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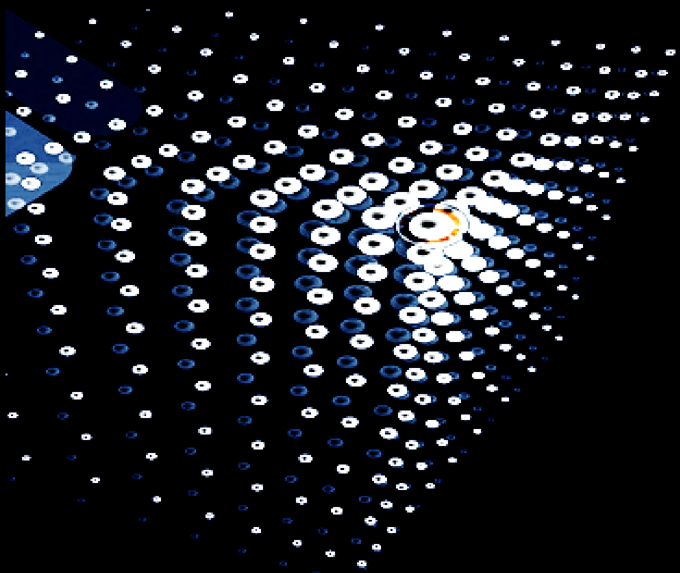


From Metamaterials To Metasurfaces

Vladimir M. Shalaev

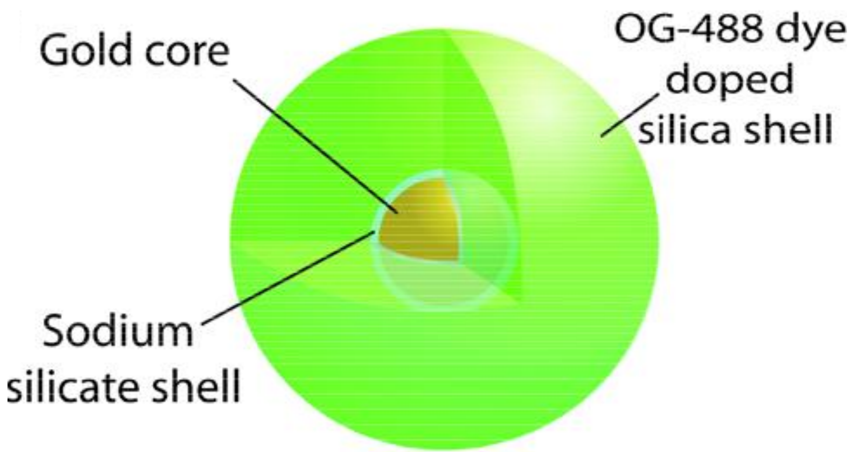
Outline

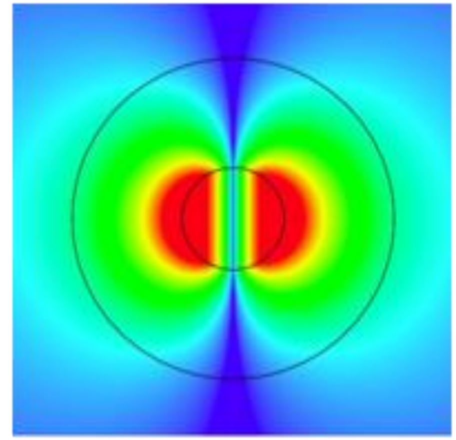
- **Electrical metamaterials (plasmonics) as a route to nanophotonics: Nanolasers/SPASERS**
- **Enginenering Photonic Density of States and sub-wavelength light confinement with Hyperbolic MMs**
- **Metasurfaces**
- **Meta-lens and Meta-hologram**

Nanolasers/SPASERS

Optical Nanolaser Enabled by SPASER

Related theory:
Stockman (SPASER)

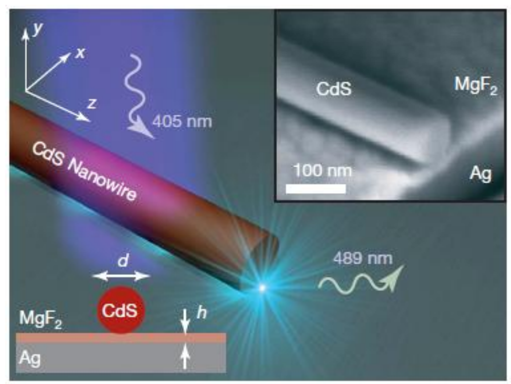




Noginov, Shalaev, Wiesner groups, Nature (2009)

Optical MOSFET
(Stockman)

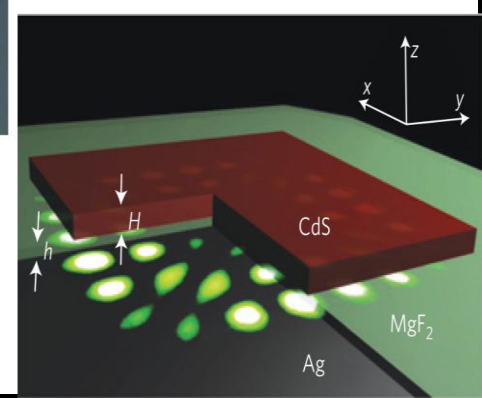
Zhang group: Plasmon Laser (Nature,2009)
Room-T Plasmon Laser (Nat. Mat, 2010)



"Spasing Laser" – Zheludev, Stockman

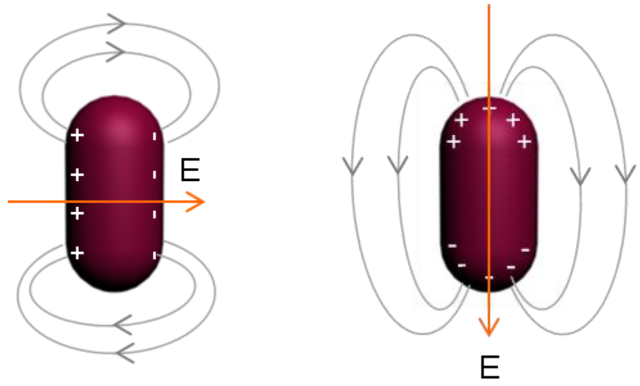
M. T. Hill, et al; C. Z. Ning, et al (electr. pump)

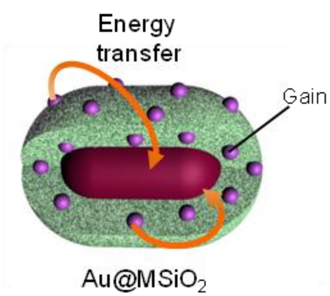
S. Fainman et al – thresholdless laser (Nature, 2012)

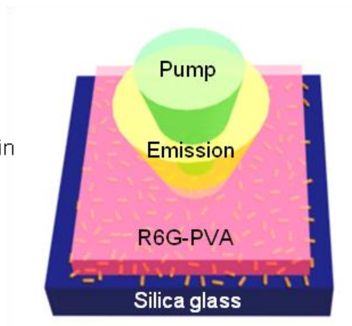


Plasmon Lasers: a Single-Particle (Nanorod) Cavity

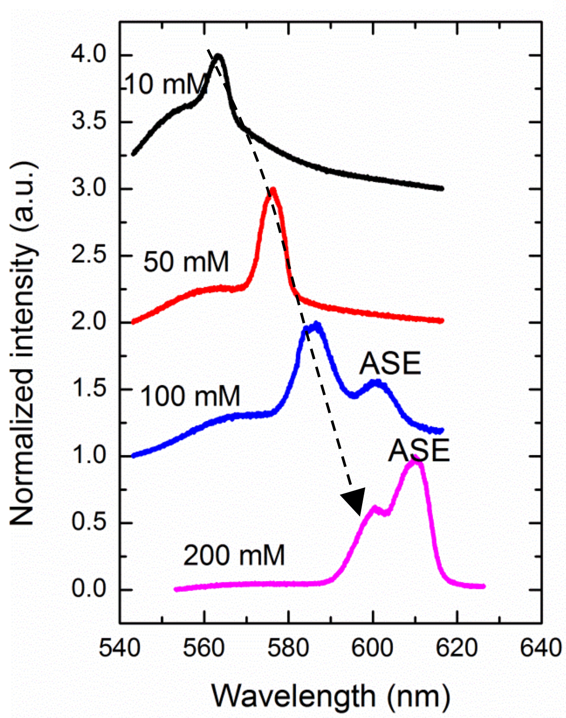
A single metal nanorod serves as a low-loss plasmon nanocavity



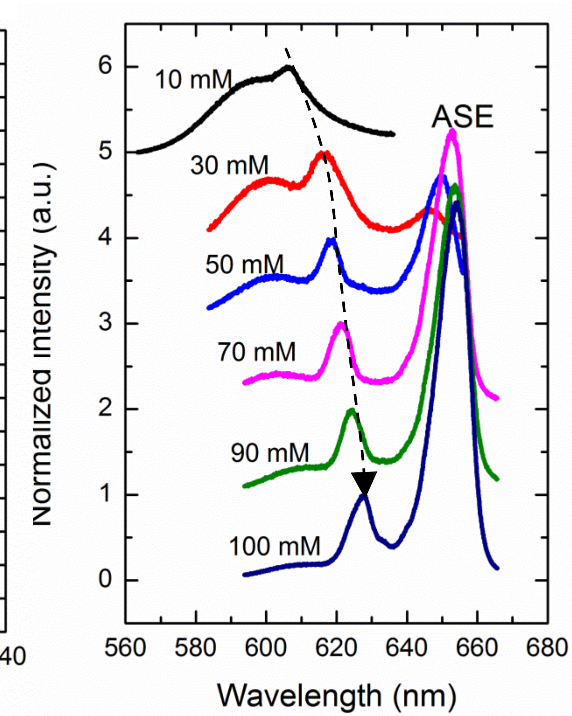


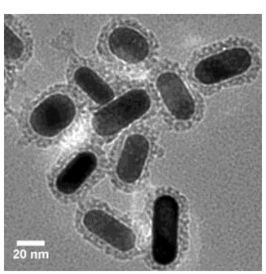


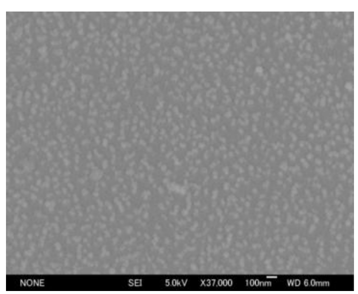
Gain: Rhodamine 6G



Gain: Rhodamine 101



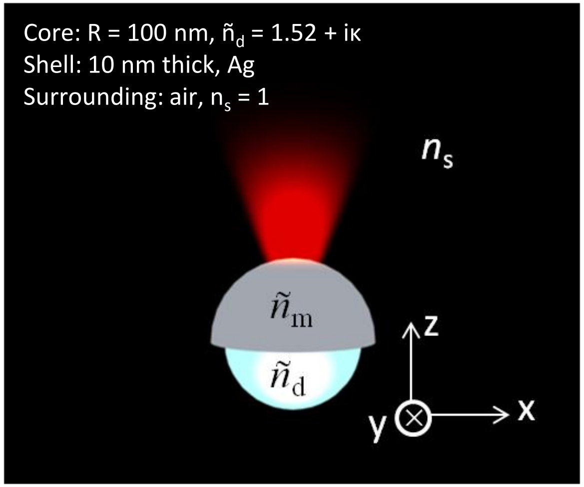


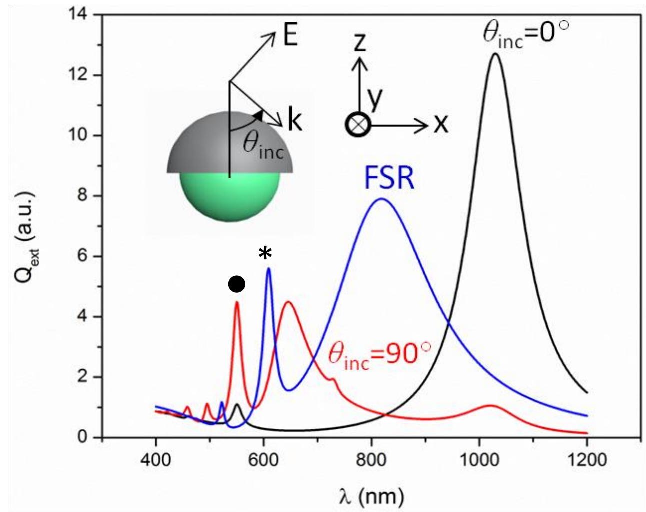


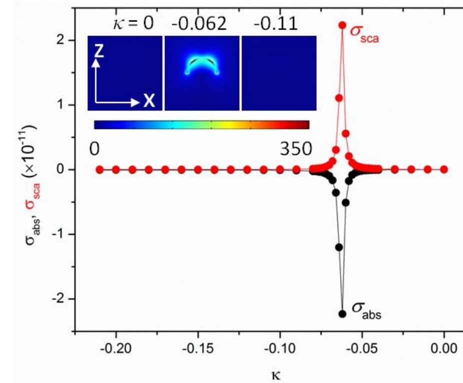
Plasmon lasing: 562 ~ 627 nm;
Linewidth: 5 ~ 11 nm;
Mode volume: ~ 10^{-5} $(\lambda/n_{eff})^3$
Purcell factor: ~ 10^4

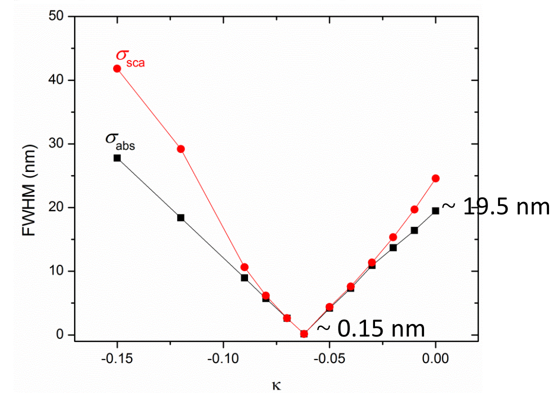
X. G. Meng *et al.*, submitted

Unidirectional Spaser: metal semi-shell



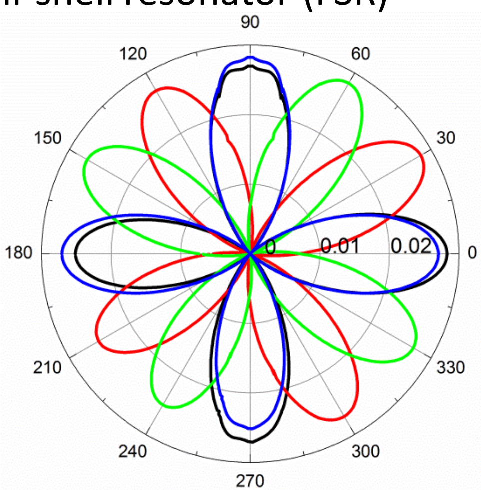






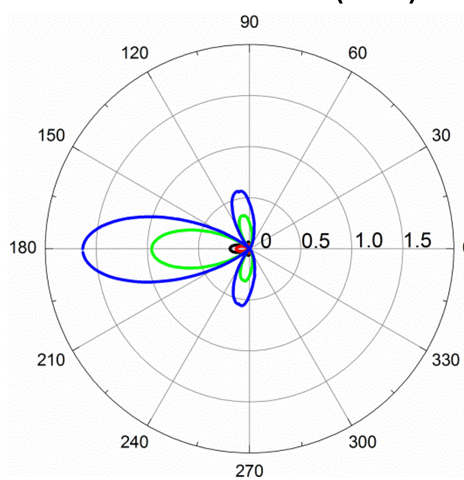
- θ_{inc}-sensitive extinction
- Spectral narrowing with gain

Full-shell resonator (FSR)



$^*\lambda_{res}$ = 608 nm

Semi-shell resonator (SSR)

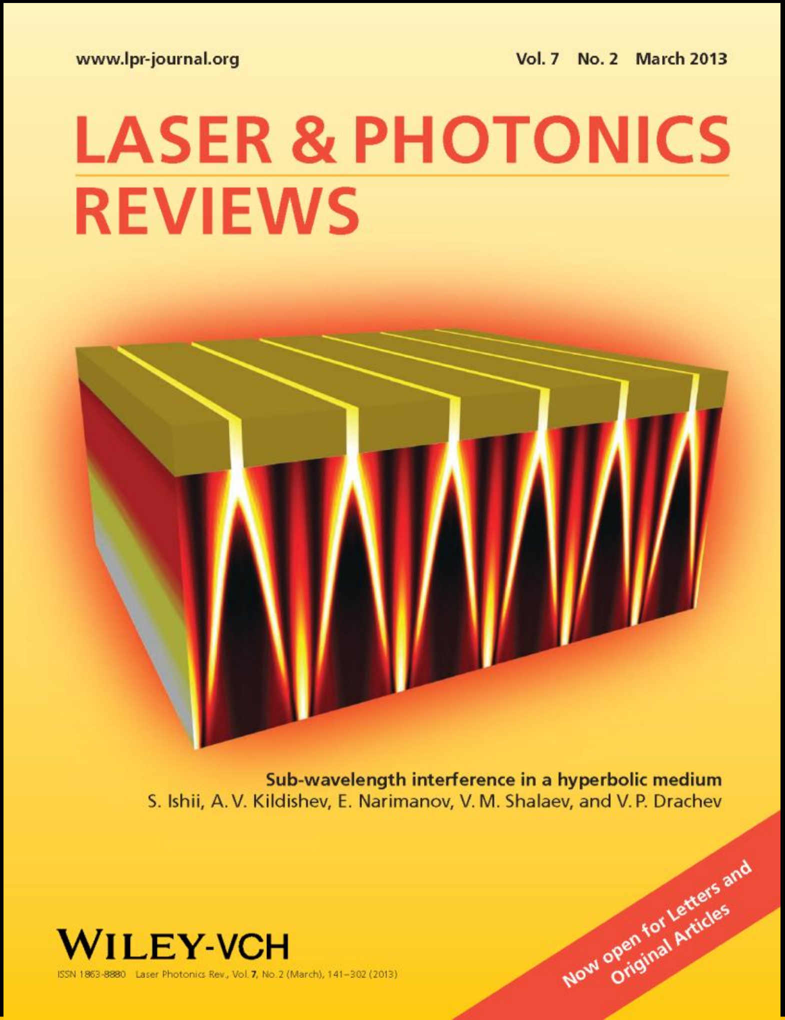


λ_{res} = 549 nm

- θ_{inc}-independent directionality
- significant enhancement compared to FSR

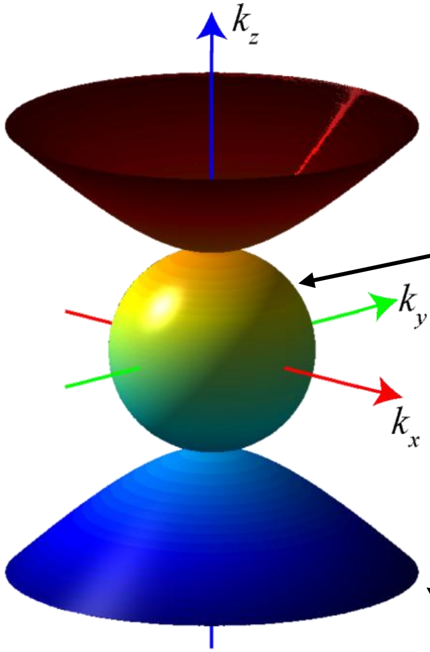
X. Meng *et al.*, *Scientific Reports*, 2013

Engineering Photonic Density of States and Subwavelength Light Confinement with Hyperbolic Metamaterials



Hyperbolic Metamaterials (HMMs)

A metamaterial has hyperbolic dispersion relation



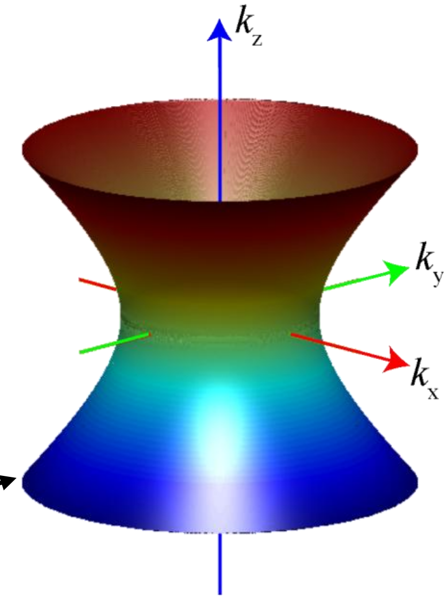
normal dispersion

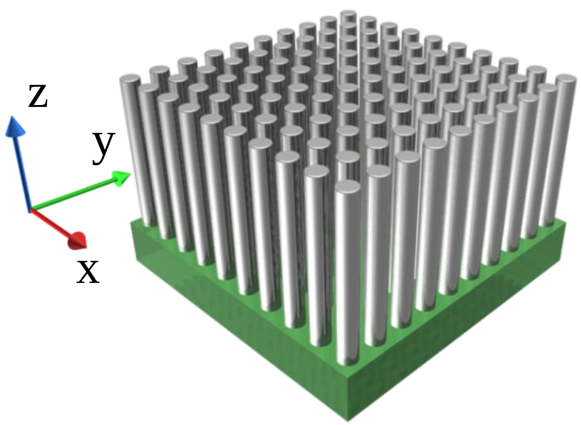
$$\frac{k_x^2 + k_y^2 + k_z^2}{\varepsilon} = \left(\frac{\omega}{c}\right)^2$$

hyperbolic dispersion

$$\frac{k_x^2 + k_y^2}{\varepsilon_{\parallel}} - \frac{k_z^2}{|\varepsilon_{\perp}|} = \left(\frac{\omega}{c}\right)^2$$

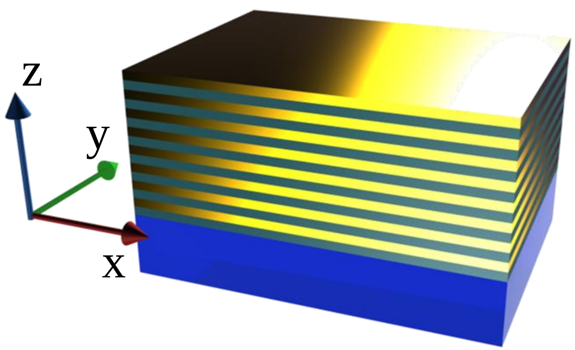
$$-\frac{k_x^2 + k_y^2}{|\varepsilon_{\parallel}|} + \frac{k_z^2}{\varepsilon_{\perp}} = \left(\frac{\omega}{c}\right)^2$$





Transverse Positive (TP)

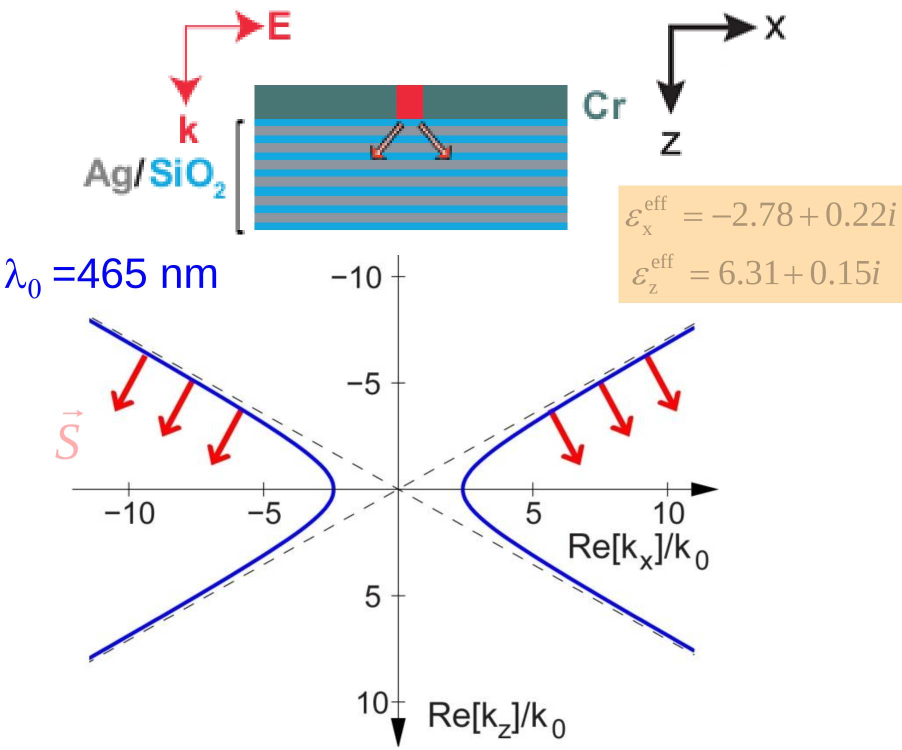
Jacob, et al., Opt. Express, 2006



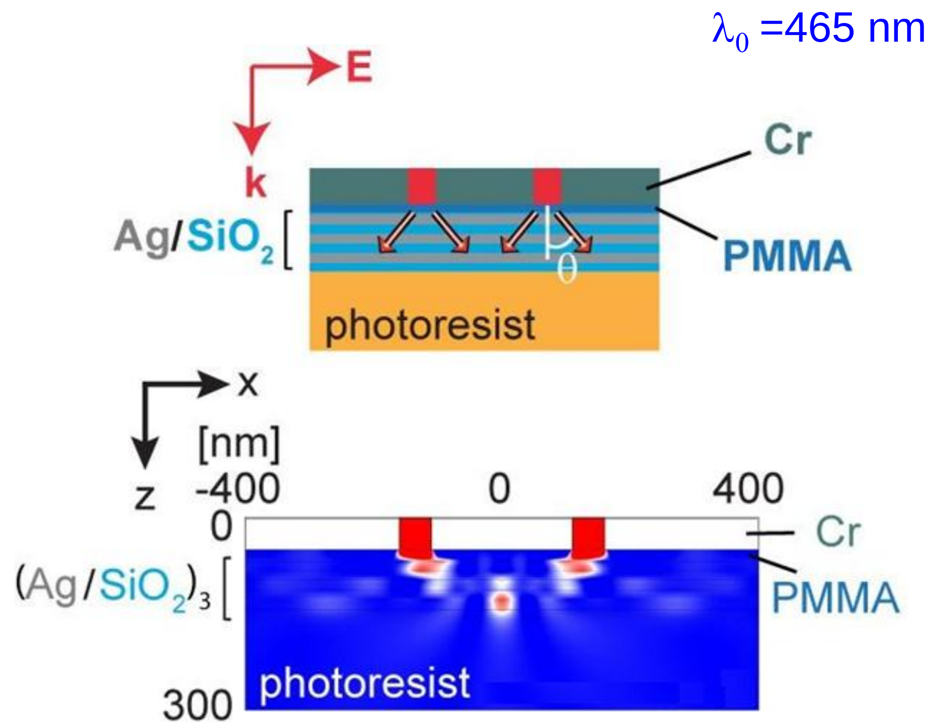
Transverse Negative (TN)

Diffraction inside Hyperbolic Media

- Hyperbolic metamaterial (HMM)
  - Ag/SiO_2 lamellar HMM



  - High-k waves are supported
  - Propagation of high-k waves is confined



(15 nm Ag/15 nm SiO_2)$_3$

- Diffraction from double slits
  - FWHM = 45 nm at λ_0 = 465 nm

S. Thongrattanasiri and V. A. Podolskiy, Opt. Lett. (2009)
Satoshi Ishii et al, LPR, in press

Subwavelength Interference (Experiment)

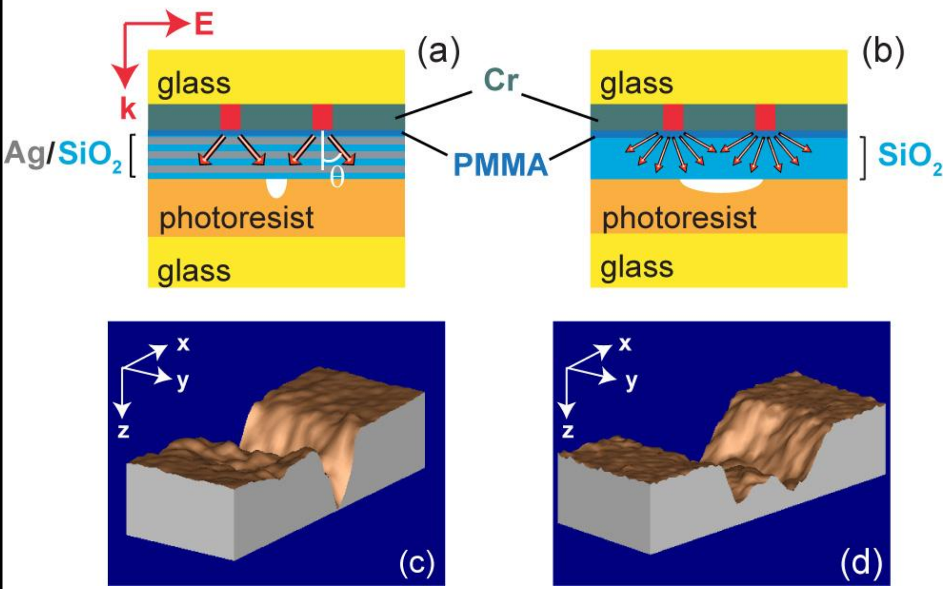
1. Sample fabrication

   Deposition and FIB

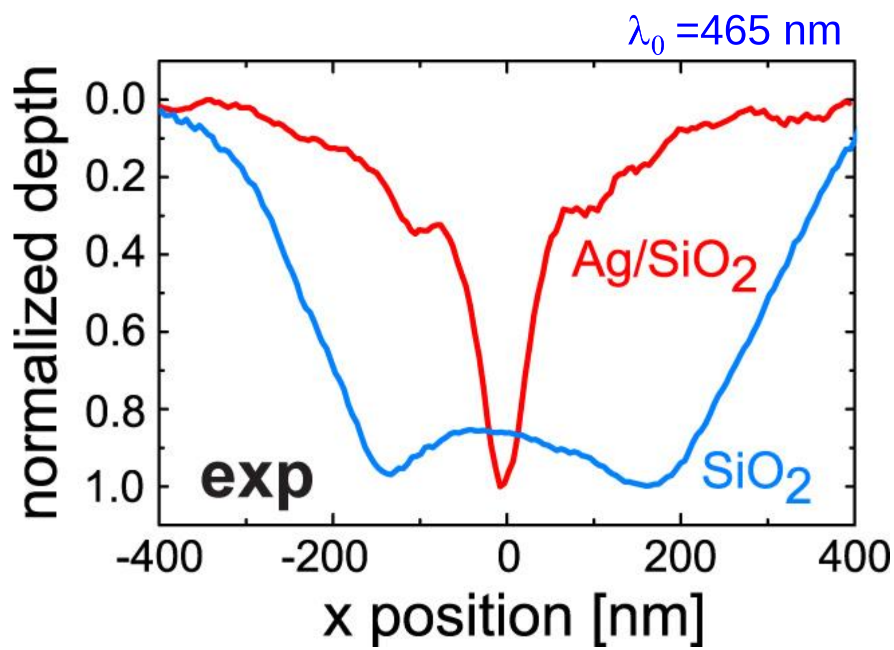
2. Photolithography

   Photoresist exposure, develop

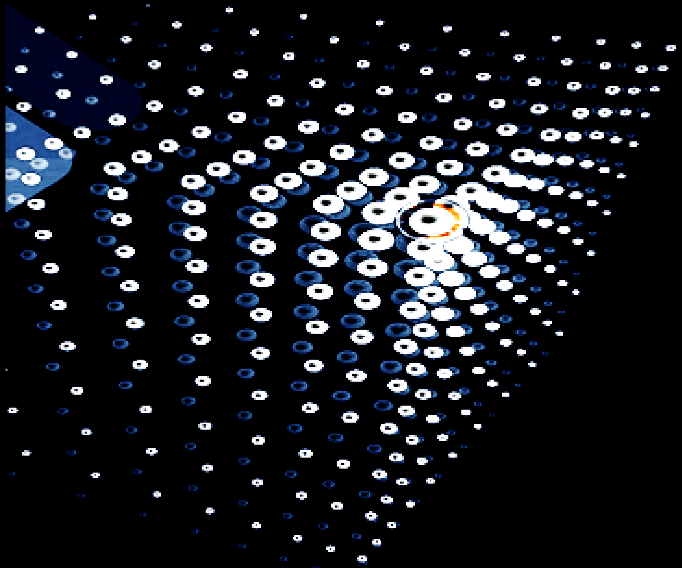
3. AFM scan



Ag/SiO_2 HMM sample **SiO_2 sample**



- For Ag/SiO_2 HMM sample: FWHM = 83 nm (< λ_0)
- For SiO_2 sample: FWHM = 542 nm (~ λ_0)



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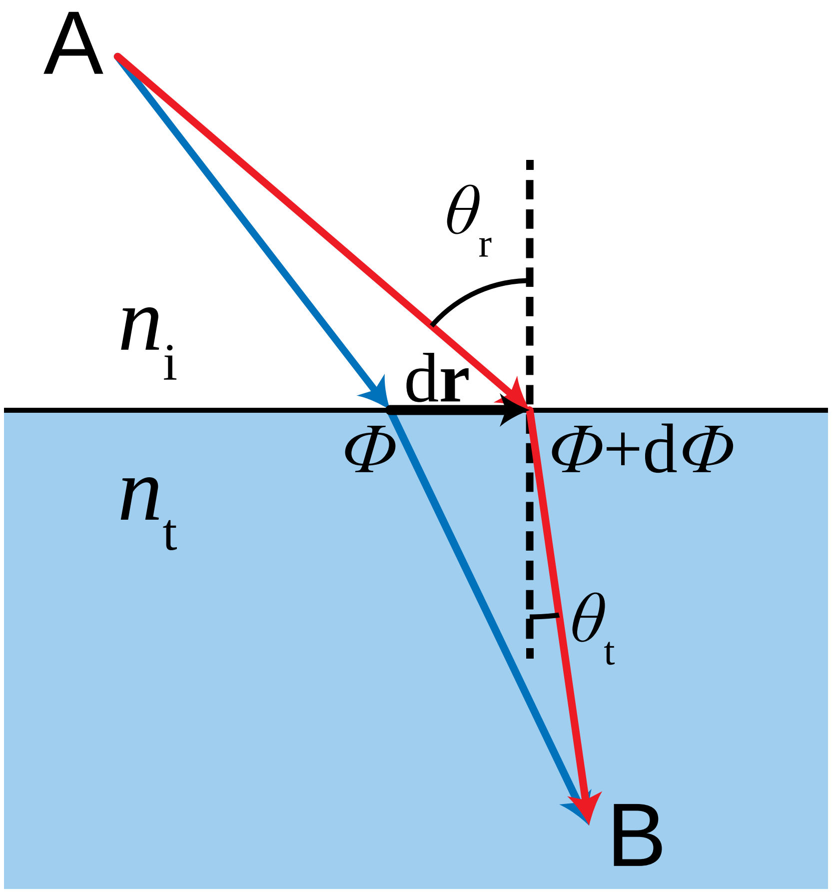
Metasurfaces

A. V. Kildishev. A. Boltasseva, and V. M. Shalaev, Science, in press (2013)

Generalized Snell's Law (Capasso Group)



Principle of least action → The momenta difference between blue and red path is zero

$$(n_i \mathbf{k}_0 \sin\theta_i + \nabla\Phi)\mathrm{d}\mathbf{r}$$
$$-(n_t \mathbf{k}_0 \sin\theta_t)\mathrm{d}\mathbf{r} = 0$$

since $\mathbf{k} = \nabla\Phi$ †

For reflection

$$\sin\theta_r - \sin\theta_i = n_i^{-1} k_0^{-1} \nabla\Phi$$

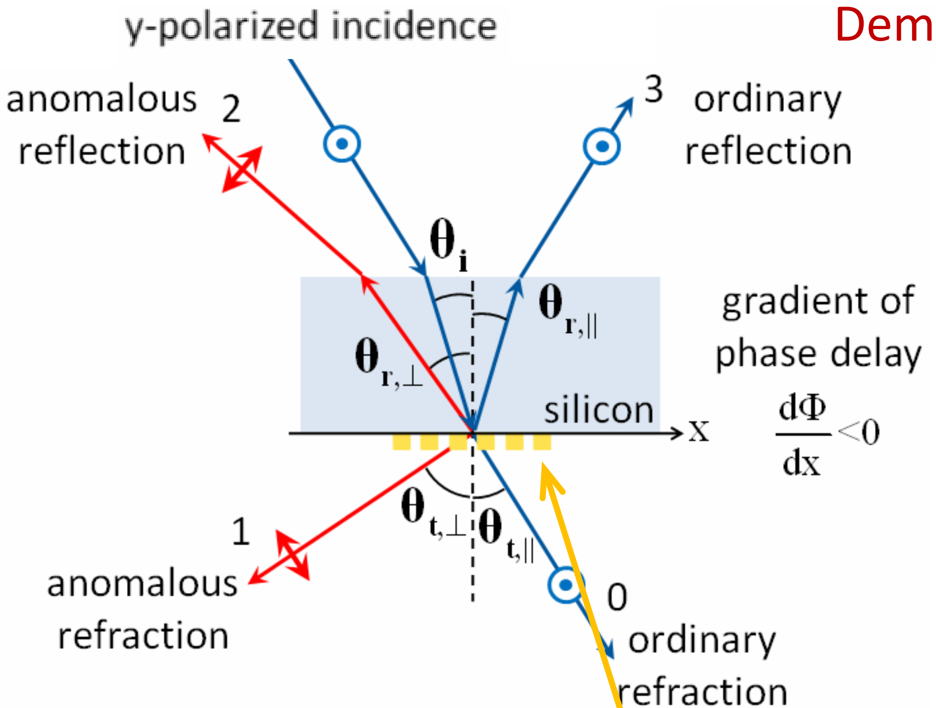
For refraction

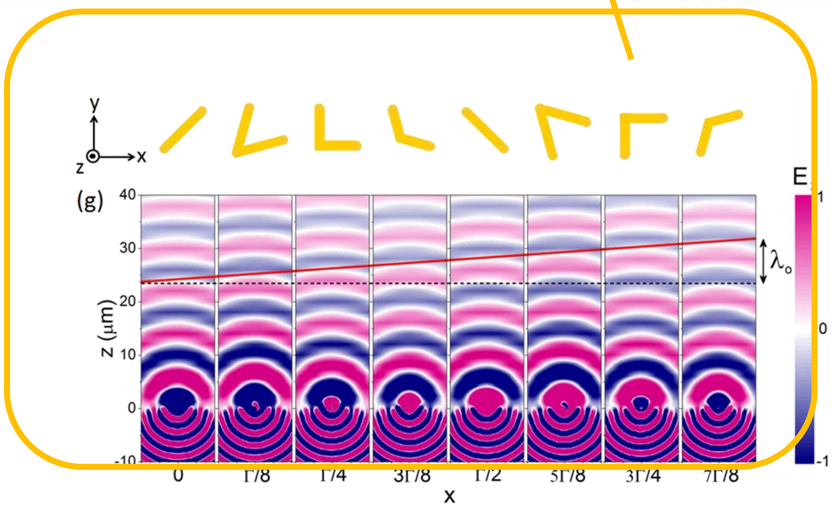
$$n_t \sin\theta_t - n_i \sin\theta_i = k_0^{-1} \nabla\Phi$$

In essence, momentum conservation!

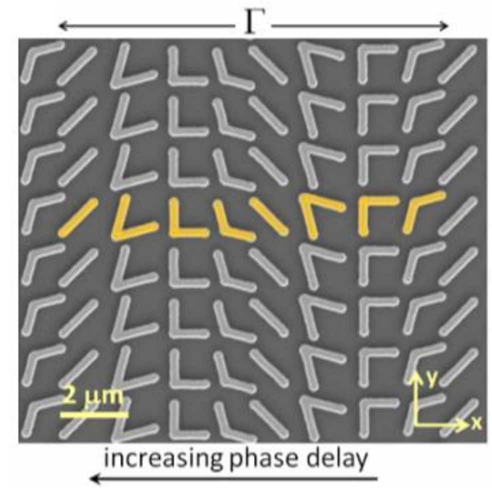
see also S. Larouche and D.R. Smith, OL v. 37, 2391 (2012)

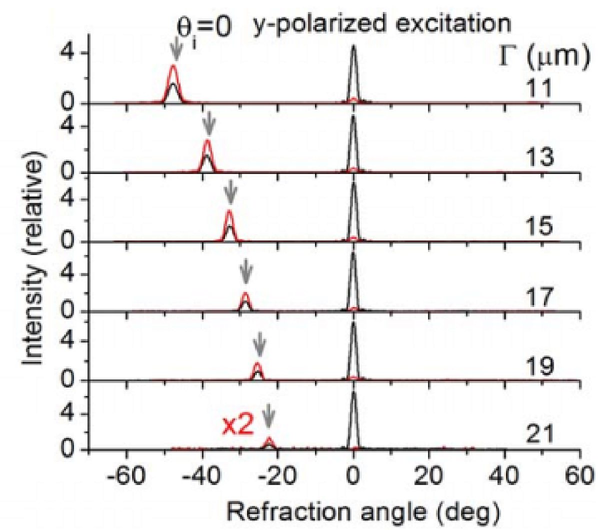
Generalized Snell's Law





Demonstrated at 8 μm wavelength





N. Yu, et al. Science, 2011 (Capasso Group)

Broadband light bending with plasmonic nanoantennas

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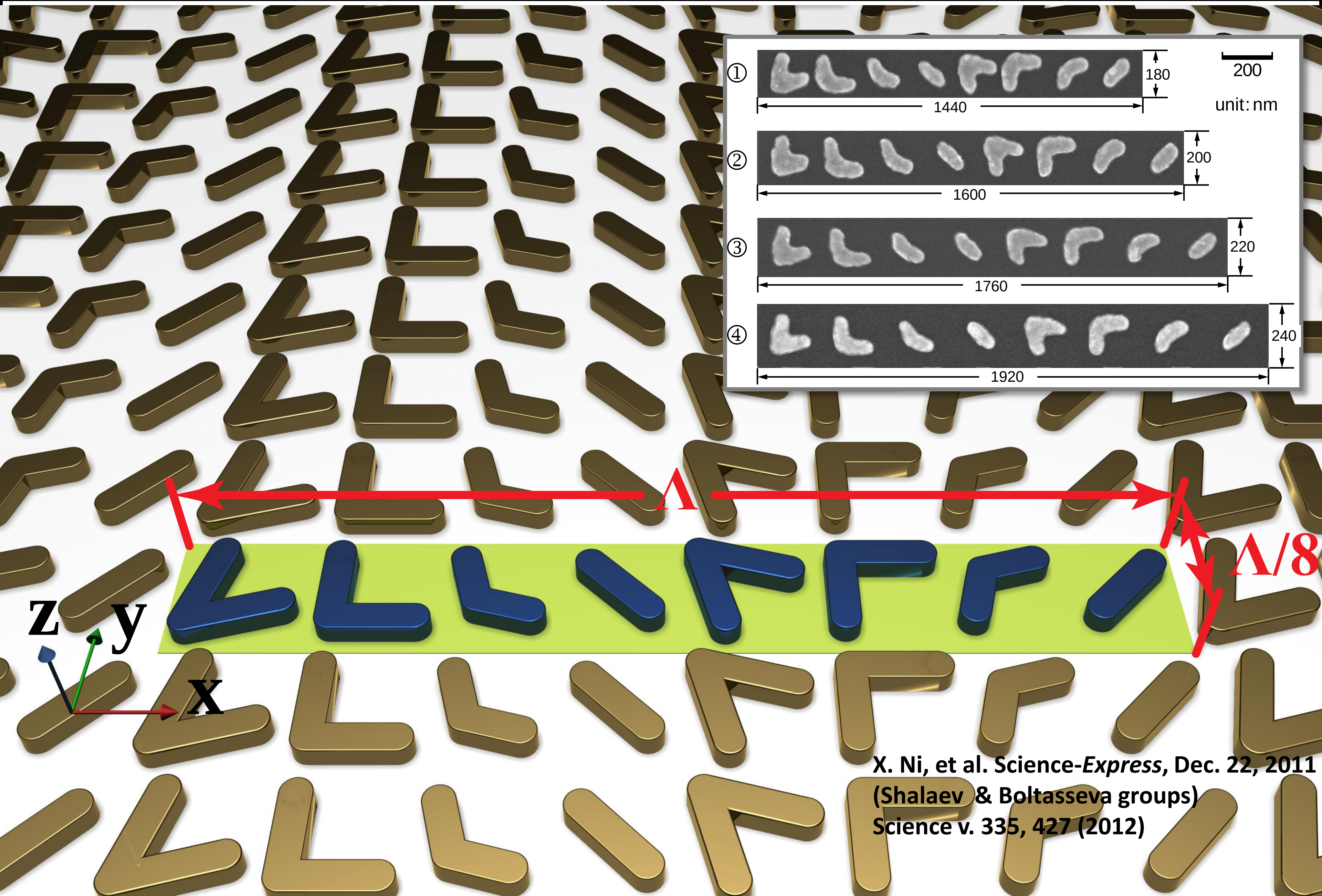
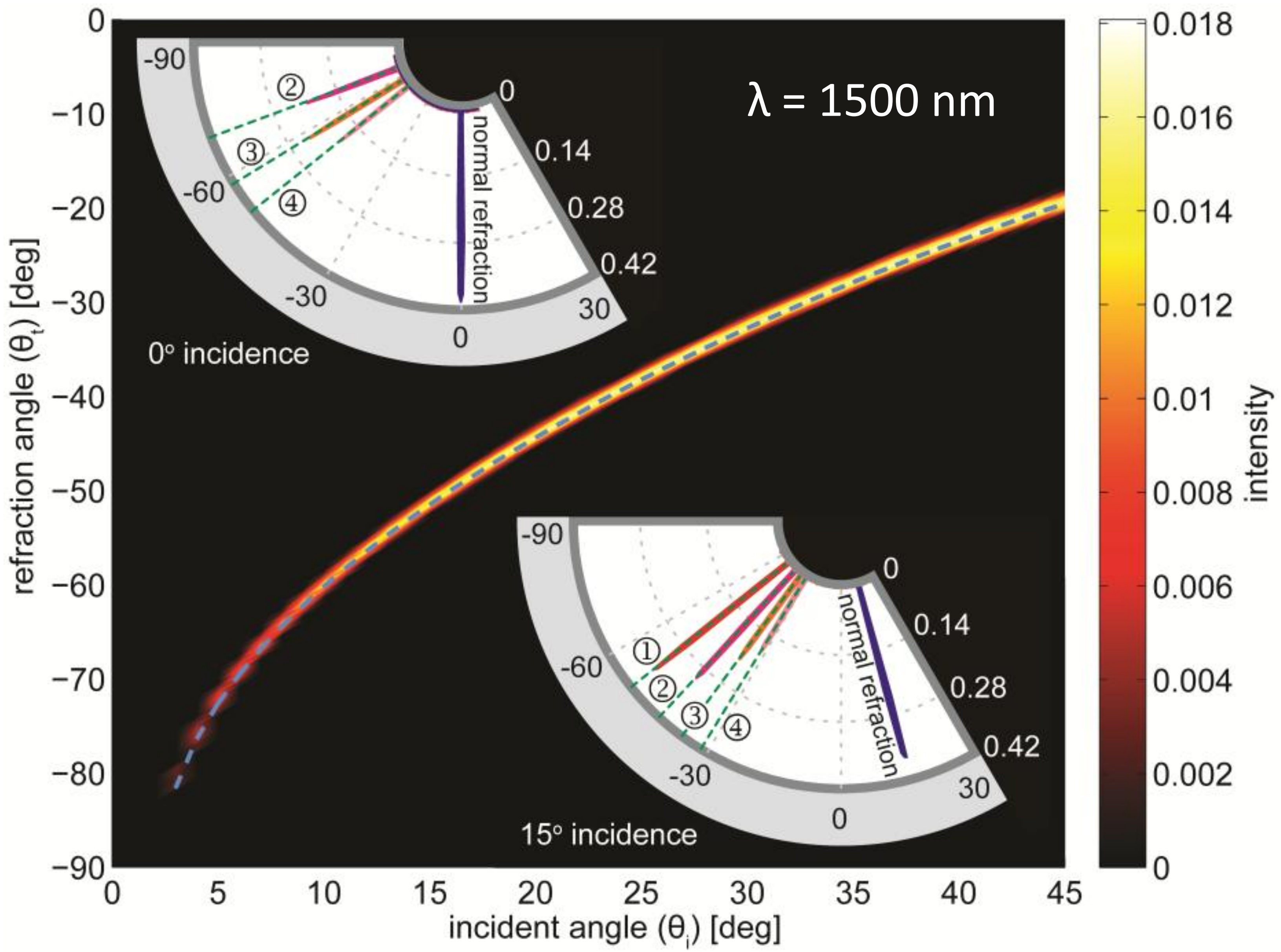
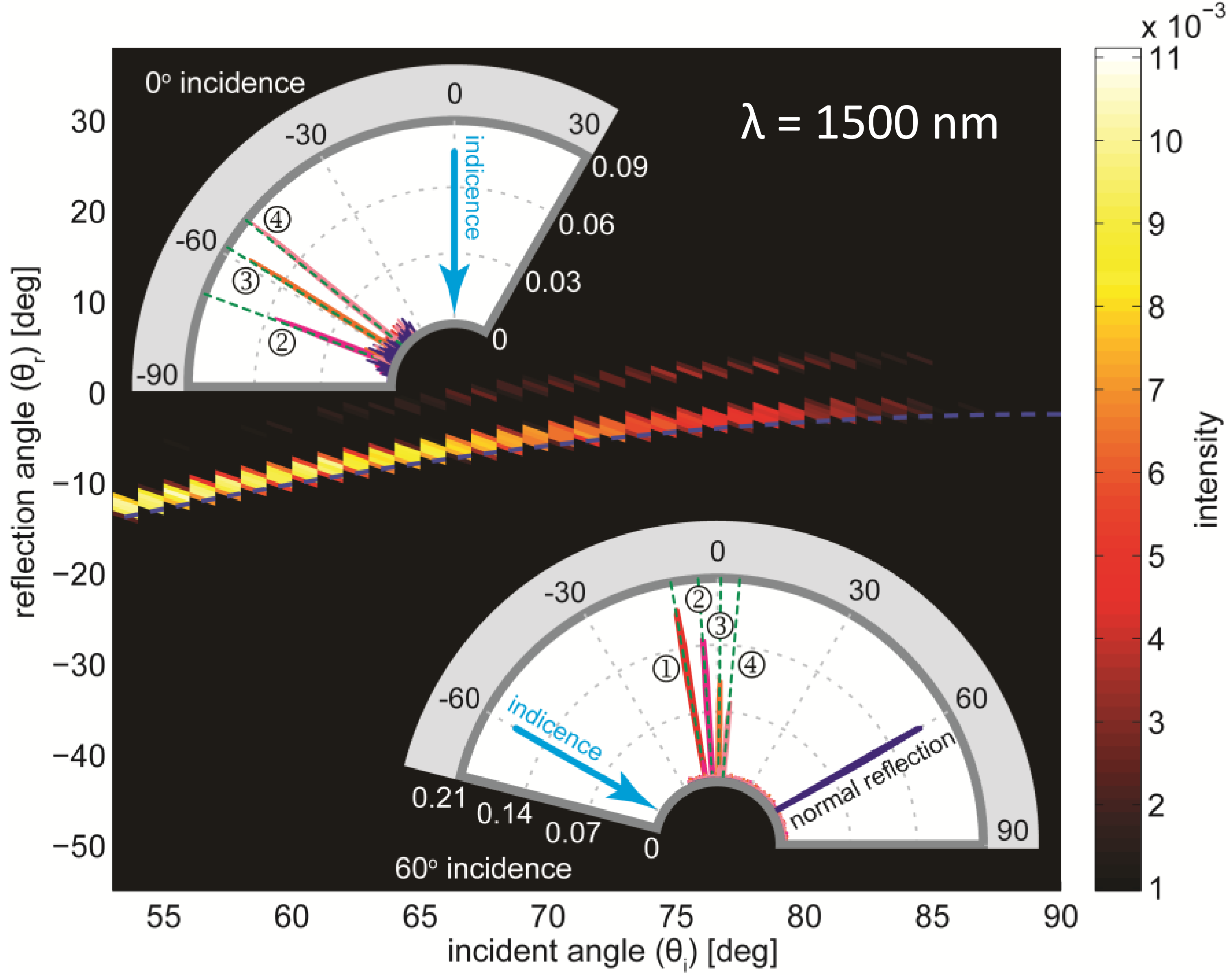


X. Ni, et al. Science-*Express*, Dec. 22, 2011
(Shalaev & Boltasseva groups)
Science v. 335, 427 (2012)

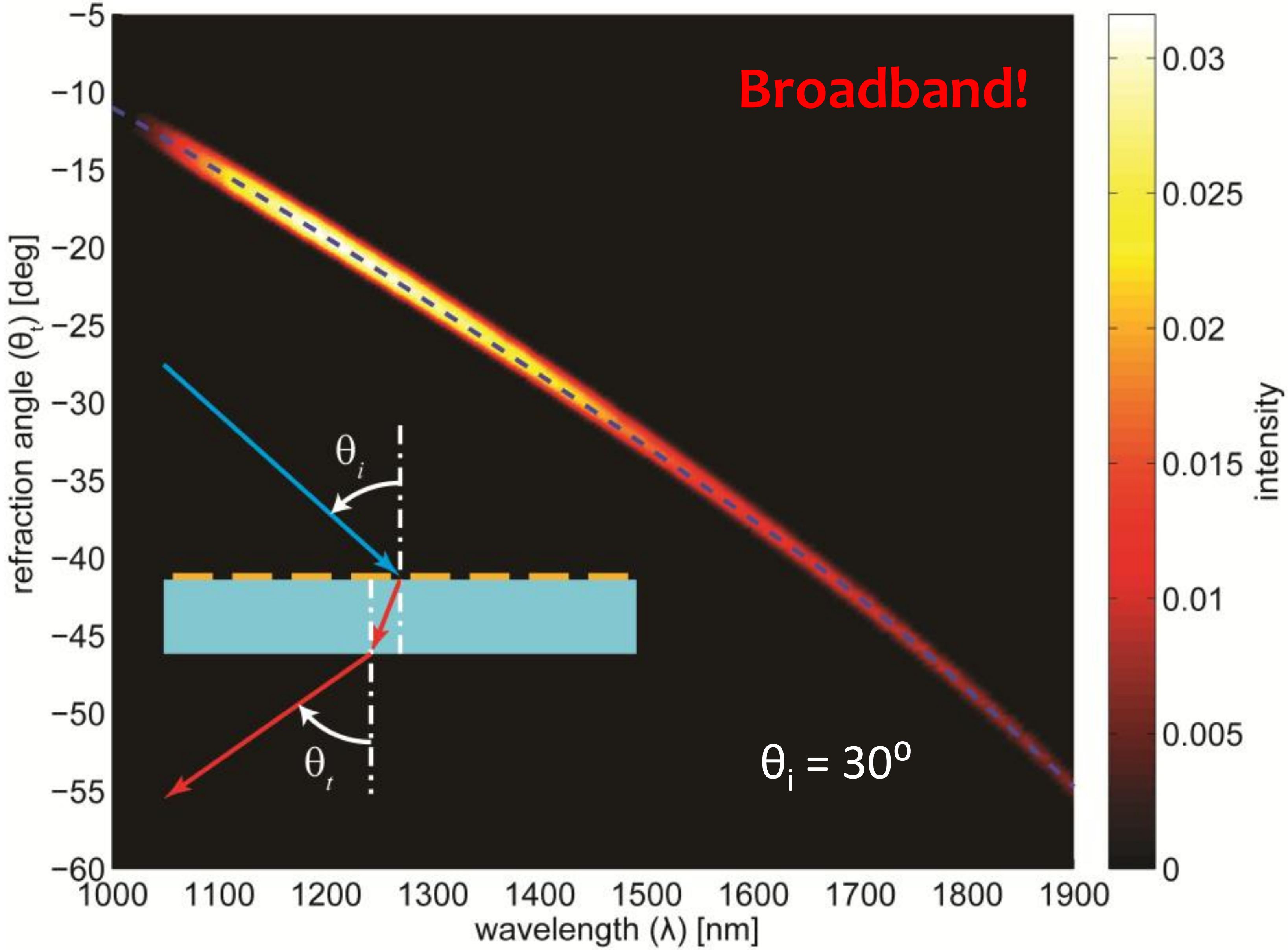
Incident Angle Sweep – Refraction



Incident Angle Sweep – Reflection



Broadband Negative Refraction

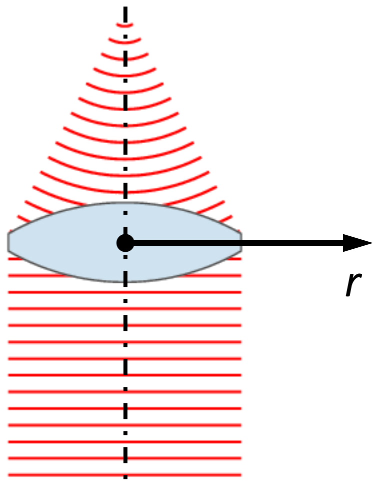


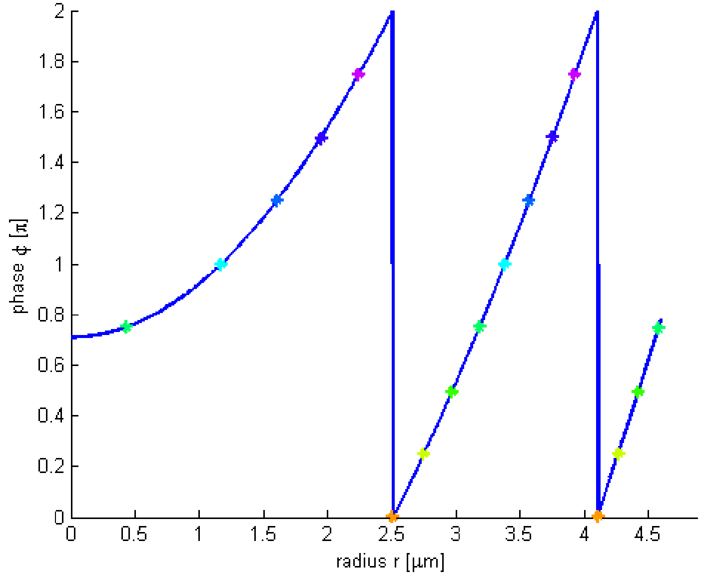
Meta-Lens & Meta-Hologram

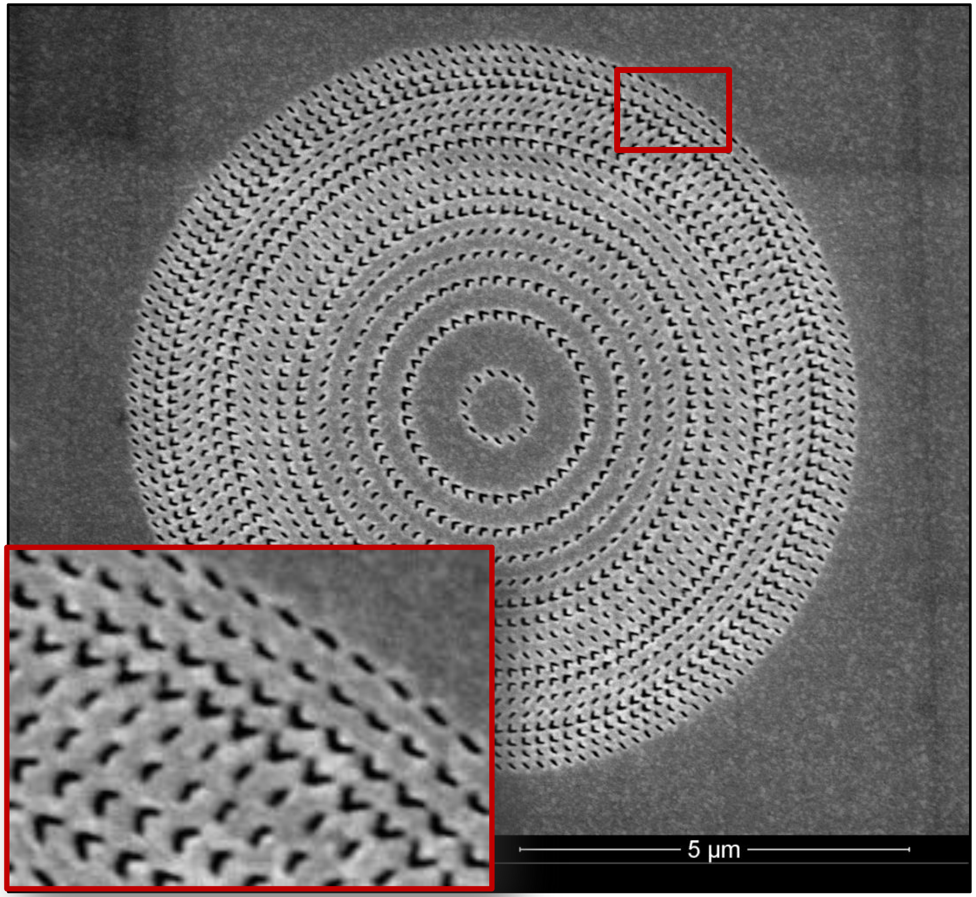
Prior most relevant work:
Meta-lens: F. Aieta *et al*., Nano Lett. **12**, 4932 (2012)
Meta-hologram: S. Larouche *et al*., Nat. Mat. **11,** 450 (2012)

Other relevant work:
Meta-lens: T. Roy, et al, arXiv:1211.1496, 2012 (Zheludev group)
Meta-hologram: P. Genevet, et al, Ncomms2293, 2012 (Capasso group)

Ultra-thin planar meta-lense







Au film (30 nm) by electron beam evaporation

Babinet antennas fabrication by focused ion beam

X. Ni, et al, (Nature) Light: Science and Applications (2013)

Ultra-thin planar meta-lenses: experiment

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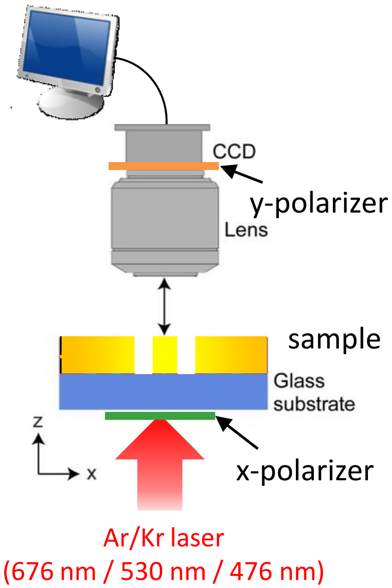
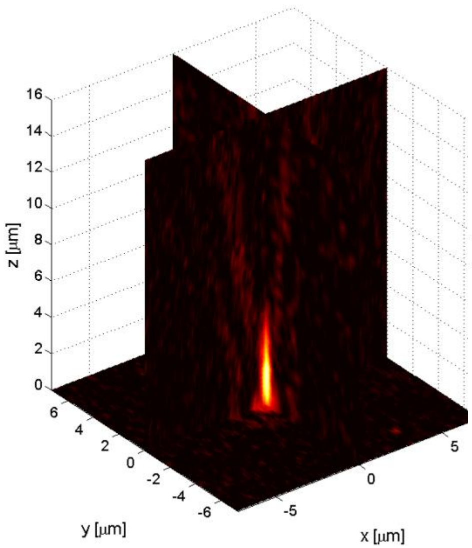
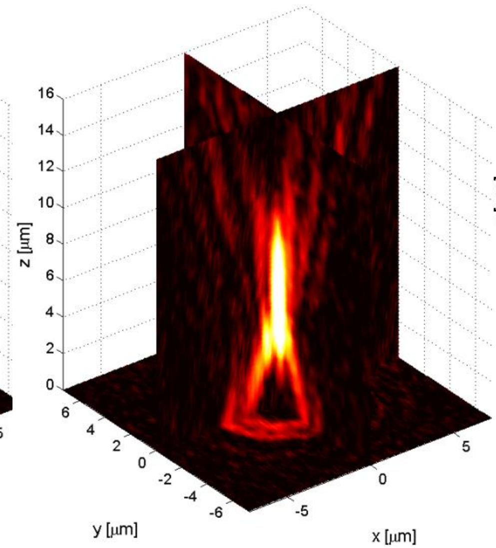


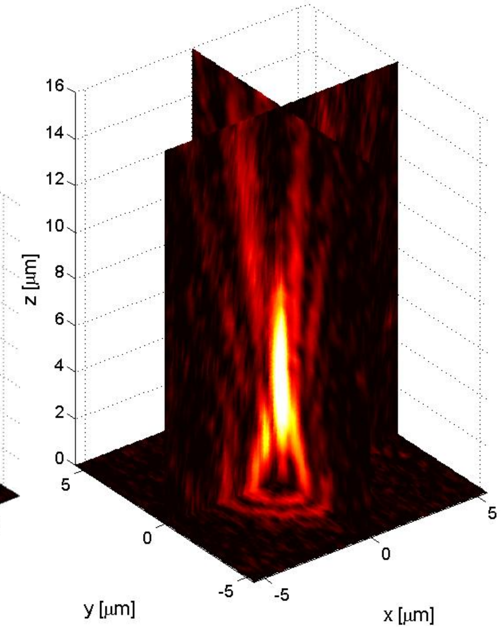
Focal length: 2.5 µm

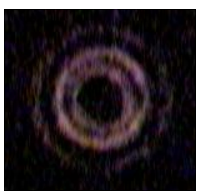


Focal length: 4 µm



Focal length: 7 µm

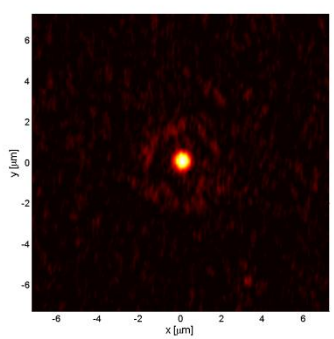


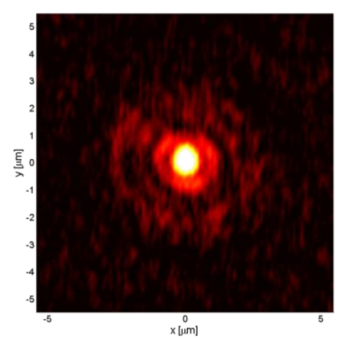


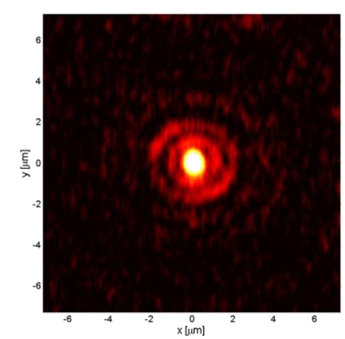
Z = 0 µm

Z = 7 µm

Z = 10 µm







wavelength 676 nm

Summary

- Nanophotonics & nanolasers
- Engineering Photonic Density of States and sub-wavelength light confinement with Hyperbolic MMs
- Metasurfaces
- Meta-lens and Meta-hologram