Metasurfaces for Optical Wave-front Engineering

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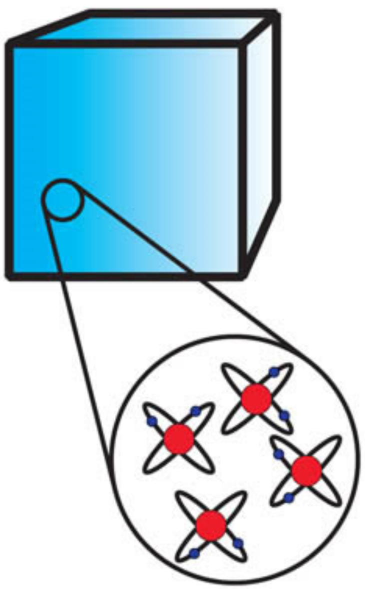
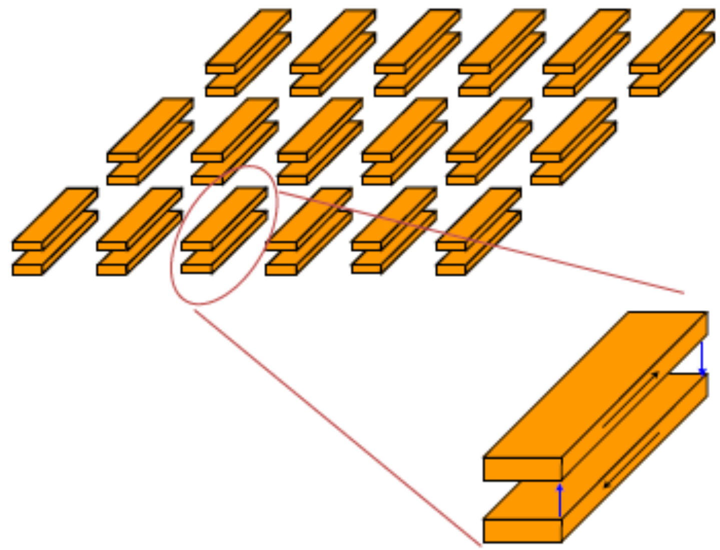
Outline

- From metamaterials to metasurfaces
- Phase Gradient Metasurfaces: Meta-lens, Meta-hologram, Color-hologram
- Power Efficiency: Huygens' Metasurface, Dielectric Metasurface, Gap-plasmon Metasurface
- Polarization Gradient: ¼ wave plate, ½ wave plate
- Photonic Spin Hall Effect: Circular Dichroism Spectrometer, Optical Rotation
- Metasurface Based Nano-Cavities.
- Active Metasurfaces & Nano-lasers
- Nonlinear Metasurfaces
- Broadband Absorber
- Hyperbolic Metasurfaces
- Time-Varying Metasurfaces

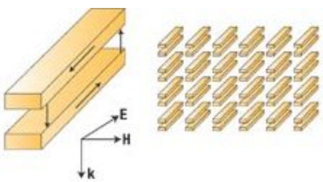
Introduction: From Meta-Materials to Meta-Surfaces

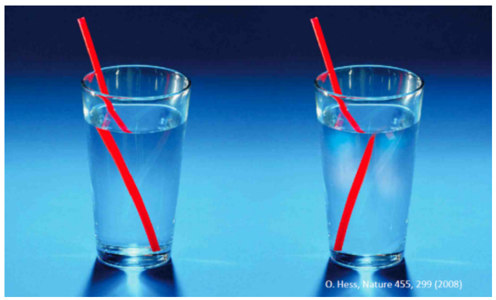
- Optical Meta-Materials are artificial materials
- Transcend properties of natural materials
- By engineering light-matter interaction at the structural level rather than the atomic\molecular level.

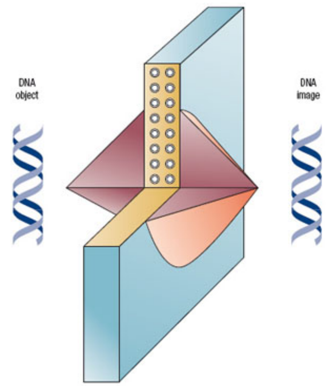


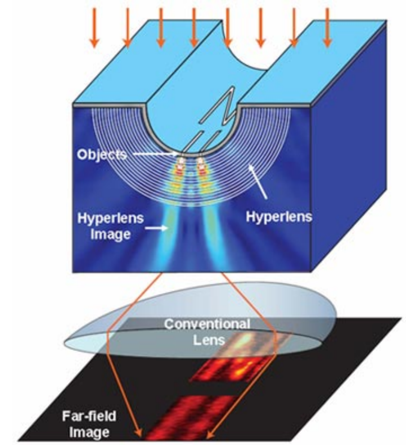


Bulky Metamaterials: Prospects and challenges





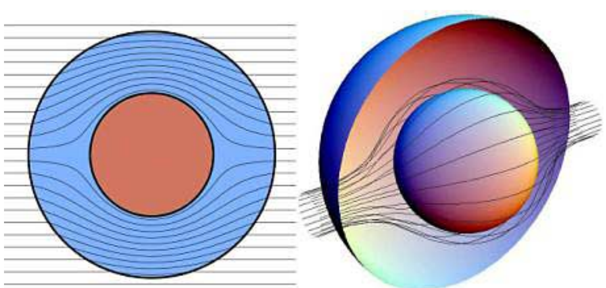


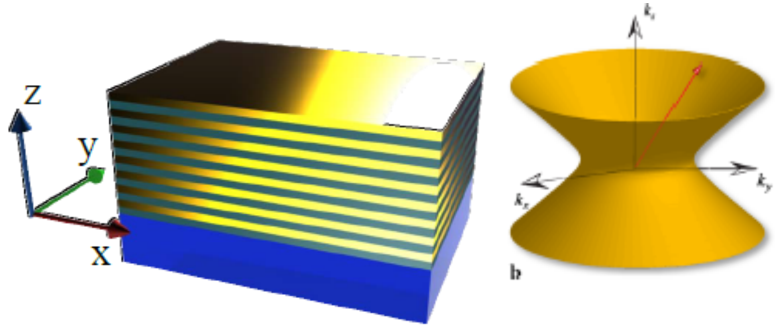


Shalaev, *Nat Photonics* **1**, 41 (2007)
Hess, *Nature* 455, 299 (2008)

Zhang & Liu, Nature Materials7, 435 (2008)

Liu et al, science 23, 1686 (2007) (Zhang group)





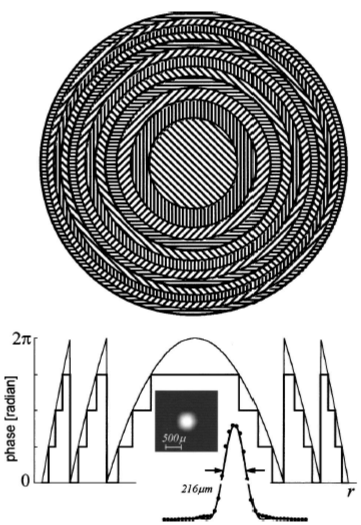
Pendry, et al, Science 312, 1780 (2006)

Jacob et al, Appl Phys B 100, 215 (2010)

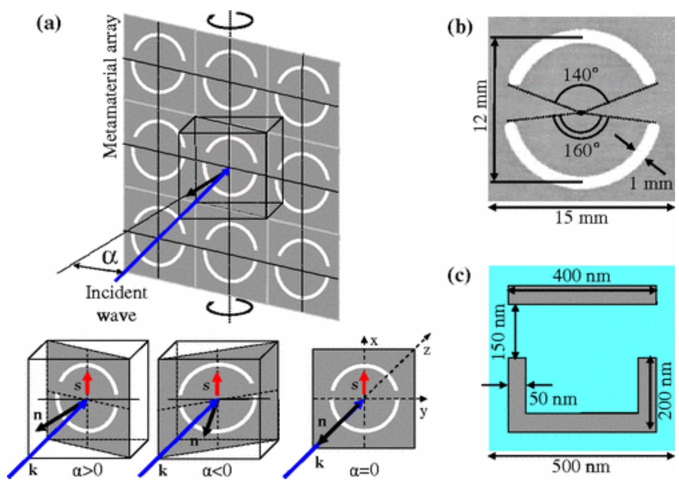
Gansel et al, Science 18, 1513 (2009)

Optical Metasurfaces (MS's)

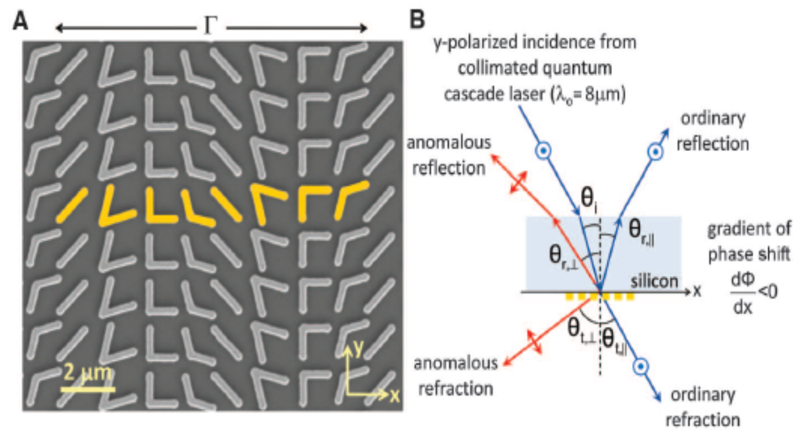
- Wave-front discontinuity instead of accumulative response
- Overcome Bulk MM's challenges:
- Easier to fabricate, more readily assembled, suitable for on-chip applications, reduced losses
- Open new applications not found with bulky MM's (phase-gradient MS)



E. Hasman, et al, APL 82, 328 (2003)

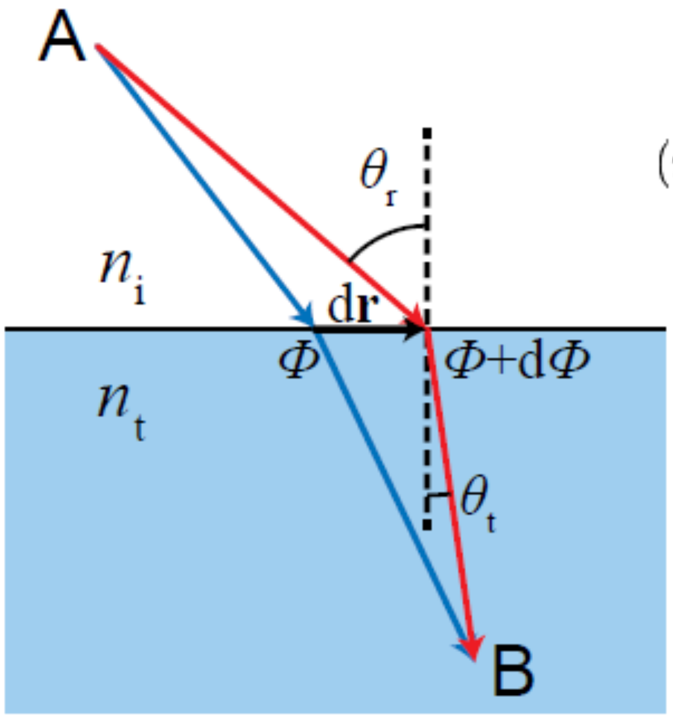


Plum et al, *phys Rev Lett, 102, 113902* (2009) (Zheludev group)



Yu et al, *Science 21, 334* (2011) (Capasso group)

Phase-Gradient MS: Generalized Snell's law



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

$$(n_i k_0 sin\theta_i + \nabla\Phi)dr - (n_t k_0 sin\theta_t)dr = 0$$

For reflection

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

For refraction

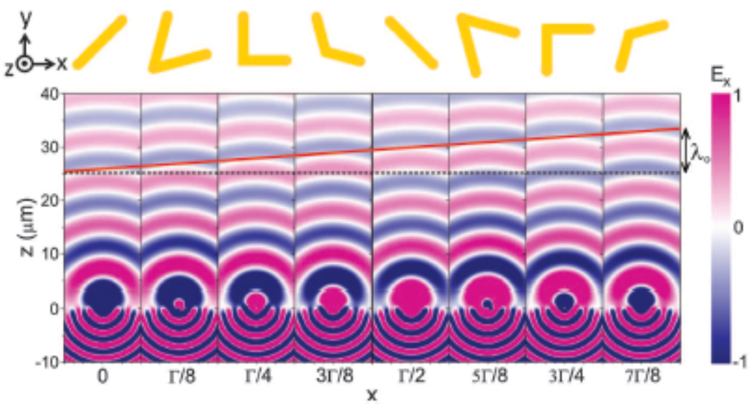
$$n_t sin\theta_t - n_i sin\theta_i = k_0^{-1} \nabla\Phi$$

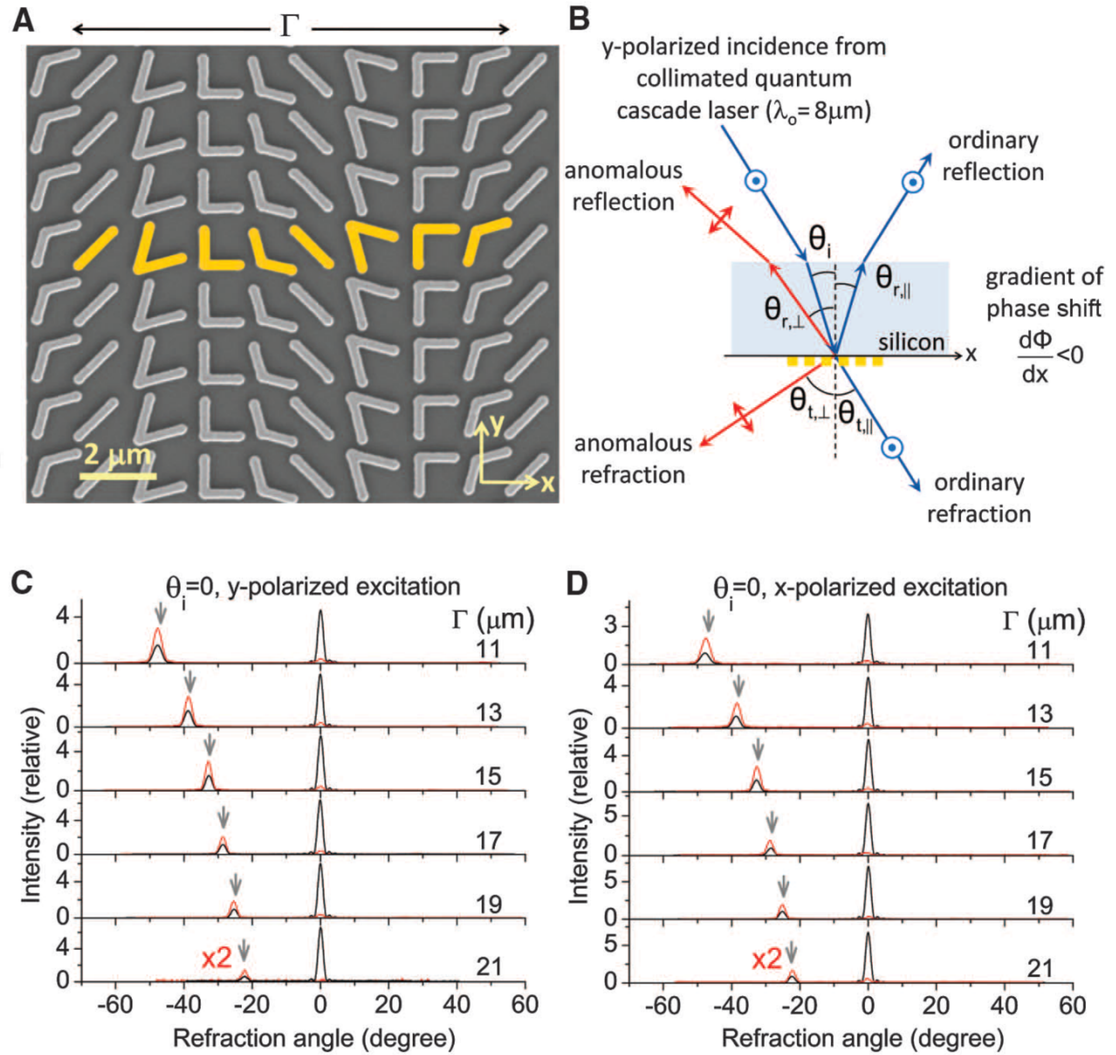
Yu et al, *Science 21, 334* (2011) (Capasso group)

In essence, momentum conservation!

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

Generalized Snell's law





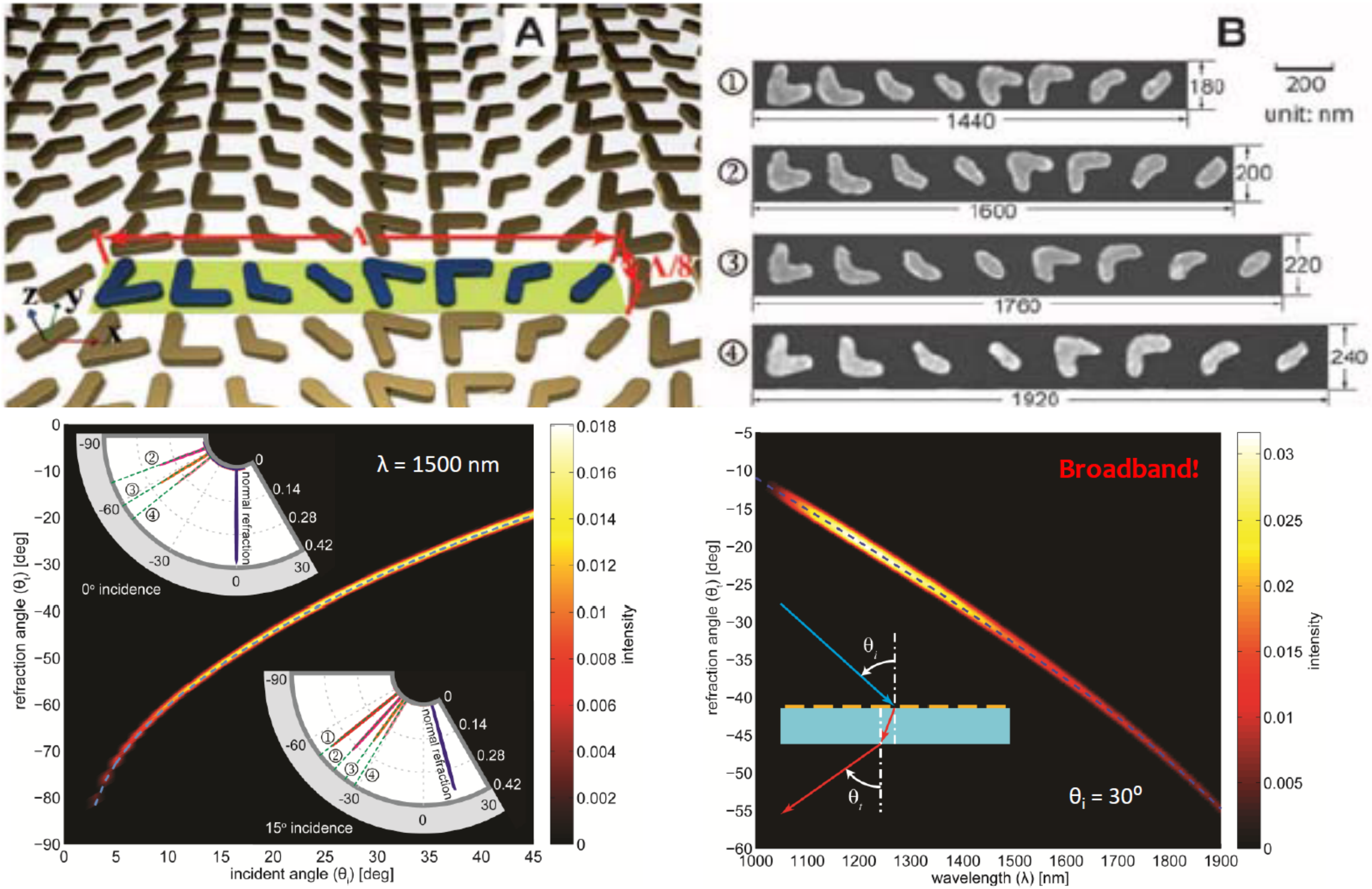
Yu et al, *Science 21, 334* (2011) (Capasso group)

Operating at 8μm

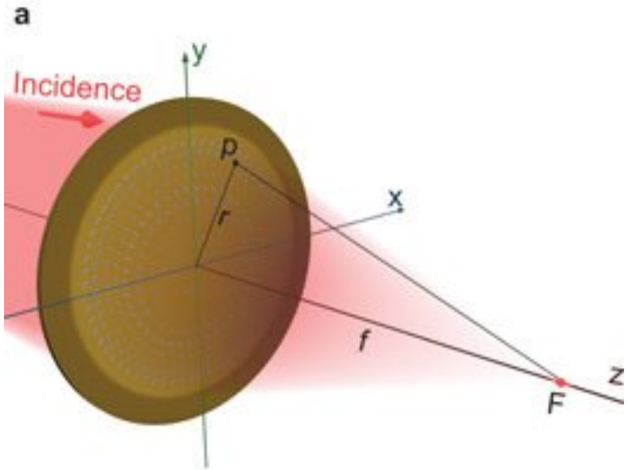
Broadband Light Bending

Operating at 1–1.9μm

Ni et al, *Science* *335* (2012)
(Shalaev group)

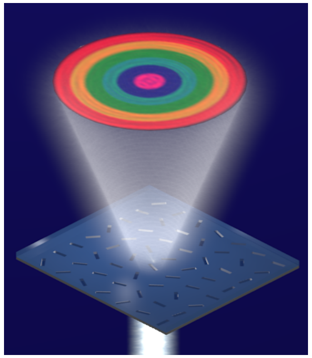


Meta-lens and Meta-holograms



Ni et al, *LSA 2, e72,* (2013)

Ni et al, *Nat Comm 4, 2807* (2013)



Choudhury et al, *CLEO, JTu5A* (2015)

See also:

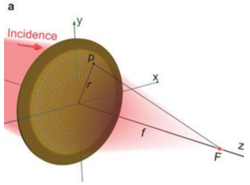
Meta-lens:

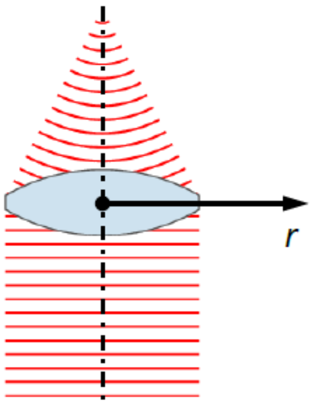
- Aieta et al., Nano Lett. 12, 4932 (2012) (Capasso group)
- Chen et al., Nat Comm 3, 1198 (2012) (S. Zhang & Zentgraf groups)

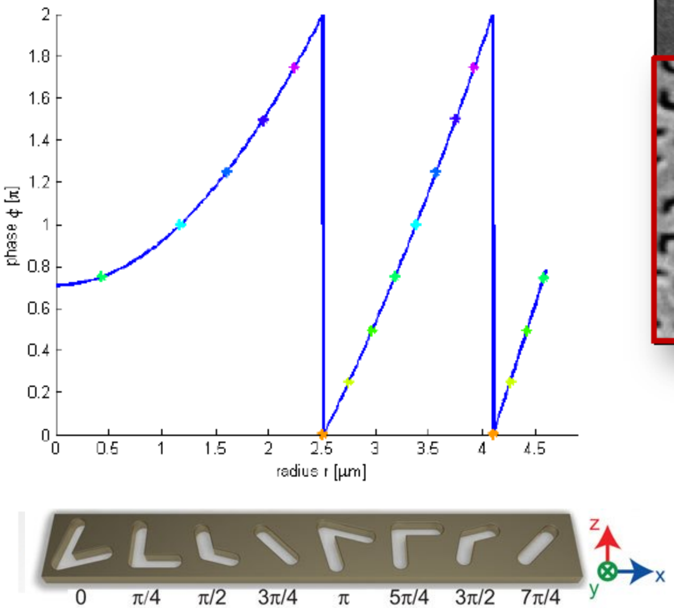
Meta-holograms:

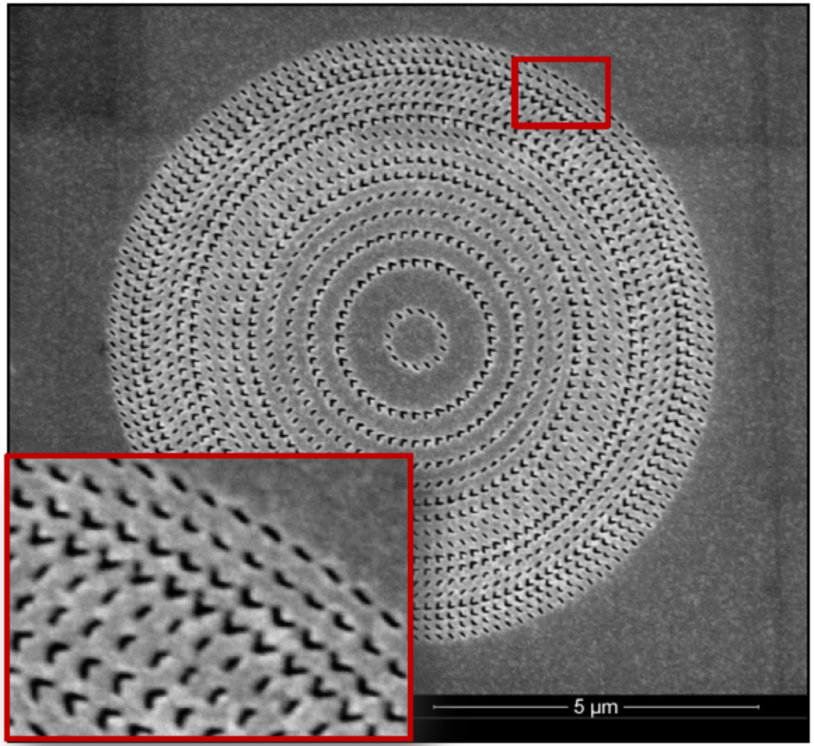
- S. Larouche et al., Nat. Mat. 11, 450 (2012) (D Smith group)
- Lin et al, Nano Lett 13, 4269 (2013) (Capasso group)
- Huang et al, Nano Lett 15, 3122 (2015) (Tsai group)
- Zheng et al, Nat Nanotechnology 10, 308 (2015) (Guixin Li, Zentgraf, S Zhang groups)
- Kuznetsov et al, Sci Reports 5, 7738 (2015)

Ultra-thin, planar, Babinet-inverted plasmonic metalens: Design







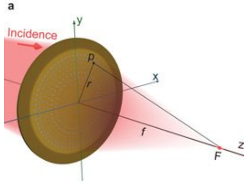


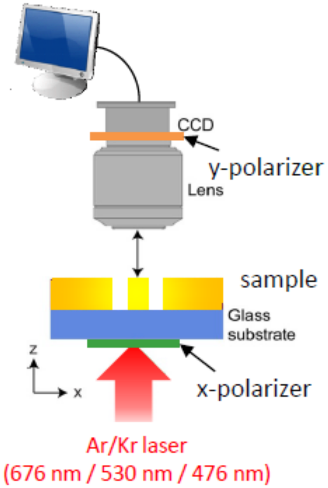
- Au film (30 nm) by electron beam evaporation
- Babinet antennas fabrication by focused ion beam (FIB)

Ni et al, *LSA 2, e72,* (2013)

Ultra-thin, planar, Babinet-inverted plasmonic metalens: Experiment

a

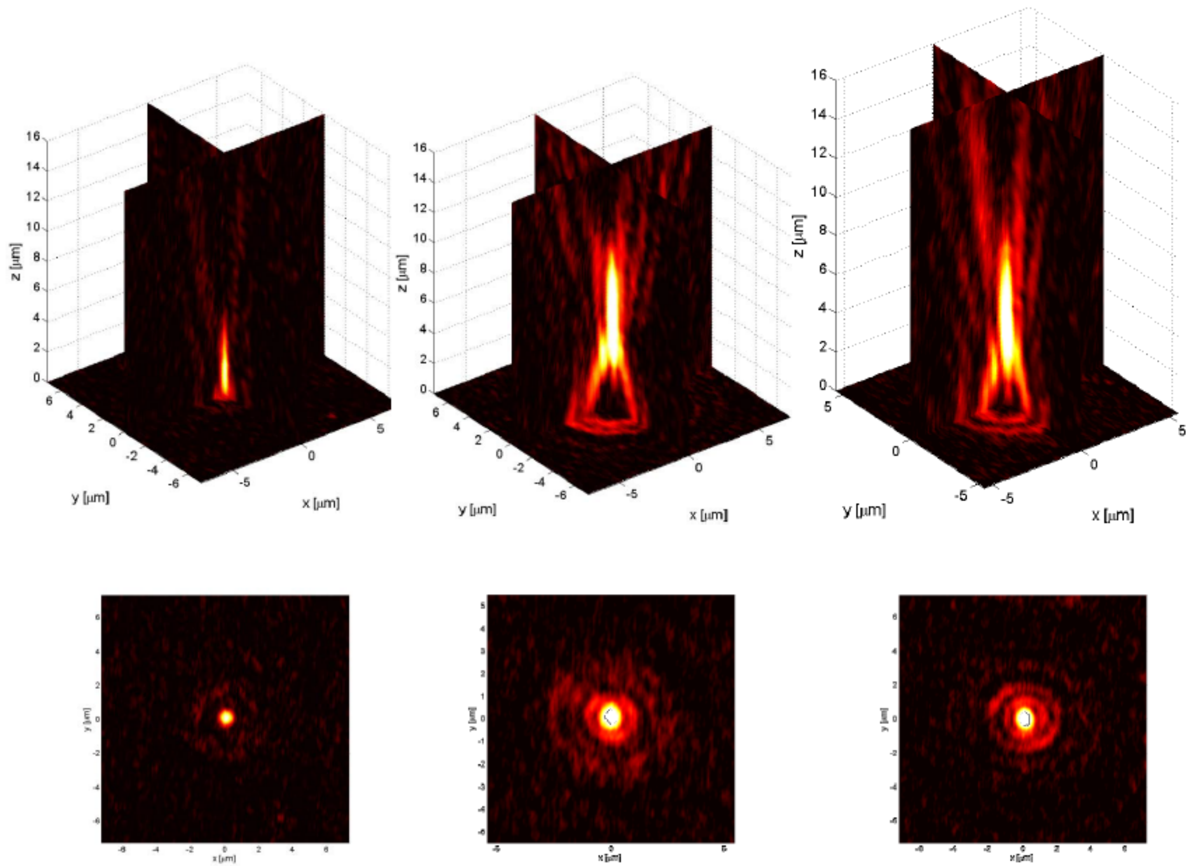




Focal length: 2.5 µm

Focal length: 4 µm

Focal length: 7 µm



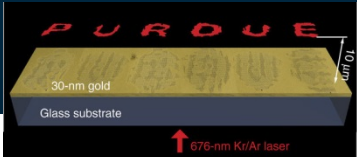
Z = 0 µm

Z = 7 µm

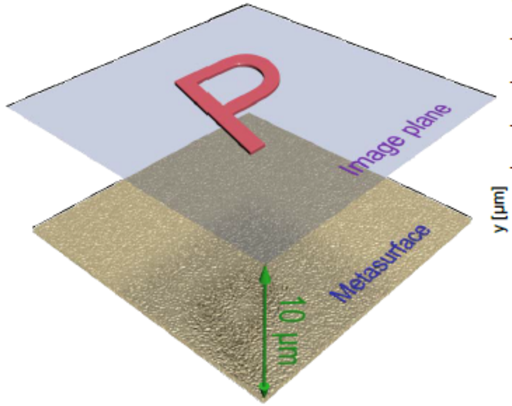
Z = 10 µm

wavelength 676 nm

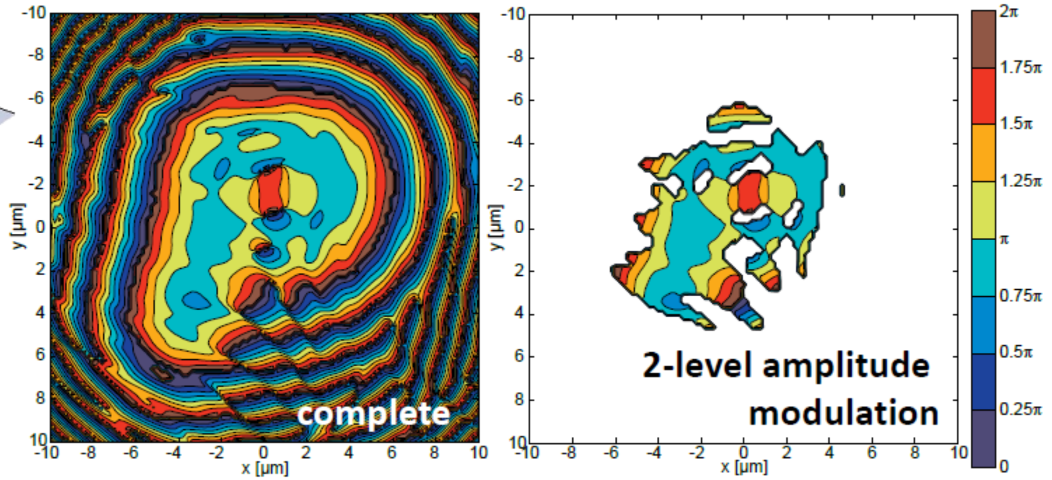
Metasurface Holograms for Visible Light



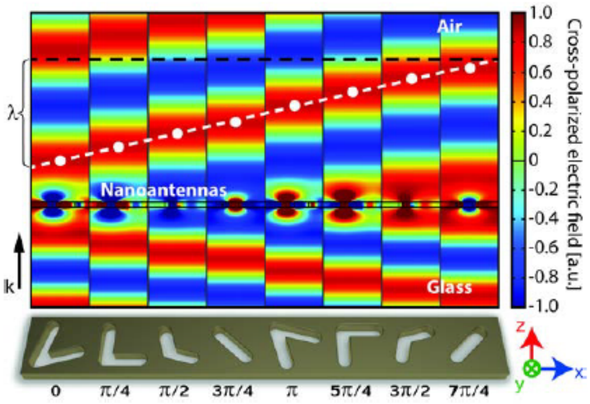
Ni et al, *Nat Comm 4, 2807* (2013)

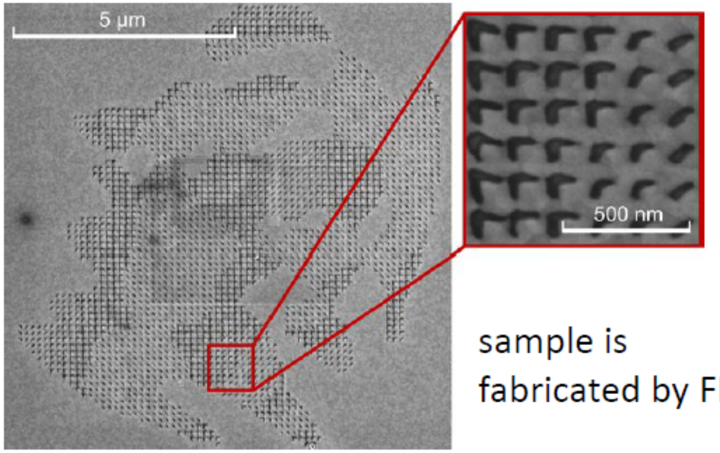


8-leveal phase modulation



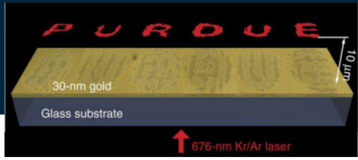
phase shifts by the antennas



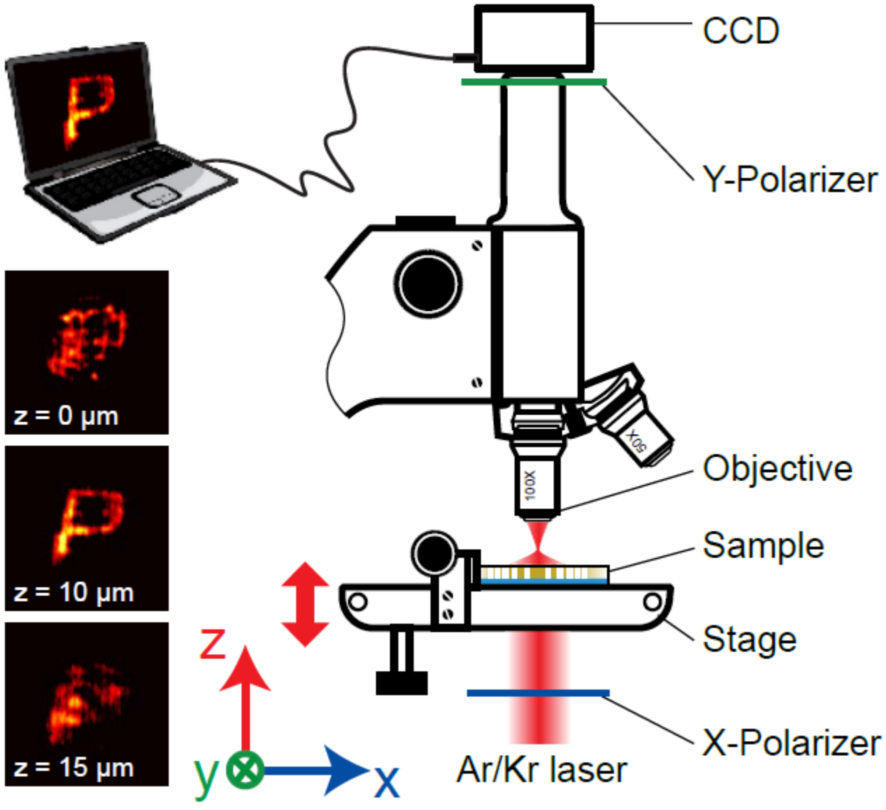


sample is fabricated by FIB

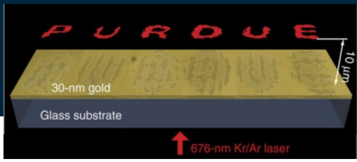
Metasurface Holograms for Visible Light: Experiment

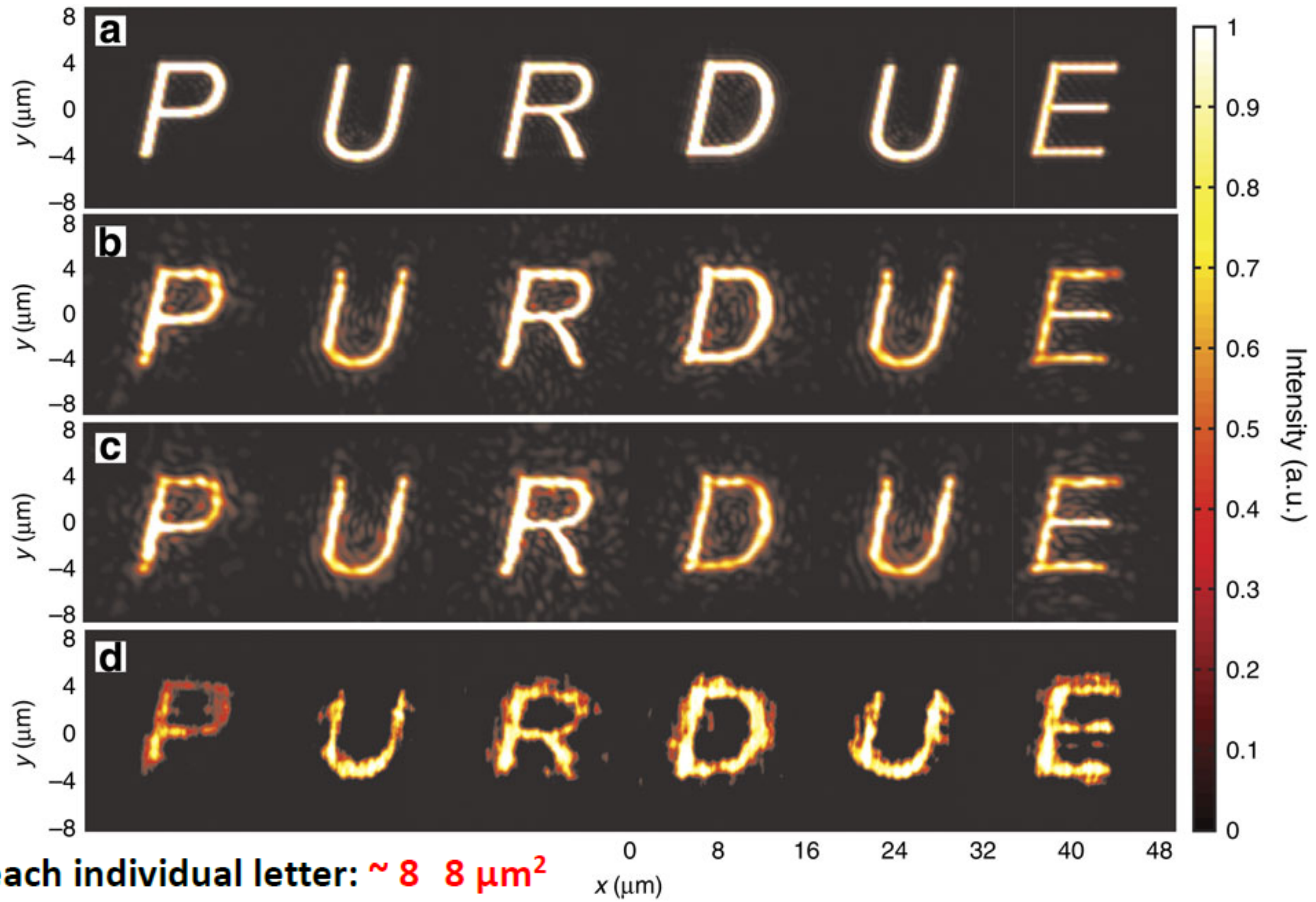


- Intensity profile at different distance is obtained by scanning sample stage vertically

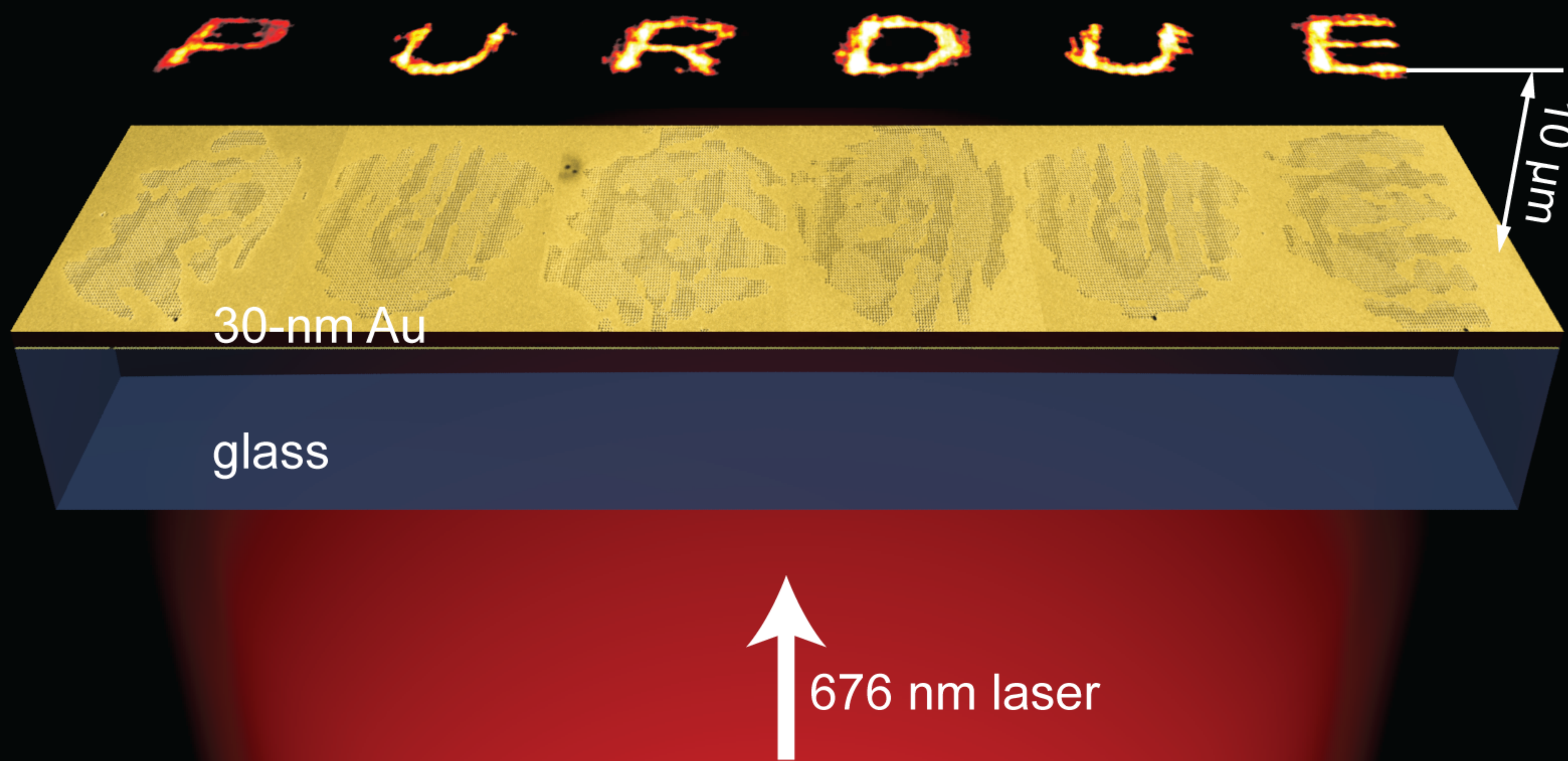


Metasurface Holograms for Visible Light: Experiment



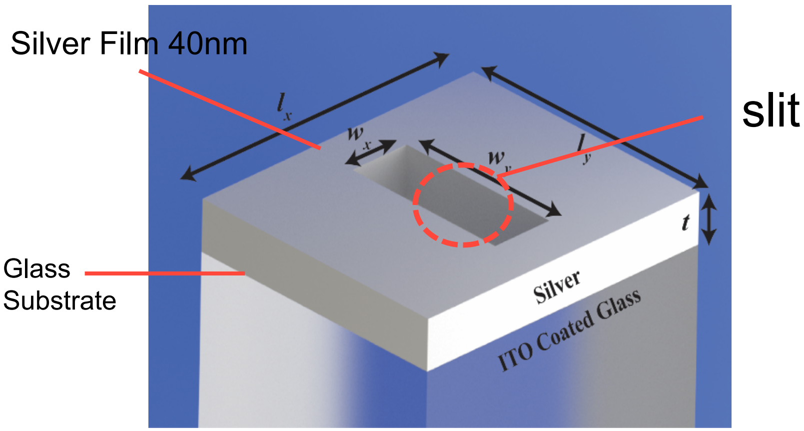


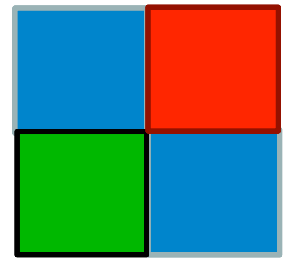
size of each individual letter: ~ 8 8 μm^2
size of patch for each letter: 12 12 μm^2
the width of the stokes: ~ 1 μm

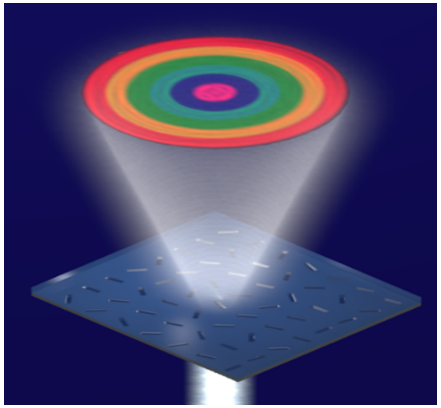


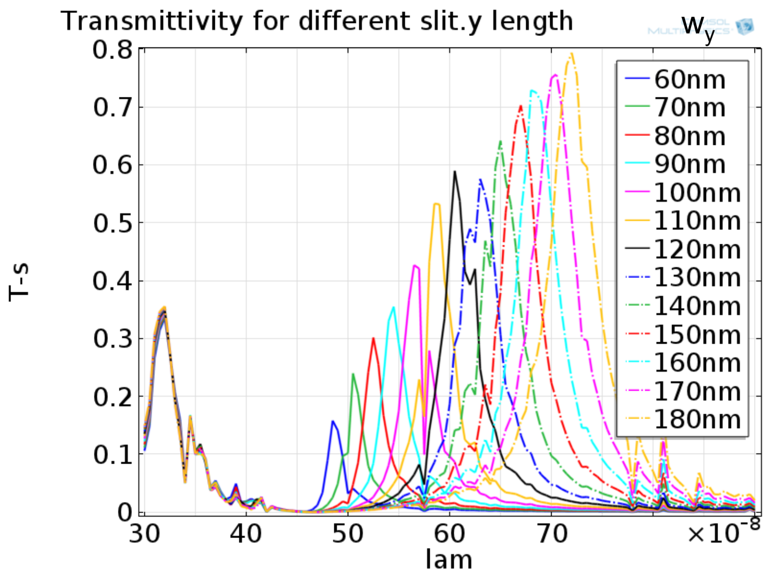
PURDUE
10 μm
30-nm Au
glass
676 nm laser

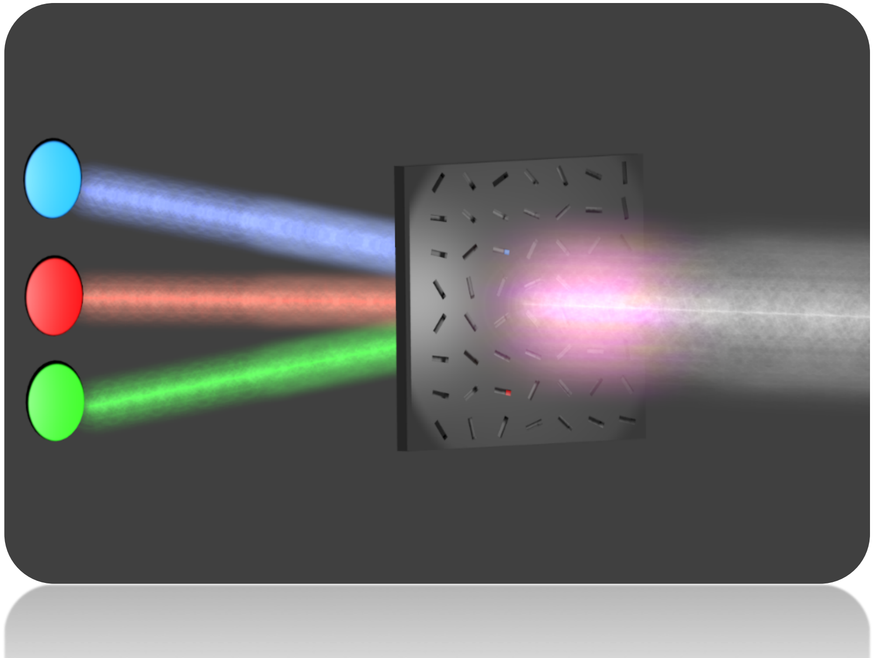
Color Phase Hologram







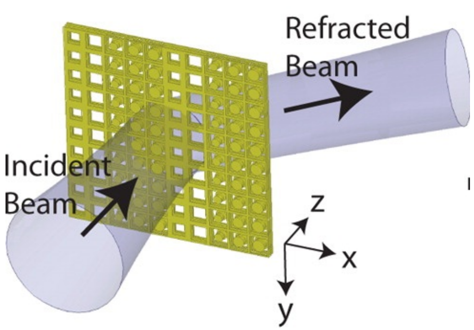




Increasing Efficiency of Metasurfaces

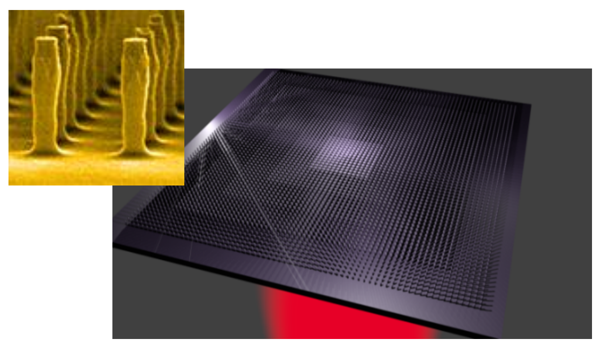
- Efficiency of previous phase-gradient metasurfaces <10%
- Unlike bulky MM's, the primary issue is not metallic loss. More power is wasted in unwanted modes (like 0^{th} order mode, or power splitting between reflection and transmission)
- Approaches to overcome this issue include:

<u>Huygens' surfaces</u>



Pfeiffer et. al., *Nano Lett.*, *14* (5), (2014) (Grbic& Shalaev groups)

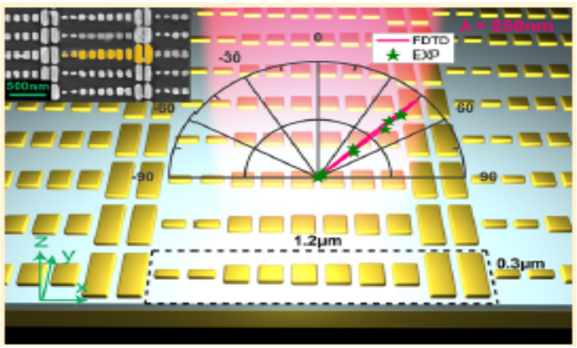
<u>Dielectric Metasurface</u>



West et. al., *Opt Express.*, *21*, 26212 (2014) (Shalaev group & Raytheon)

See also: Decker et al, Adv. Opt. Mat.3, 813 (2015) (Kivshar group)

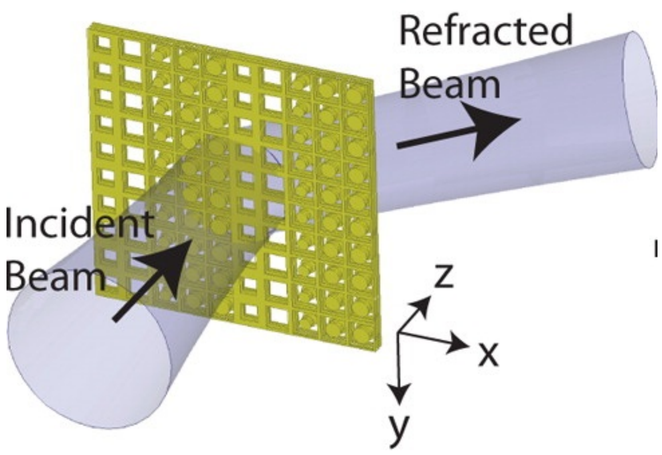
<u>Gap-plasmonic Metasurface</u>

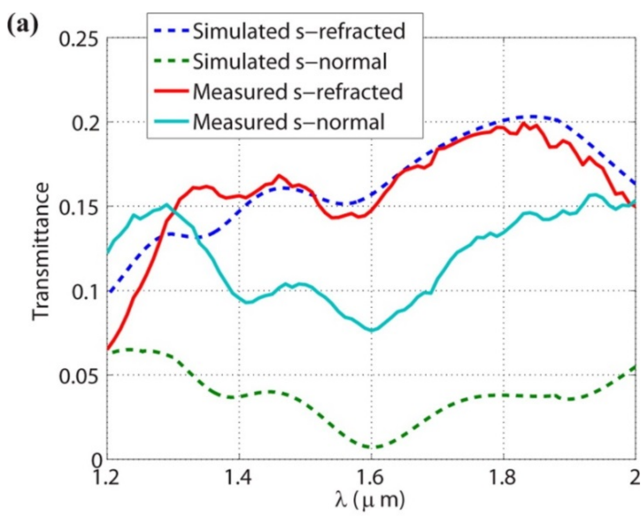


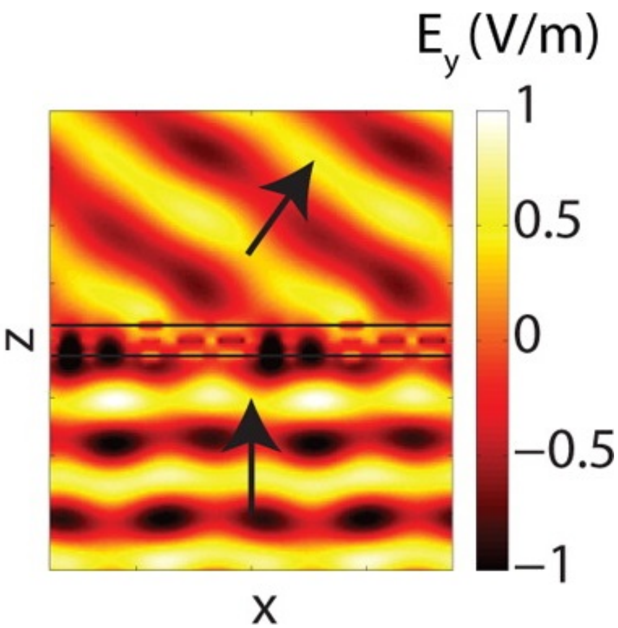
Sun et. al., *Nano Lett.*, *12*, 6223 (2012) (Tsai group)

See also: Pors et. al., *Sci Reports 3.*, 2155 (2013) (Bozhevolnyi group)

Metamaterial Huygens' Surfaces





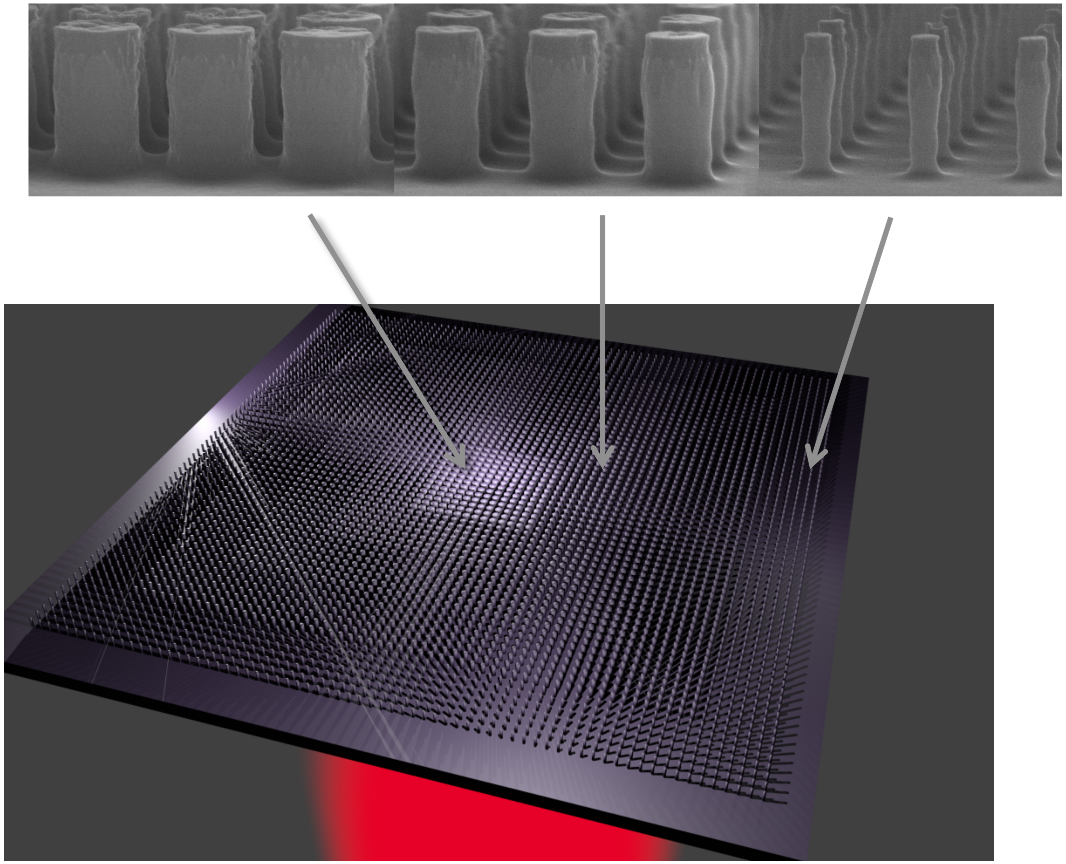


- Efficient beam bending by control of both electric and magnetic polarizations
- 20% of s-polarized light and 18% of p-polarized light is refracted into anamalous direction

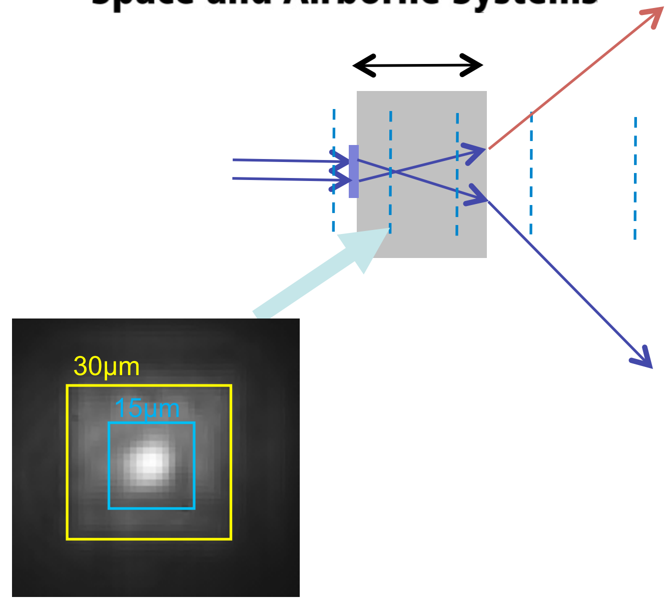
Pfeiffer et. al., *Nano Lett.*, *14* (5), (2014)
(Grbic& Shalaev groups)

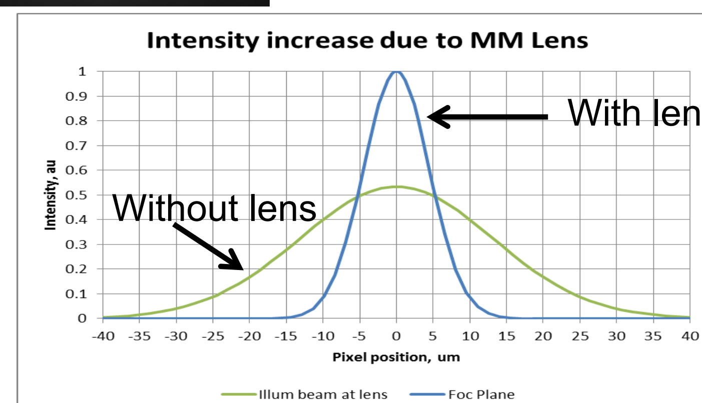
Planar Dielectric Focusing Lens

West et. al., *Opt Express.*, *21*, 26212 (2014)
(Shalaev group & Raytheorn)



Raytheon
Space and Airborne Systems

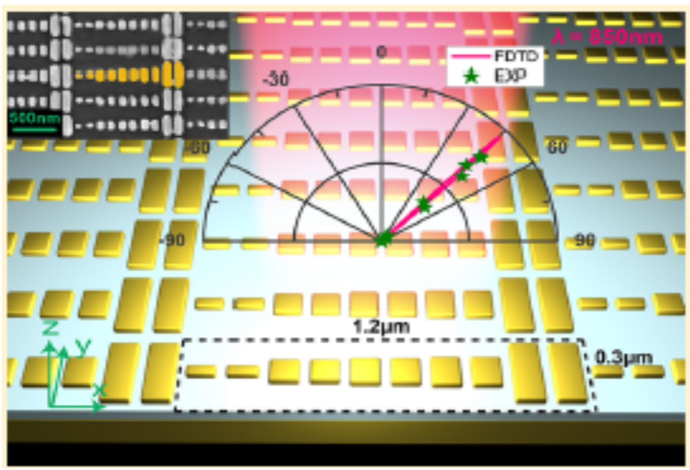




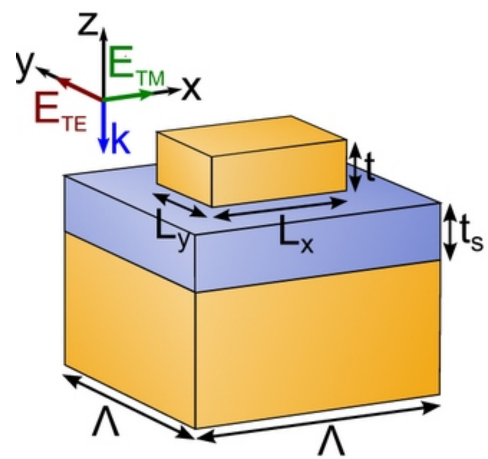
See also: Decker et al, Adv. Opt. Mat.3, 813 (2015)
(Kivshar group)

Gap-plasmon Metasurface

- Slow gap-plasmonic waves are excited inside the dielectric spacer between two metals. Their propagation delay along the antenna length is enough to make 2π phase-shift.
- Efficiency is up to 80%. Most compact structure for same efficiency.

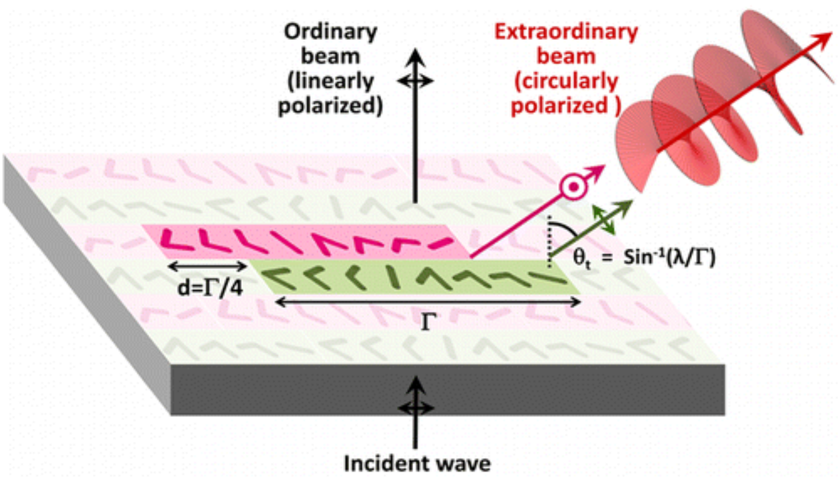


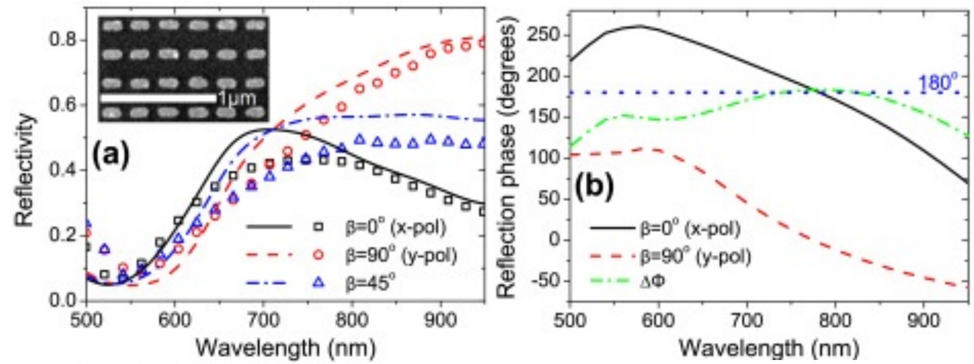
Sun et. al., *Nano Lett.*, *12*, 6223 (2012) (Tsai group)



Pors et. al., *Sci Reports 3.*, 2155 (2013) (Bozhevolnyi group)
See other applications of gap-plasomincs done at Bozhevolnyi group

Polarization Gradient Metasurfaces: ½ and ¼ Wave-Plates



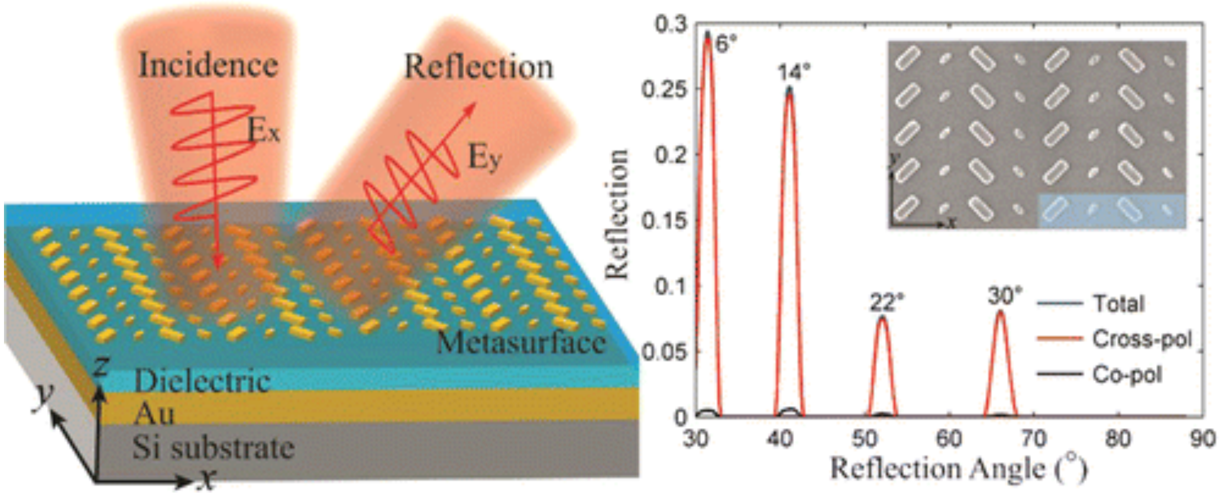


<u>¼ Wave-Plate operating in anomalous mode</u>
N. Yu, et al, NL 12, 6328 (2012) (Capasso's group):
- background-free (unwanted background is in 0th order mode)
- Efficiency ~ 10%

<u>½ Wave-Plate operating in normal mode (Gap-plasmonic)</u>
A.Pors, et al, OL 38, 513 (2013) (Bozhevolyi group):
- Efficiency ~ 50%
- Have some unwanted background

See also for polarization metasurfaces:
Pors and Bozhevolnyi, OE 21, 3, 2942 (2013)
Jiang et al, Phys Rev X 4, 021026 (2014) (Wang group)

Polarization Gradient Metasurfaces: ½ and ¼ Wave-Plates



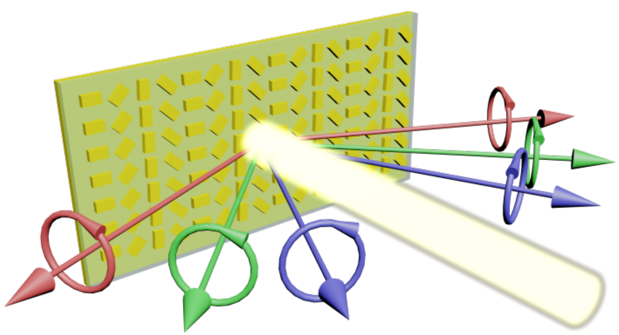
<u>½ Wave-Plate operating in anomalous mode with Gap-plasmonic antennas:</u>

Ding et al, ACS Nano 9, 4111 (2015) (Shalaev group):

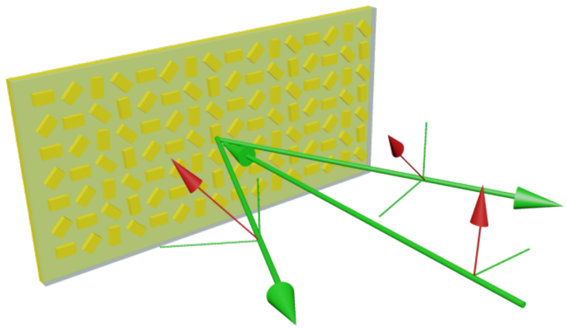
- background-free
- Efficiency ~ 30%

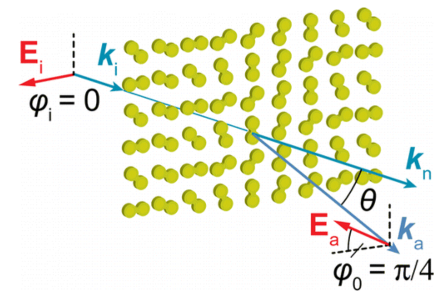
Photonic Spin Hall Effect

Circular Dichroism Spectrometer



Optical Rotation



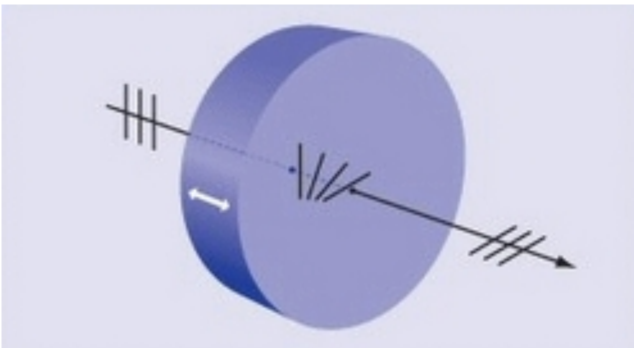


- Shaltout et al,*"Photonic Spin Hall Effect in Gap-Plasmon Metasurfaces for On-Chip Chiroptical Spectroscopy*" submitted (Shalaev Group)
- Shaltout et al, *Nano Lett 14*, 8, 4426 (2014) (Shalaev Group)

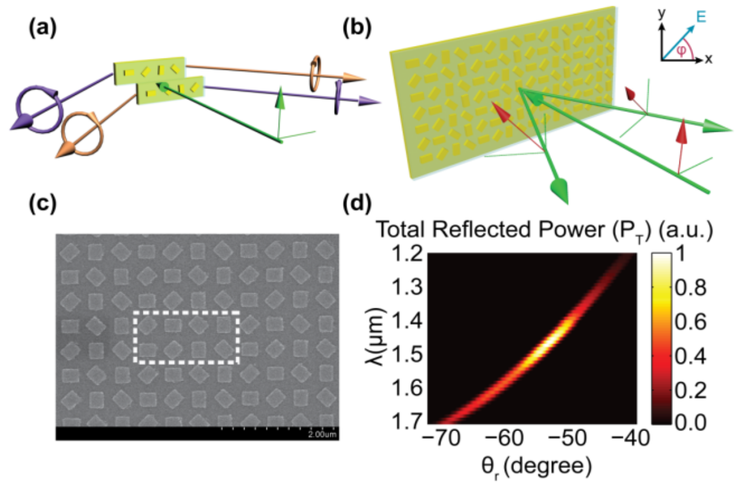
See also:

- Yin et al, Science 339, 6216 (2013) (X. Zhang group)
- Shitrit et al, *Nano Lett 11*, 2038 (2011) (Hasman group)
- Li et al, OE 23, 6, 7227 (2015) (Yang Hao group)
- Luo et al, "Photonic Spin Hall Effect with Nearly 100% efficiency", adv. optical mater. (2015) (Zhou group)

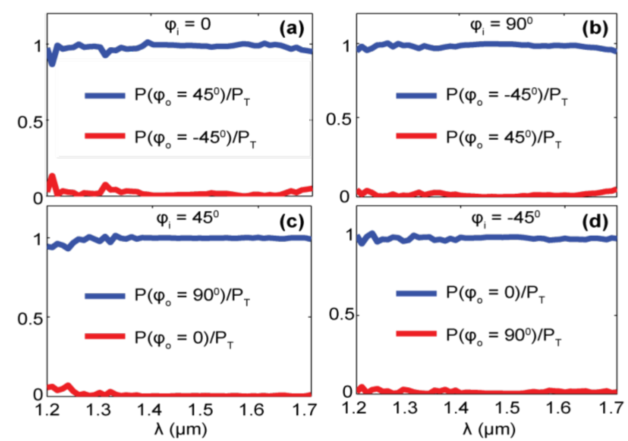
Optical Rotation



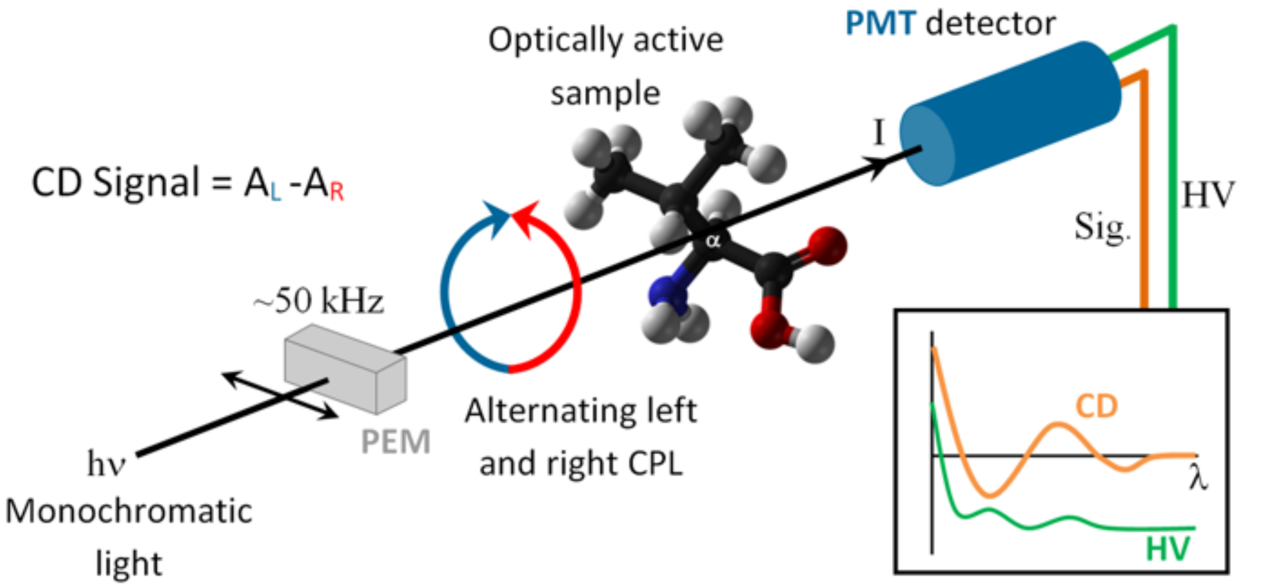
$$\mathbf{E} = E_0\left(\hat{\mathbf{x}}\cos\varphi + \hat{\mathbf{y}}\sin\varphi\right) = \frac{E_0}{\sqrt{2}}\left(\hat{\mathbf{r}}e^{-i\varphi} + \hat{\mathbf{l}}e^{i\varphi}\right)$$



- Requires phase delay between LCP and RCP
- Metasurface is designed to split LCP and RCP and induce optical path delay
- Reflected beam is rotated by 45^0 as indicated by results at required and perpendicular polarizations



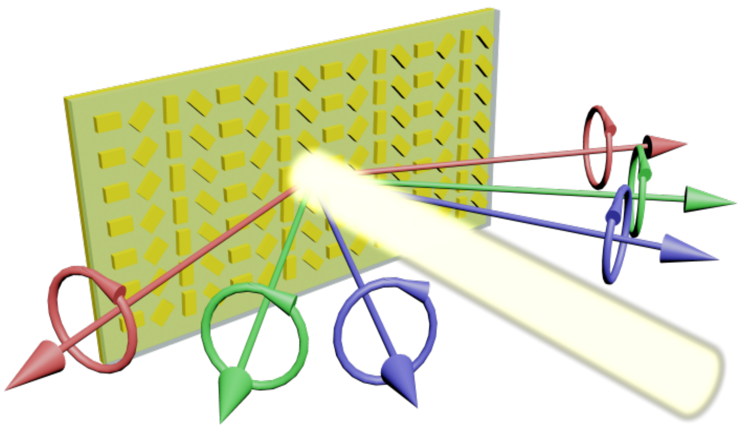
Circular Dichroism (CD) Spectrometer

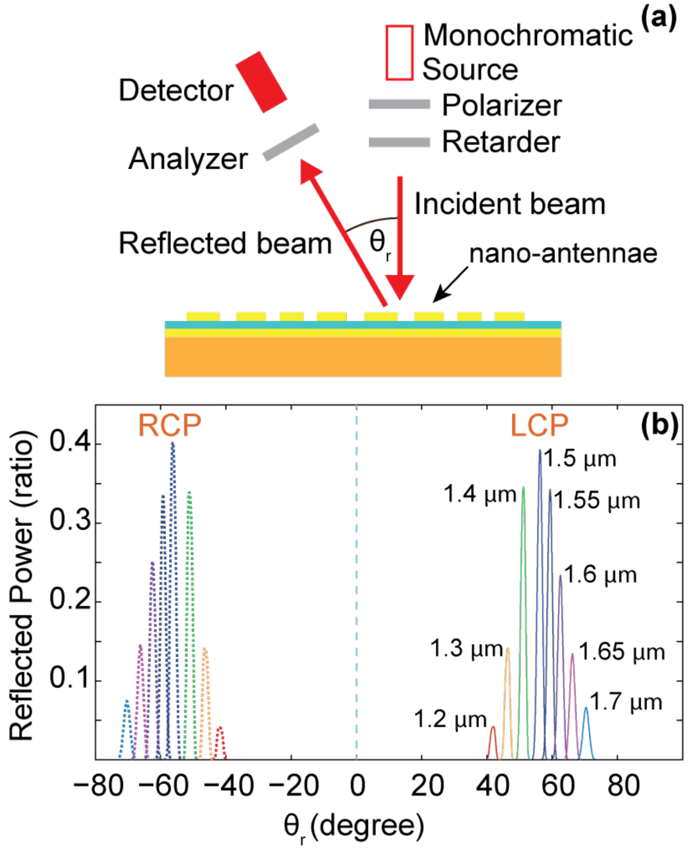


http://www.isa.au.dk/facilities/astrid2/beamlines/AU-cd/AU-CD_3.asp

- Used in bio-sensing
- Measures differential absorption of LCP and RCP
- Requires modulation of source & sequential data acquisition
- Large size and complex hardware

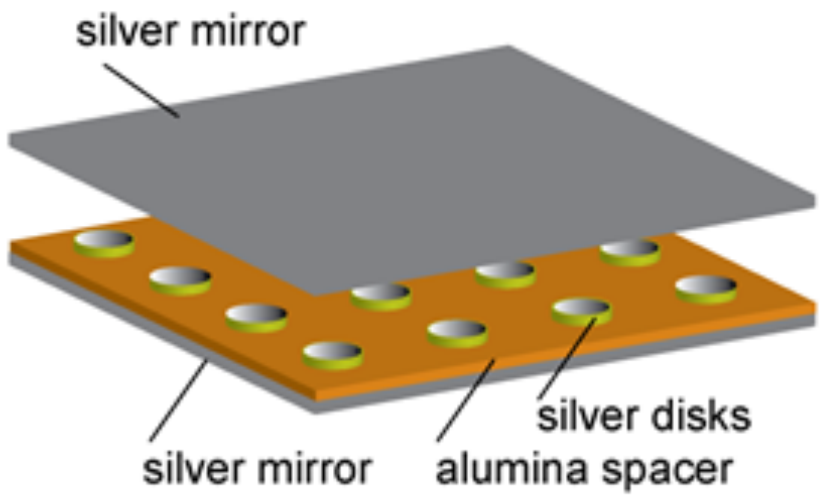
Compact & Real-Time CD Spectrometer Metasurface

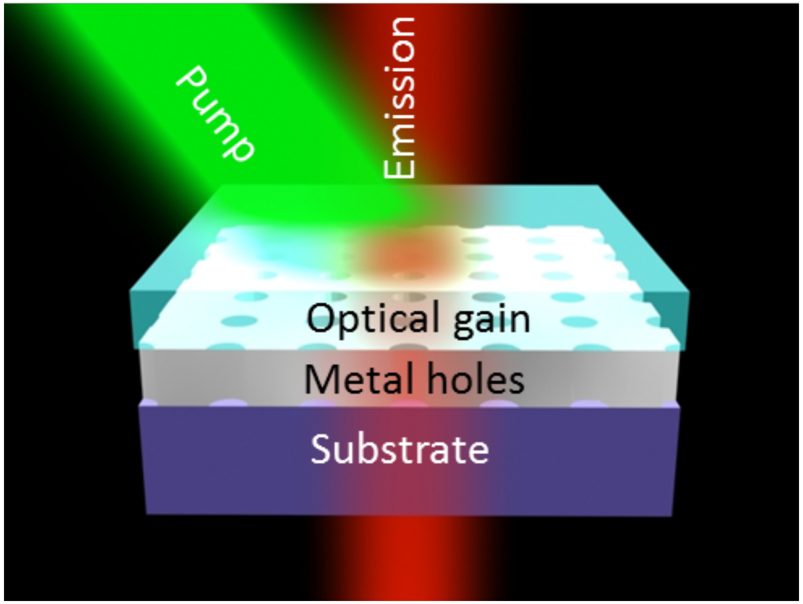




- Real-time (Photonic Spin Hall Effect)
- Efficiency up to 40% (Gap-plasmon)
- Compact (130 nm thickness) (smallest CD spectrometer to our knowledge)
- Simple: No need for switchable laser source

Metasurface Based Nano-Cavities and Nano-Lasers





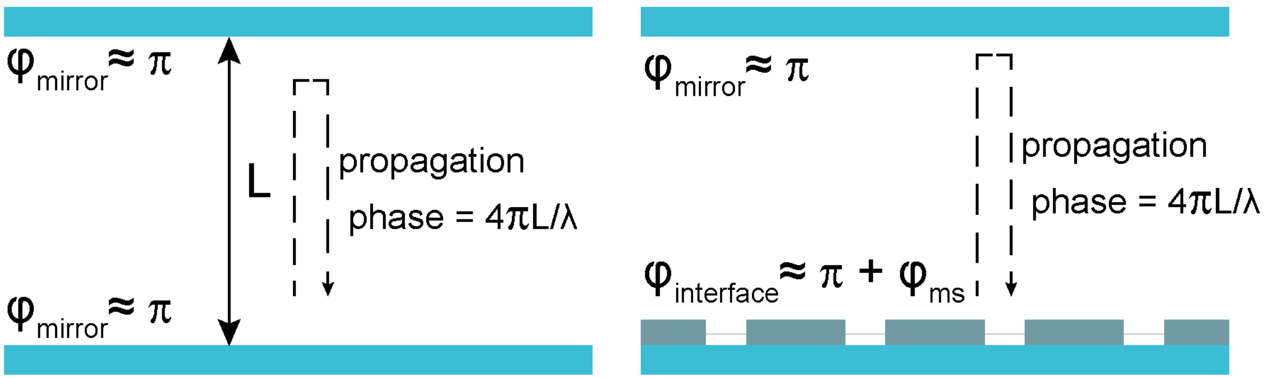
- Shaltout et al, CLEO, JW2A.116 (2014) (Shalaev Group)
- Shaltout et al, CLEO, JTu5A.100 (2015) (Shalaev Group)

Meng et al, LPR 8, 896 (2014) (Shalaev group)

Metasurface Based Nano-cavity

Motivation:
- Overcome diffraction limit
- Enhance DOS (Purcell Effect)
- Nano-lasers, thresholdless lasing

Shaltout et al, CLEO, JW2A.116 (2014)



Resonant Condition:

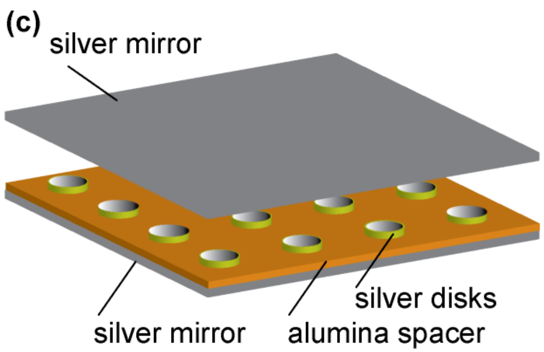
$4\pi L/\lambda = 2m\pi$

Resonant Condition:

$4\pi L/\lambda + \varphi_{ms} = 2m\pi$

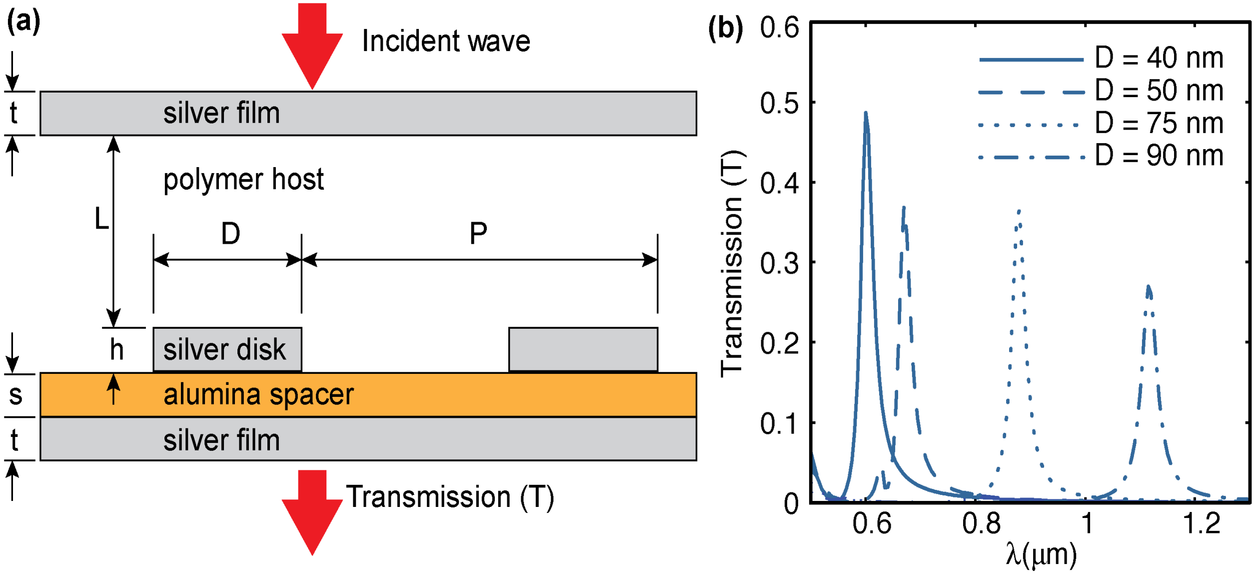
Compact Cavity

Shaltout et al, CLEO, JW2A.116 (2014)



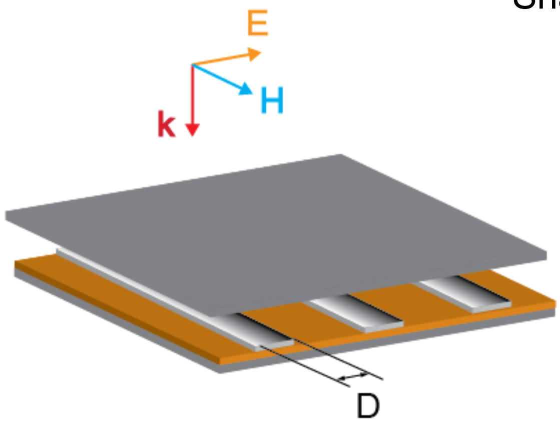
- Gap-plasmonic wave excitation
- *100nm* cavity support resonance at λ=0.6–1.1μm

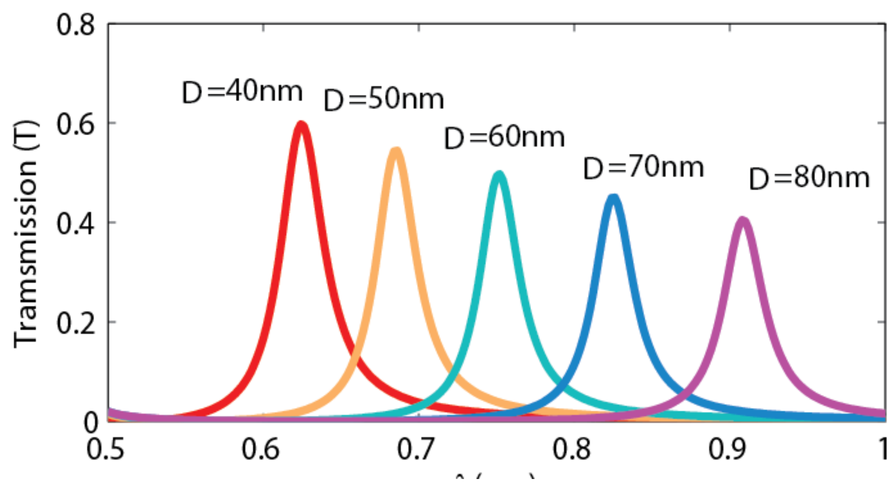
P = 100 nm, *h* = 20 nm, *L* = 60 nm, *s* = 20 nm, and *t* = 25 nm

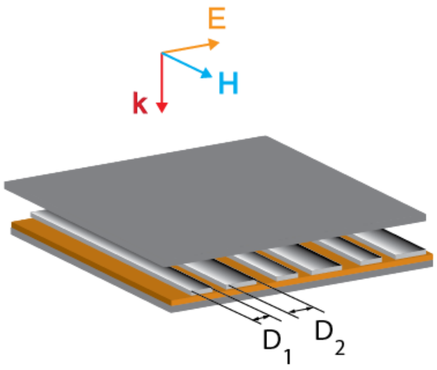


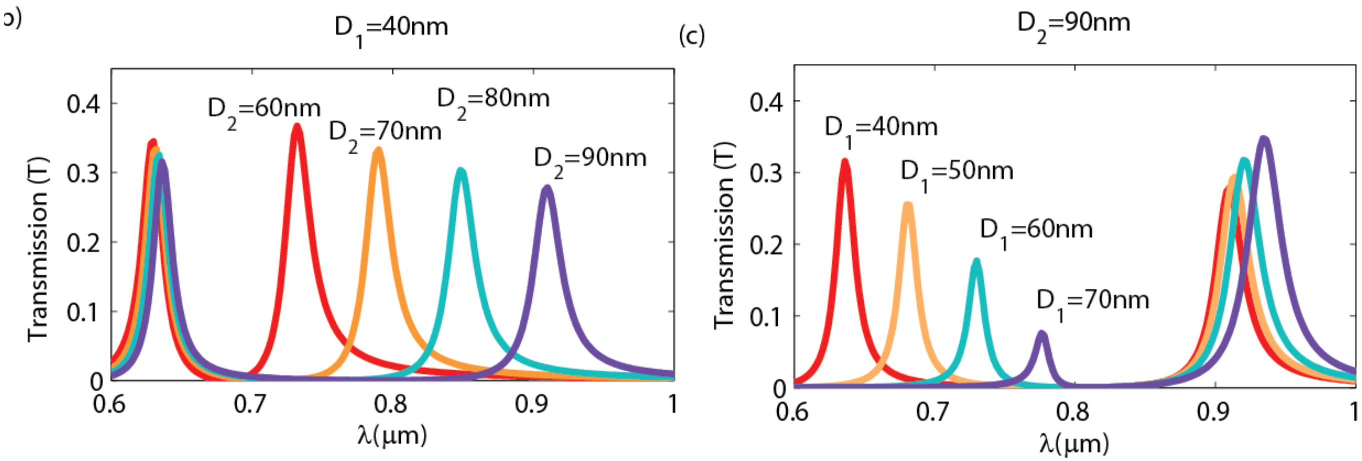
Anisotropic & Multi-band Cavities

Shaltout et al, CLEO, JTu5A.100 (2015) (Shalaev Group)



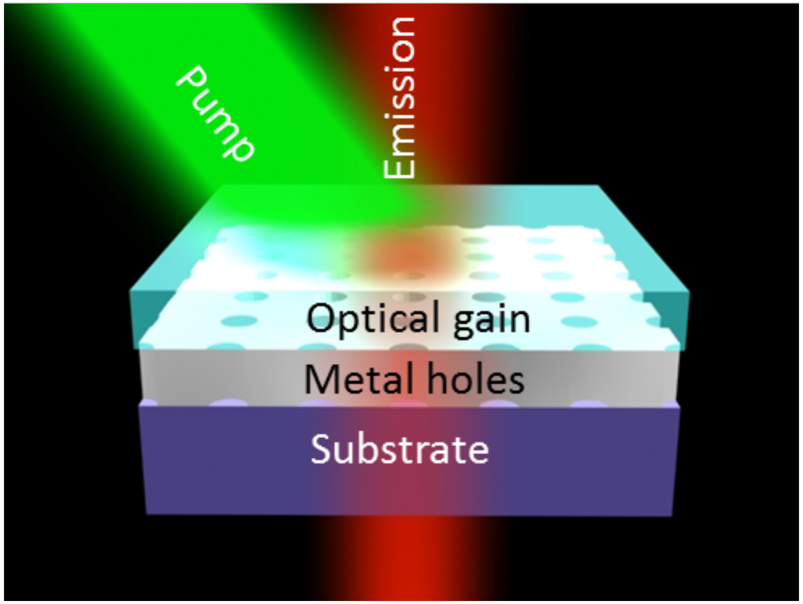


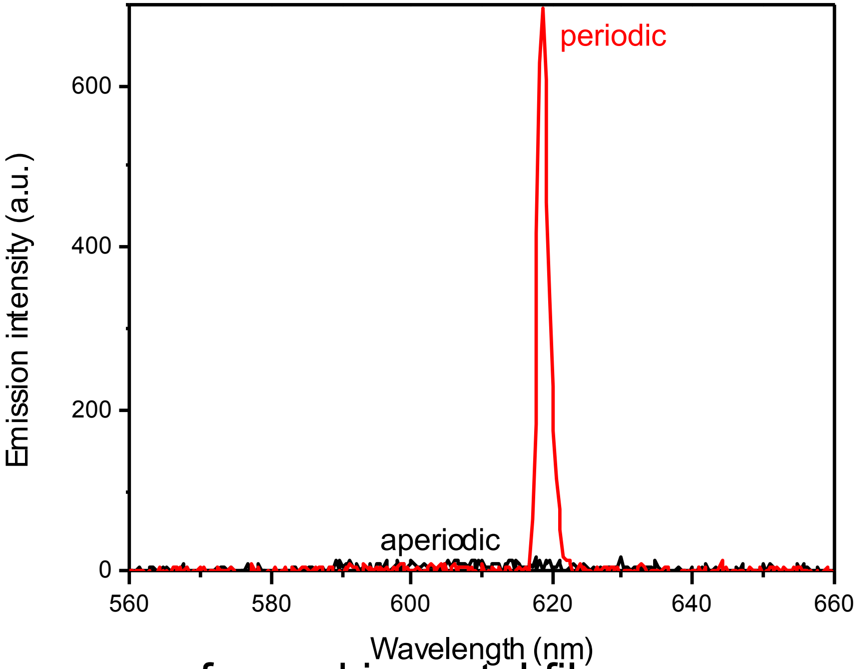




Nano-hole Array Lasing

- **Room-temperature, directional, single-mode plasmonic lasing in the visible**

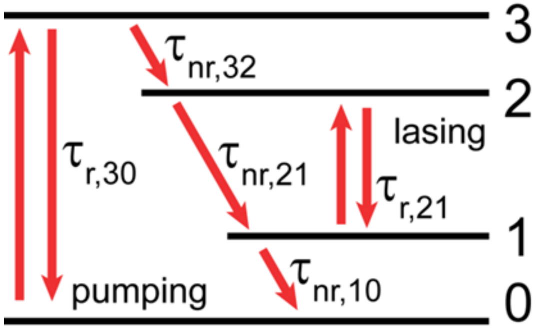




- Optical resonant cavity: periodic hole arrays performed in metal film
- Gain medium: organic laser dye
- SPP-Bloch wave formed on metal-dielectric interface provides intense optical feedback for SPP amplification and enables low-threshold lasing at room-temperature with high directionality

Meng et al, LPR 8, 896 (2014) (Shalaev group)

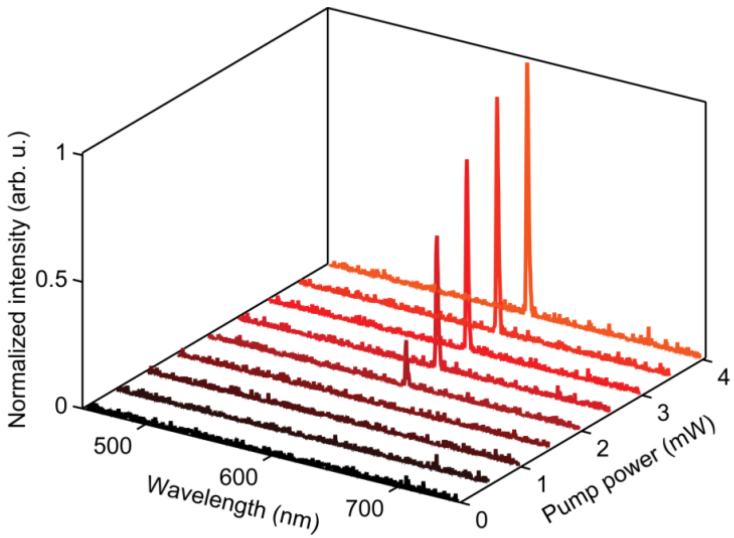
Nano-hole array lasing: simulation



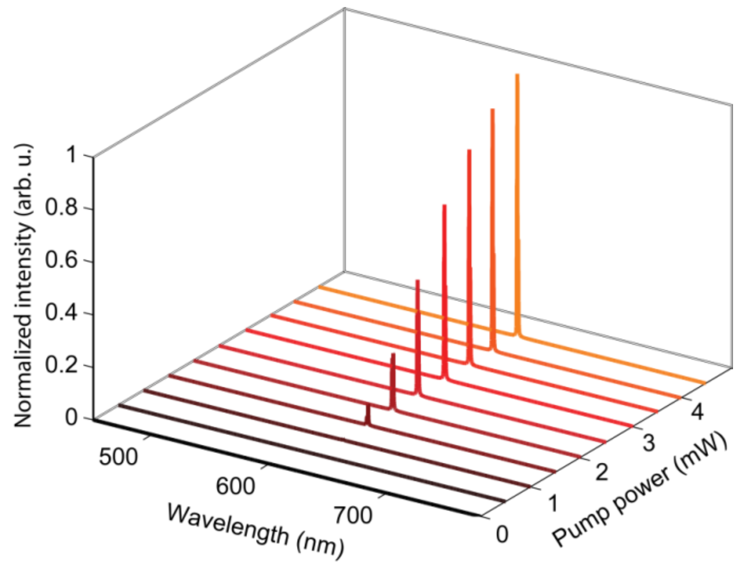
Rhodamine 101

Wavelength [nm]		Beam waist [µm]		Durations [fs]	
3-0	2-1	Pump		T_{pulse}	
575	605	239		150	
Thickness [µm]			Population [cm^{-3}]	Dephasing time [fs]	
Epoxy	Ag	Glass	N_{eq}	$T_{2,30}$	$T_{2,21}$
2.05	0.1	1000	6×10^{18}	9	25.5
$\tau_{r,30}$ [ns]	$\tau_{nr,32}$ [ps]	$\tau_{r,21}$ [ns]	$\tau_{nr,21}$ [ns]	$\tau_{nr,10}$ [ps]	τ_{21} [ns]
5	0.3	6	4.37	0.35	3.3

Table I. Simulation parameters

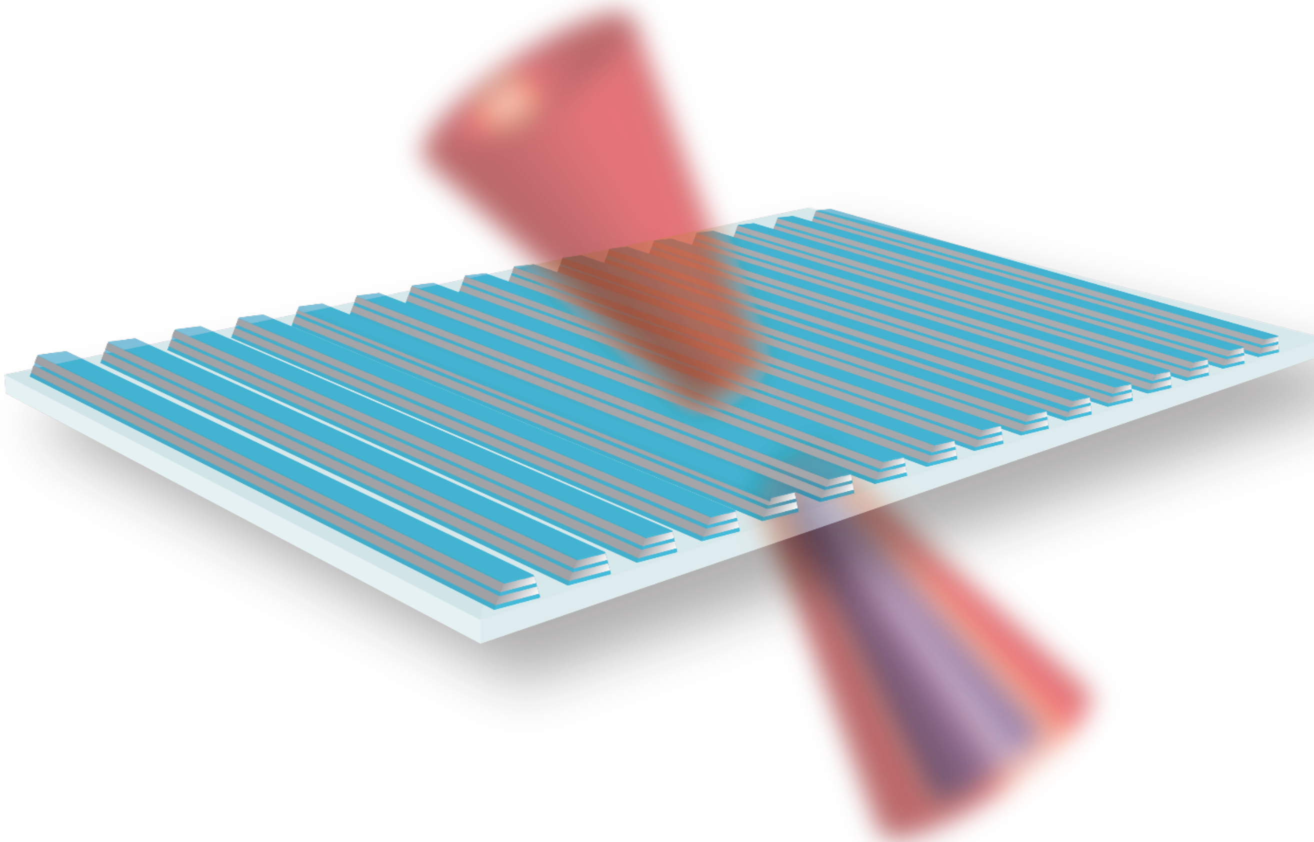


Experiment



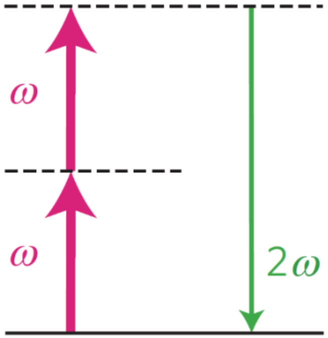
Simulation

Second Harmonic Generation Using Metasurafes



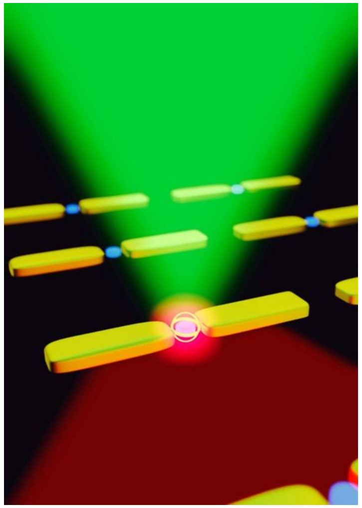
R. Chandrasekar et al. “Second Harmonic Generation by Optical Metasurfaces: Interplay of Electric and Magnetic Resonances”, Submitted (2015)

Second Harmonic Generation using Metasurfaces



Nature Photonics, Vol. 6, Nov 2012, p. 737

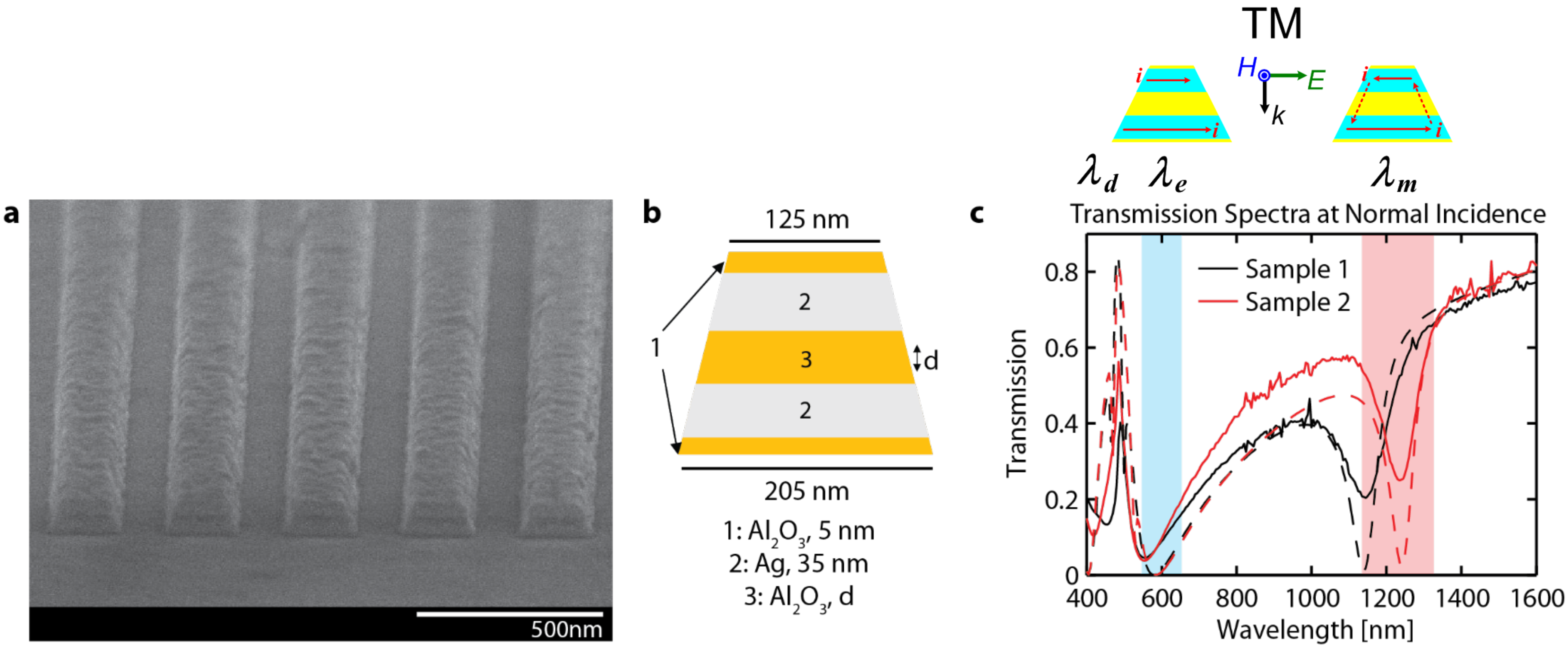
$$P = \epsilon_0[\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ \ldots]$$



Nature Nano, Vol. 9, 290-294 (2014)

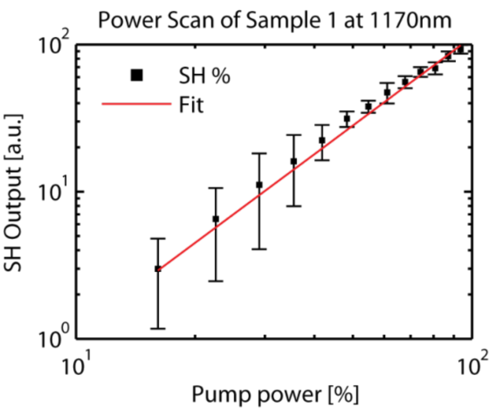
- Can achieve higher field intensities using plasmonic nanoparticles
- Higher intensities in the near field yields larger nonlinear response

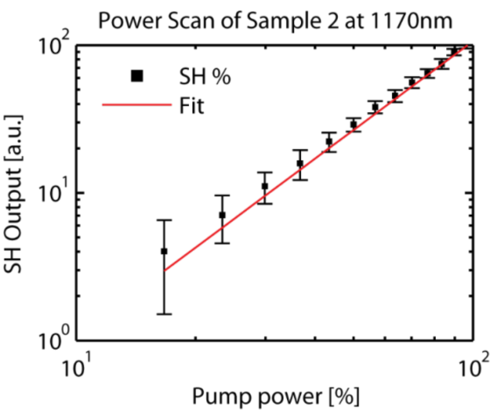
Study of Electric and Magnetic Resonances with SHG

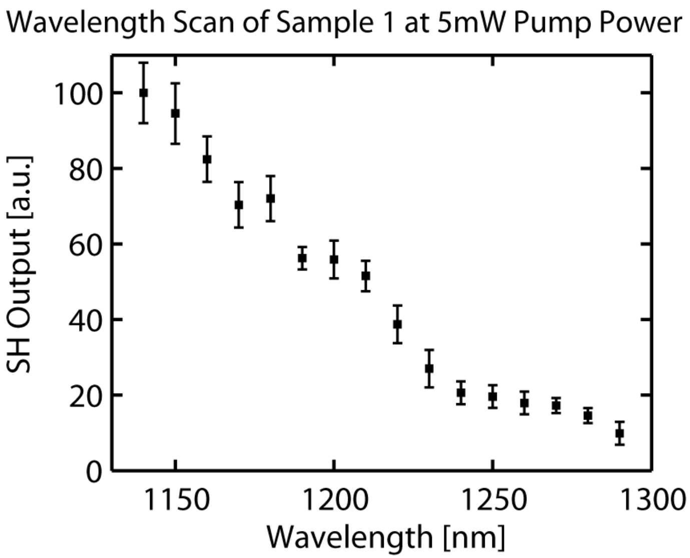


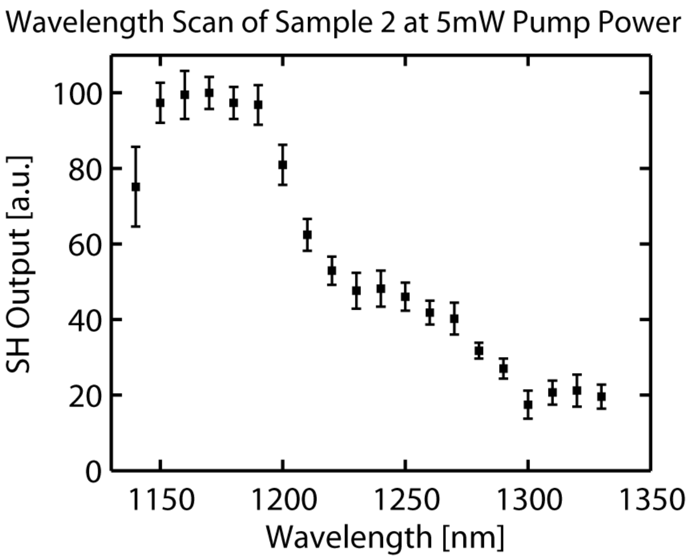
Resonance	Sample 1	Sample 2
Electric Resonance	570nm	570nm
Magnetic Resonance	2*570nm= 1140nm	1240nm

Study of Electric and Magnetic Resonances with SHG

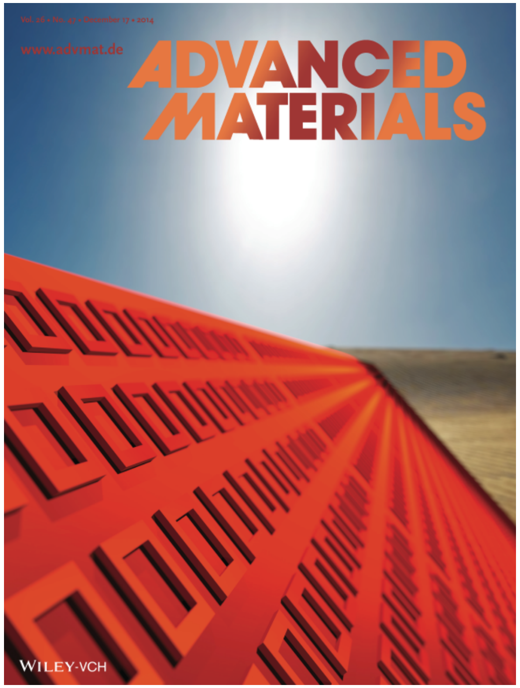




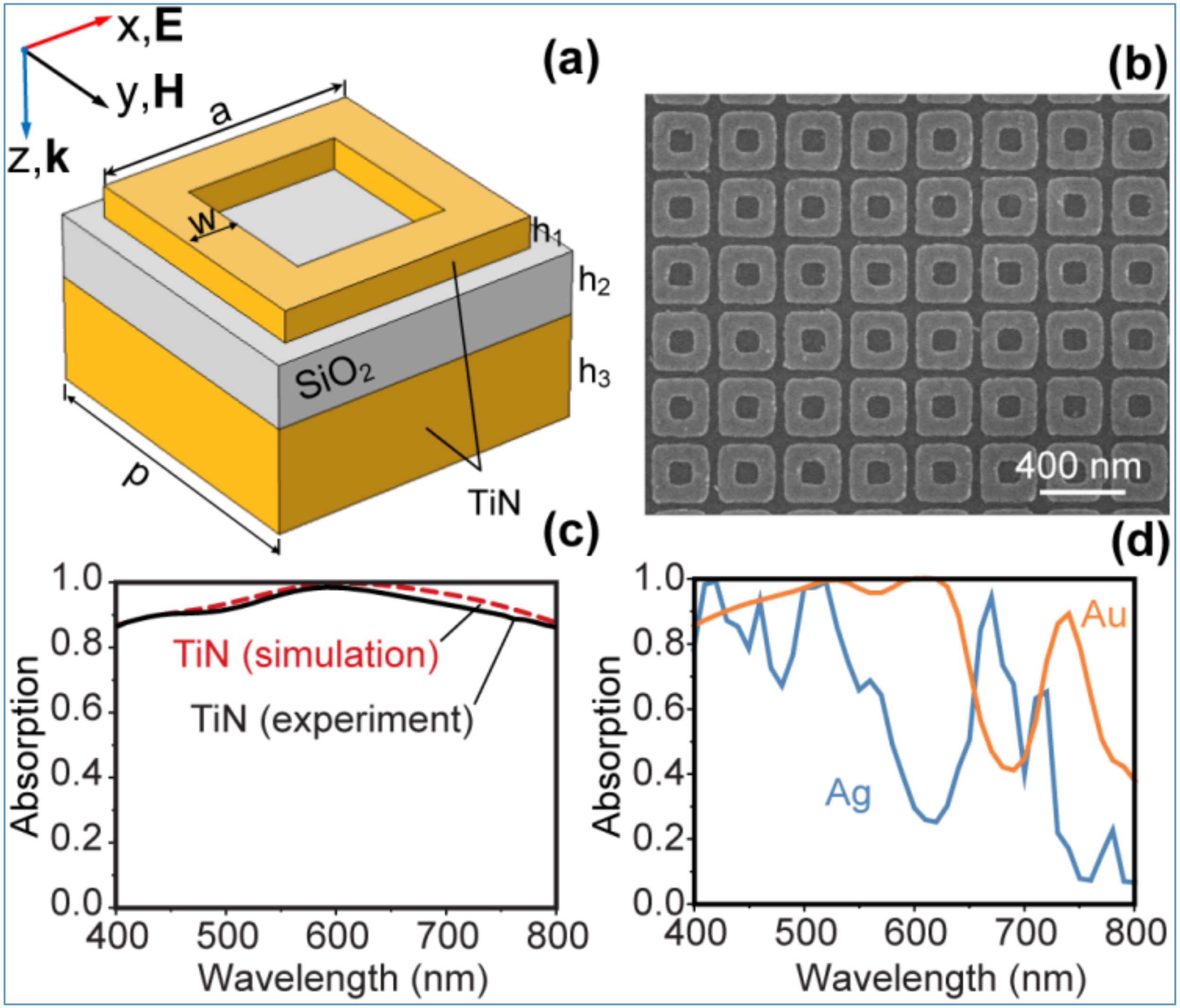




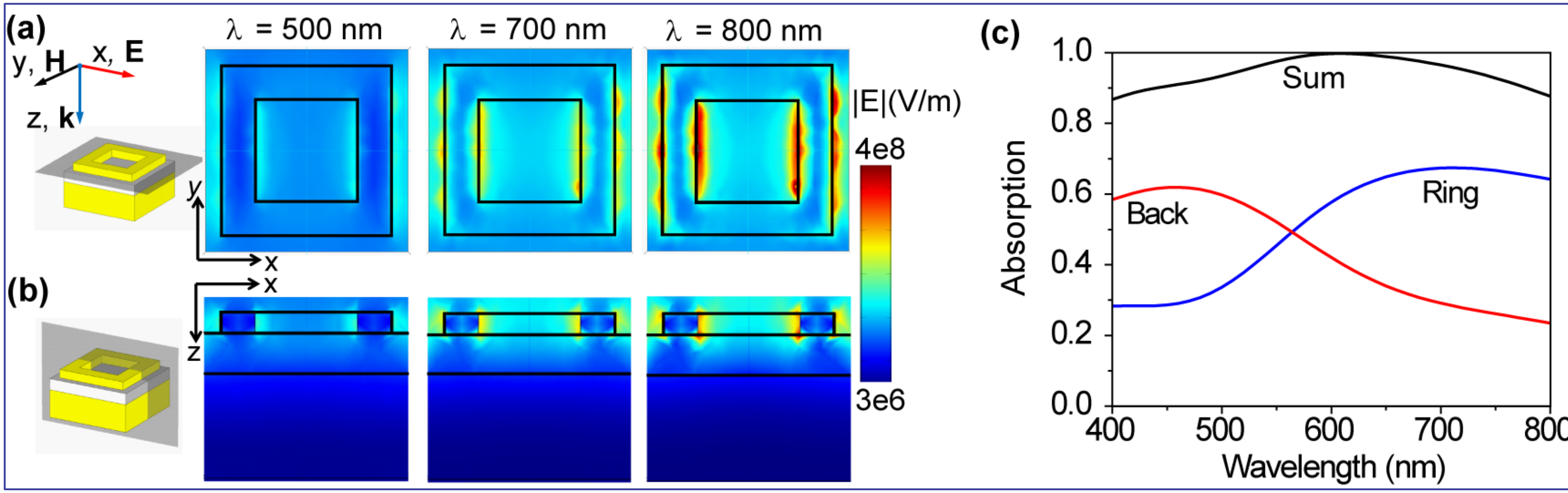
Broadband Metasurface Absorber

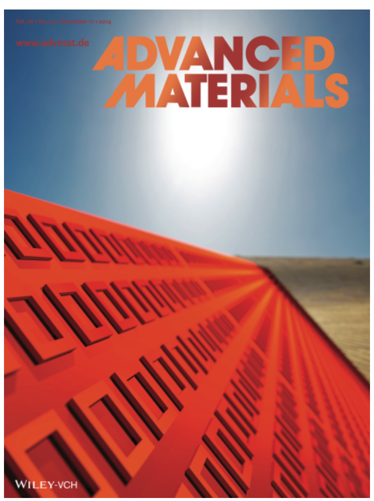


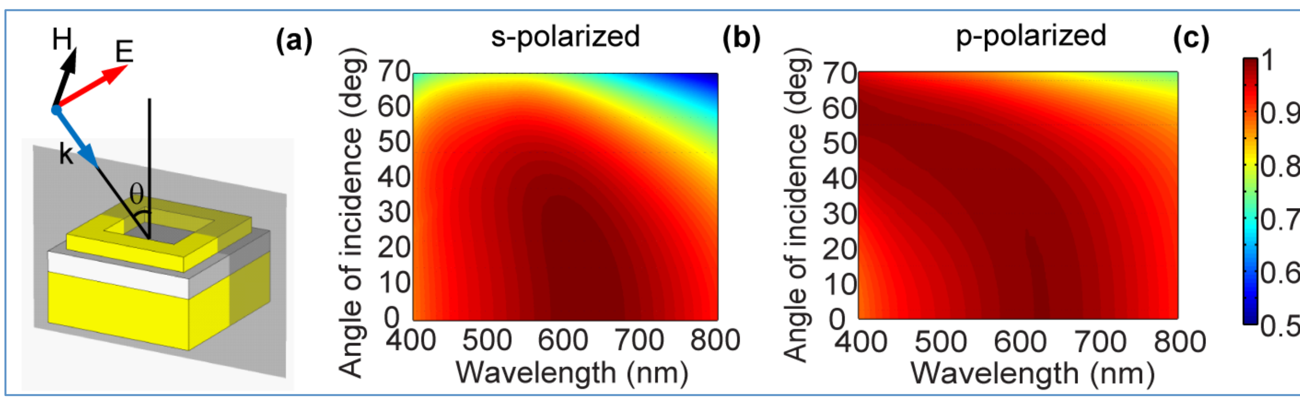
Li et al., Adv. Mater. **26** (2014)



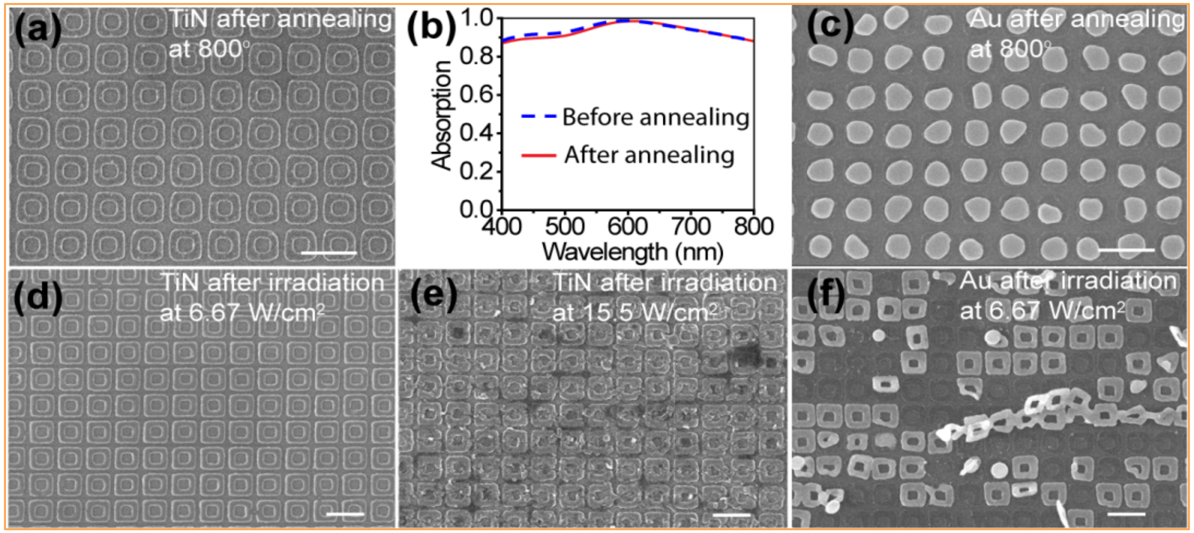
Broadband Metasurface Absorber

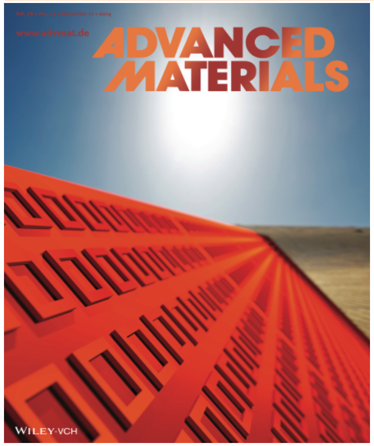




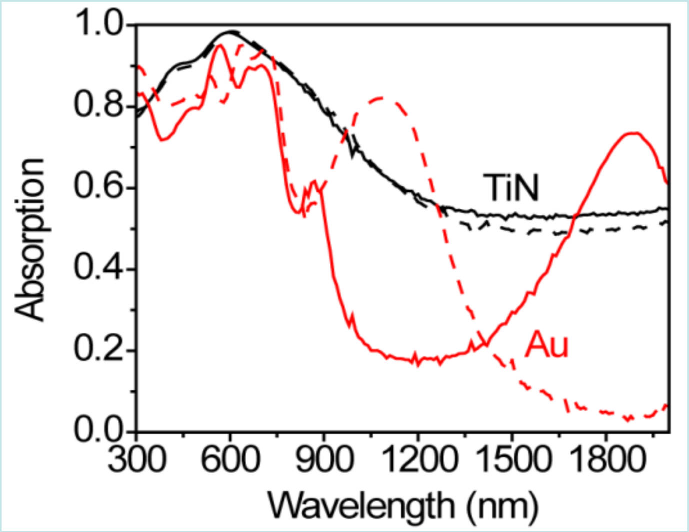


Broadband Metasurface Absorber



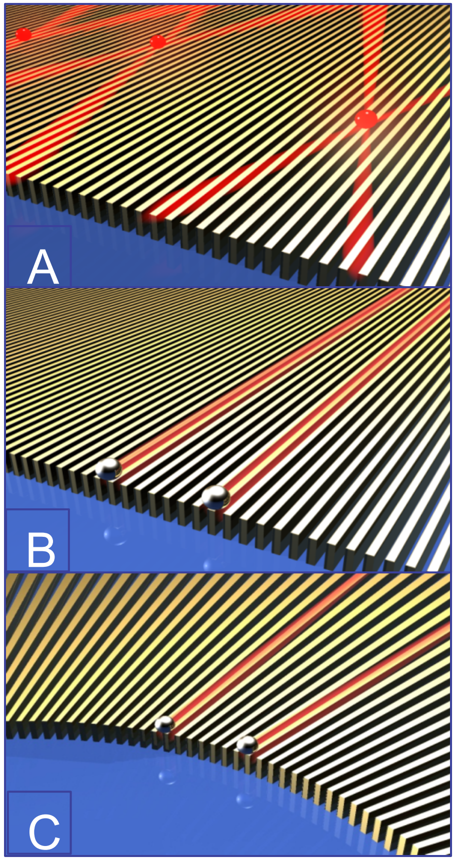


Li et al., Adv. Mater. **26** (2014)



Hyperbolic Metasurface

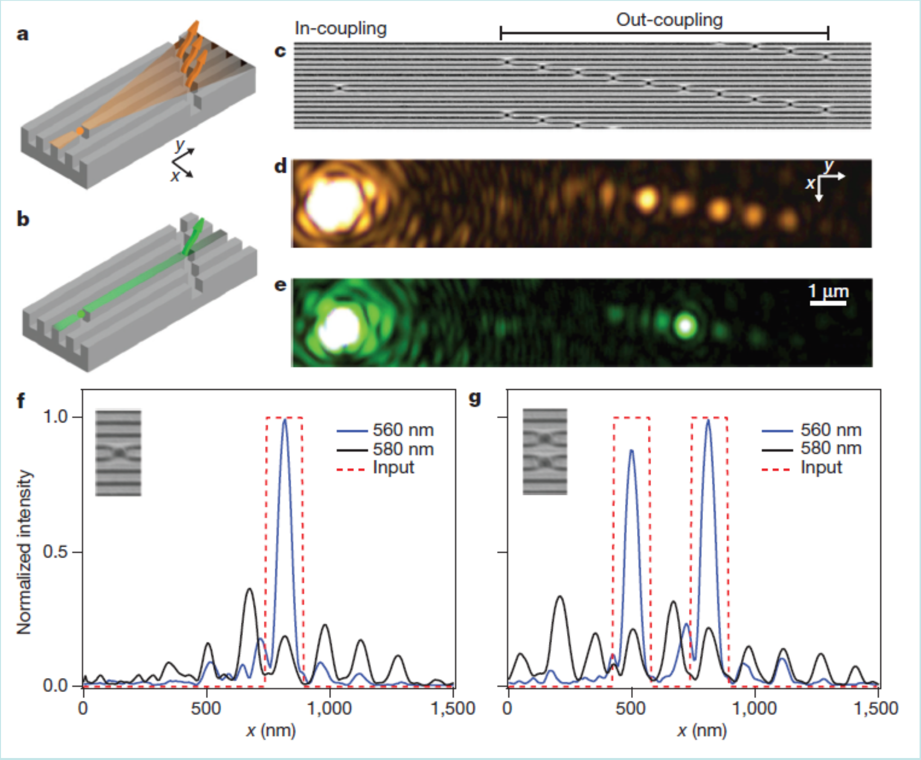
Science AAAS
Planar Photonics with Metasurfaces
Alexander V. Kildishev *et al.*
Science **339**, (2013);
DOI: 10.1126/science.1232009



NATURE | LETTER

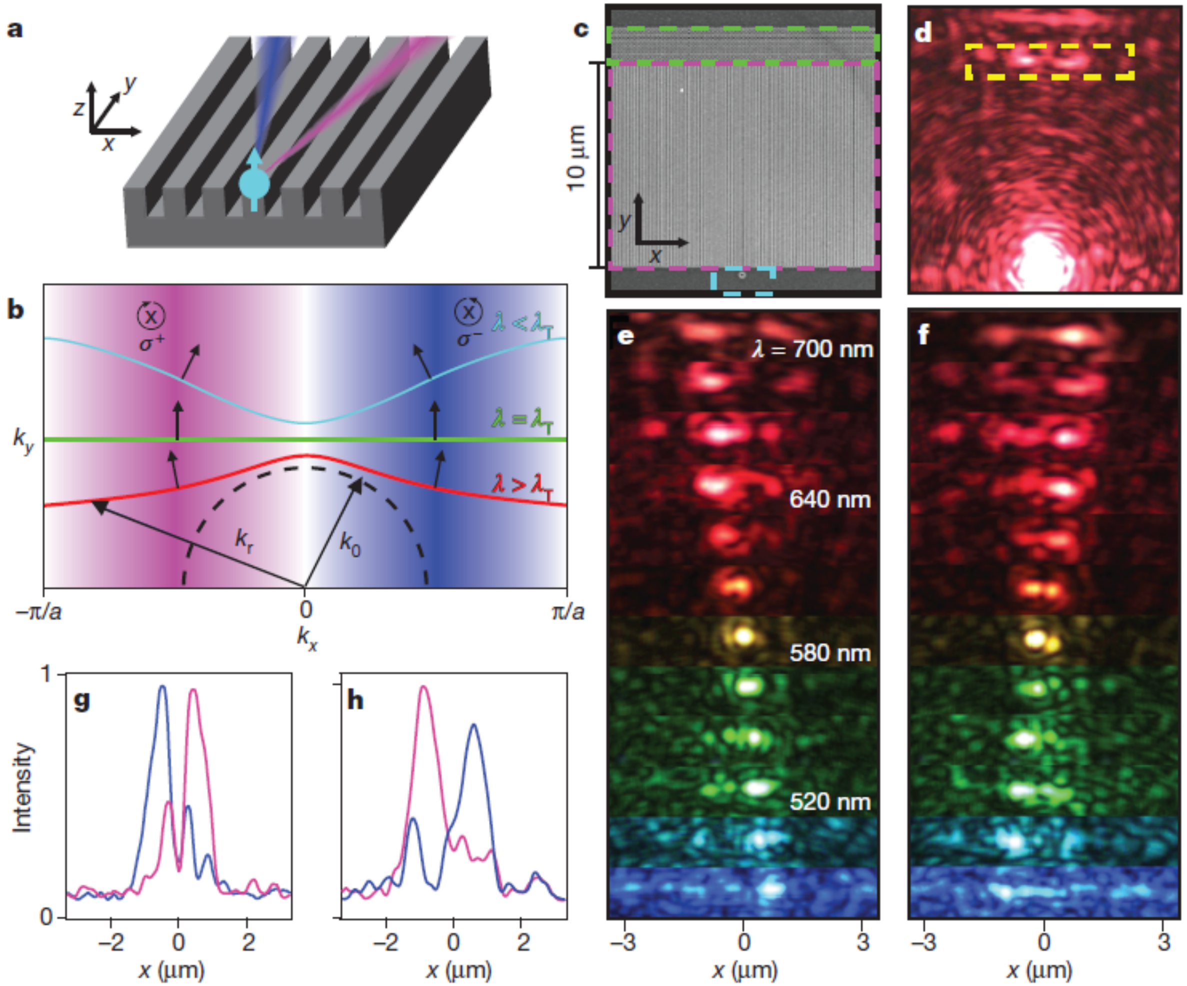
Visible-frequency hyperbolic metasurface

Alexander A. High et al., *Nature* **522**, 192–196 (11 June 2015)
doi:10.1038/nature14477



Hyperbolic Metasurface

Dispersion dependent plasmonic spin-Hall Effect



elliptical

hyperbolic

Outline

- From metamaterials to metasurfaces
- Phase Gradient Metasurfaces: Meta-lens, Meta-hologram, Color-hologram
- Power Efficiency: Huygens' Metasurface, Dielectric Metasurface, Gap-plasmon Metasurface
- Polarization Gradient: ¼ wave plate, ½ wave plate
- Photonic Spin Hall Effect: Circular Dichroism Spectrometer, Optical Rotation
- Metasurface Based Nano-Cavities.
- Active Metasurfaces & Nano-lasers
- Nonlinear Metasurfaces
- Broadband Absorber
- Hyperbolic Metasurfaces
- Time-Varying Metasurfaces