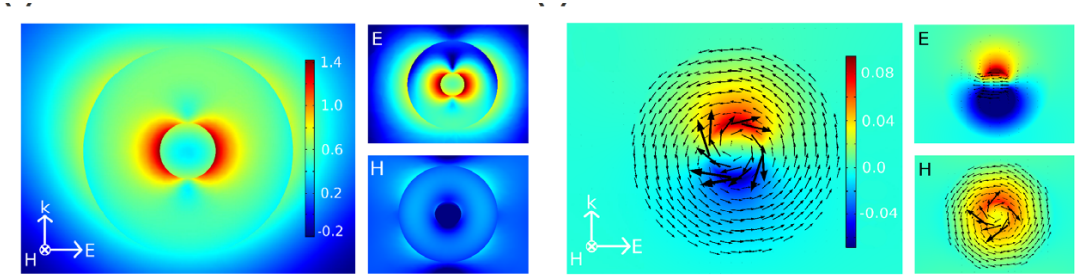
Ag/Si Core-Shell NSs

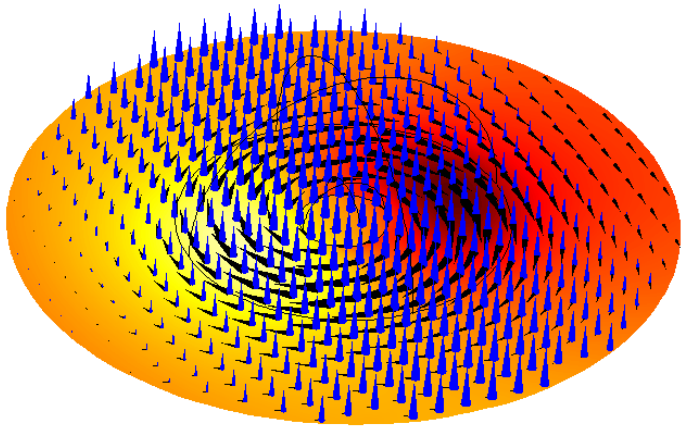
YES, E,M resonances SURVIVE & OVERLAP?

Metal Core: LSP
Electric resonance

Semiconducting Shells:
Magnetic resonance



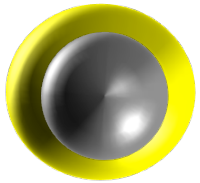




Ag/Si core-shell Sphere
r,R~50,170 nm: Extended Mie

Paniagua-Domínguez, López-Tejeira, Marqués, JASG, NJP 2011

Optical NIMs: core-shell NS ARRAYS

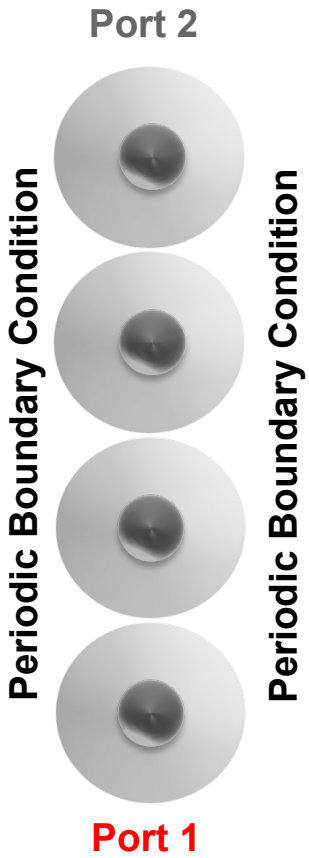


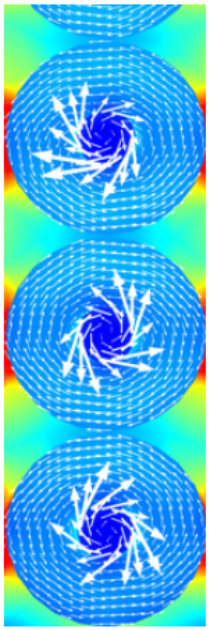
Periodic arrangement, Effective parameters ➔NIMs?

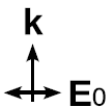
Ag/Ge core-shell Spheres r,R~55,190 nm, d=385 nm

Up to 21 u.c.

$(l \sim 8\mu m)$

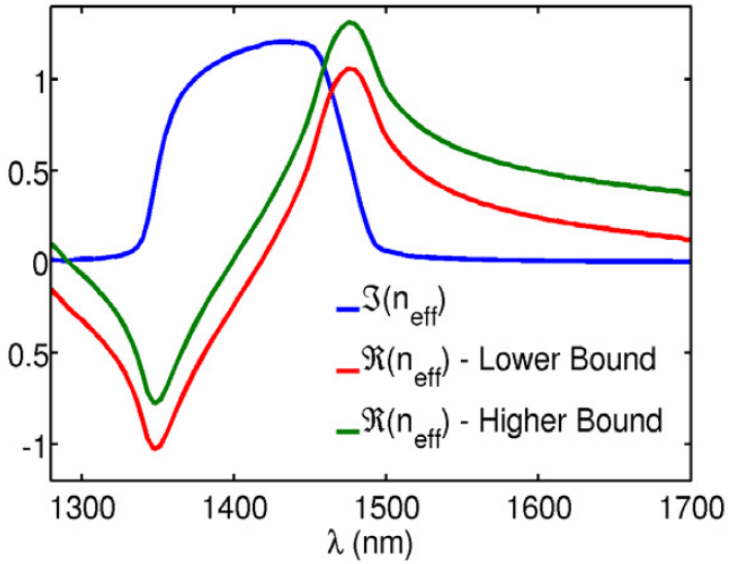






S_{11}, S_{21}

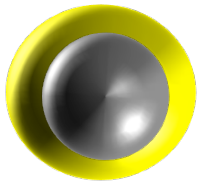
FEM calcs



NIM OK, but…??

Paniagua-Domínguez, López-Tejeira, Marqués, JASG, NJP 2011

Optical NIMs: core-shell NSs



Optical NIM,

3D

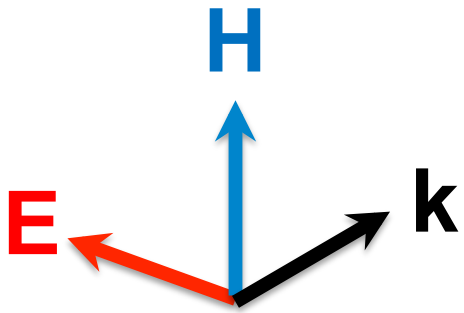
highly isotropic

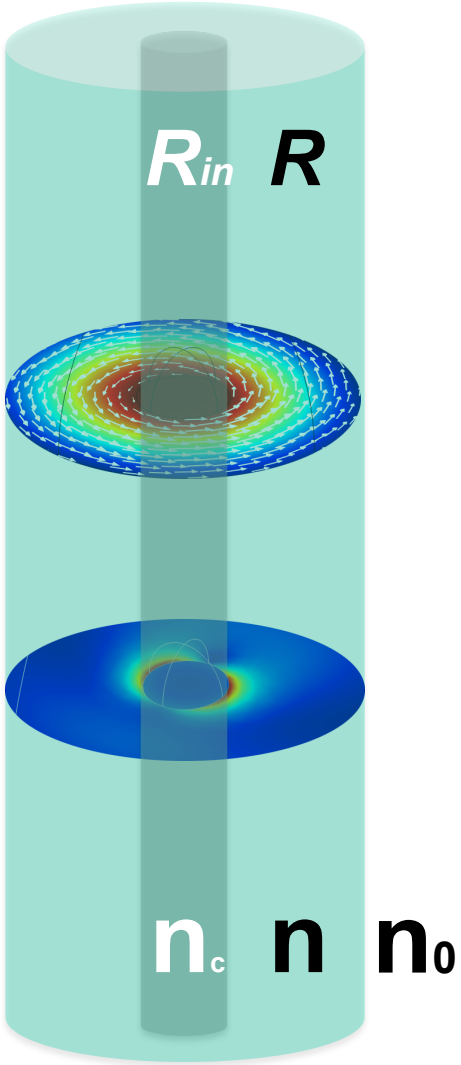
But…

Moderate losses

Challenging fabrication

2D Analogy

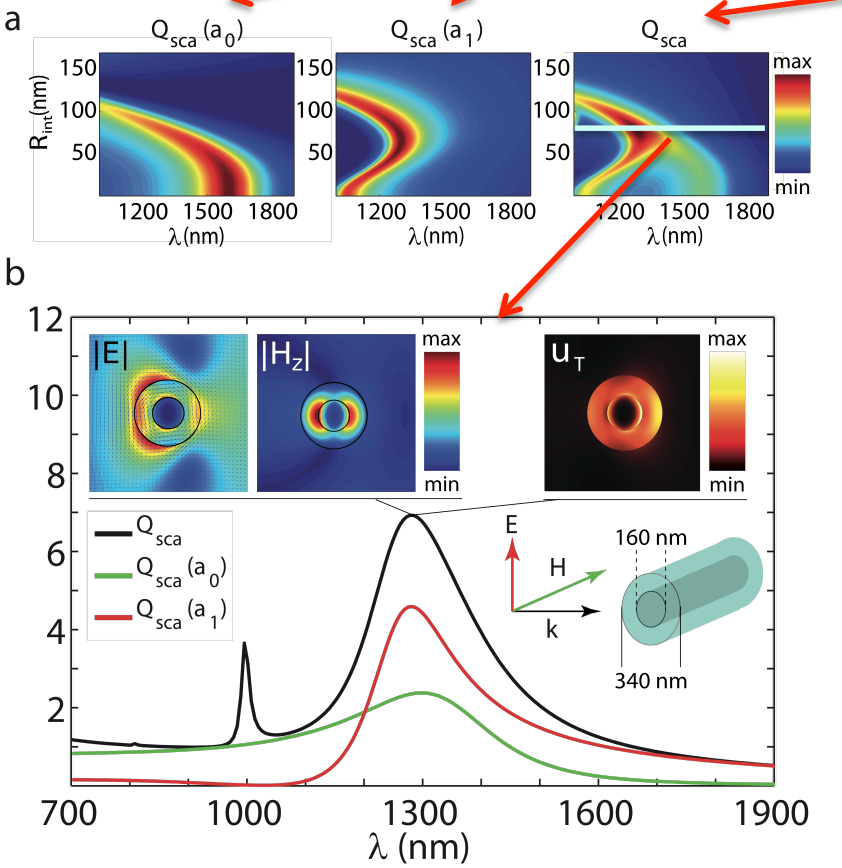




in-plane isotropy…
but polarization dependence!

Paniagua-Domínguez, Abujetas, JASG, Sci. Rep. 2013

2D Analogy: E,M resonances overlap?➔ Yes



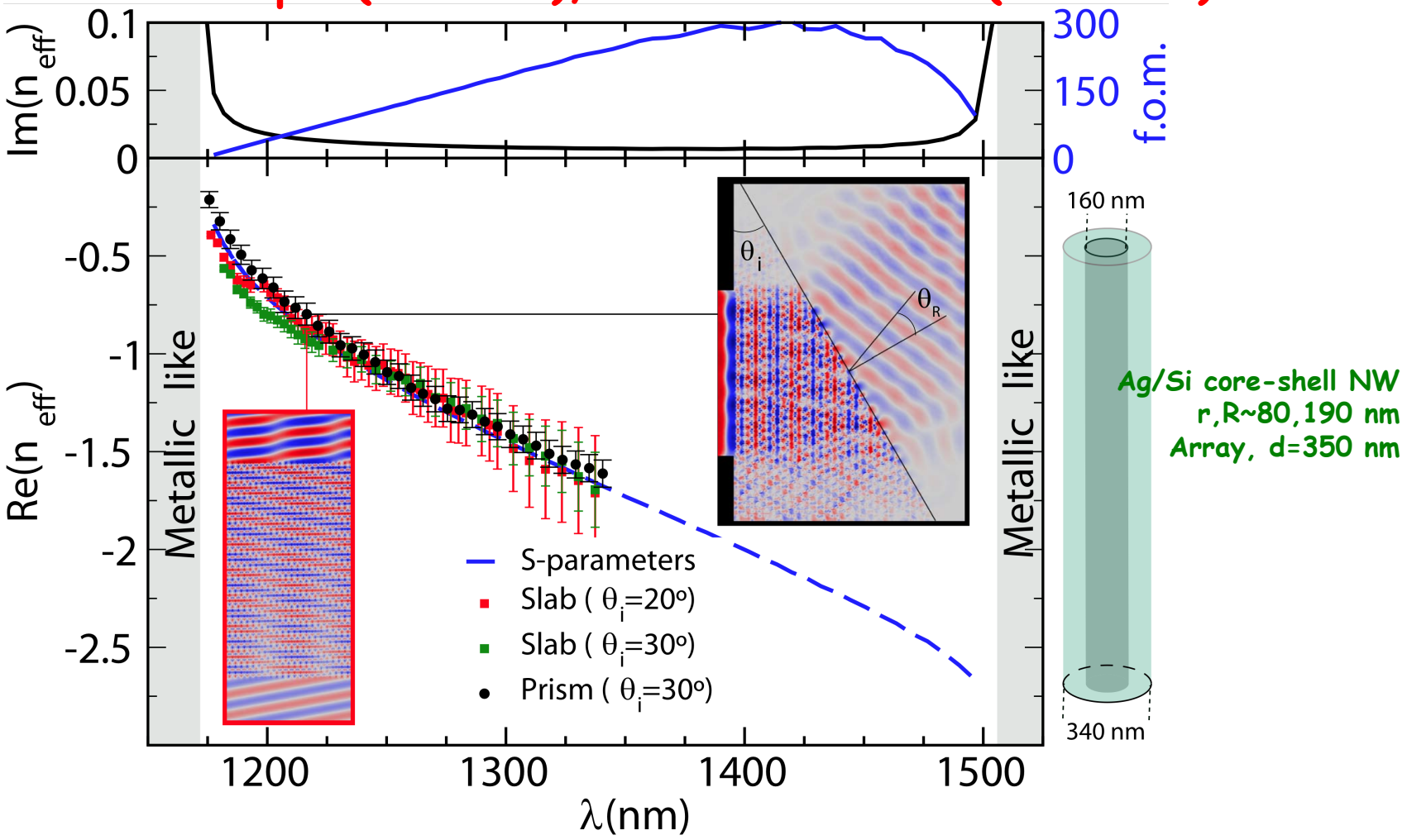
Ag@Si, R = 170 nm

Paniagua-Domínguez, Abujetas, JASG, Sci. Rep. 2013

Optical NIMs: core-shell NWArrays

Ag/Si Core-Shell NW array

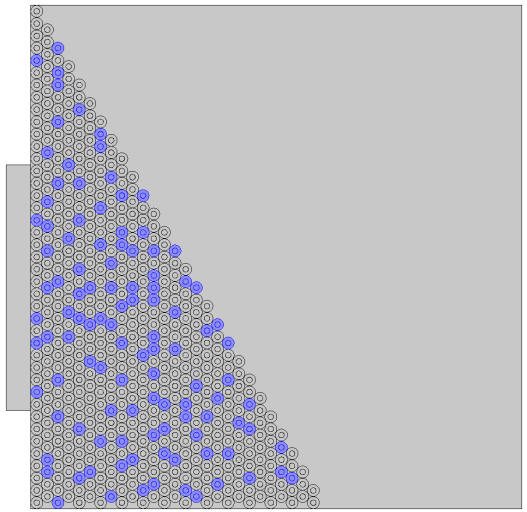
~Isotropic (Δθ~50º), Ultra-low losses (fom≤200)

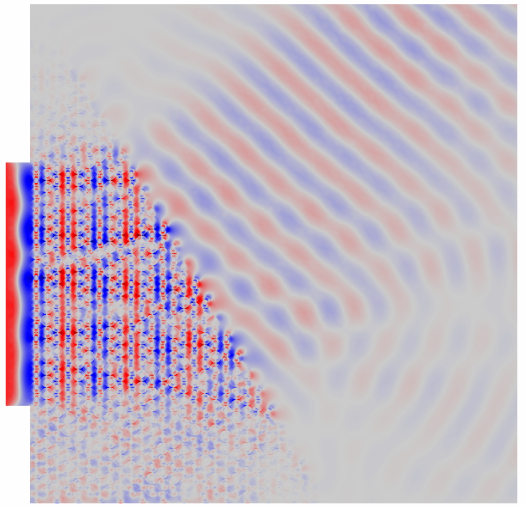


Paniagua-Domínguez, Abujetas, JASG, Sci. Rep. 2013

Ag/Si Core-Shell NW array

What if disordered? ➔ ROBUST✓



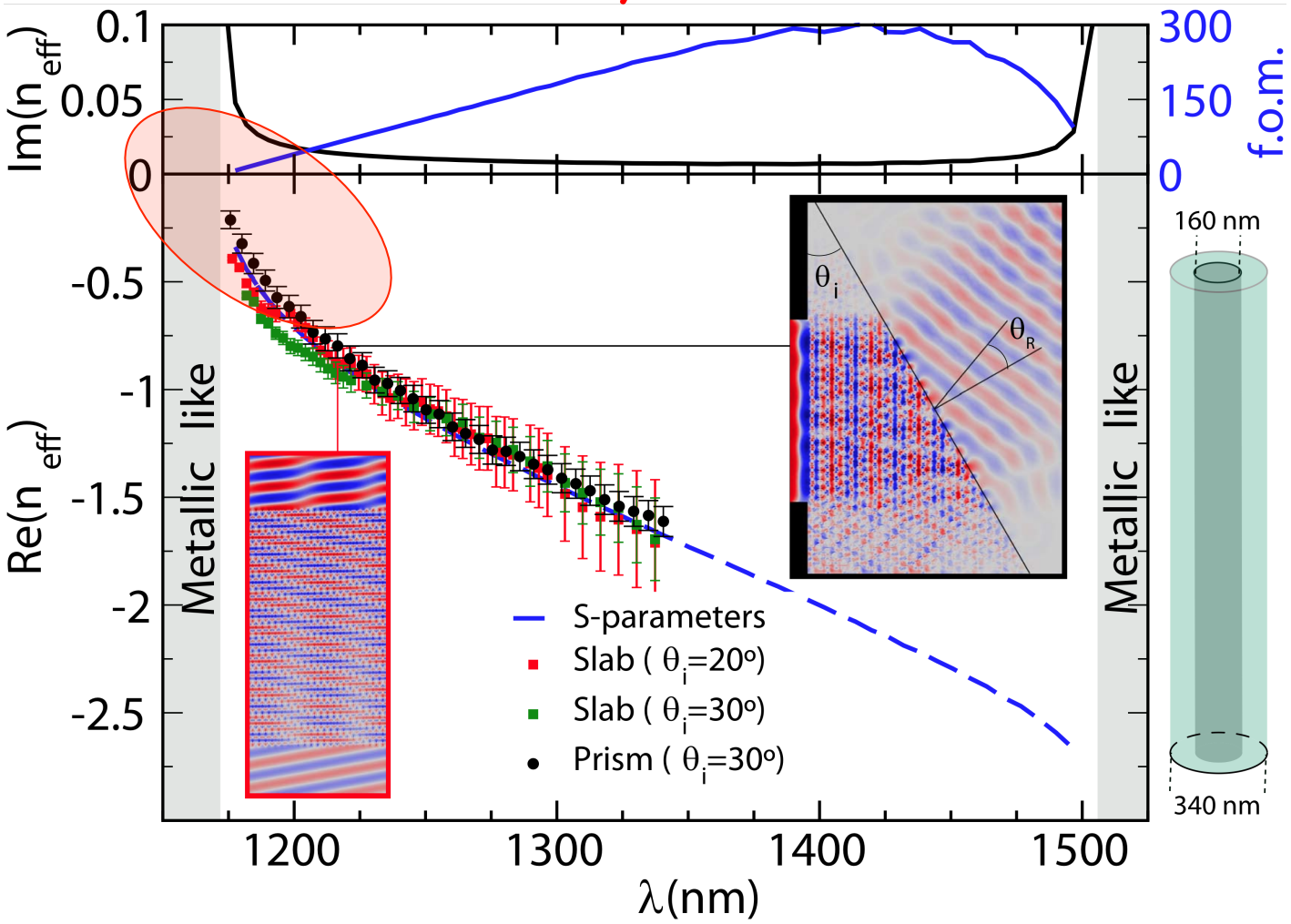


Ag/Si core-shell NW
r,R~80,170 nm
Hex. Array, d=350 nm

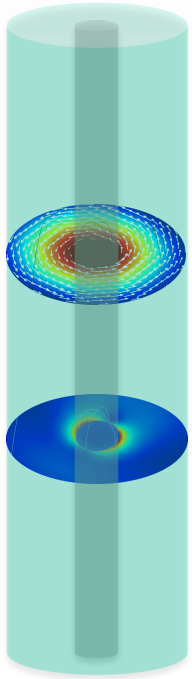
Optical ZIMs: core-shell NWArrays??

Ag/Si Core-Shell NW array

n~0??, low-losses??

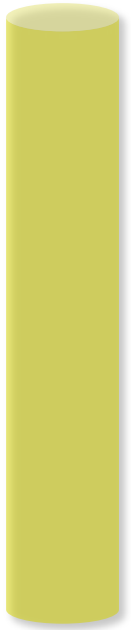


Optical ZIMs??



Lower filling fraction
(core-shell NWs)
…or

Similar, doubly (E,H) resonant
(but weaker) Nanostructures…
Simple dielectric NWs

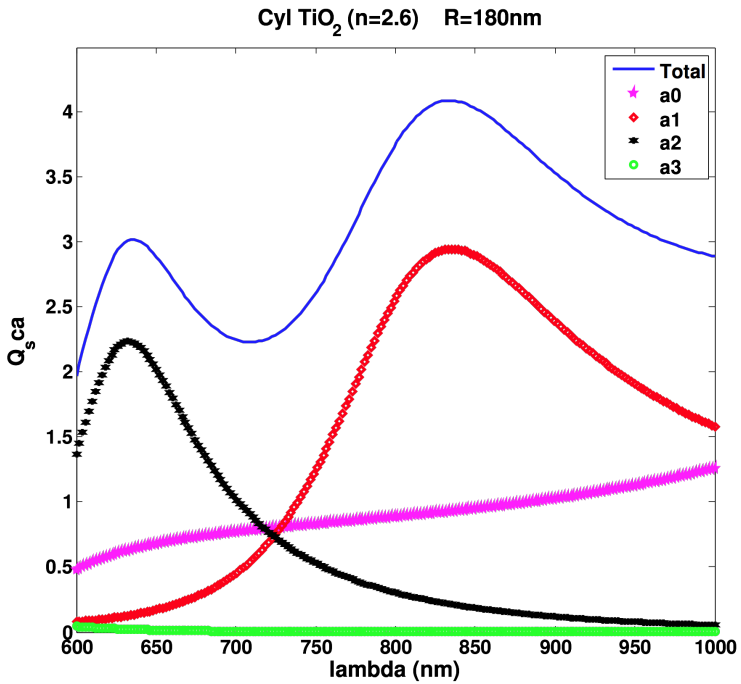


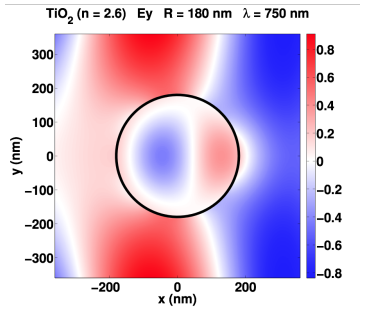
Optical ZIMs: Single dielectric NWs

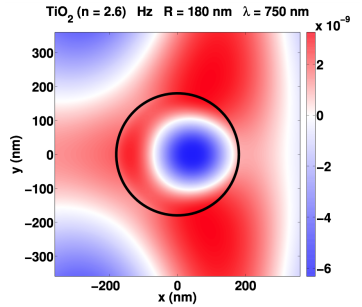
TiO_2 NWs

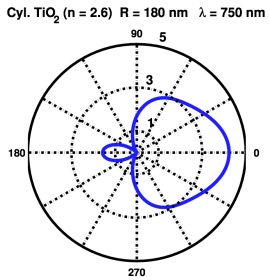
YES, weak (E,M) resonances can roughly OVERLAP

Electric (a_1) &
Magnetic (a_0) resonances







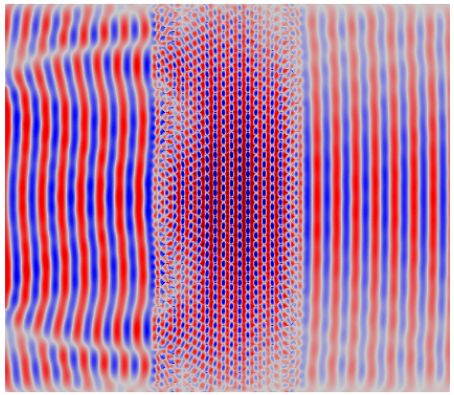


TiO_2 Cylinder R=180 nm (Mie)

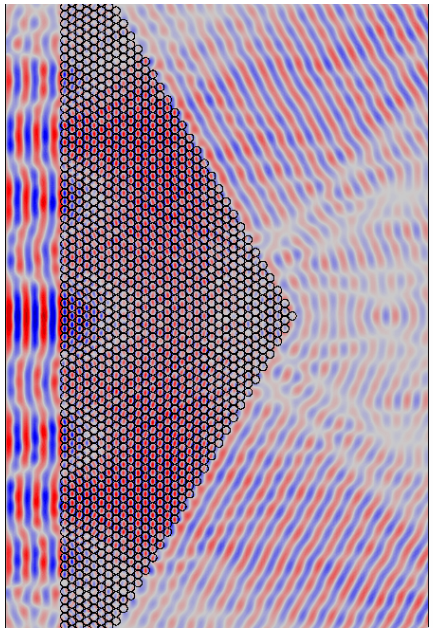
Optical ZIMs: NW Arrays

TiO_2 NW arrays

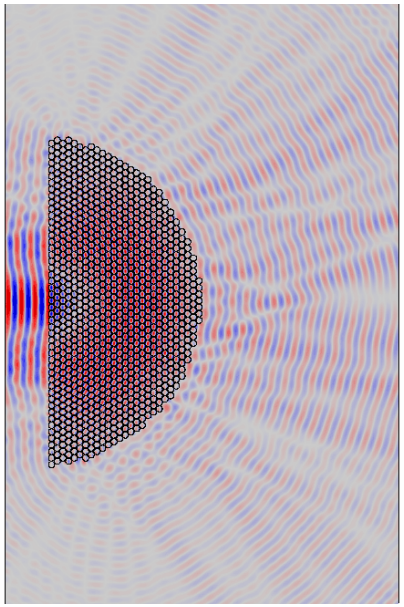
Slab…



Beam splitter



Plane-to-Cyl converter



TiO_2 Cylinder R=180 nm, λ=750 nm (COMSOL)

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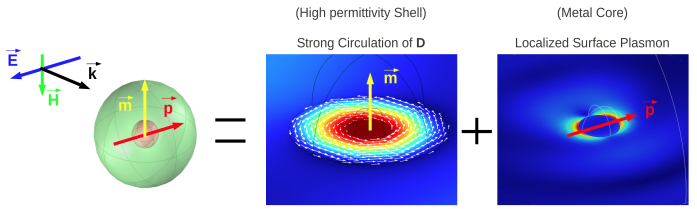
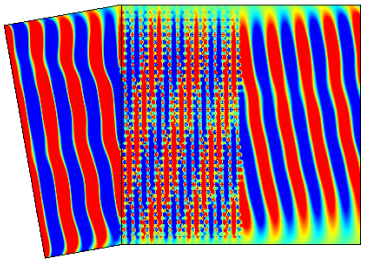
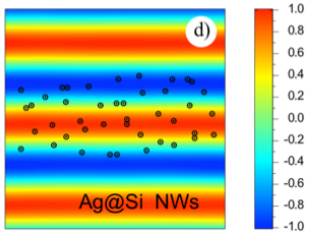
- Metal-SC core-shell NSs & NWs: 3D/2D bulk Opt. NIMs & ZIMs?



- **Other light-scattering properties**
  Transparent Metallo-dielectric NWs





- Making it VISIBLE
- Conclusions

Core-shell M@D NPs

Other optical properties: Theoretical proposals

Broadband Unidirectional Scattering by Magneto-Electric Core–Shell Nanoparticles

Wei Liu, Andrey E. Miroshnichenko, Dragomir N. Neshev, and Yuri S. Kivshar*

Nonlinear Physics Centre, Centre for Ultrahigh-Bandwidth Devices for Optical Systems (CUDOS), Research School of Physics and Engineering, Australian National University, Canberra, ACT 0200, Australia

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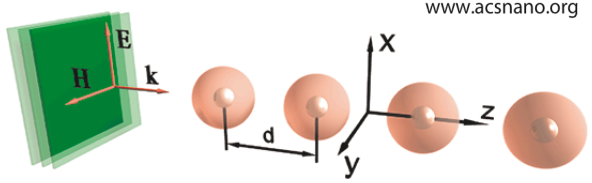
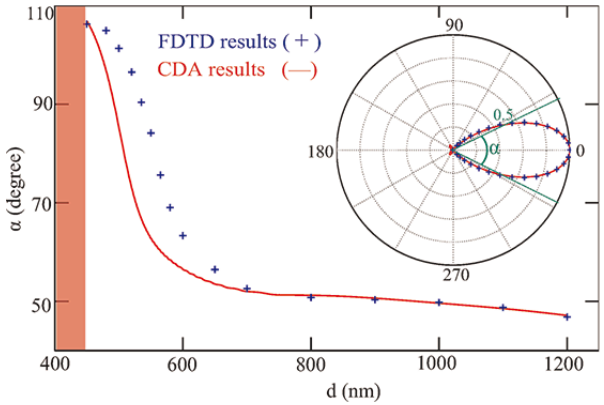
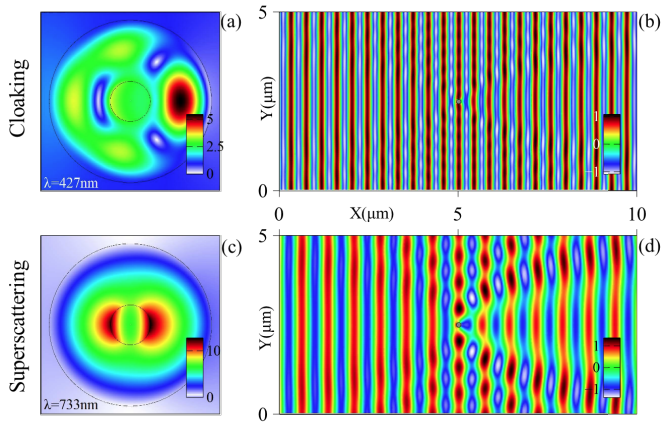




Cloaking and enhanced scattering of core-shell plasmonic nanowires

Ali Mirzaei,* Ilya V. Shadrivov, Andrey E. Miroshnichenko, and Yuri S. Kivshar

6 May 2013 | Vol. 21, No. 9 | DOI:10.1364/OE.21.010454 | OPTICS EXPRESS 10454



RAPID COMMUNICATIONS

PHYSICAL REVIEW B **86**, 081407(R) (2012)

Polarization-independent Fano resonances in arrays of core-shell nanoparticles

Wei Liu, Andrey E. Miroshnichenko, Dragomir N. Neshev, and Yuri S. Kivshar

inear Physics Centre, Centre for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS), Research School of Physics

Directional Scattering, Fano interference, Superscattering & cloaking,…

Invisible NWs?

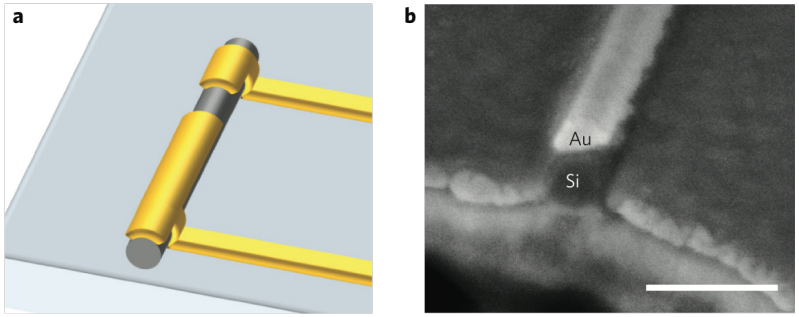
nature photonics

ARTICLES

PUBLISHED ONLINE: 20 MAY 2012 | DOI: 10.1038/NPHOTON.2012.108

An invisible metal–semiconductor photodetector

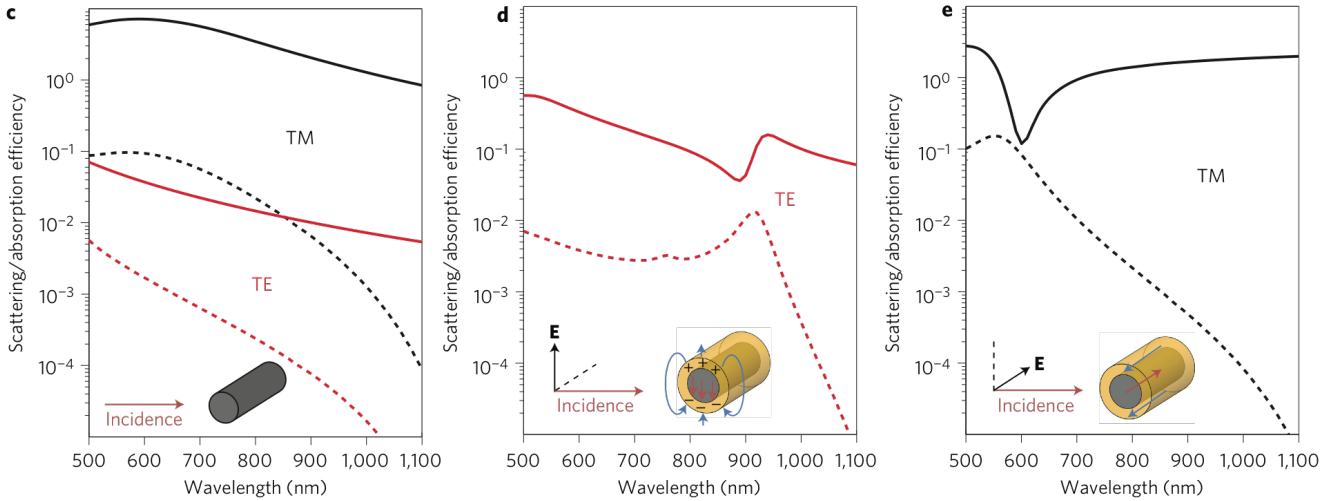
Pengyu Fan[1], Uday K. Chettiar[2], Linyou Cao[1†], Farzaneh Afshinmanesh[1], Nader Engheta[2] and Mark L. Brongersma[1*]



~Approx (quasi-static) TRANSPARENCY conds

Alú & Enghetta PRE 2005

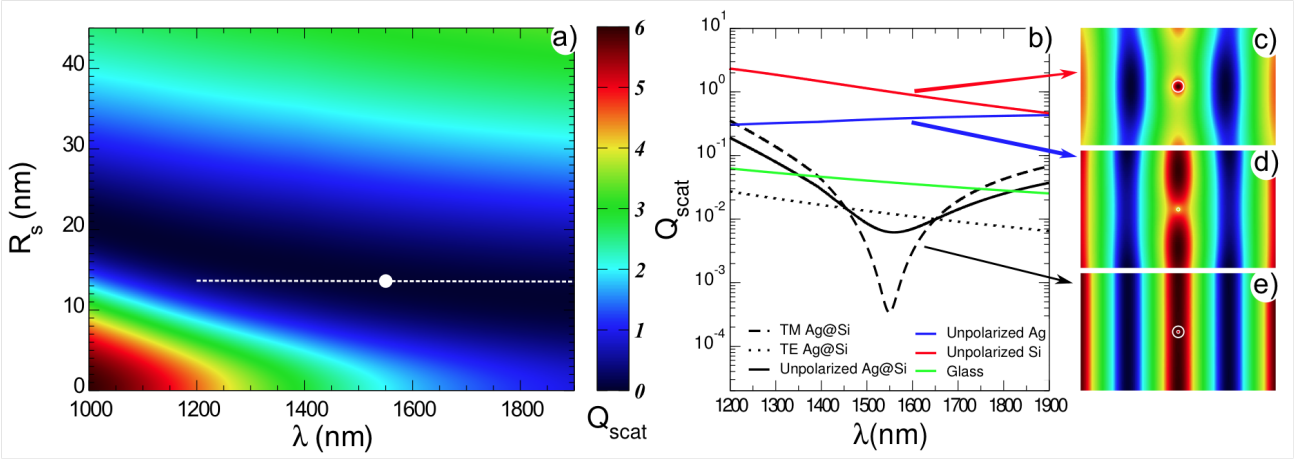
Alú et al NJP 2010



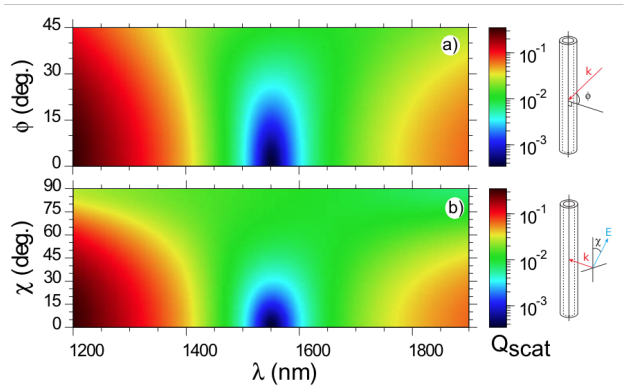
Transparent core-shell NWs

Ag@Si Core-Shell NW ~Low Q_{scatt}??

Ag@Si NWs,
R= 45 nm



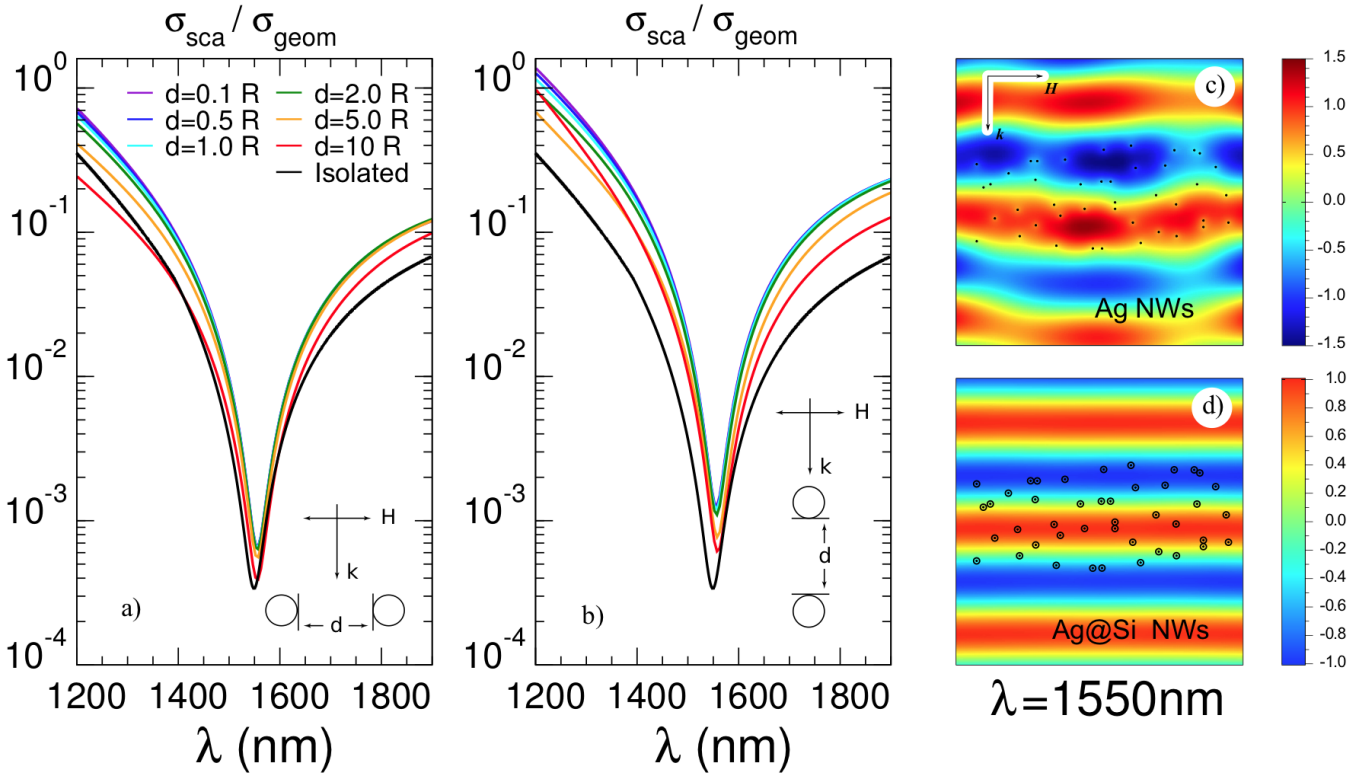
~Broad (incidence, polarizaton) angles!!



~Approx (quasi-static)
TRANSPARENCY conds

Ag@Si Core-Shell NW arrays

~weak coupling ✔ ➔TRANSPARENCY ✔

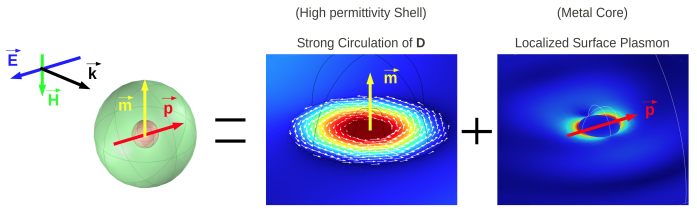


Ag@Si NWs,
R_s=13.6 nm
R_c= 45 nm

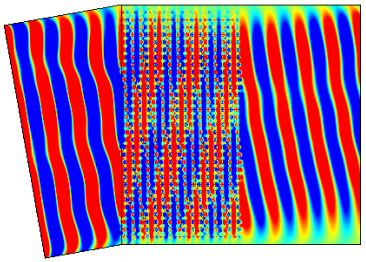
Froufe-Pérez, Paniagua-Domínguez, Abujetas, Saenz, JASG, Opt Exp. 2013

Outline

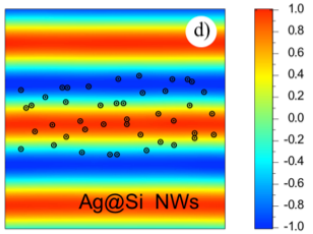
- Motivation: Optical Negative-Index Metamaterials (NIMs)
- Metal-SC core-shell NSs & NWs: 3D/2D bulk Opt. NIMs & ZIMs?



- Other light-scattering properties Transparent Metallo-dielectric NWs



- **Making it VISIBLE**



- Conclusions

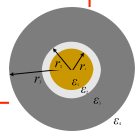
Making it VISIBLE

1.5 μm

0.5 μm

Low-loss NIMs & ZIMS

↓E,M resonances
↓Size
and/or 3-layers
(Wu et al, Opt. Exp. 2013)



Low-loss, high-index
(↑n, ↓k)
SEMICONDUCTORS
InAs✔

Transparent Metal NWs

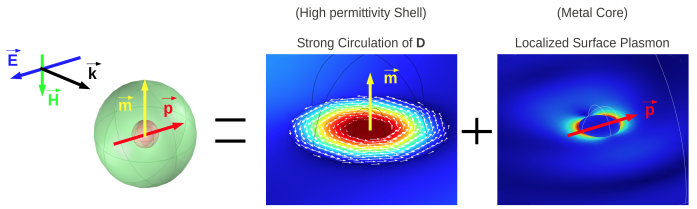
Size: Irrelevant if <<λ
(only aspect ratio)

Moderately large index contrast
Low-loss
SEMICONDUCTORS/ OXIDES✔

Low-loss metal core: *Ag*✔

Outline

- Motivation: Optical Negative-Index Metamaterials (NIMs)
- Metal-SC core-shell NSs & NWs: 3D/2D bulk Opt-NIMs?



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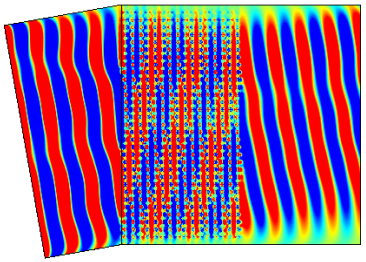
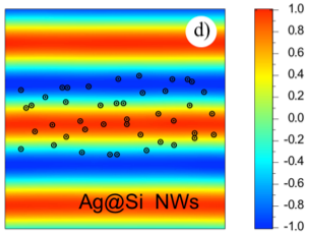


- Making it VISIBLE



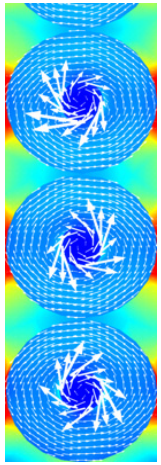
- **Conclusions**

Concluding remarks

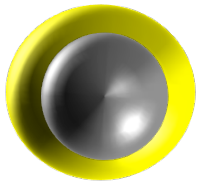
New approach:
magnetic resonances in high-index semiconductors
+LSP metal NPs

Optical Negative-Index Metamaterials (NIMs)

3D core-shell NSs

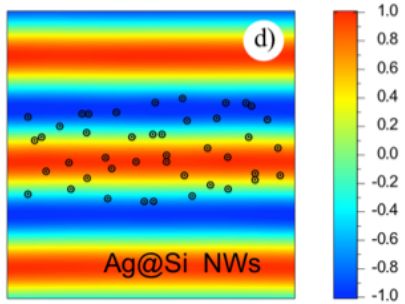


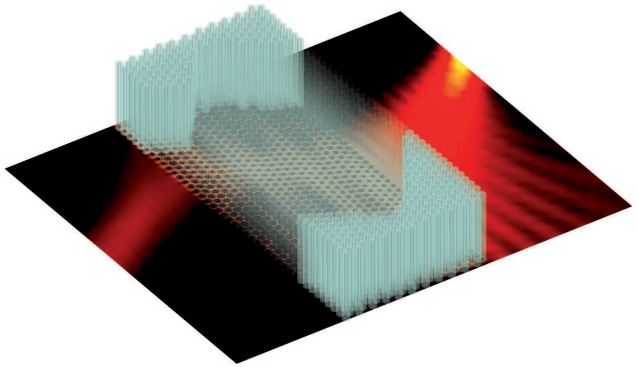
Fully isotropic,
moderate losses



2D core-shell NWs

Ultra-low losses, isotropic,
polarization dependent





Other phenomena:

Transparency

Fabrication!!

Acknowledgements

Coworkers

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…Thank you