Nanophotonics based on Metasurfaces

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Tutorial
CLEO 2015, San Jose', CA, MAY 13, 2015

N. Yu and F. Capasso ,"Flat Optics with Designer Metasurfaces"
Nature Materials **13**, 139 (2014)
Minovich et al., "Functional and Nonlinear Optical Metasurfaces"
Laser & Photonics Review **9**, 195 (2015)

MURI: Control of Light propagation with Metasurfaces

MURI: Control of Light Propagation with Metasurfaces

http://projects.iq.harvard.edu/muri_metasurfaces/overview

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Lars Samuelson

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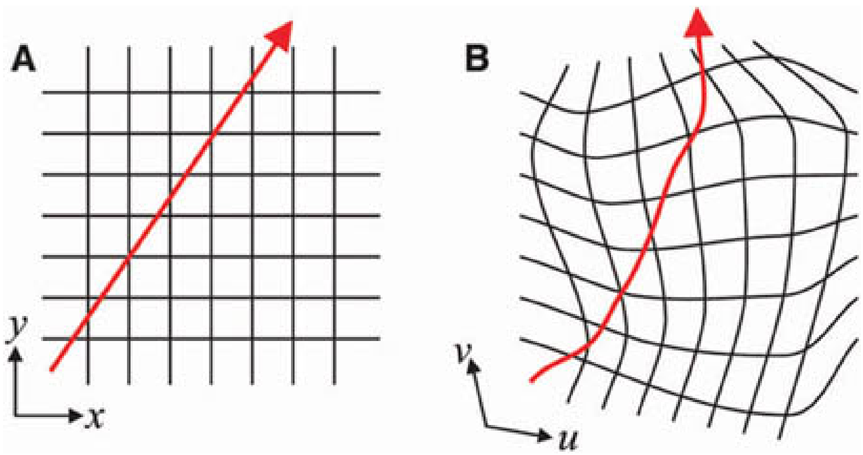
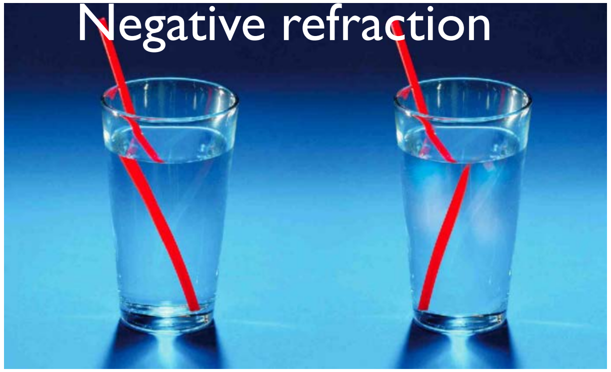
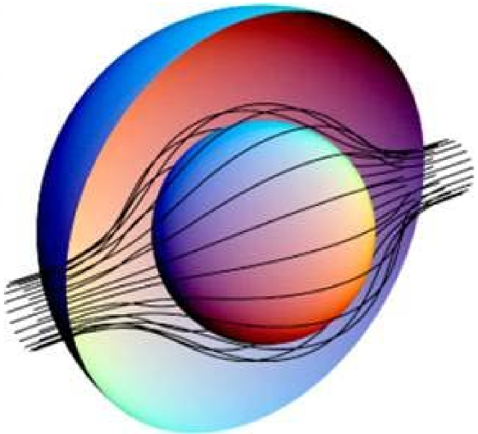
Bulk Metamaterials

Metamaterials and Transformation Optics







Optical cloaking

Viktor G Veselago 1968 *Sov. Phys. Usp.* **10** 509
A.J. Ward and J.B. Pendry, *J. Mod. Opt.* **43** (1996)
J.B. Pendry, D. Schurig and D.R. Smith, Science 312, 1780 (2006)

Propagation of light is controlled by considering artificial 3D materials with designed permittivity and permeability.

What can we do in 2D ? "**Metasurfaces**"

Metasurfaces

- *Metasurfaces enable new physics and phenomena that are distinctly different from those observed in three dimensional (3D) metamaterials, providing us with the unique capability to fully control light with planar elements and thus realize "planar photonics".*

- *The reduced dimensionality of the optical metasurfaces opens up new physics and leads to novel functionalities distinctly different from those in 3D metamaterials*

Metasurfaces: a new technology platform ?

- Planar technology is central to Integrated Circuit technology ($ 300 B industry): Technology platform.
- Because of fabrication complexity 3D optical materials (metamaterials etc.) don't have a good chance of a major technology impact (large scale applications) at optical wavelengths.
- We should look at what we can do in 2D with metasurfaces

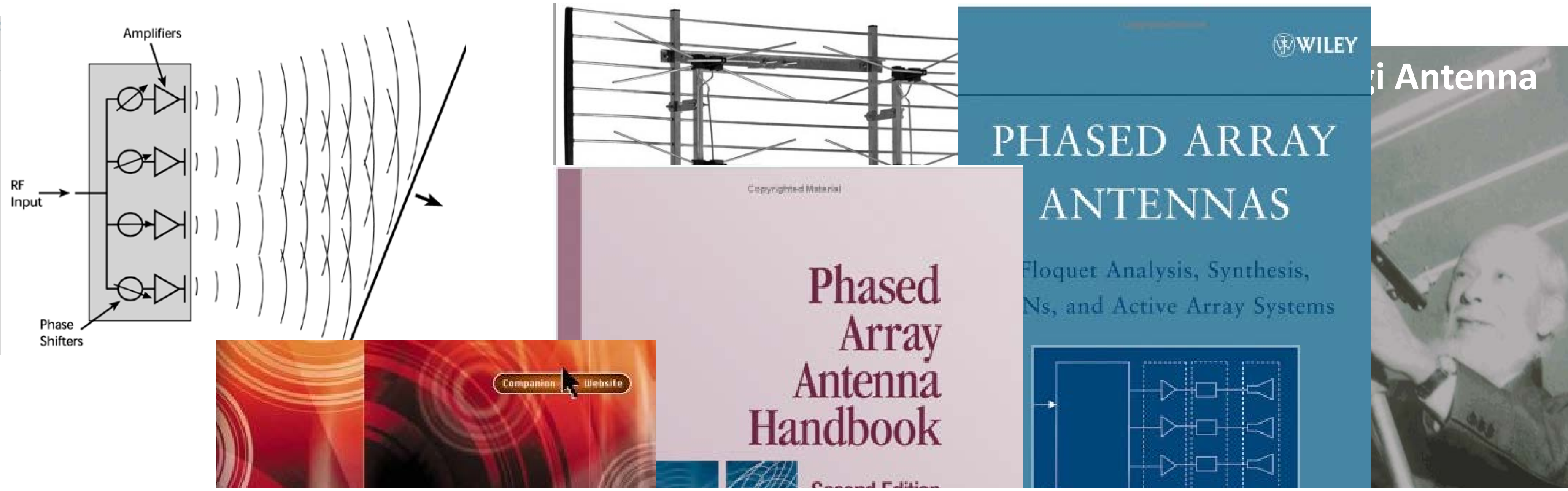
METASURFACES FOR FLAT OPTICS

- **Local phase, amplitude and polarization control of light along the surface using optical resonators: dielectric; metallic**
- Optically thin engineered metasurfaces *for wavefront and waveguiding control*
- New class of flat, compact and broadband components:(lenses, polarizers, etc.), be-yond conventional diffractive optics
- Optical phased arrays for high speed wavefront control; **new spatial light modulators**

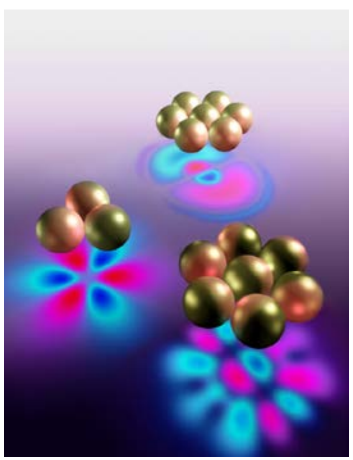
Topics

- Wavefront Control: amplitude, phase, polarization (transmittarrays & reflectarrays)
- Gradient and Huyghens metasurfaces
- Flat optical components
- Graphene (VdW Heterostructures) metasurfaces
- Aberrations and Achromatic metasurfaces
- Structured Light: vector beam generation
- Holographic metasurfaces
- Active (Nonlinear Optical) Metasurfaces
- Waveguide control: guided and free space mode conversion
- Polarization controlled routing
- Materials

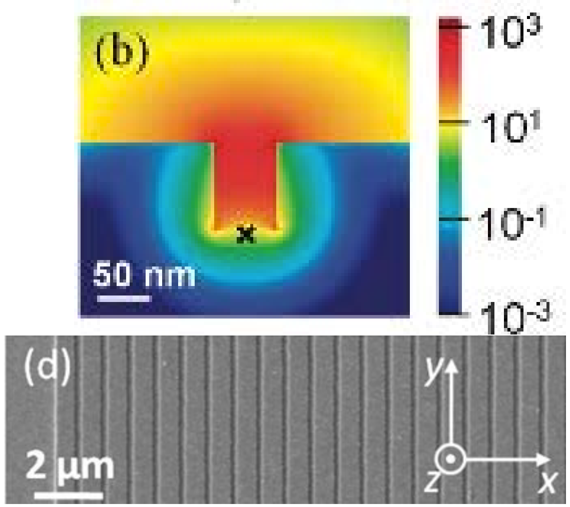
Phased-array antennas



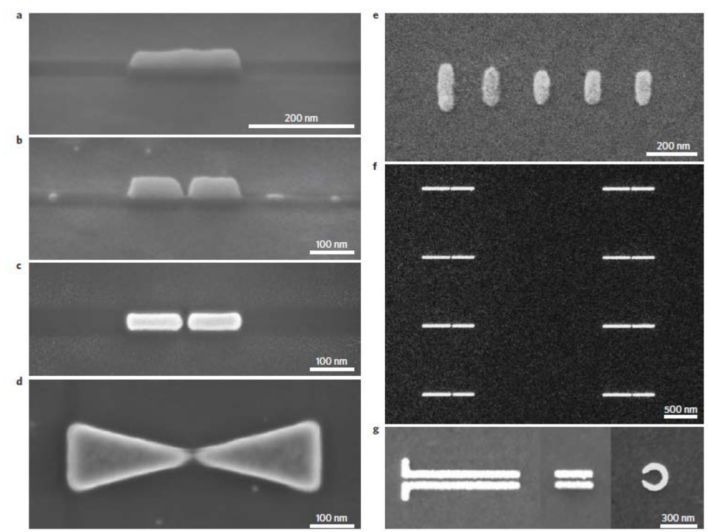
Phased-array antennas for light



J. A. Fan et al., ***Science*** 328, 1135 (2010)

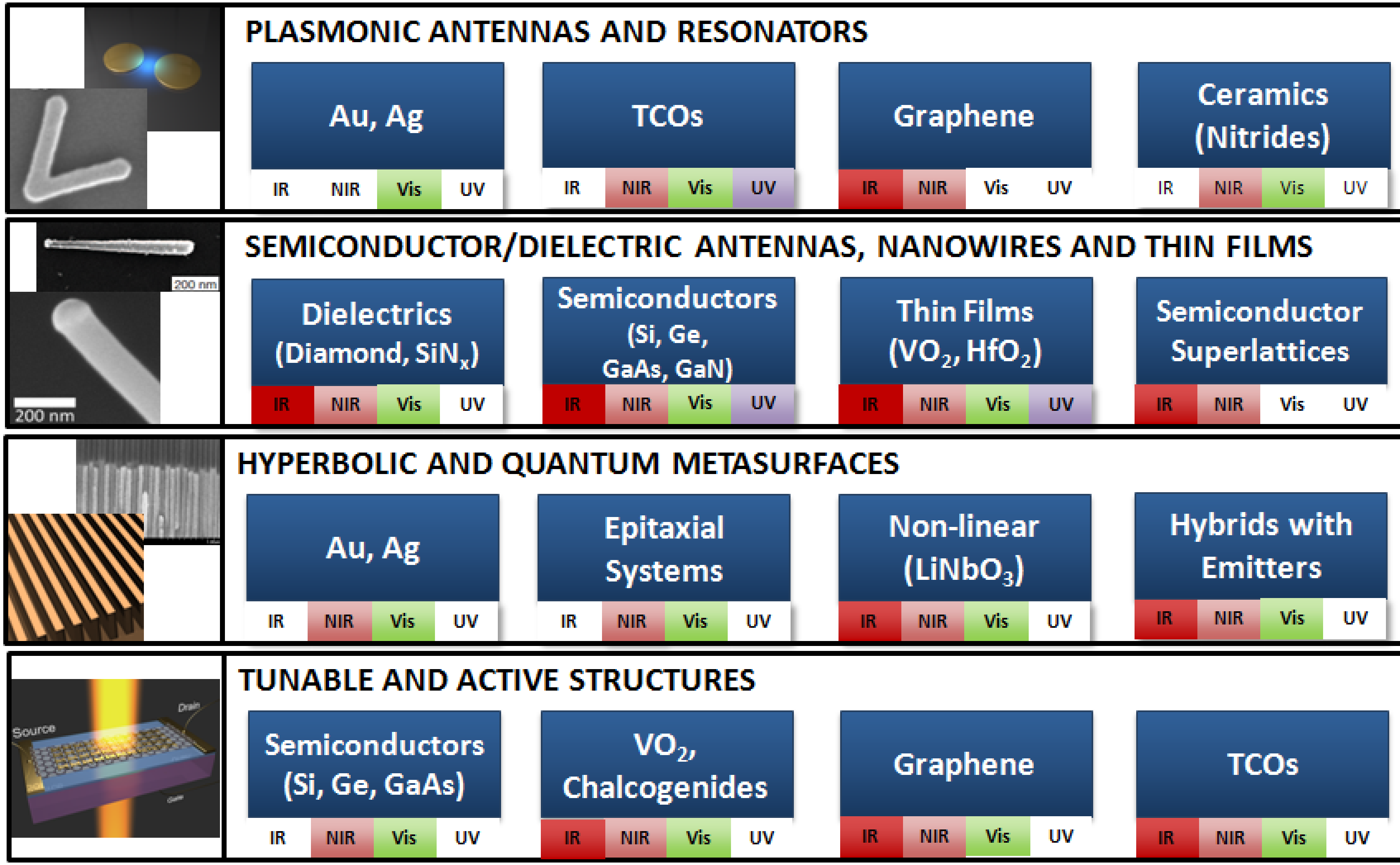


P. Genevet et al, **Nano Lett.** 10, 4880–4883 (2010)



L. Novotny et al., ***Nature Photon.***, 5, 83 (2011)

Metasurface Building Blocks

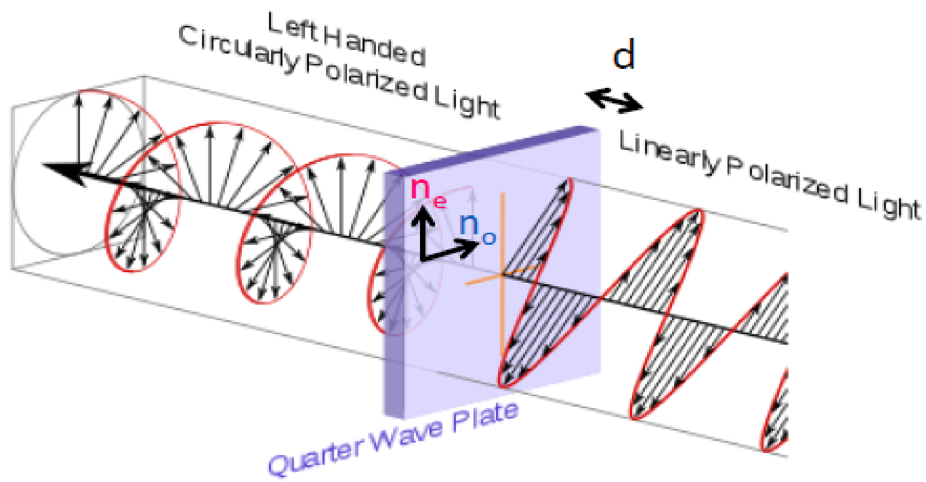


Constituent materials for metasurface building blocks and architectures at various wavelengths ranges (IR to UV) that could offer novel functionalities and provide low-loss behavior as well as tunability and modulation/switching capability

Conventional optical components rely on propagation effect

Camera lens (cross-section)

Quarter-wave plate



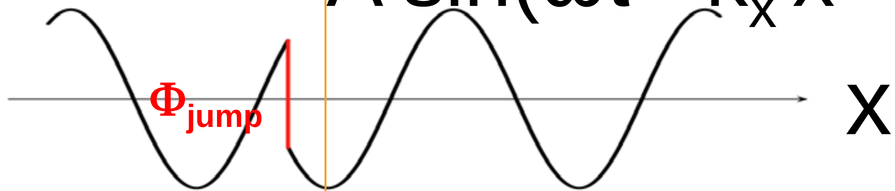
Propagation phase: $\int_A^B k_o n(r) dr$

Bulk birefringence: $d|n_e - n_o| = \lambda/4$

What if we introduce in the path a distribution of phase jumps?

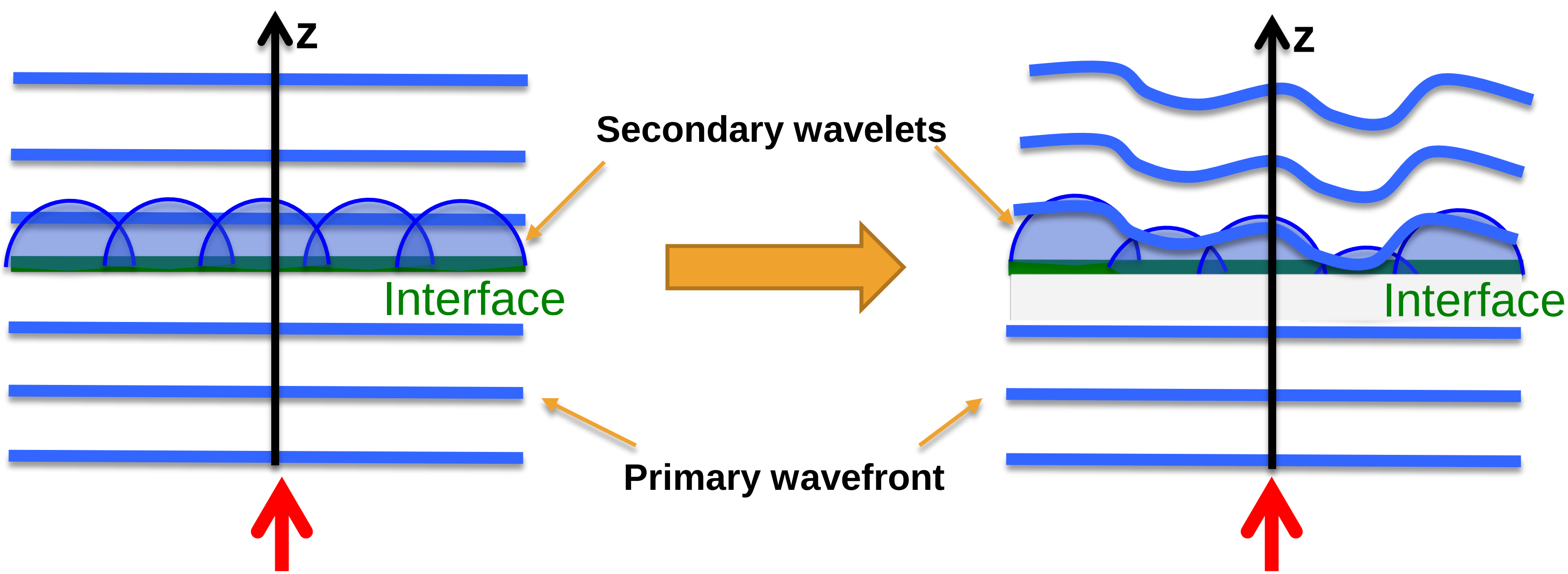
Designer Metasurfaces

$$A\sin(\omega t - k_x x) \qquad A\sin(\omega t - k_x x + \Phi_{jump})$$



What if could have a spatial distribution of different phase discontinuities along the entire interface? → can make any desired wave front !

How? → Optically thin array of sub-wavelength spaced resonator

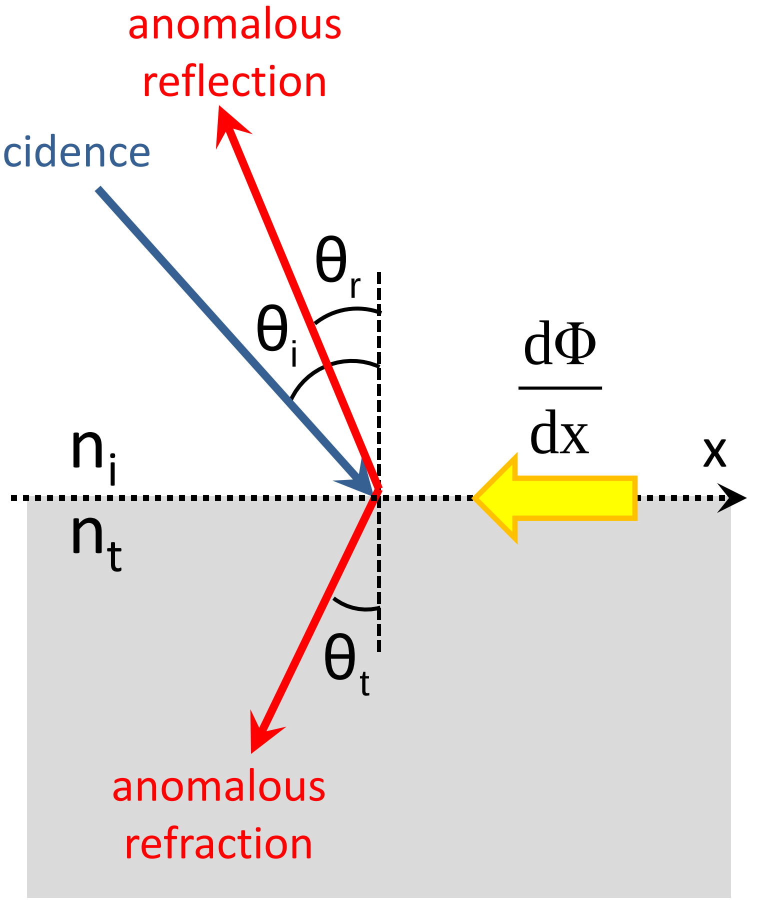


Tools: Heuristic: Huyghens' and Fermat's Principles, Young's experiment
Numerical: FDTD etc.

Generalized laws of reflection and refraction of light

N. Yu, *et al.*, *Science* **334**, 333 (2011)

Gradient Metasurface: $\frac{d\Phi}{dx} = const$



Using Fermat's principle of stationary phase one finds:

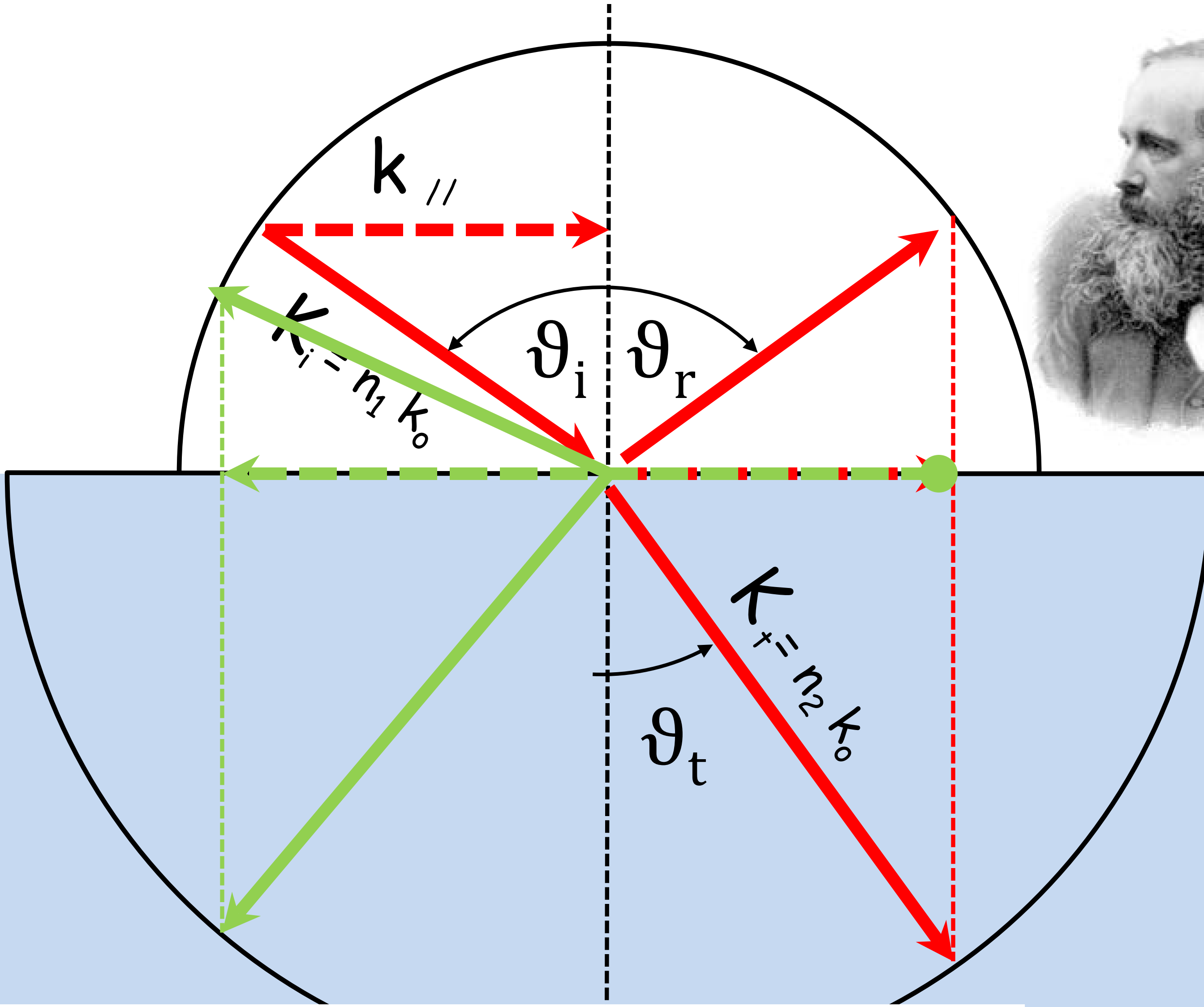
$$n_t \mathrm{Sin}(\theta_t) - n_i \mathrm{Sin}(\theta_i) = \frac{1}{k_o}\frac{d\Phi}{dx}$$

$$\mathrm{Sin}(\theta_r) - \mathrm{Sin}(\theta_i) = \frac{1}{n_i k_o}\frac{d\Phi}{dx}$$

Free-space wavevector $k_o = \frac{2\pi}{\lambda}$

$\frac{d\Phi}{dx} \Leftrightarrow k_{eff}$

Wavevector conservation at gradient metasurface

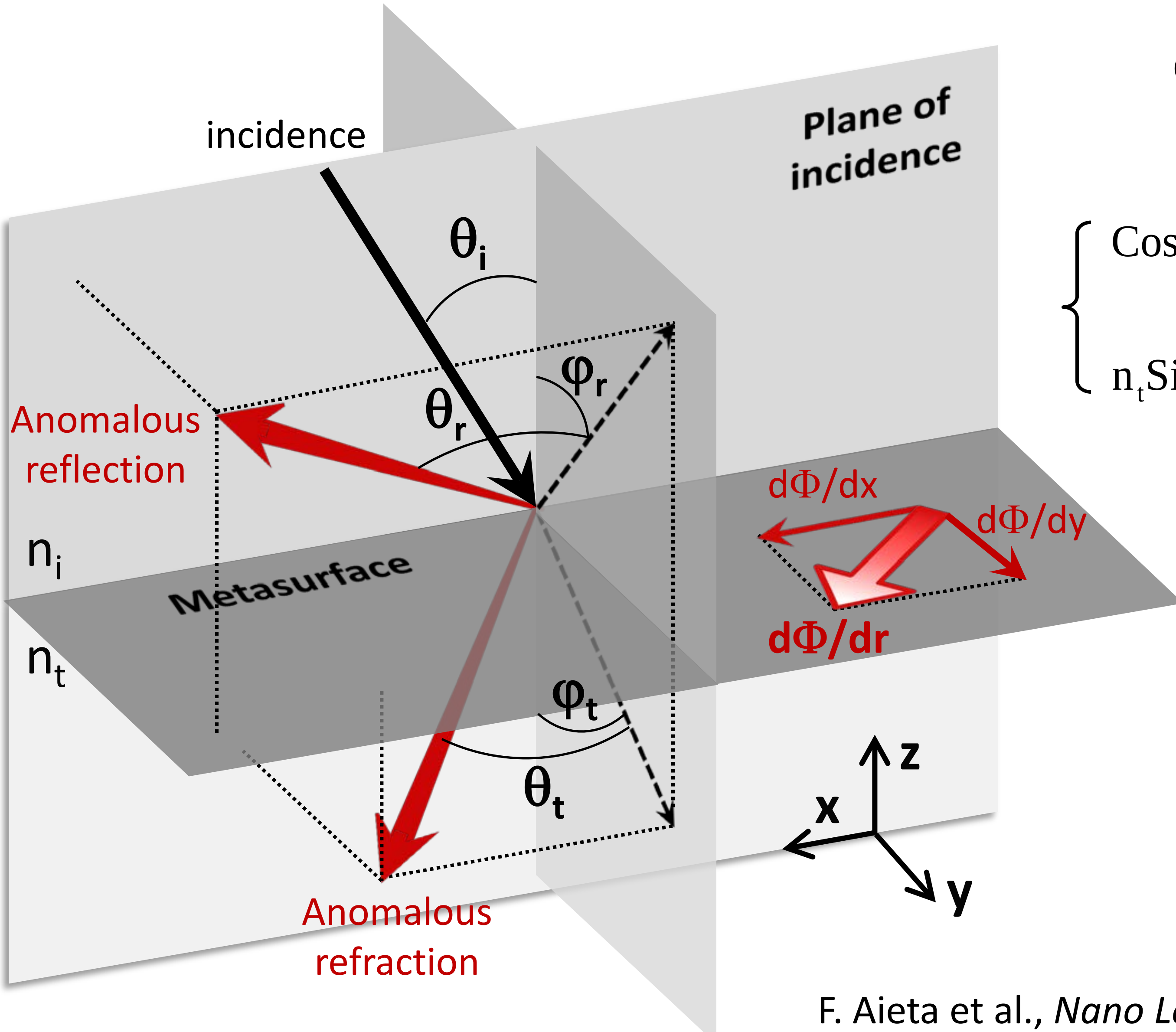


Conservation tangential components of EM

$$k_{//,2} = k_{//,1} + \partial\Phi/\partial r$$

Phase gradients out of the plane of incidence

$d\Phi/dr \leftrightarrow k_{eff}$

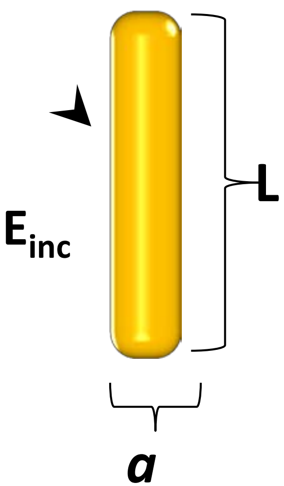


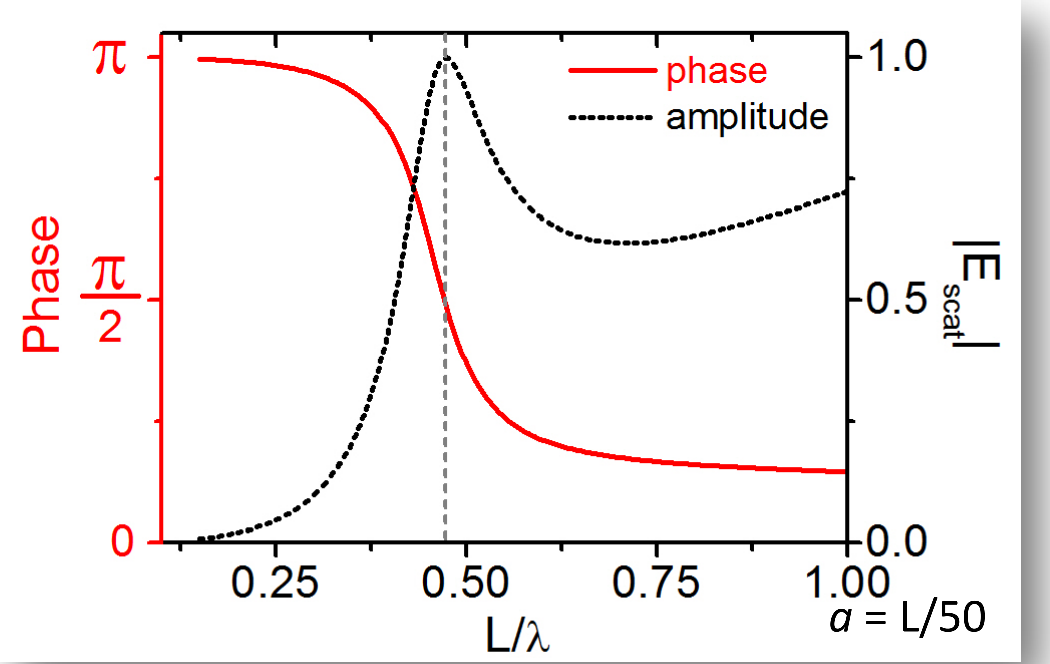
Generalized law of refraction in 3D

$$\begin{cases} \cos(\theta_t)\sin(\varphi_t) = \dfrac{1}{n_t k_o}\dfrac{d\Phi}{dy} \\ n_t \sin(\theta_t) - n_i \sin(\theta_i) = \dfrac{1}{k_o}\dfrac{d\Phi}{dx} \end{cases}$$

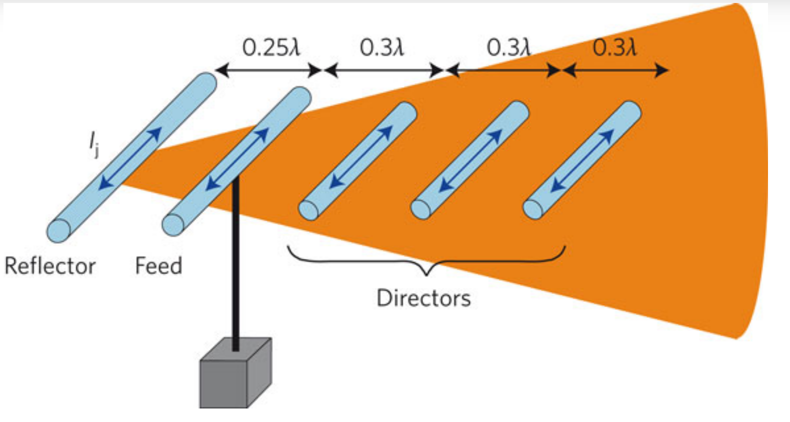
F. Aieta et al., *Nano Letters* **12**, 1702 (2012)

Phase response of rod antennas



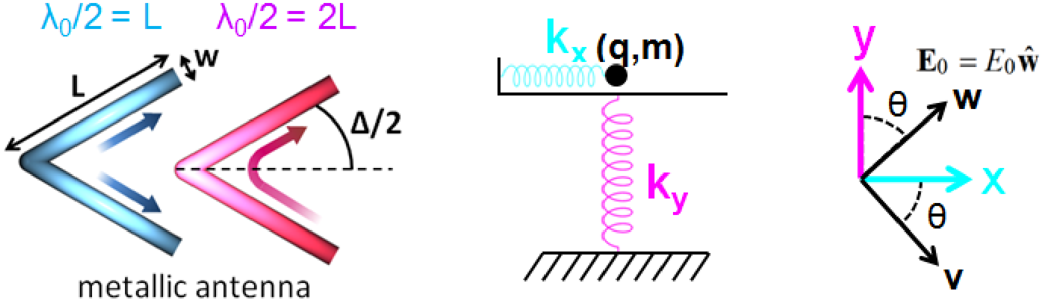


Yagi-Uda antenna

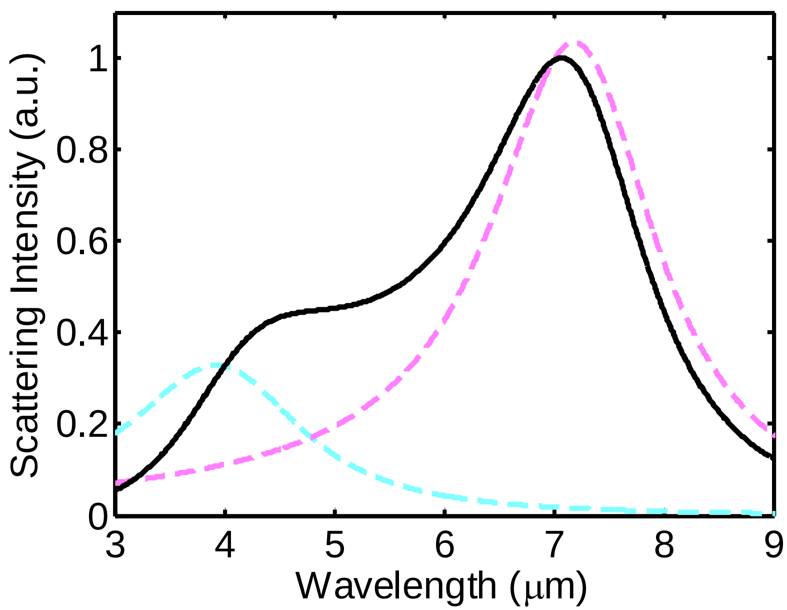


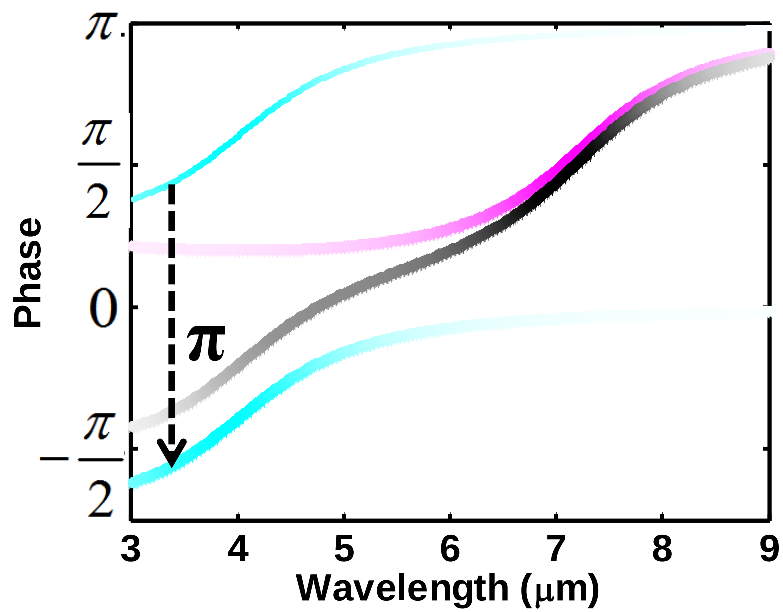
The antenna resonance is like any other resonance. Across the resonance peak there is a phase shift close to pi. Therefore for a fixed wavelength, one can choose different antenna lengths to address different amount of phase change in the scattered light.

V-shaped antennas for broad phase coverage



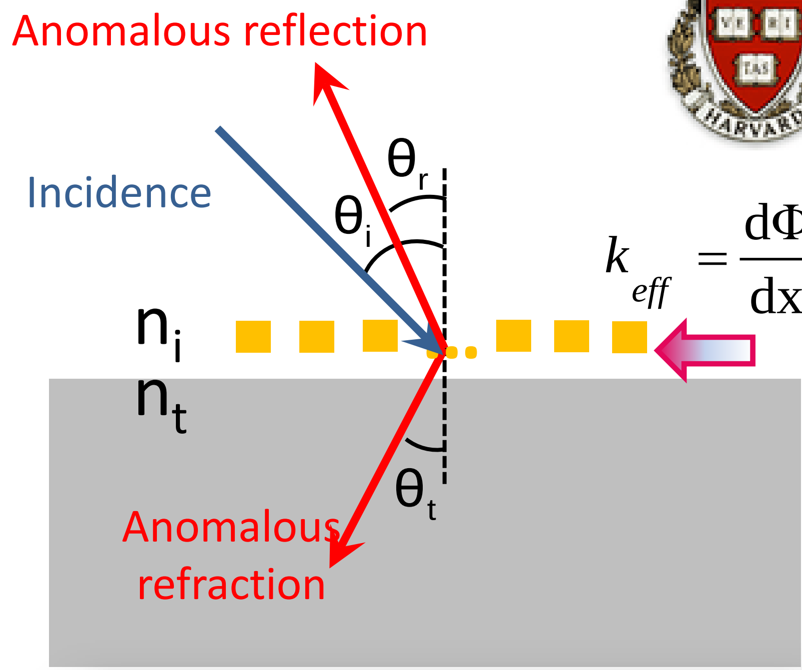
$$E_{s,v}(\omega) \propto E_0 \sin(2\theta)\omega^2 \left[\sqrt{\Gamma_{s,x}}\,x(\omega)e^{i\pi} + \sqrt{\Gamma_{s,y}}\,y(\omega)\right]$$

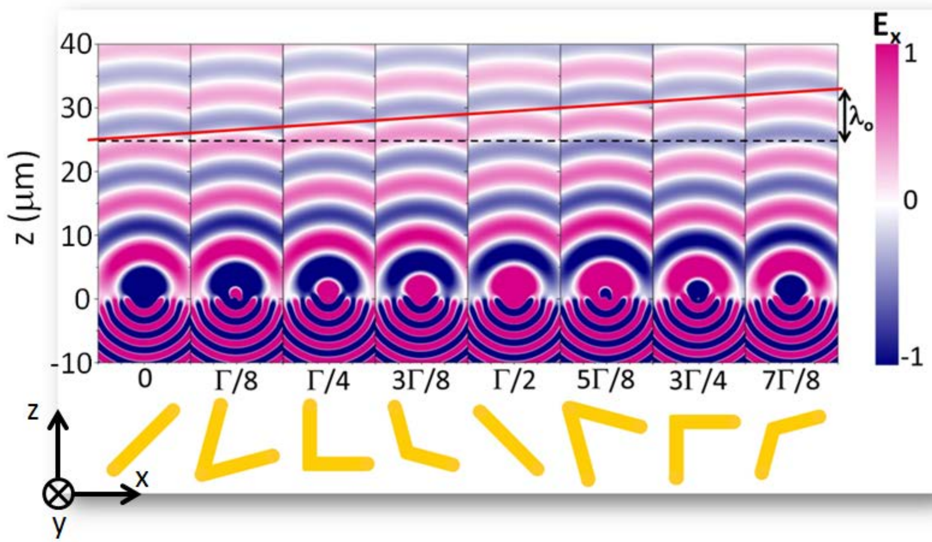


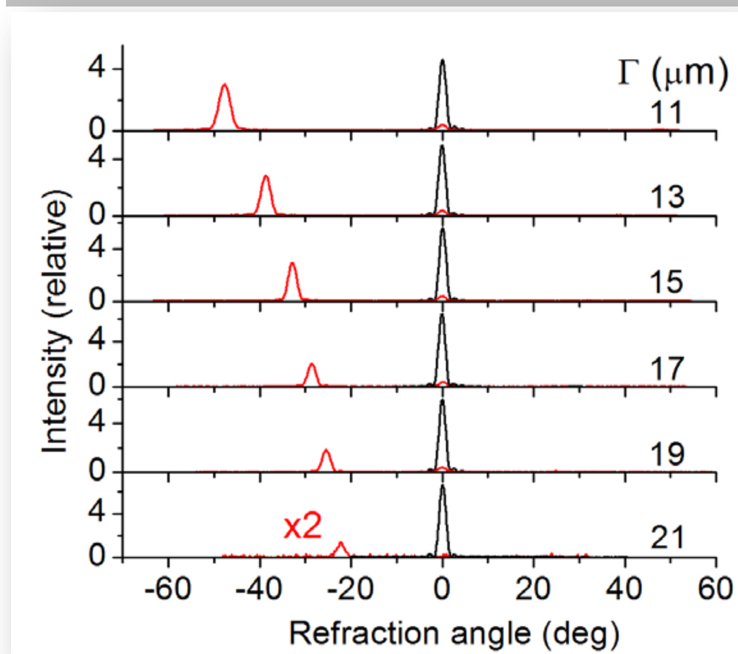


This antenna has a broader resonance and greater phase coverage than a linear one

Phase gradient = Effective wavevector

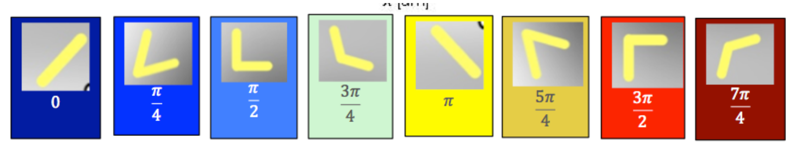


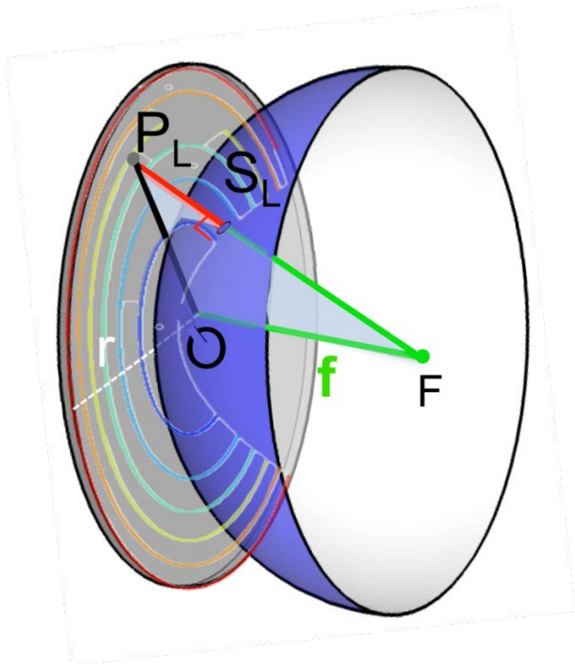




.N. Yu, *et al.*, *Science* **334**, 333 (2011)

Flat lens based on Metasurfaces





To focus at a certain focal f the interface must compensate for the distance of every point from a spherical surface centered in the focus and with radius f.

$$\varphi_L(x,y) = \frac{2\pi}{\lambda}\overline{P_L S_L} = \frac{2\pi}{\lambda}\left(\sqrt{(x^2+y^2)+f^2} - f\right)$$

No spherical aberration and large numerical aperture; poor focusing efficiency

F. Aieta et al *Nano Letters* **12**, 4932 (2012)

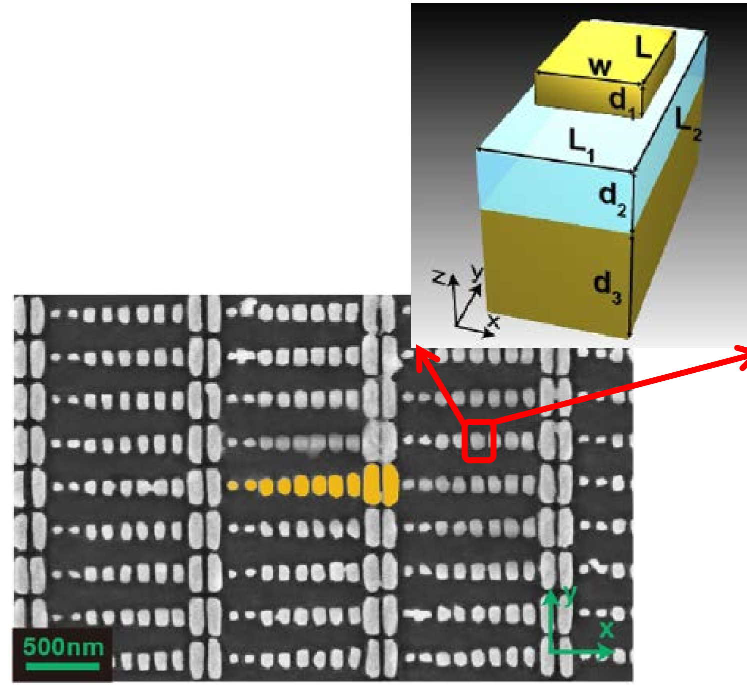
Trasmittarrays: challenges & solutions

- Optically thin and high reflections
- Poor efficiency, exacerbated by optical losses for visible/near-ir in the case of metals;
- Solutions:
  - Reflectarrays
  - Dielectric structures
  - Impedance matching

Antennas providing 2π phase coverage

Yu et al., *Science* **334**, 333 (2011)
Ni, et al. *Science* **335**, 427 (2012)

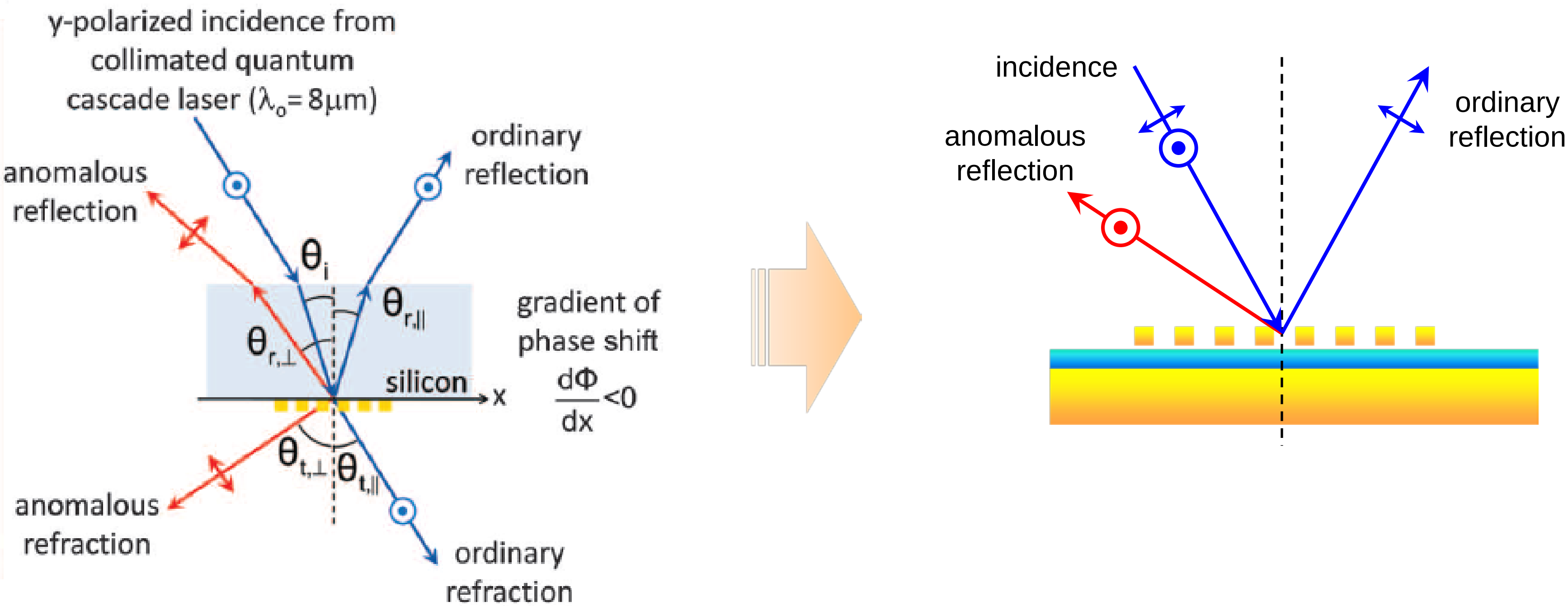
- Single-layered antennas supporting multiple antenna resonances. V antennas and V-apertures.
- Reflect array structures consisting of an antenna layer and a metallic ground plane separated by an insulating dielectric spacer.



Sun et al., *Nano Lett* **12**, 6223 (2012)
Sun, et al., *Nature Mater.* **11**, 426 (2012)

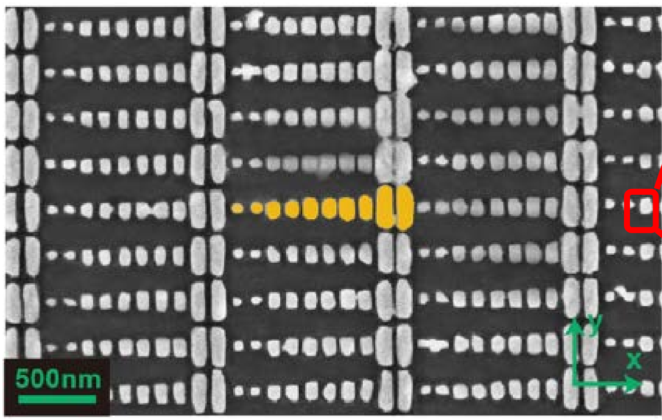
Reflection-Only Meta-Surface

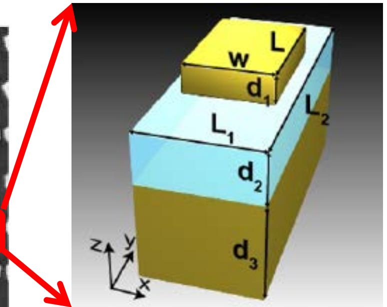
❑ Major Efficiency Improvement



- Nano-antennas capped above a metal sheet separated by a dielectric layer
- The metal sheet serve as:
  - **Reflected mirror**: Cancel the transmitted components
  - **Magnetic-response :** Dipoles of nanoantennas couple to backplane to induce anti-parallel currents: induced magnetic mode, 2π-phase modulation can be achieved
- Lei Zhou (Fudan U) and Din Ping Tsai (Acad. Sinica, Taiwan) Groups

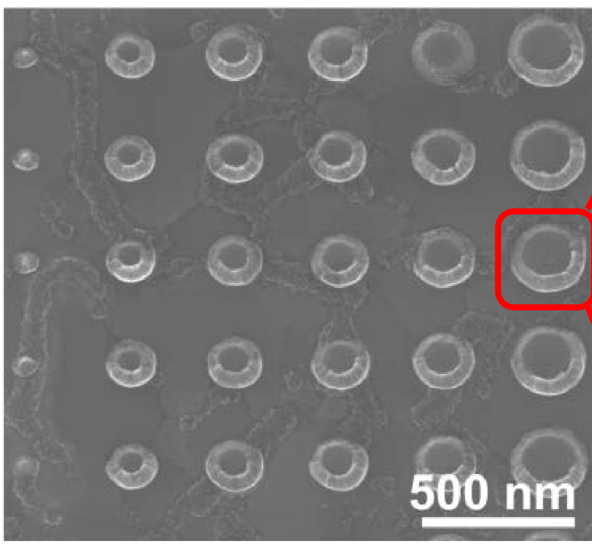
High-efficiency reflectarrays

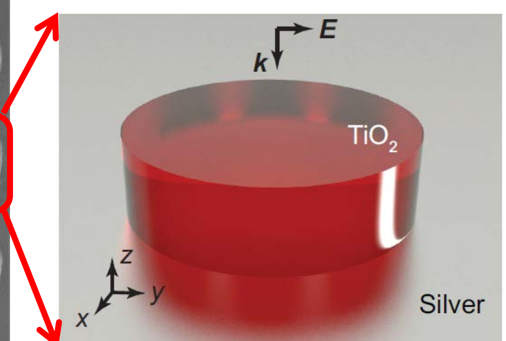




λ = 750-900 nm

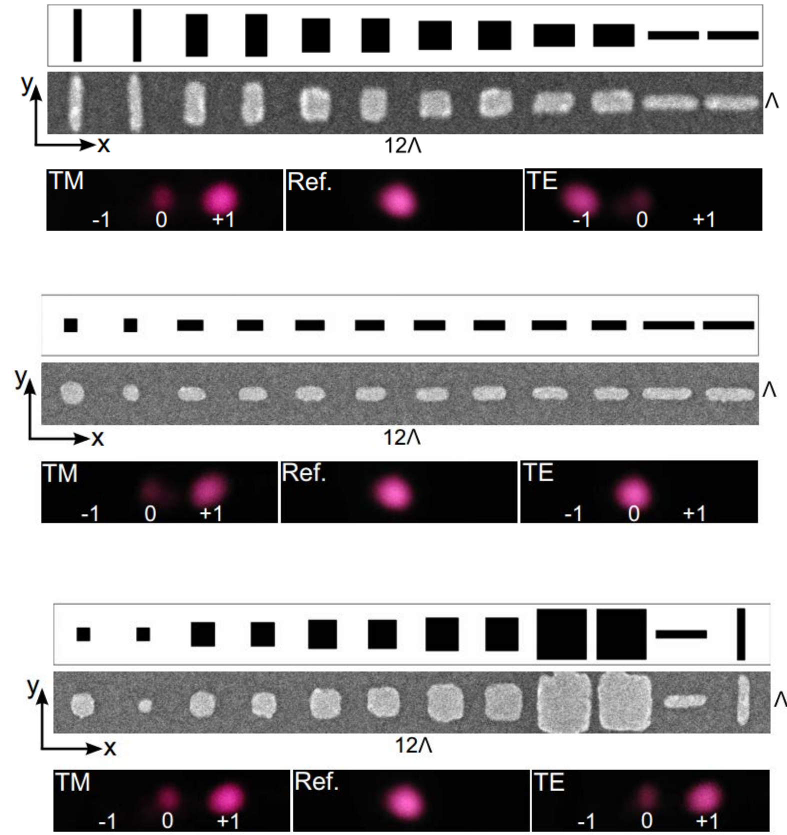
S. Sun … D. P. Tsai, *Nano Lett.* **12**, 6223 (2012)





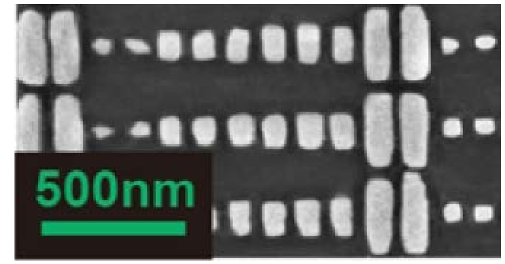
λ = 633 nm

L. Zou … C. Fumeaux, *Opt. Express* **21**, 1344 (2013)

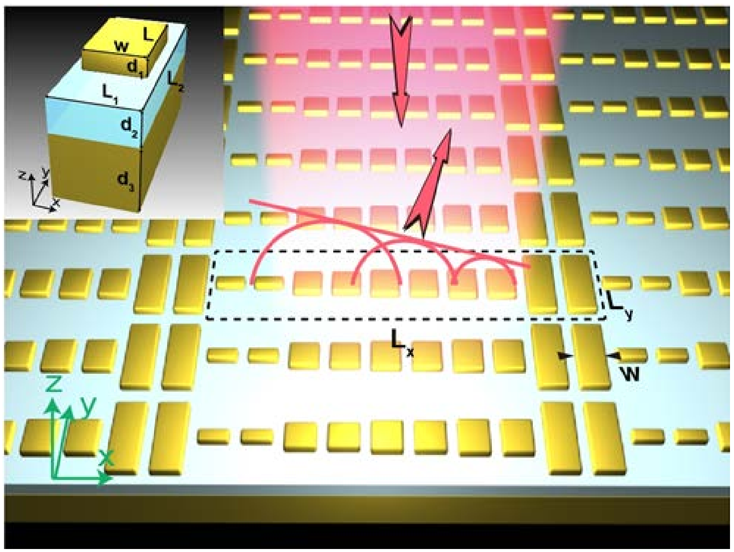


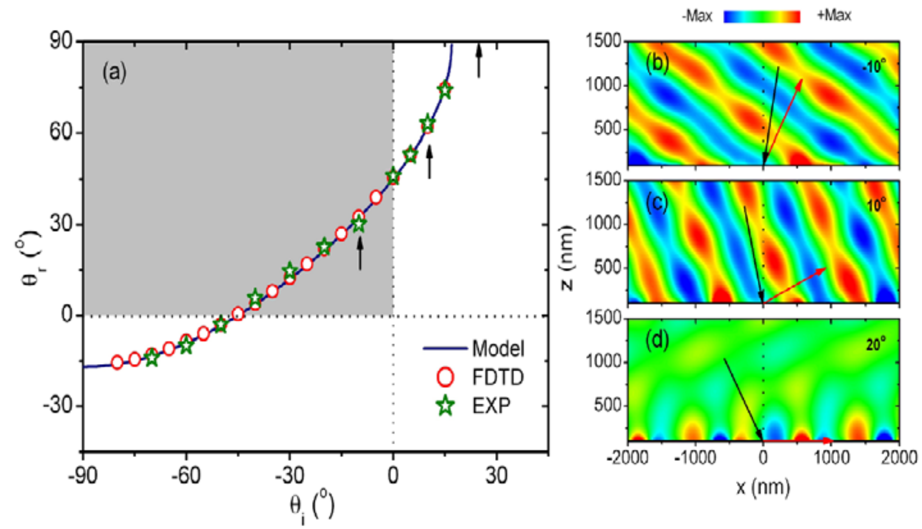
A. Pors … S. I. Bozhevolnyi, *Scientific Reports* **3**, 2155 (2013)

Metal-insulator-metal structure or dielectric antenna patterned on a metallic substrate



❑ Schematics of the designed meta-surface



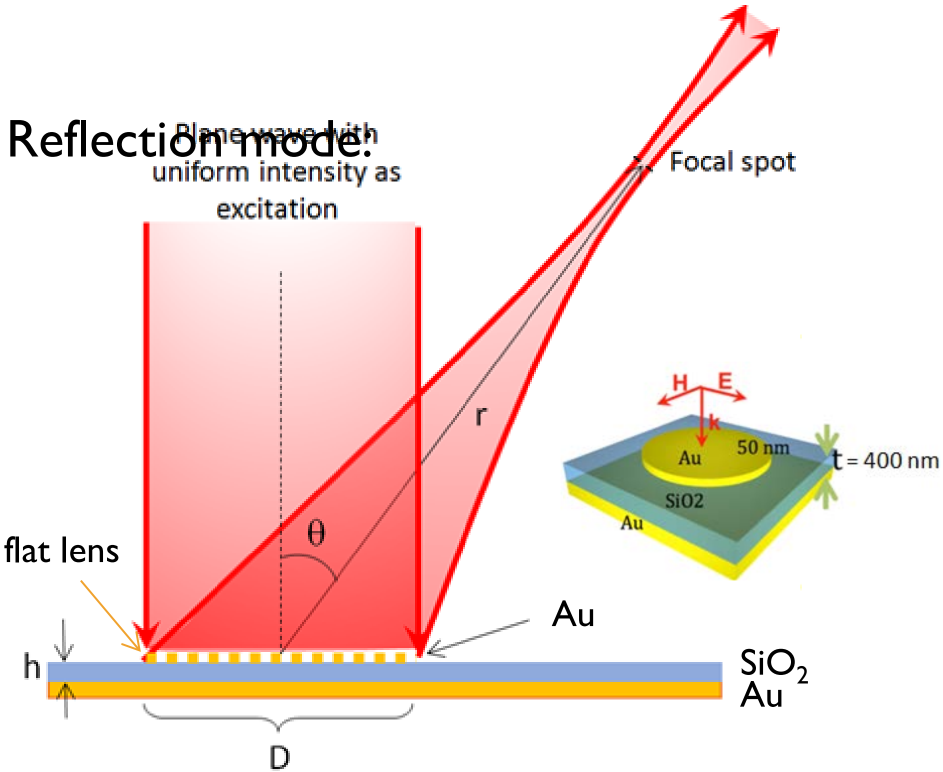


- Working wavelength around 850nm
- Sandwich structure of Au bars (30nm) / MgF_2 (50nm) / Au film (130nm)
- Unit cell: $L_x \times L_y$ = 1200 nm × 300 nm
- Linear reflection phase distribution along *x*-direction
- 70% to 80% efficiency in anomalous beam

S. Sun *et al.*, *Nano Lett.* **12**(12), 6223-6229 (2012).

Mid-IR Flat Lens for Imaging: Design & Fabrication

Reflection mode:



Design parameters:

D=3.08 mm (size of lens, 1401 antennas)

θ=45° (beaming angle), **h**=400 nm

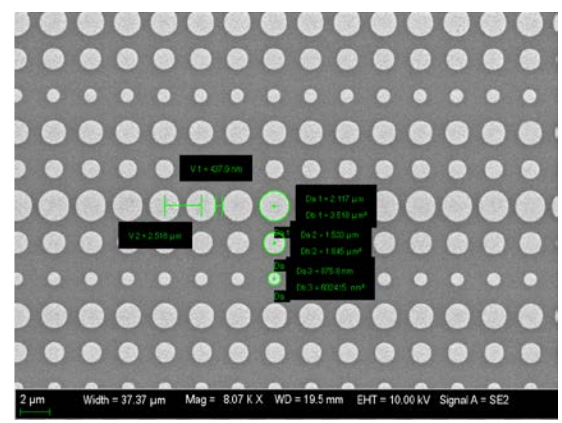
r=4 cm (focal distance)

Design principles:

- Cylindrical phase profile to focus light
- Linear phase profile to direct light at an angle

Fabrication techniques:

- E-beam evaporation, PECVD, photolithography
- Materials: Au and SiO_2

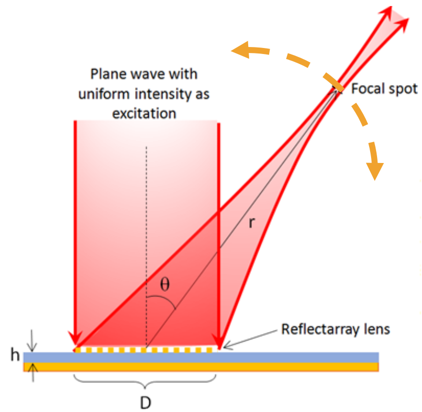


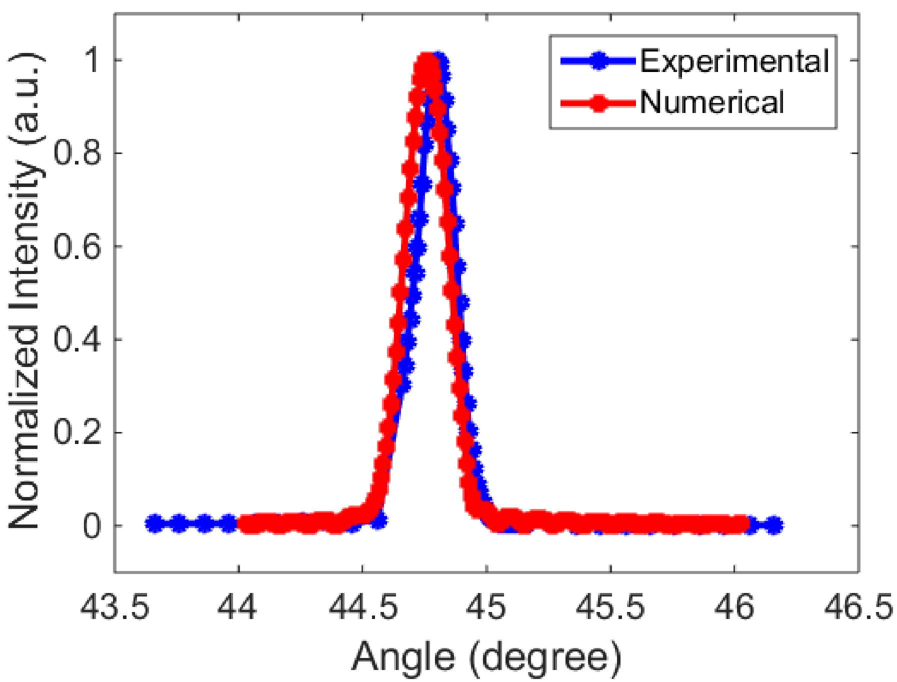
Shuyan Zhang, Capasso group
Nanfang Yu group (Columbia)

Experiment vs Simulation

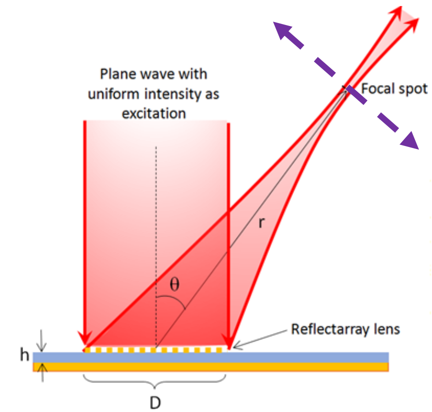
S. Zhang, Capasso group
N. Yu group (Columbia)

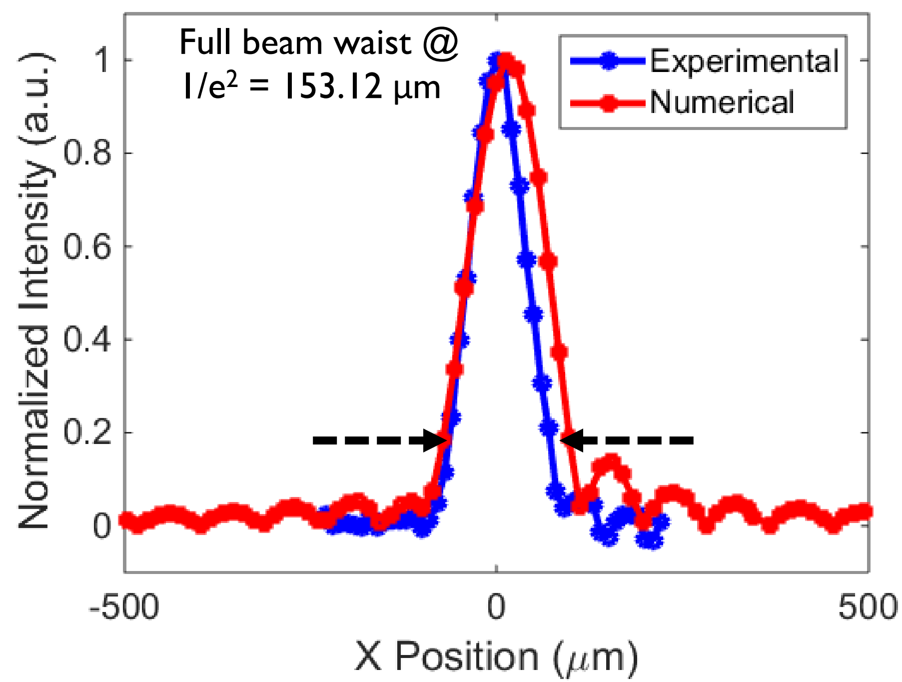
- Angle scan:



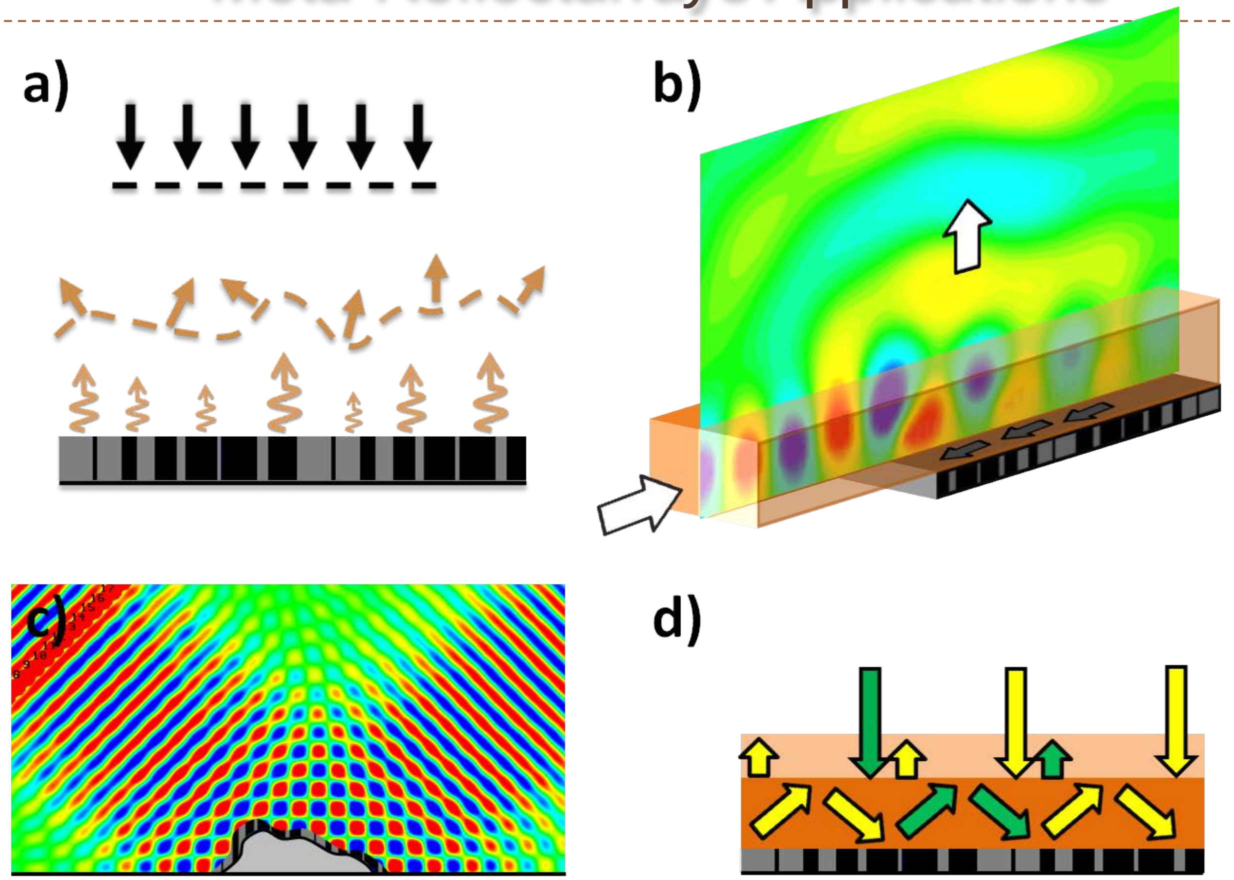


- X Scan





Meta-Reflectarrays Applications

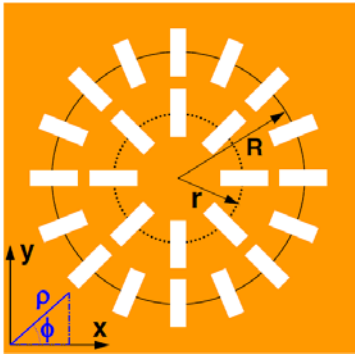


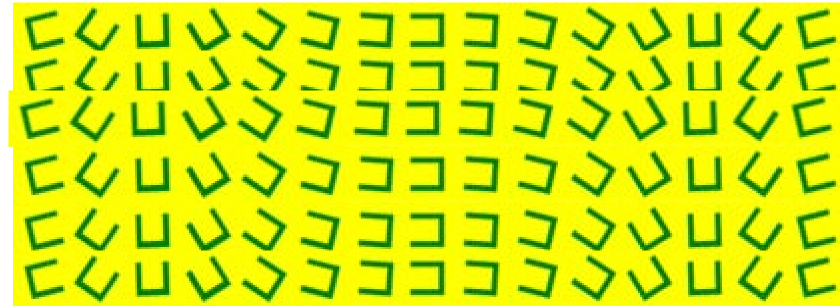
N. Mohammadi Estakhri, C. Argyropoulos, and A. Alù, *Phyl. Trans. A,* in press (2015)
N. Mohammadi Estakhri, A. Alù, *IEEE AWPL* (2015)

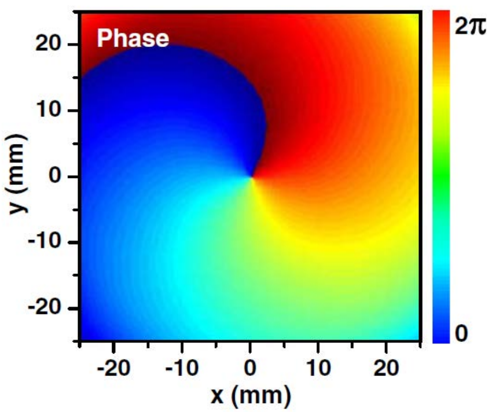
(b) in-couplingt and out-coupling energy from radiating to guided modes; (c) cloak a large object on a ground planet by ailoring the local phase of the reflected beam,, (d) trap light: by steering the reflected beam on the bottom plate of a thin film solar cell one can increase the optical path. All these phenomena are inherently broadband (non resonant elements)

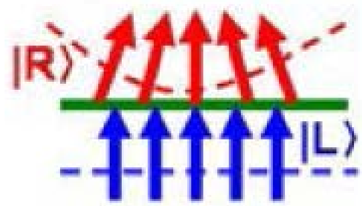
Metasurfaces based on the Geometric Phase

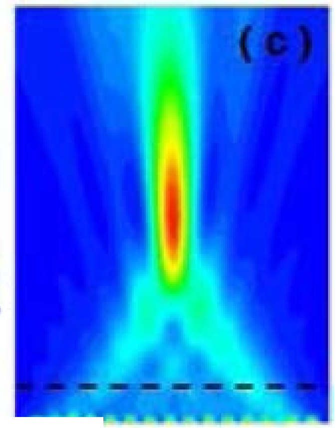
(Pancharatman Berry phase)











$$\mathbf{E}_T^{\pm} = \frac{1}{\sqrt{2}} E_0 \exp(\pm j\alpha) \begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix}$$

Kang et al., *J Opt Soc Am B* **29**, 572 (201

Kang et al., *Opt Express* **20** 15882 (201

Polarization change → Phase change **(Geometric Phase)**

Tiny apertures with different orientations defined in a metal film. The apertures are like tiny polarizers. The transmission through the apertures carries a phase of phi equal to the orientation angle of the aperture and sign equal to the helicity of the circular polarization

Pioneering work by E. Hasman group (Technion)

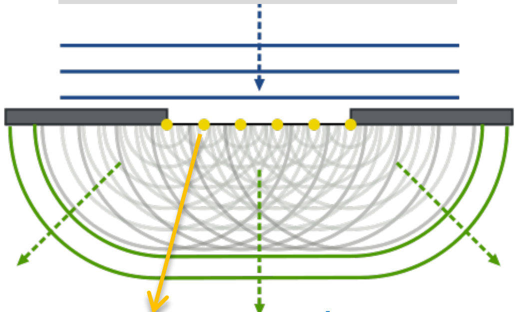
Trasmittarrays: challenges & solutions

- Optically thin and high reflections
- Poor efficiency, exacerbated by optical losses for visible/near-ir in the case of metals;
- Solutions:
  - Reflectarrays
  - Dielectric structures
  - Impedance matching

Dielectric Huygens' meta-atoms

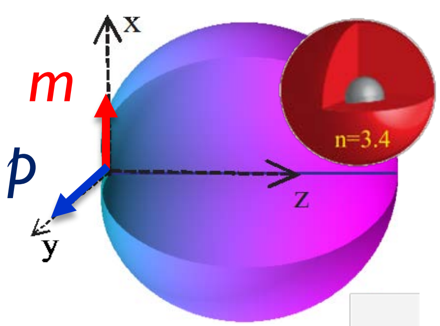
Y. Kivshar, A. Miroshnichenko,b D. Neshev, Australian National University
Igal Brener Group (Sandia)

Huygens' principle



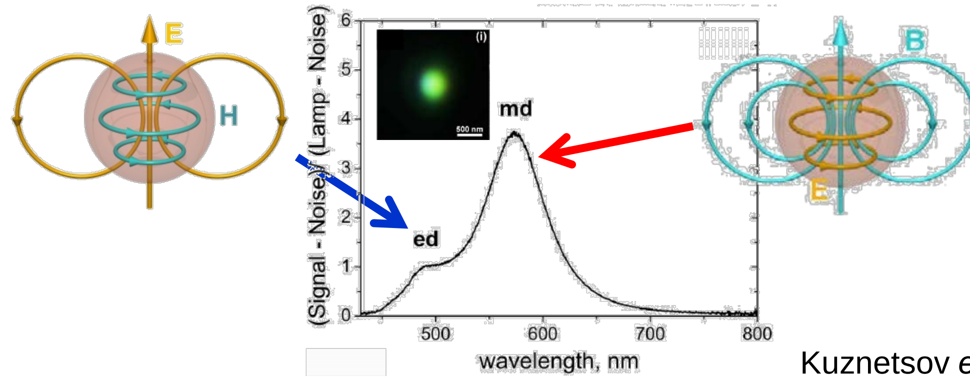
Huygens sources radiate unidirectional as superposition of electric and magnetic dipoles

Unidirectional scattering by electric & magnetic dipole



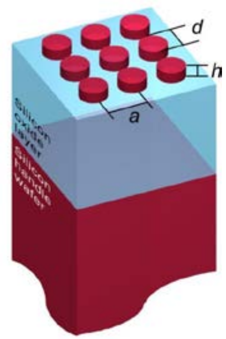
Liu *et al.*, ACS Nano **6**, 5489 (2012)

Pure electric and magnetic dipole in Si spheres

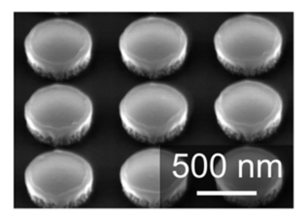


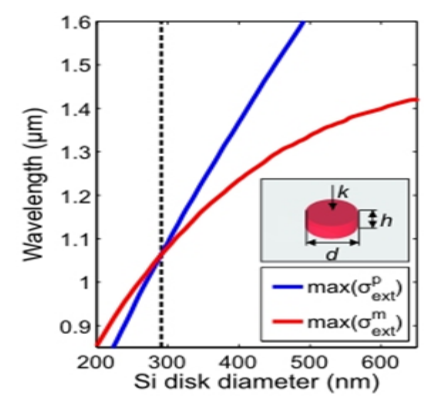
Kuznetsov *et al.*, Sci. Rep. **2**, 492 (2012)

Elec. & mag. dipole can be overlapped in Si disks



Fabrication by SoI technology





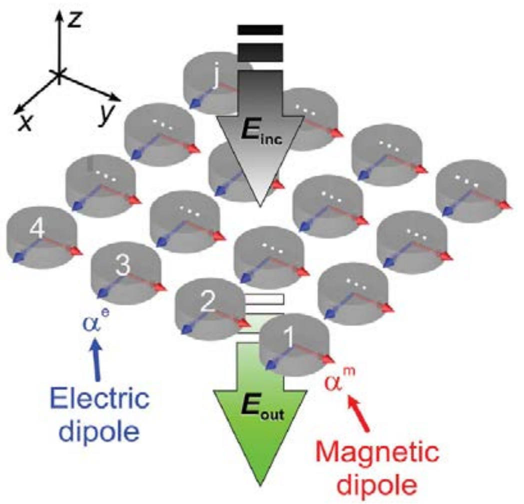
By changing the aspect ratio of the Si disks one can overlap E & M resonances, leading to zero reflection

Staude *et al.*, *ACS nano* **7**, 7824 (2013)

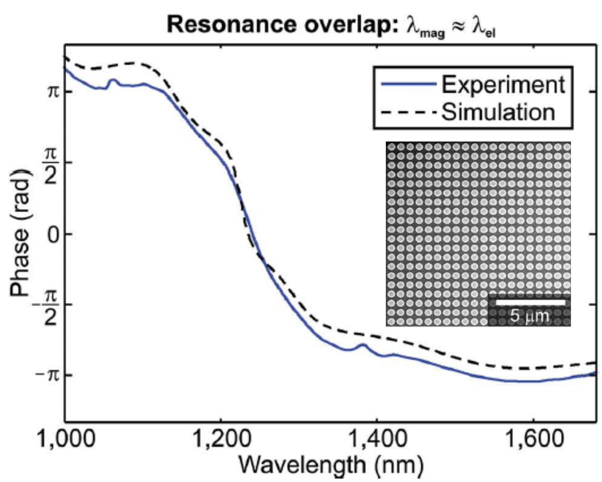
Dielectric Huygens' metasurfaces

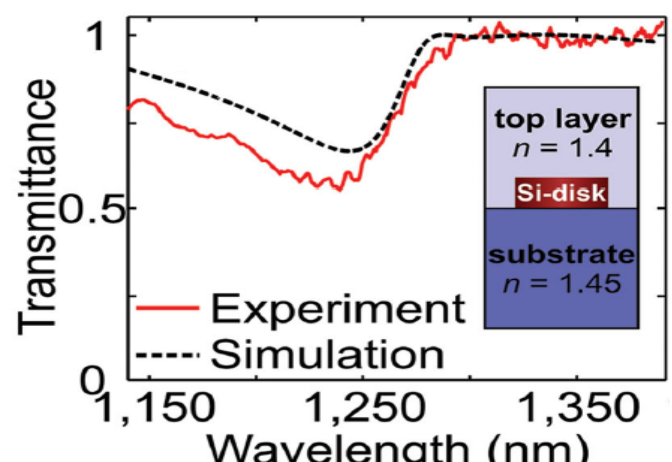
If many such disks are packed together, one can realise a dielectric metasurface with negligible reflection and no losses as in the plasmonic metasurfaces.

Arrays of silicon disks form a dielectric metasurface



- Complete 2π phase range in transmission
- Near-unity transmittance for ideal metasurface
- No reflection losses
- No absorption losses (NIR)
- No polarization conversion losses
- Single step lithography fabrication



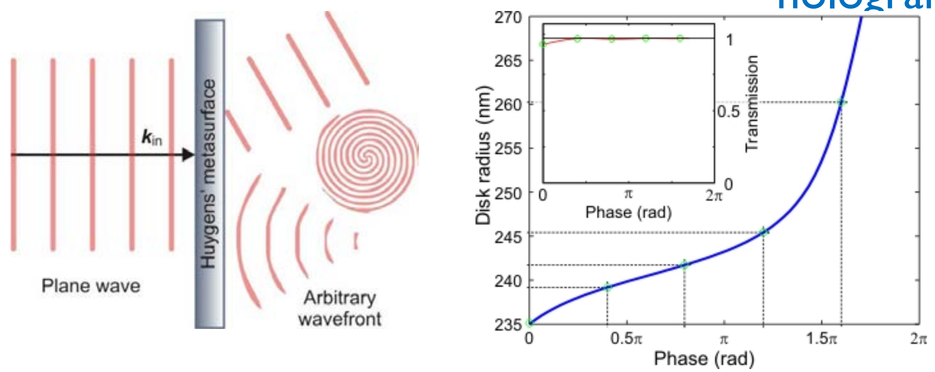


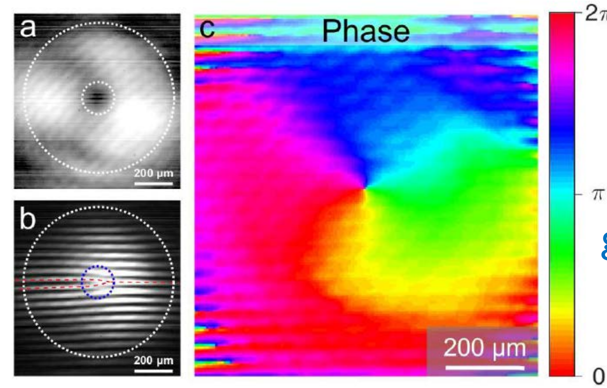
Decker *et al.*, Adv. Opt. Mat. doi: 10.1002/adom.201400584 (2015)

Applications of dielectric metasurfaces

Minovich et al., "Functional and Nonlinear Optical Metasurfaces" Laser & Photonics Review **9**, 195 (2015)

Spatial wavefront control: High-transmission-efficiency (>70%) beam-shaping or holograms





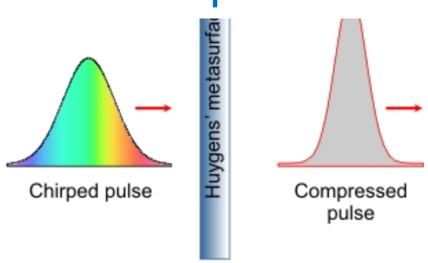
Example of optical vortex generation

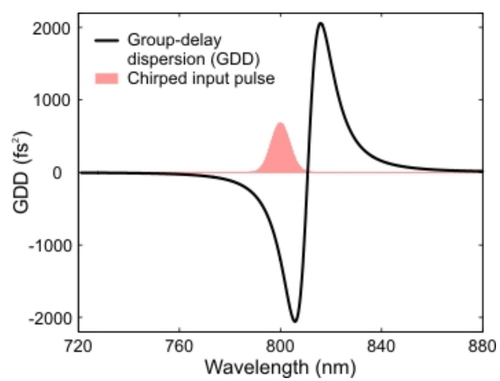
Decker *et al.*, Adv. Opt. Mat. doi: 10.1002/adom.201400584 (2015)

Chong *et al.*, submitted (2015)

Temporal wavefront control

Pulse compression

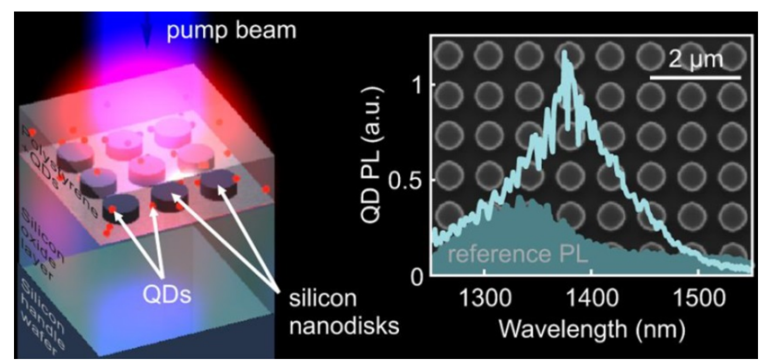




Dispersion more than 1cm of glass from a single metasurface

Decker *et al.*, Adv. Opt. Mat. doi: 10.1002/adom.201400584 (2015)

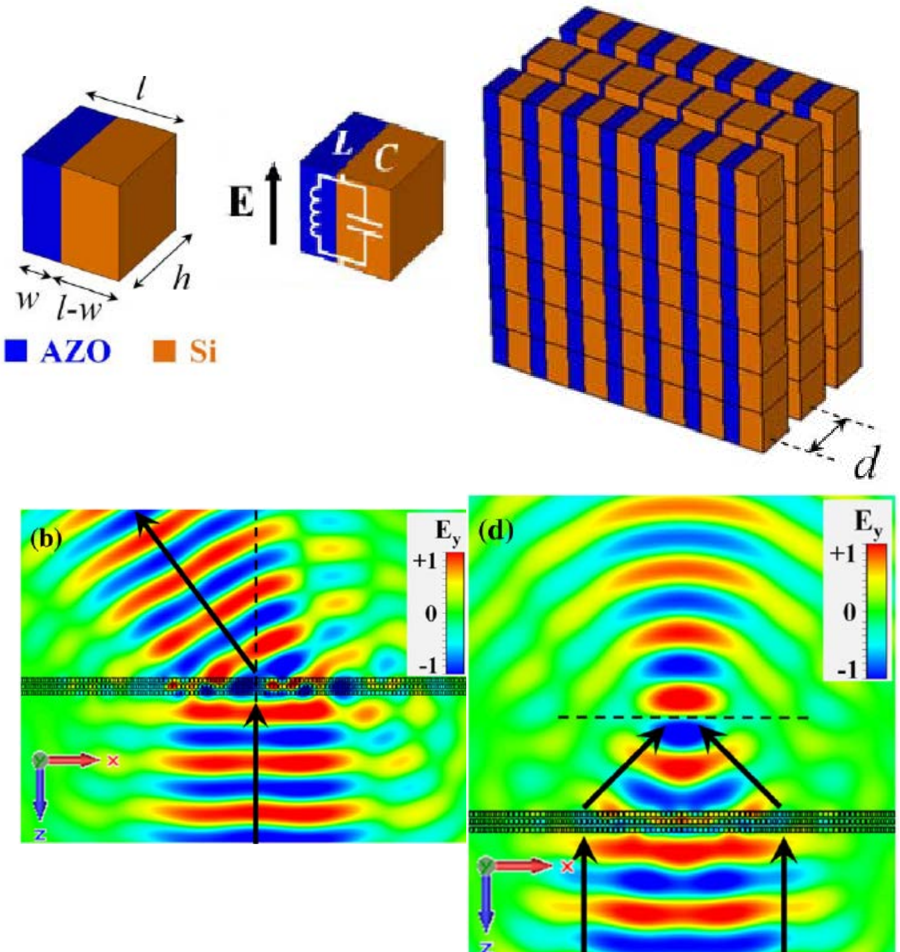
Emission control



Achieved strong emission enhancement of QDs in the resonance overlap regime

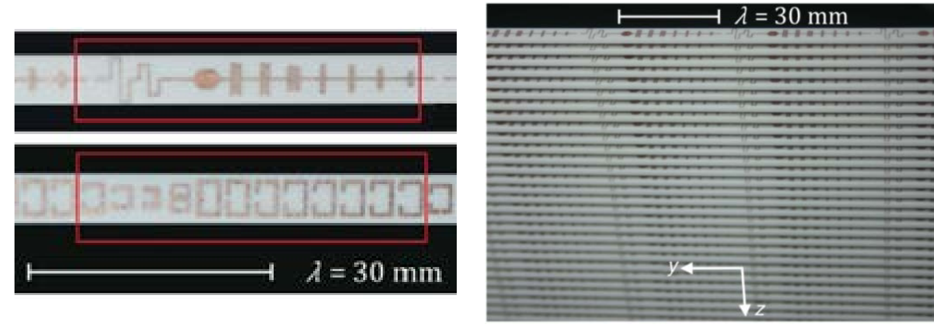
Staude *et al.*, ACS Photon. **2**, 172 (2015)

Huyghens metasurfaces:
High-efficiency transmitarray metasurfaces based on LC components

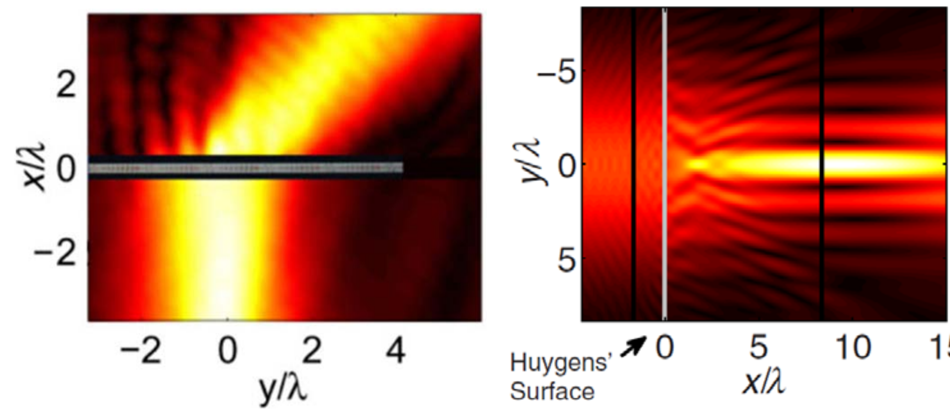


Efficiency > 75%

F. Monticone ... A. Alù, *Phys Rev Lett* **110**, 203903 (2013)



Huygens' surfaces



Efficiency ~ 86%

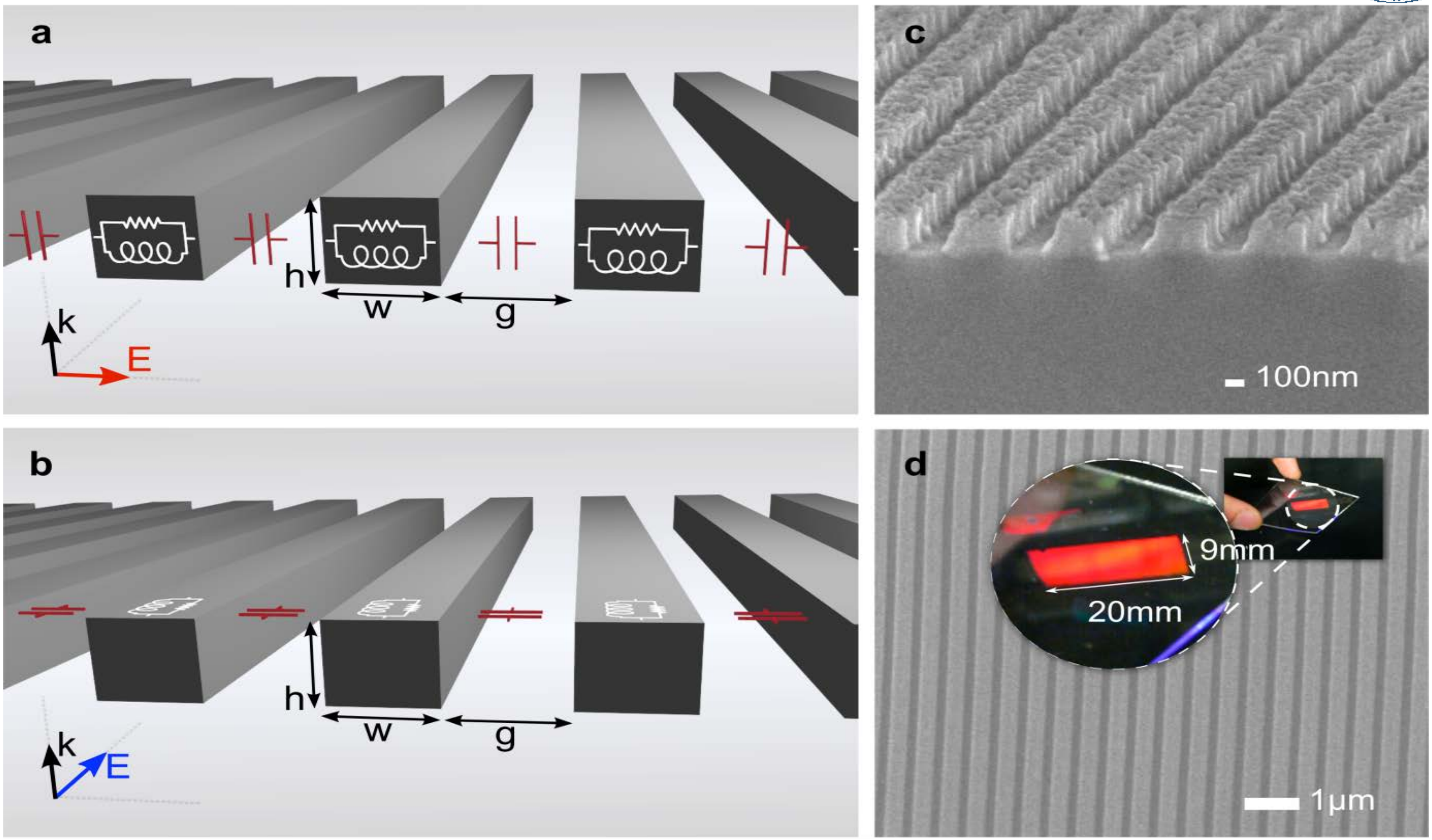
C. Pfeiffer and A. Grbic, *Phys Rev Lett* **110**, 197401 (2013)

10 GHz Screen thickness 1/5 of wavelength

Local control of electric and magnetic fields to achieve impedance matching

Metatronic Metasurfaces in Near IR

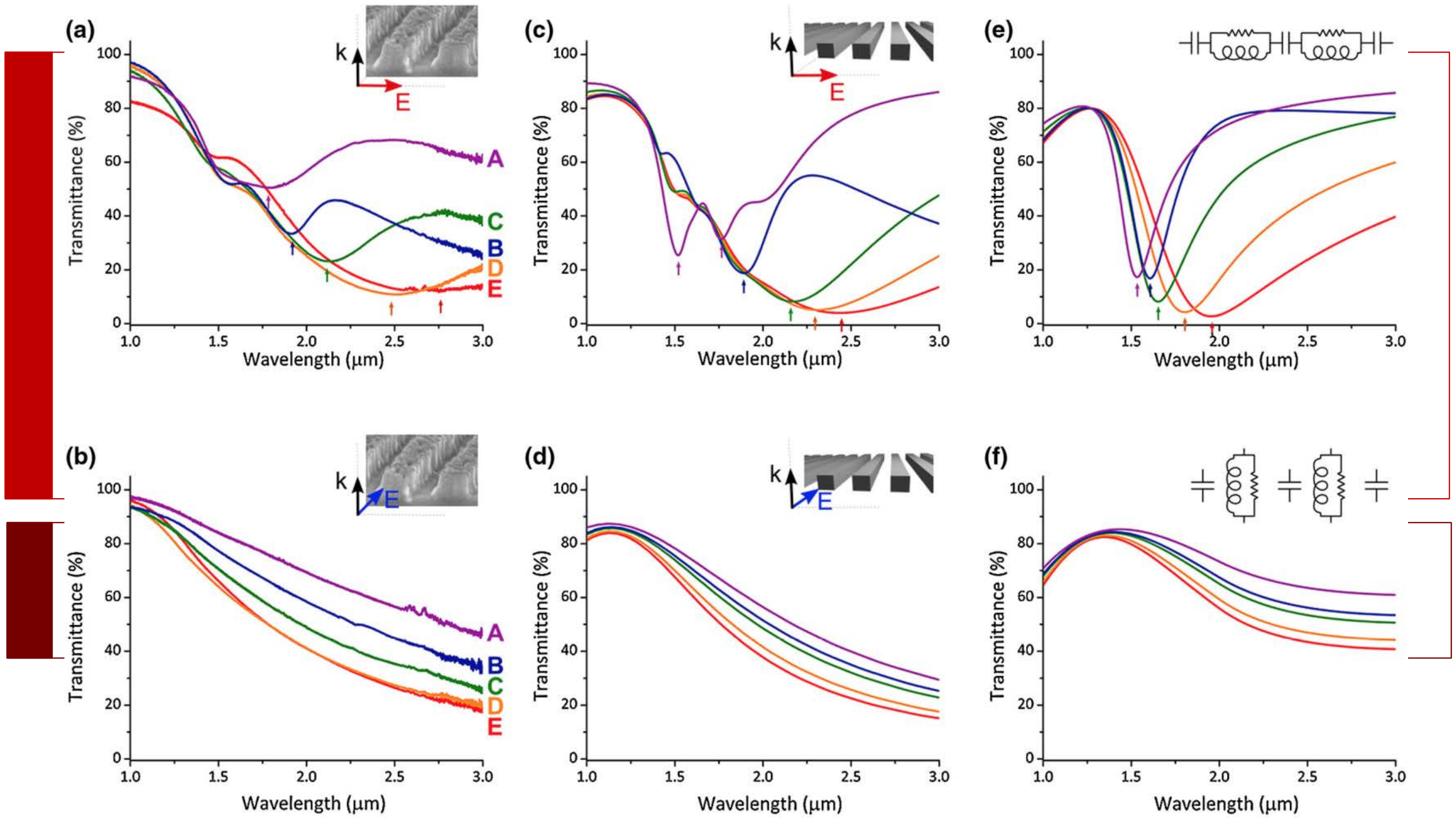
Caglayan, Hong, Edwards, Kagan, Engheta, Phys. Rev. Lett. 111, 073104 (2013)



These metasurfaces act as filters for the near IR regimes.

(a) The **E** field is perpendicular to the nanorods; therefore, nanoinductors (with nanoresistors) & nanocapacitors form a series combination, (b) the **E** field is parallel to the nanorods and thus they form a parallel

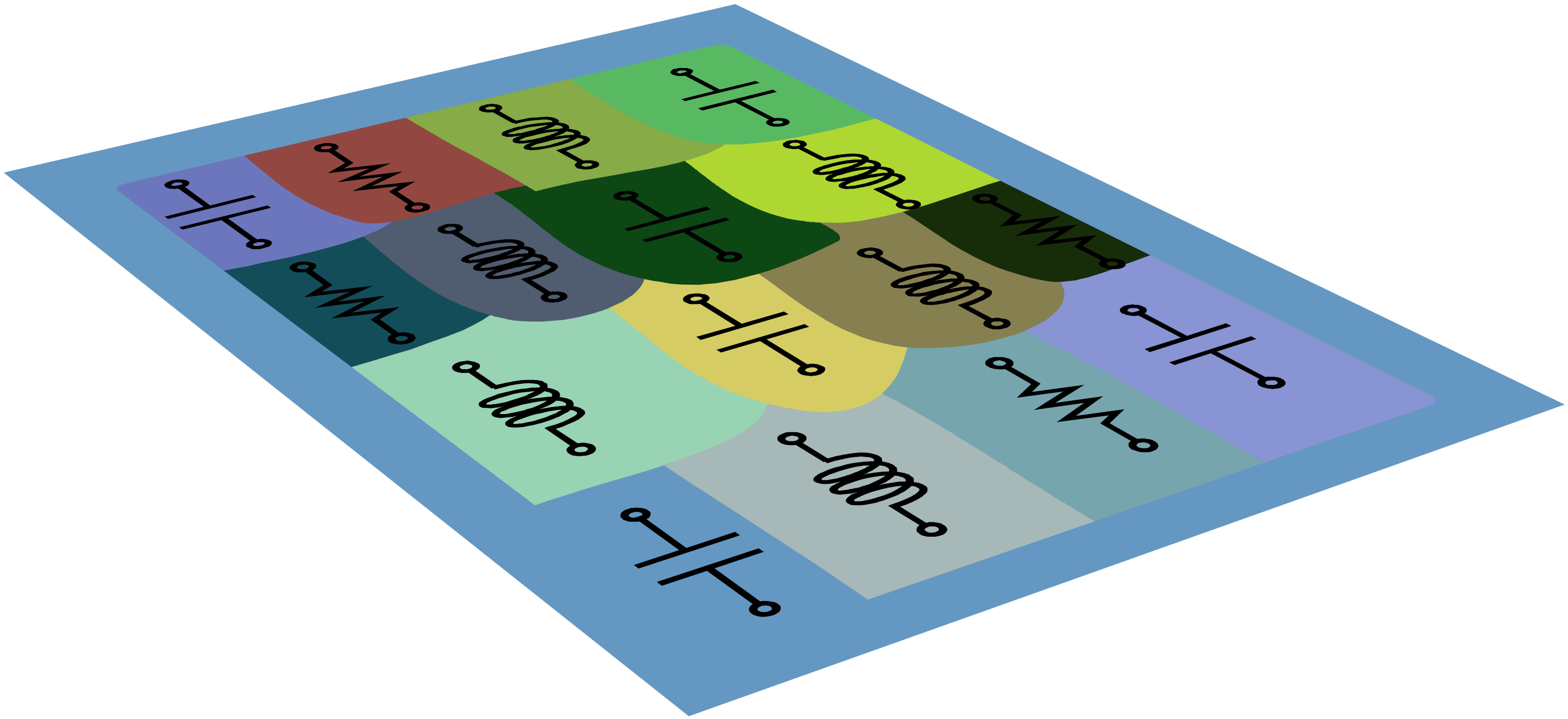
Metatronic Metasurfaces in Near IR



Caglayan, Hong, Edwards, Kagan, Engheta, Phys. Rev. Lett. 111, 073104 (2013)

One-Atom-Thick IR circuit metasurface

With proper choice of graphene conductivity for each patch (via electrostatic gating or chemical doping), we can envision one-atom-thick circuits in the mid IR, enabling one-atom-thick capacitor, one-atom-thick inductor, etc

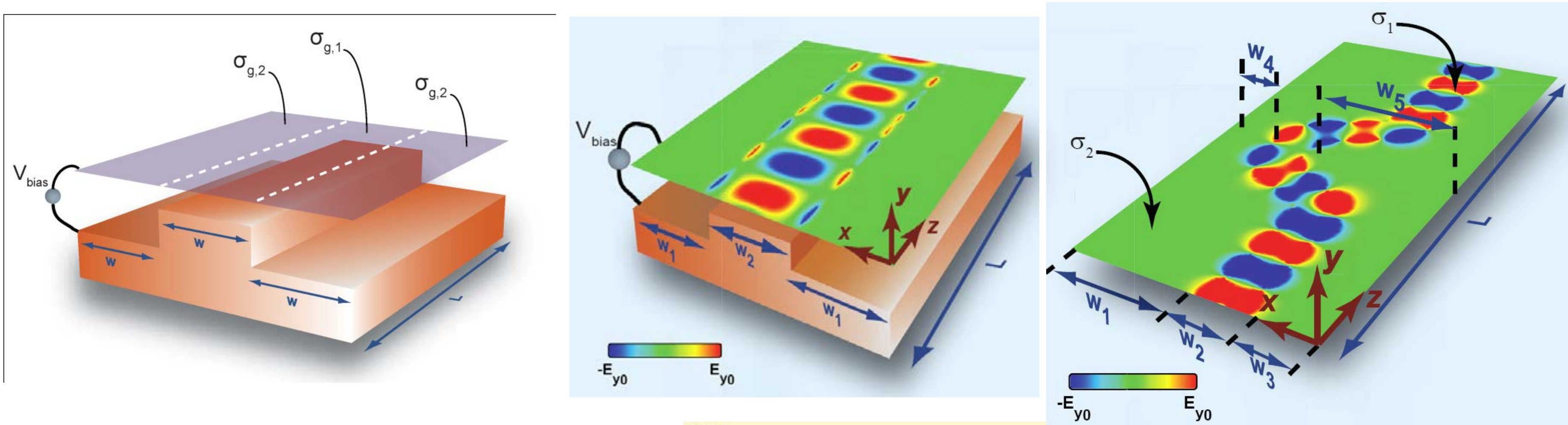


If $\mathrm{Im}(\sigma) > 0 \longrightarrow$ *Inductor* L

If $\mathrm{Im}(\sigma) < 0 \longrightarrow$ *Capacitor* C

N. Engheta, U Penn.

One-Atom-Thick Optical Devices

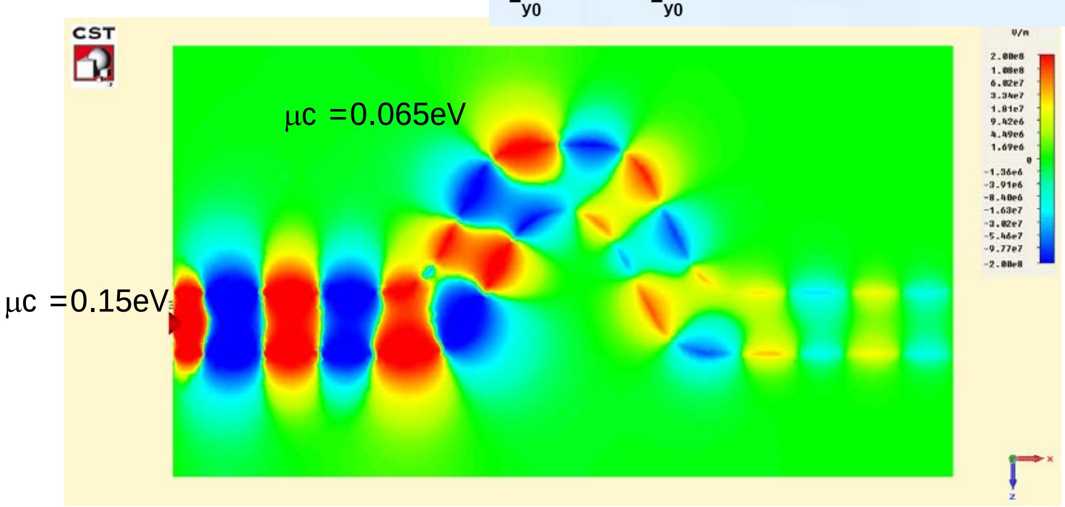


Region 1: $\mathrm{Im}(\sigma) > 0$

$$\mu_c = 150\ meV$$

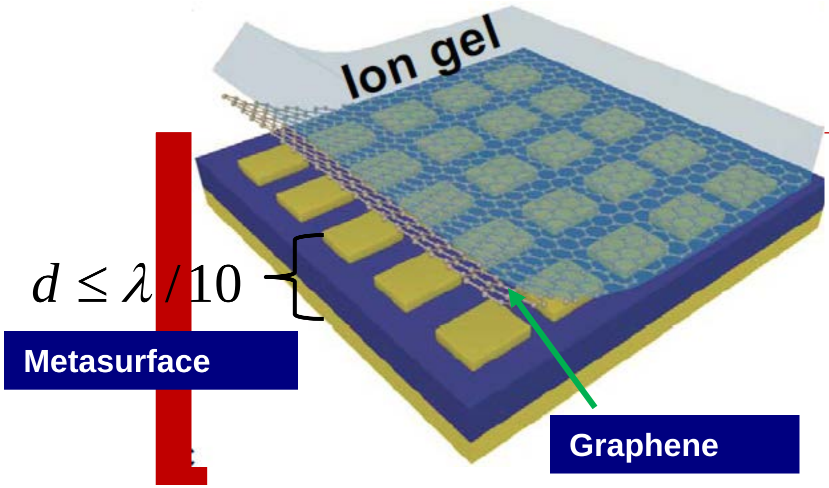
Region 2: $\mathrm{Im}(\sigma) < 0$

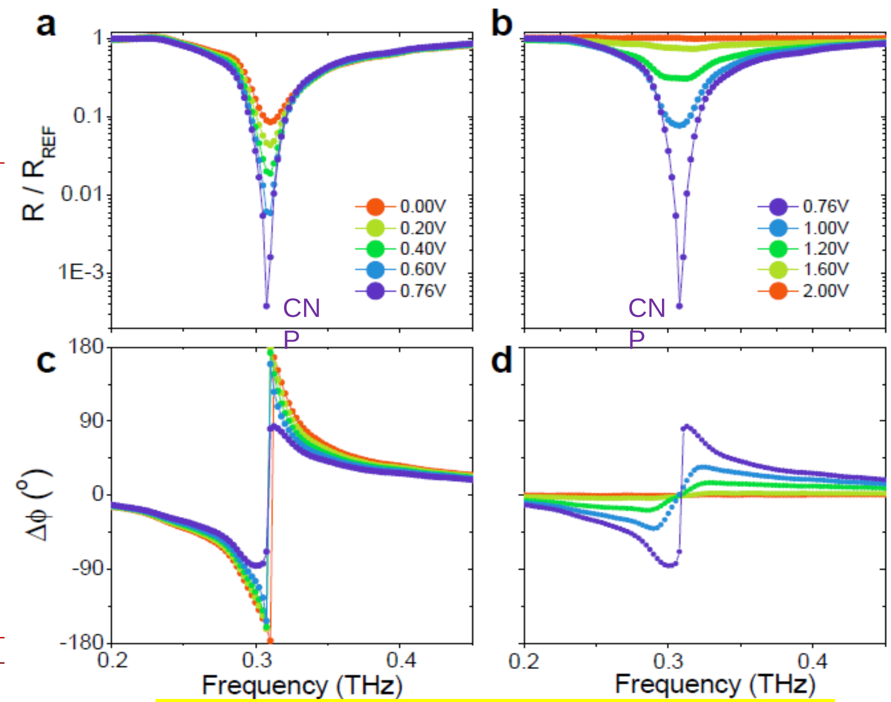
$$\mu_c = 65\ meV$$



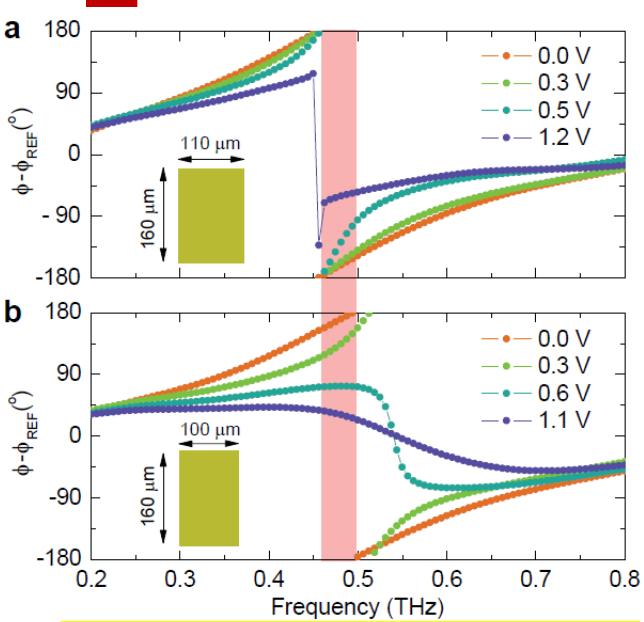
A. Vakil and N. Engheta, Science, 2011

Gate-controlled Graphene Metasurfaces for wide-range phase modulation





Amplitude/phase modulation (Expt.)



Nearly full-range phase modulation

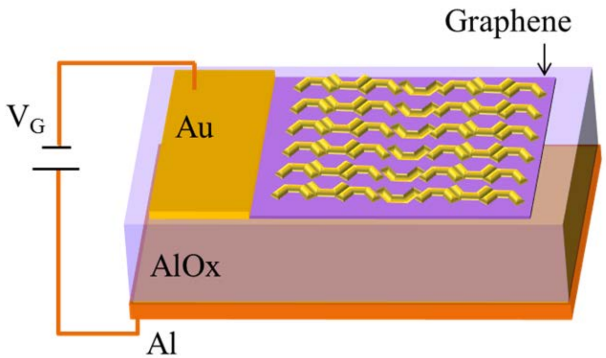
- **Gating graphene can dramatically modify the reflection-phase spectra of the coupled system**
- **Nearly full-range phase modulation realized with two independently gated “bits”.**

Lei Zhou’s group Fudan U.

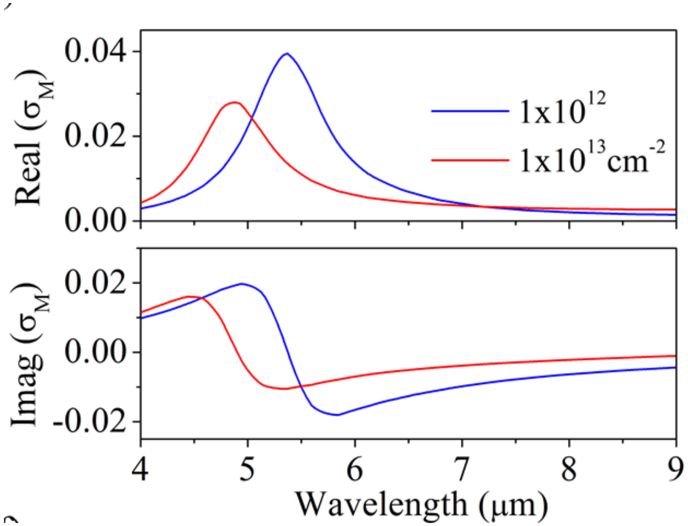
Miao *et al*., arXiv:1409.6845

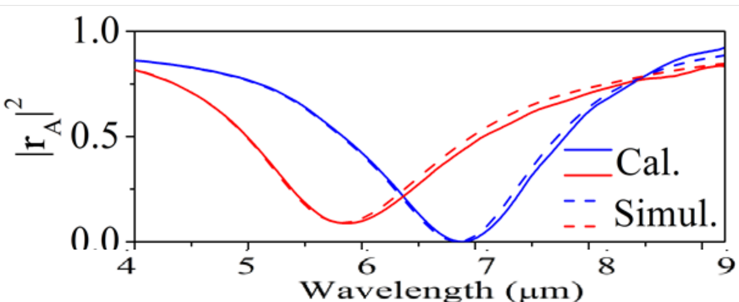
Tunable metasurface absorber: Theory

Y. Yao, et. al, *Nano Lett.*.4, 6526 (2014)



- Resonance peak of the metasurface conductivity tuned by changing the gate voltage
- → reflection minimum of the entire structure is blue shifted

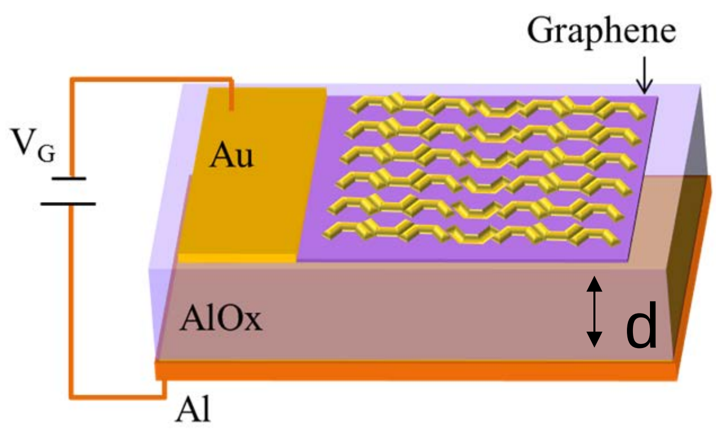




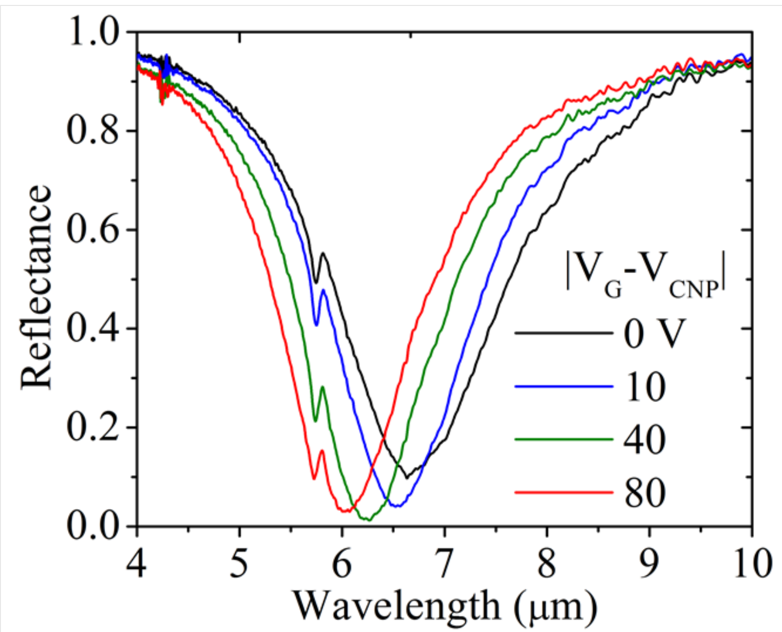
- **The phase shift of the reflection coefficients can be any value instead of the typical 0 or π as long as the optical conductiviyt σ_M is a complex number.**
- **As a result, the critical coupling condition in the metasurface resonator cannot be reduced to separate conditions for loss and roundtrip phase, as in most well studied resonators.**
- **The roundtrip phase accumulation 2βd does not have to be close to π, which makes it possible to achieve the critical coupling condition with a much smaller dielectric layer thickness d than the wavelength.**

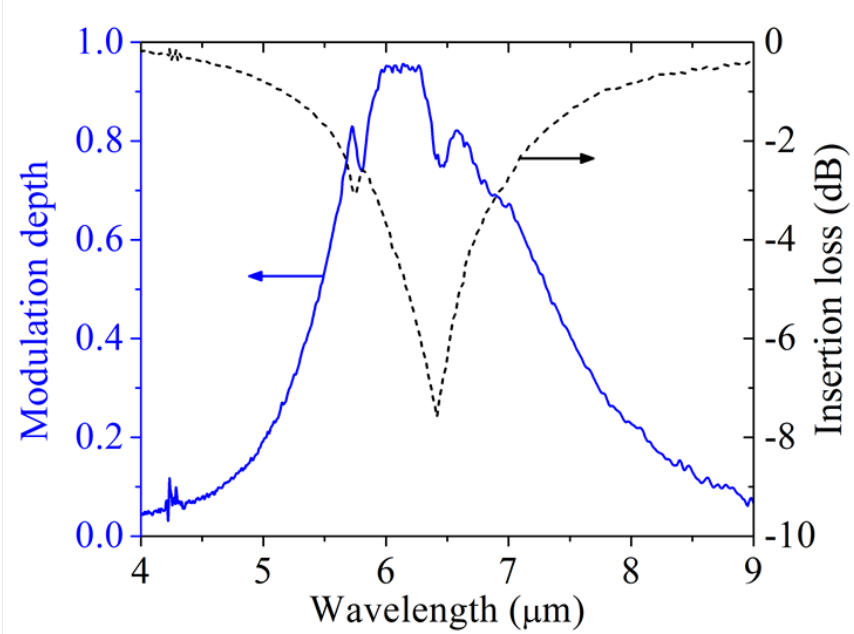
Tunable metasurface absorber: Experimen

Y. Yao, et. al, *Nano Lett.*.4, 6526 (2014)



- Maximum modulation depth : >95%
  - Optimizing the design will lead to modulation depth = 100%
- Bandwidth: 2 µm (5 µm-7 µm, for modulation depth > 50%)
- Modulation speed estimated ~1.2GHz

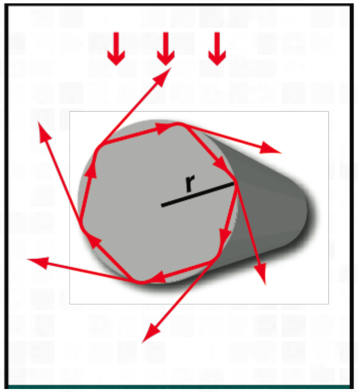




Resonant Optical Properties of Semiconductor Structures

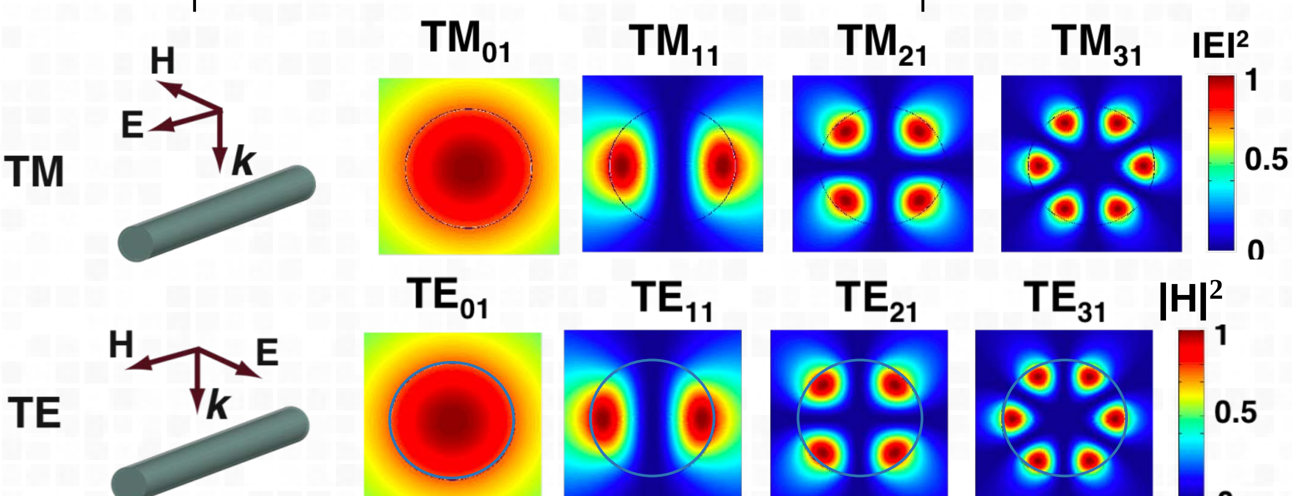
Example: Optical properties of high index semiconductor nanowires

- Free space photons can couple to Mie or leaky mode resonances



Intuitive resonance condition: $m\lambda_{eff} = 2\pi r$

- For top-illumination resonances split in TM and TE modes



Nomenclatur

e $\mathbf{TM_{ml}}$

m: # wavelengths
l : # radial maxima

Cao, et al., Nano Lett., 2649, 10, 2010.

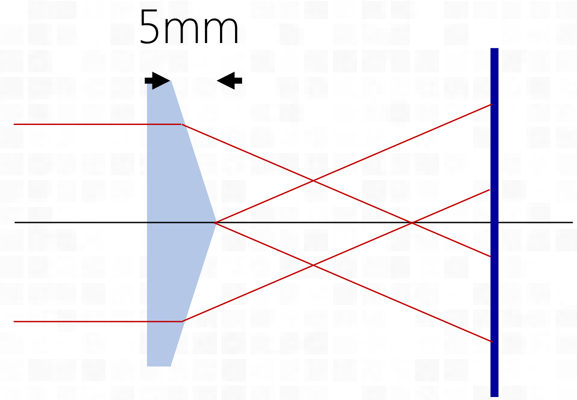
Cao, et al., Nano Lett., 10, 439 (2010).

Axicons based on Si Gradient Metasurfaces?

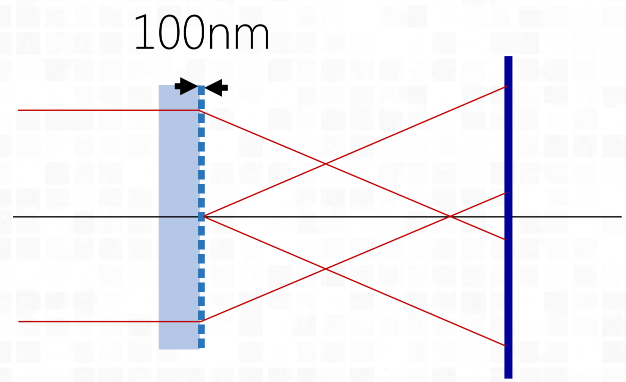
Example: Construction of a Si-based axicon

Conventional Axicon

Ref. Thorlabs.com

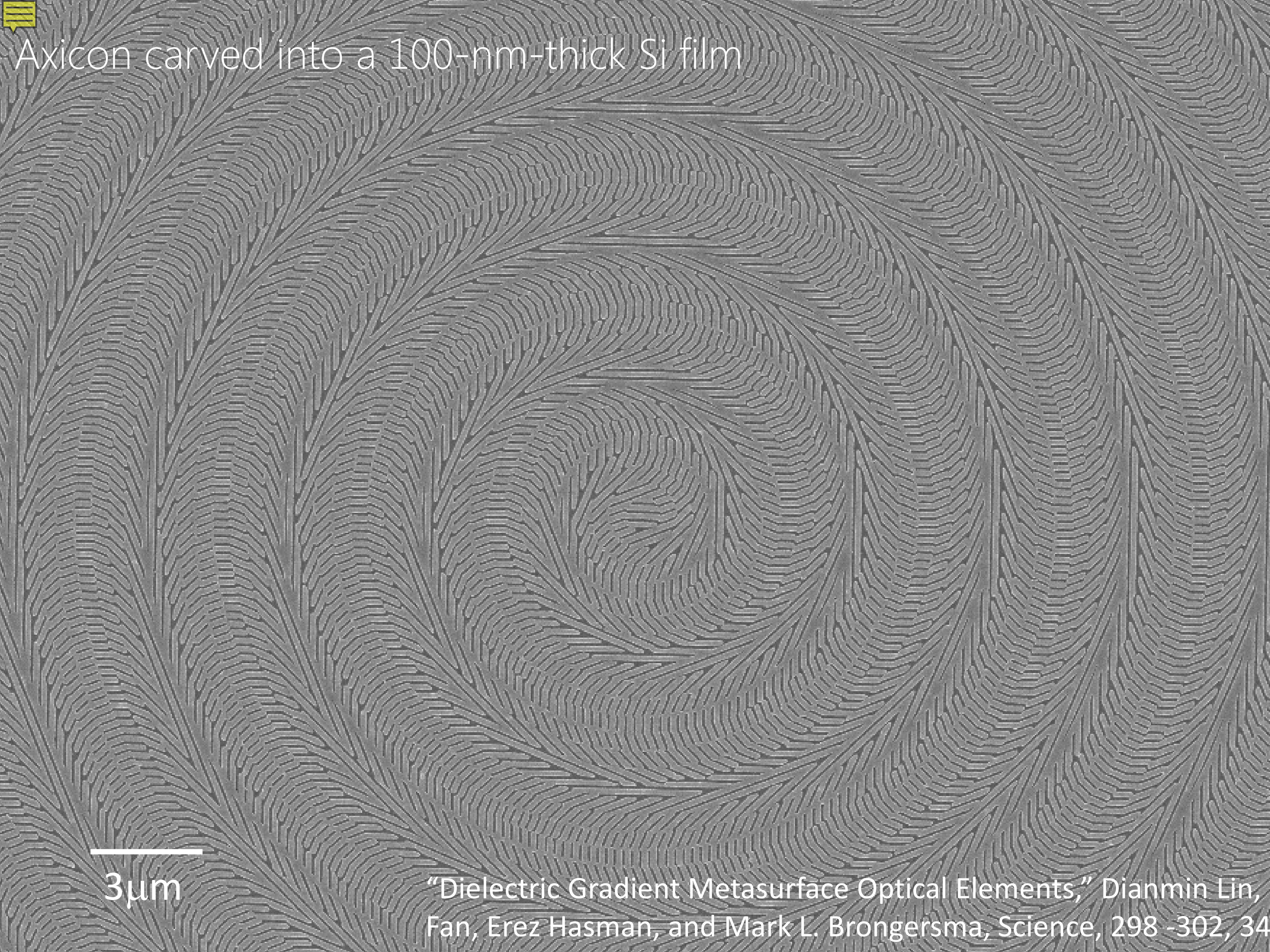


Gradient Metasurface



Phase discontinuities

Axicon carved into a 100-nm-thick Si film

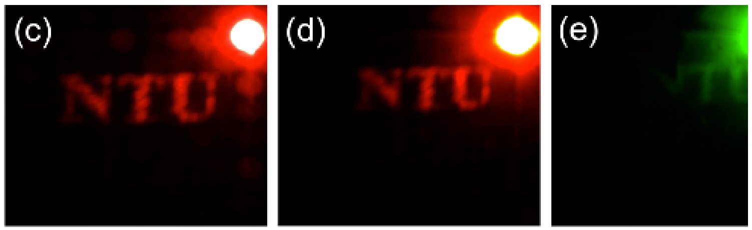


“Dielectric Gradient Metasurface Optical Elements,” Dianmin Lin,
Fan, Erez Hasman, and Mark L. Brongersma, Science, 298 -302, 34

Broadband Metasurface

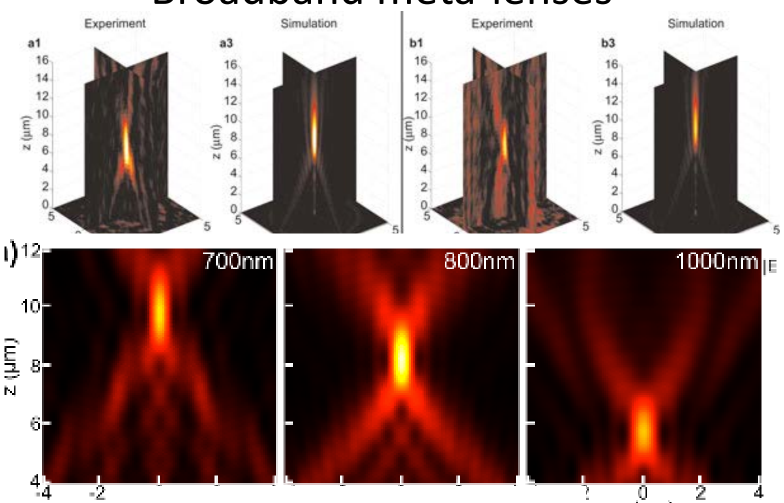
Broadband light bending

Broadband Holograms

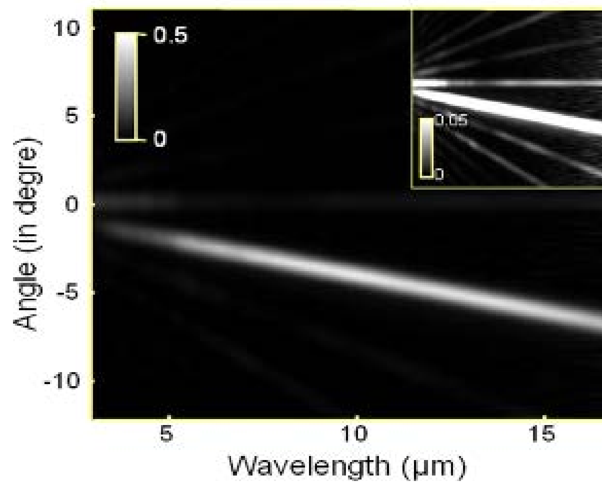


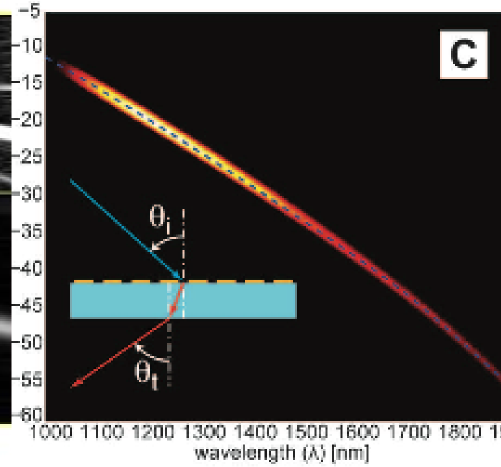
Chen et al, Nano Letters 14 2014

Broadband meta-lenses



Ni et al, Nature Light 335 2012
Pors et al Nano Letterts 13 2013

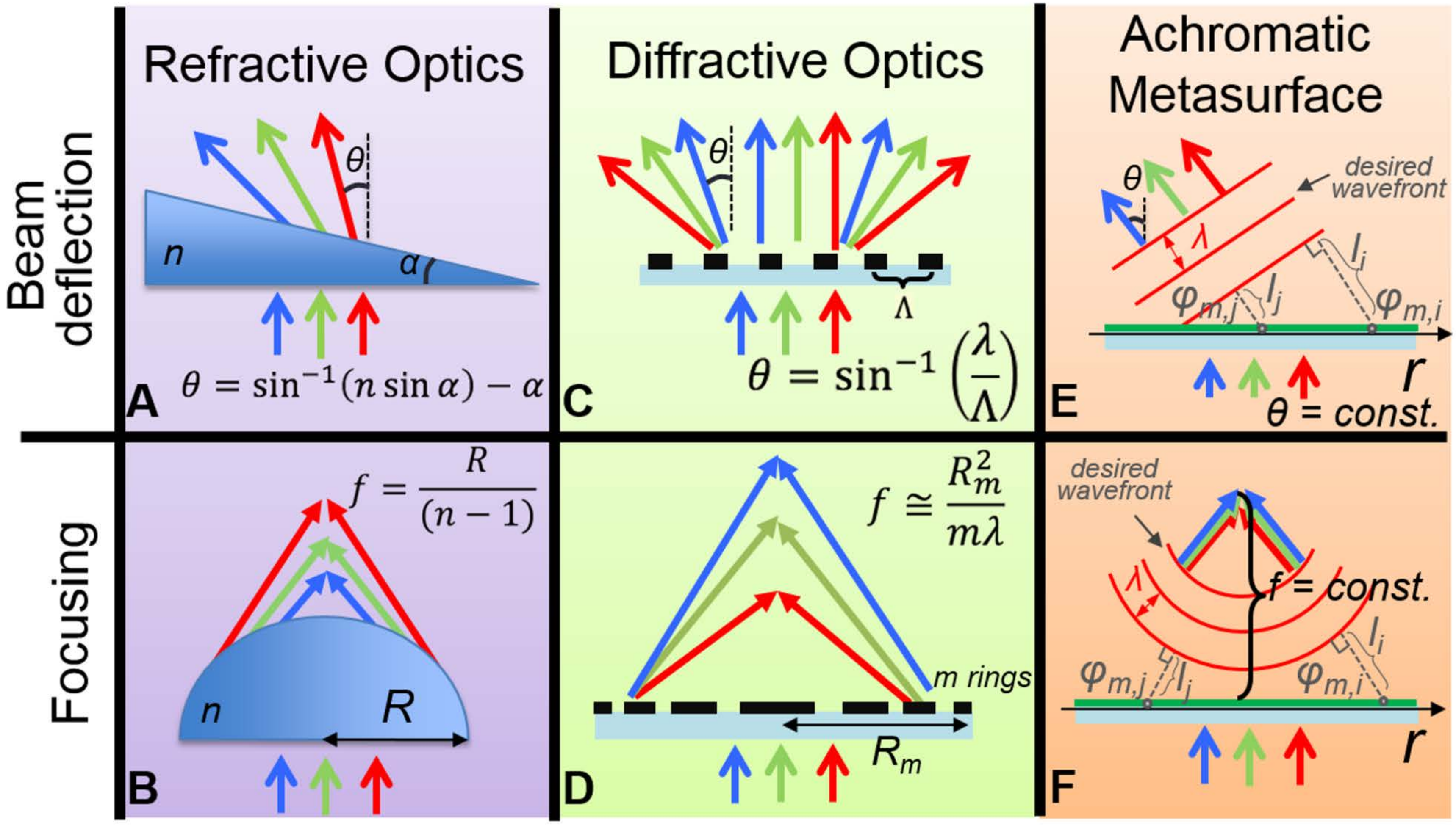




Yu et al, *Science* 334, (2011)
Ni et al, Science 335 (2012)
Ribot et al, Adv. Opti.Mater. vol 1, 7 2013

Not achromatic due to dispersive behavior

Achromatic Optics with Metasurfaces



F. Aieta et al. Science *347, 1342 (2015)*

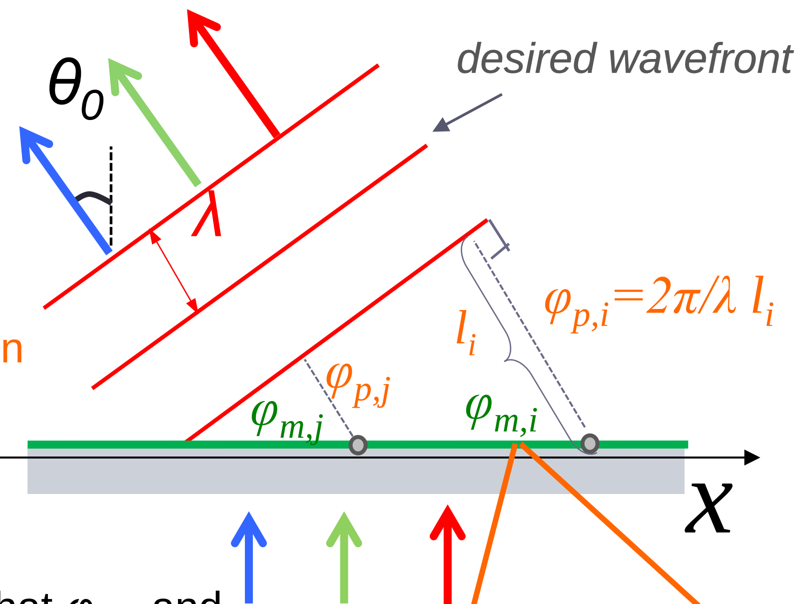
Achromatic Metasurface

total accumulated phase

$$\varphi_{tot}(r,\lambda) = \varphi_m(r,\lambda) + \varphi_p(r,\lambda)$$

matasurface phase — propagation phase

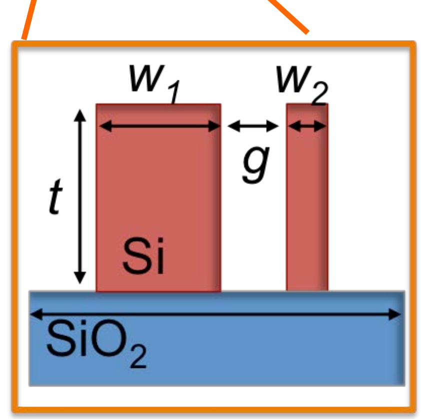
Constructive interference: Same phase for all light paths



- Chromatic effects can be overcome by compensating the **dispersion** of the propagation phase with the **wavelength-dependent phase shift** imparted by a metasurface consisting of **subwavelength resonators**
- The phase shifts $\varphi_{m,i}$ and $\varphi_{m,j}$ are designed so that $\varphi_{tot,i}$ and $\varphi_{tot,j}$ are the same (modulo 2π) at different wavelengths

$$\varphi_m(x,\lambda_i) = -\frac{2\pi}{\lambda_i}\sin\theta_0\, x$$

- The basic unit of the achromatic metasurface are **low-loss coupled dielectric resonators** that can be designed to adjust the scattered phase at different wavelengths

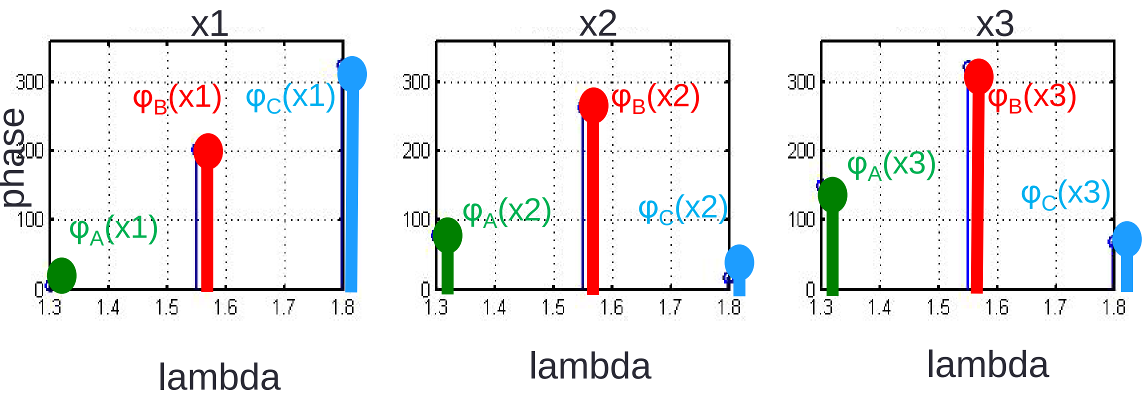


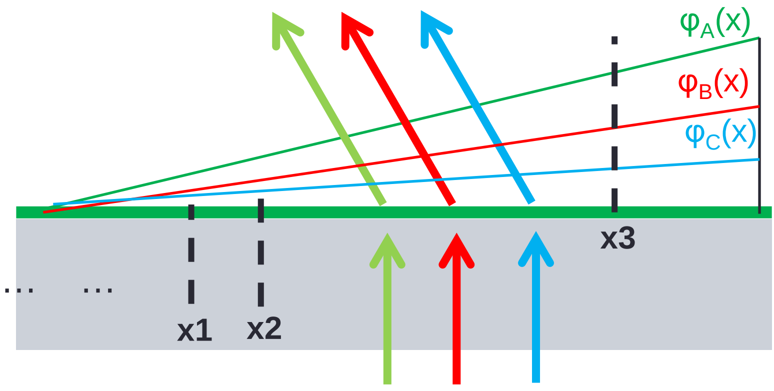
Coupled Rectangular Dielectric Resonator

F. Aieta et al. Science *347, 1342 (2015)*

Dispersion-less light bending

- Chromatic effects can be overcome by compensating the **dispersion** of the propagation phase with the **wavelength-dependent phase shift** imparted by a metasurface

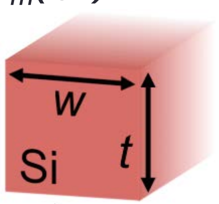




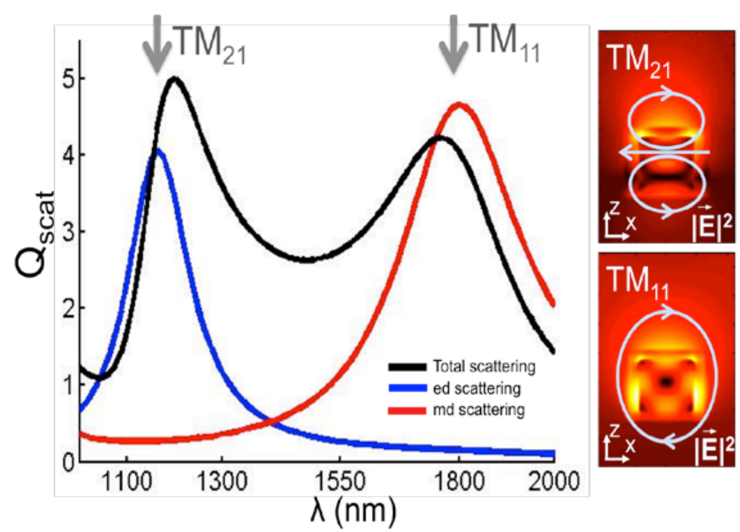
λ-independent

$$\varphi_m(x,\lambda_i) = -\frac{2\pi}{\lambda_i}\sin\theta_0\, x$$

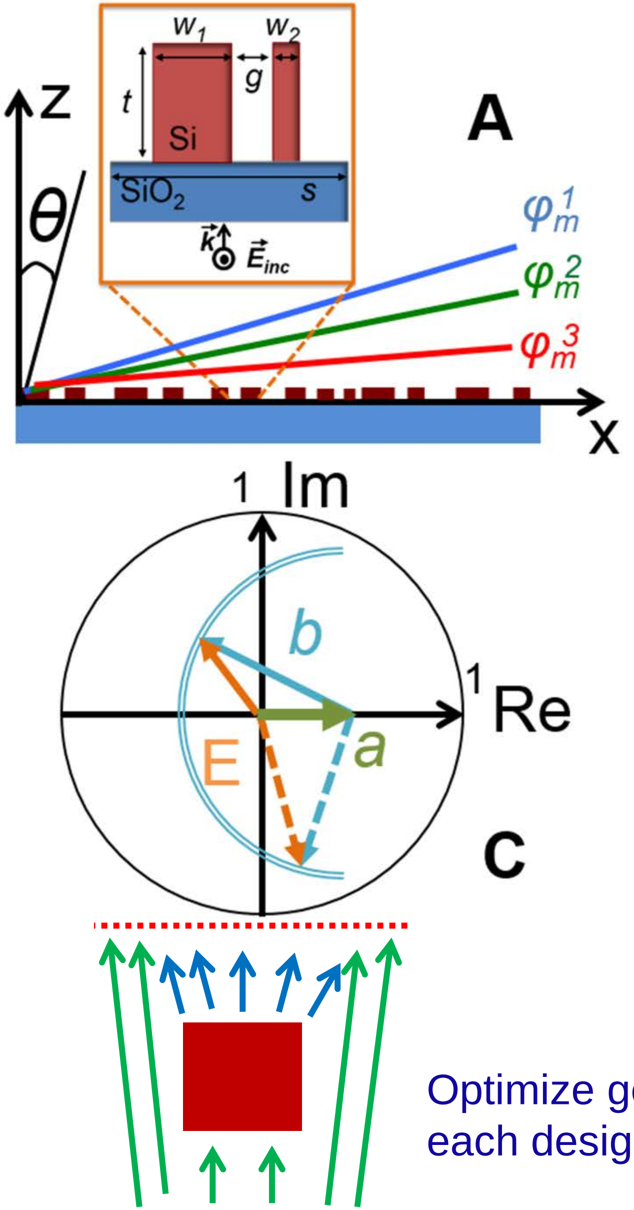
The resonators have to be designed to adjust the scattered phase at different wavelengths $\varphi_m(r,\boldsymbol{\lambda})$ in order to satisfy this equation

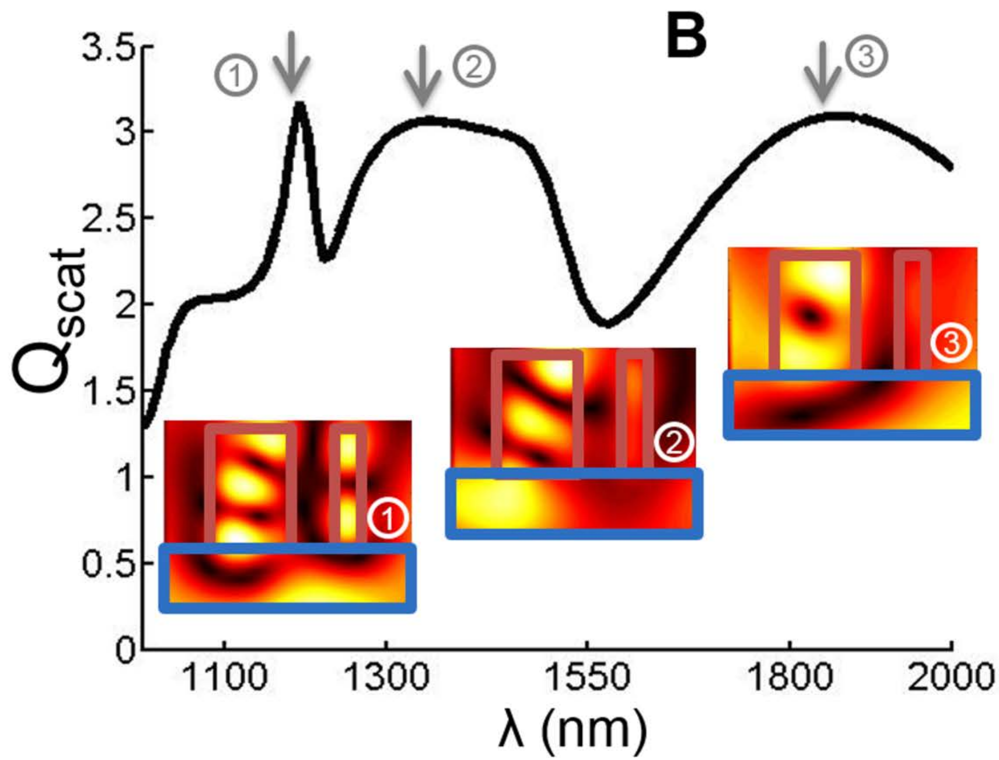


- moderate permittivity dielectrics
- several modes (dense spectrum)
- design flexibility
- low-loss



Coupled Rectangular Dielectric Resonator Design





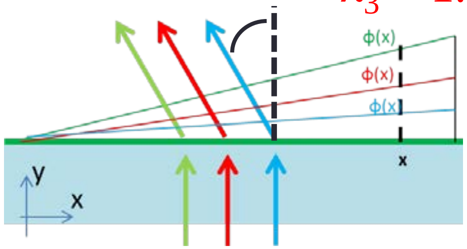
Aperiodic metasurface

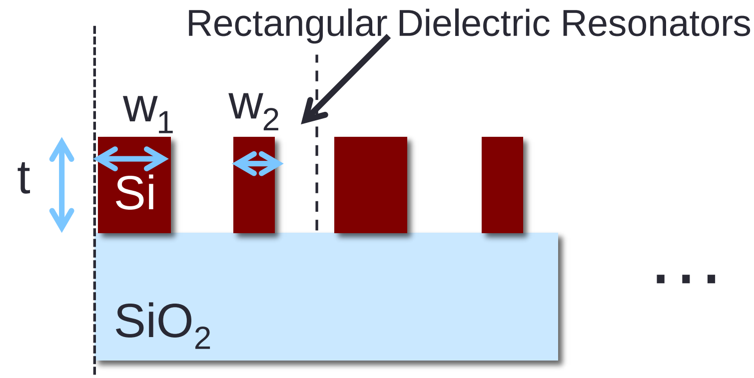
Optimize geometry of each unit cell to obtain the desired phase response at each design wavelength ~ uniform transmitted amplitude for all the unit cells

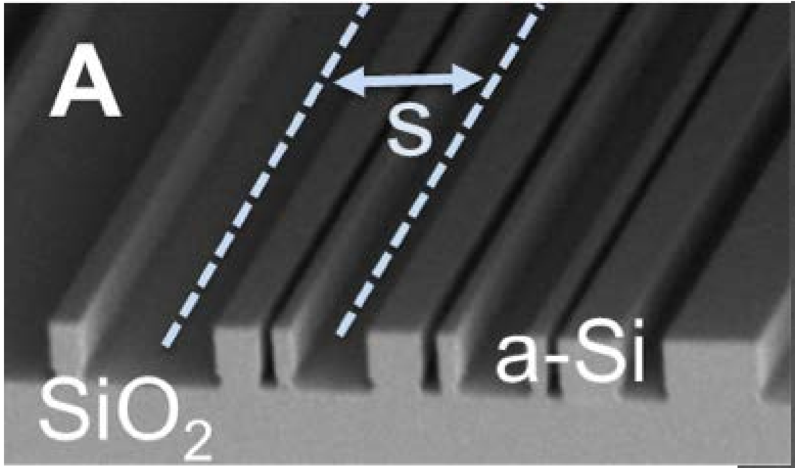
Dispersion-less light bending

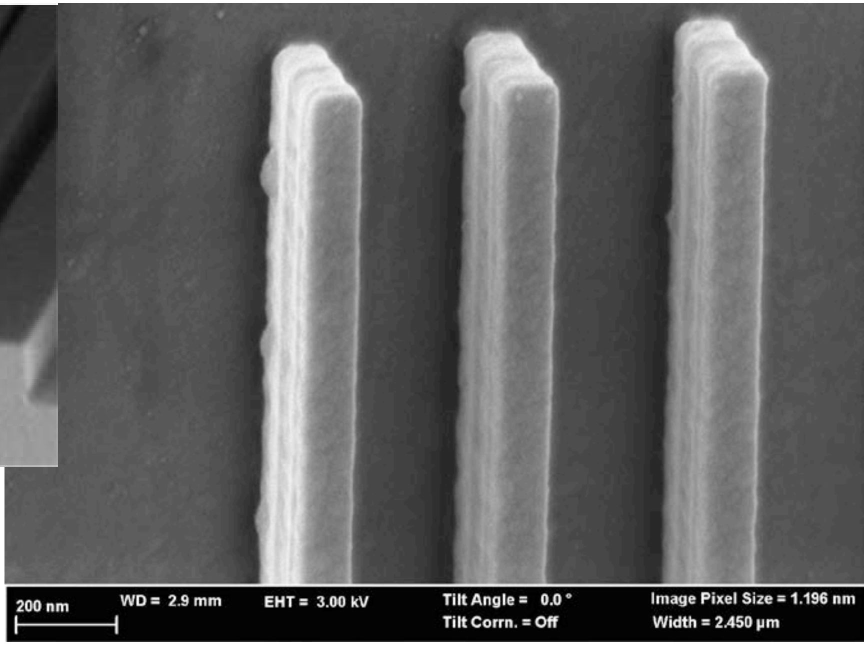
$\lambda_1 = 1.3\ \mu m$
$\lambda_2 = 1.55\ \mu m$
$\lambda_3 = 1.8\ \mu m$

ϑ_0 =-17 deg





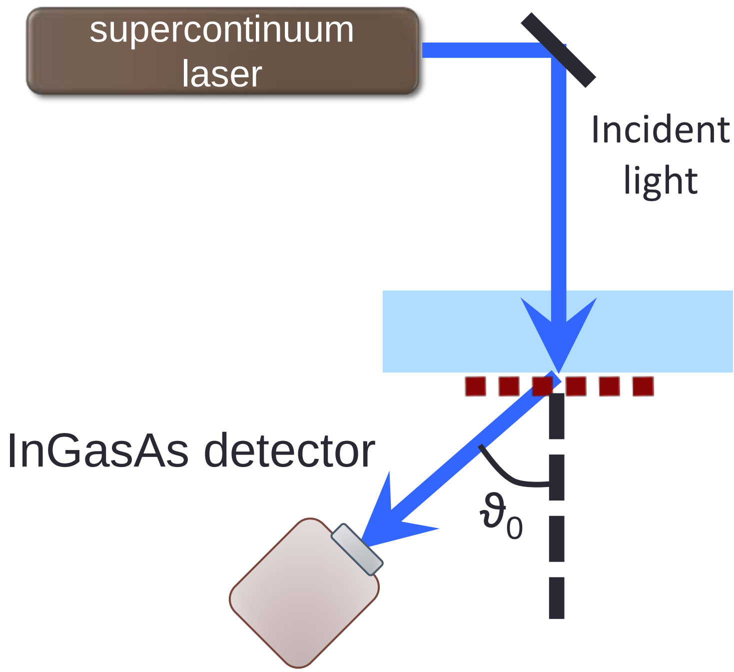




unit cell with geometry *s*=1 µm, *t*=400 nm, w_1=300 nm w_2=100 nm and *g*=175 nm.

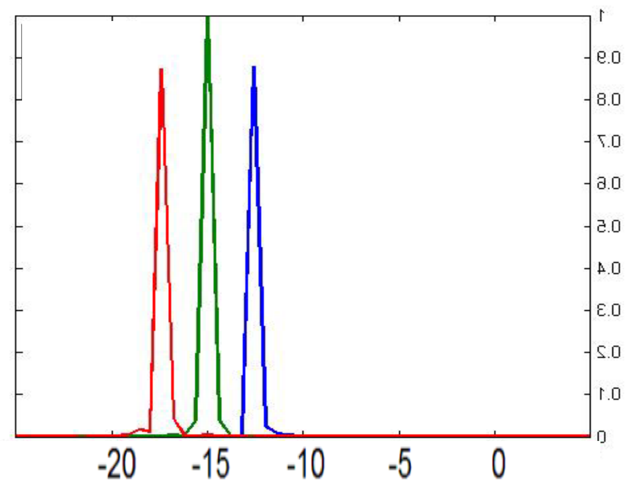
400 nm amorphous silicon (a-Si) on a fused silica (SiO_2) substrate by PECVD
240 µm X 240 µm metasurface of 240 unit cells

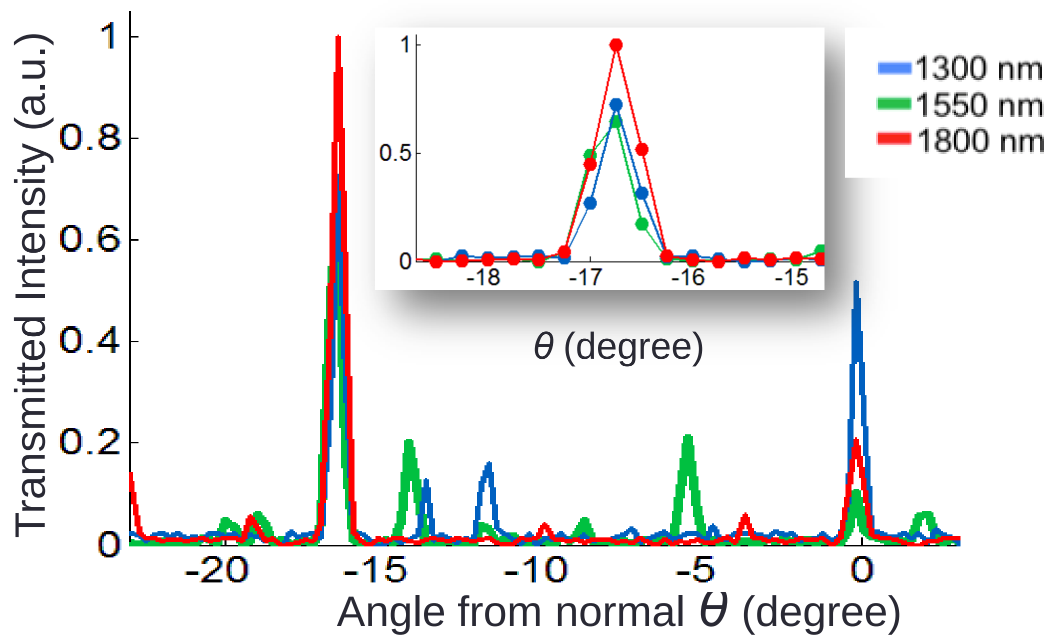
Dispersion-less beam deflector



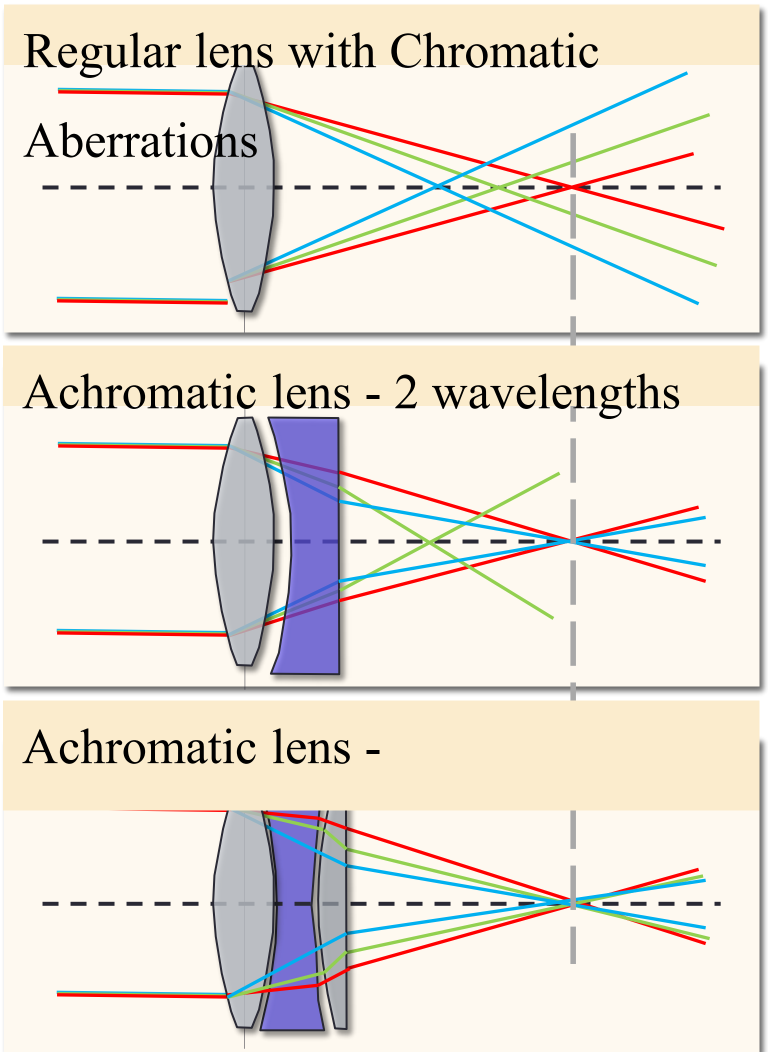
Experiment

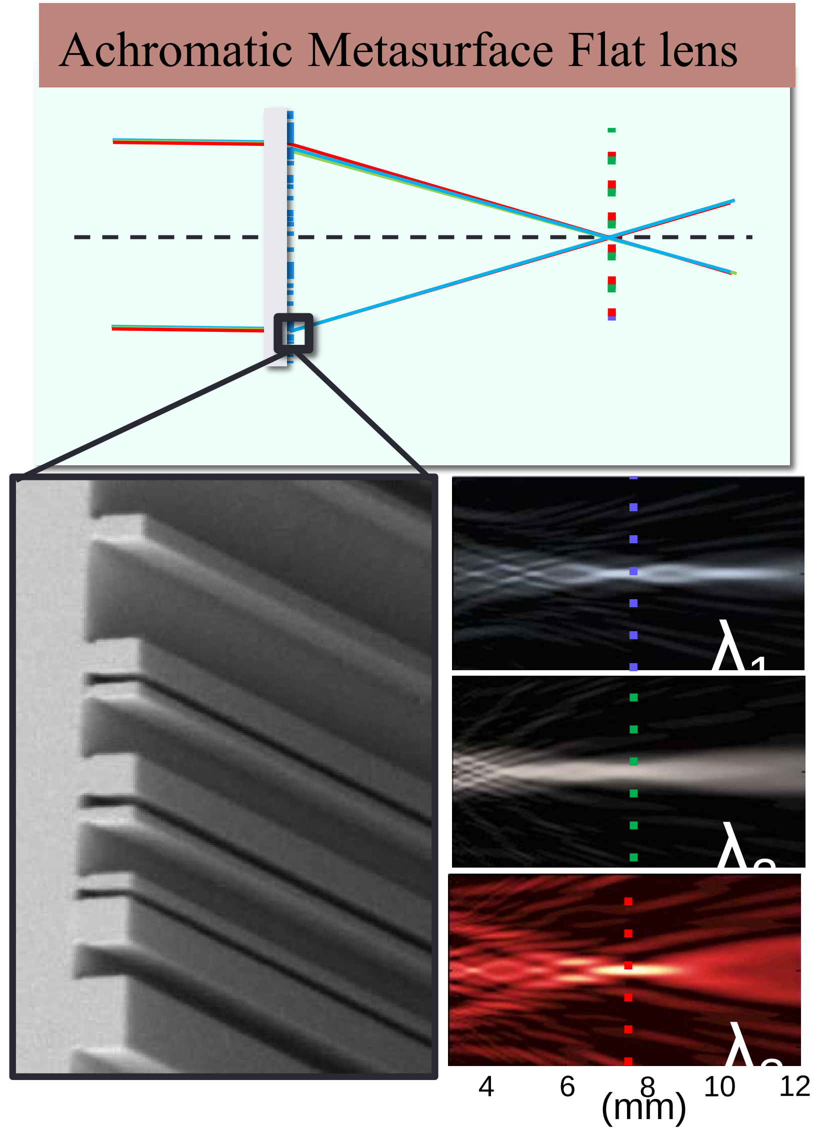
Dispersive grating





Achromatic lenses

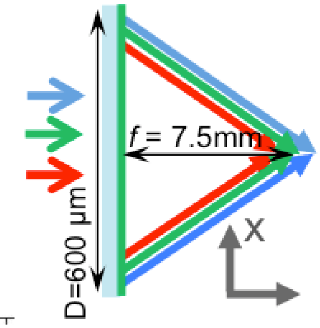




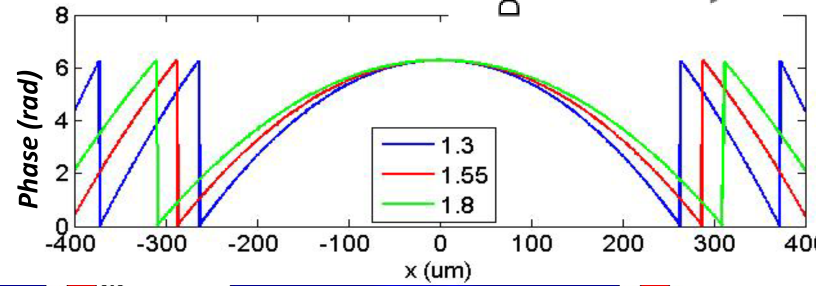
F. Aieta et al. Science *347, 1342 (2015)*

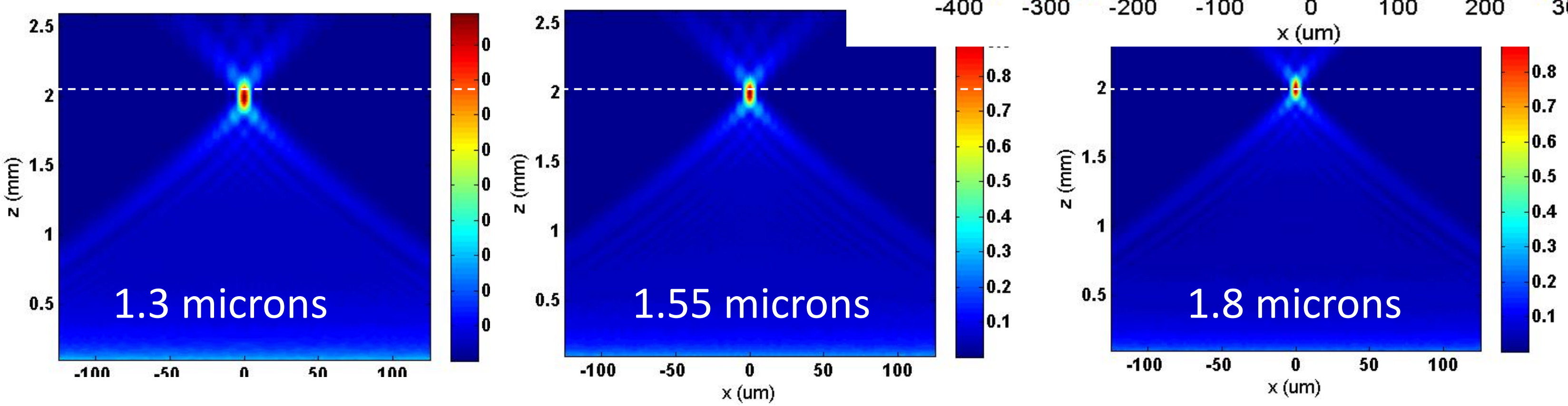
Achromatic Flat Lens

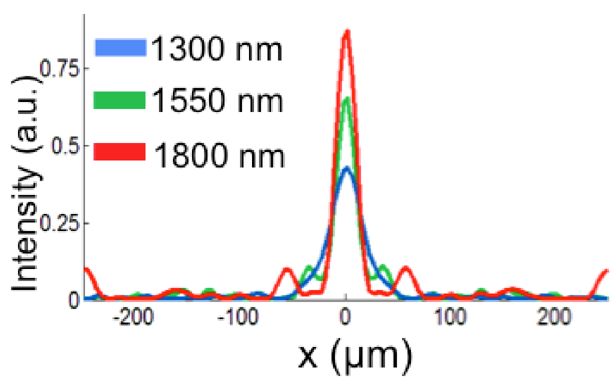
The FLAT LENS imparts with the right amount of optical path difference at each wavelength :

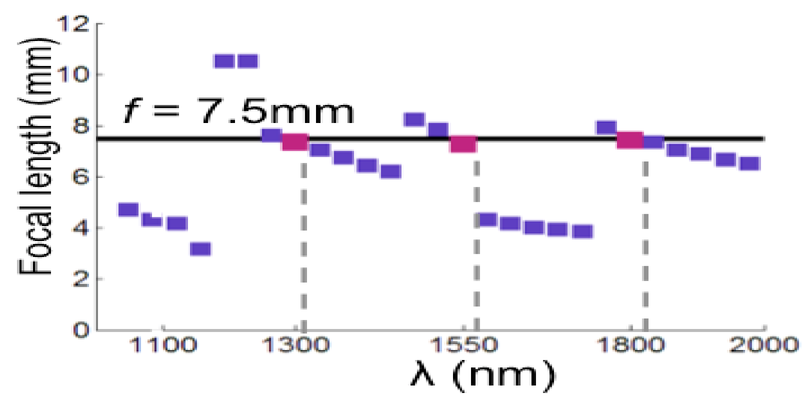


$$\varphi_m(x,\lambda_i) = -\frac{2\pi}{\lambda_i}\left(\sqrt{x^2+f^2}-f\right)$$



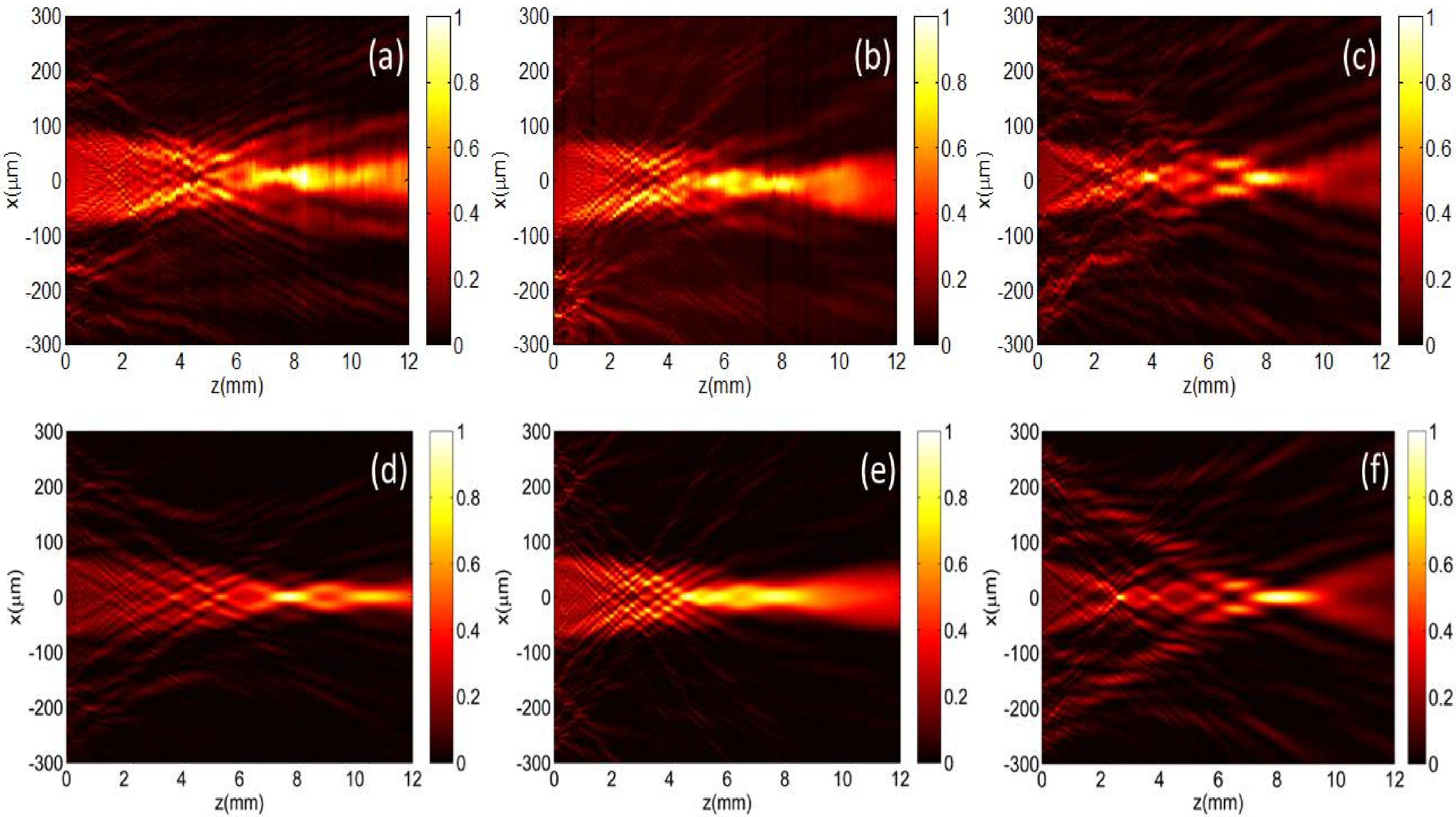






Measured intensity for three wavelengths along the optical axis

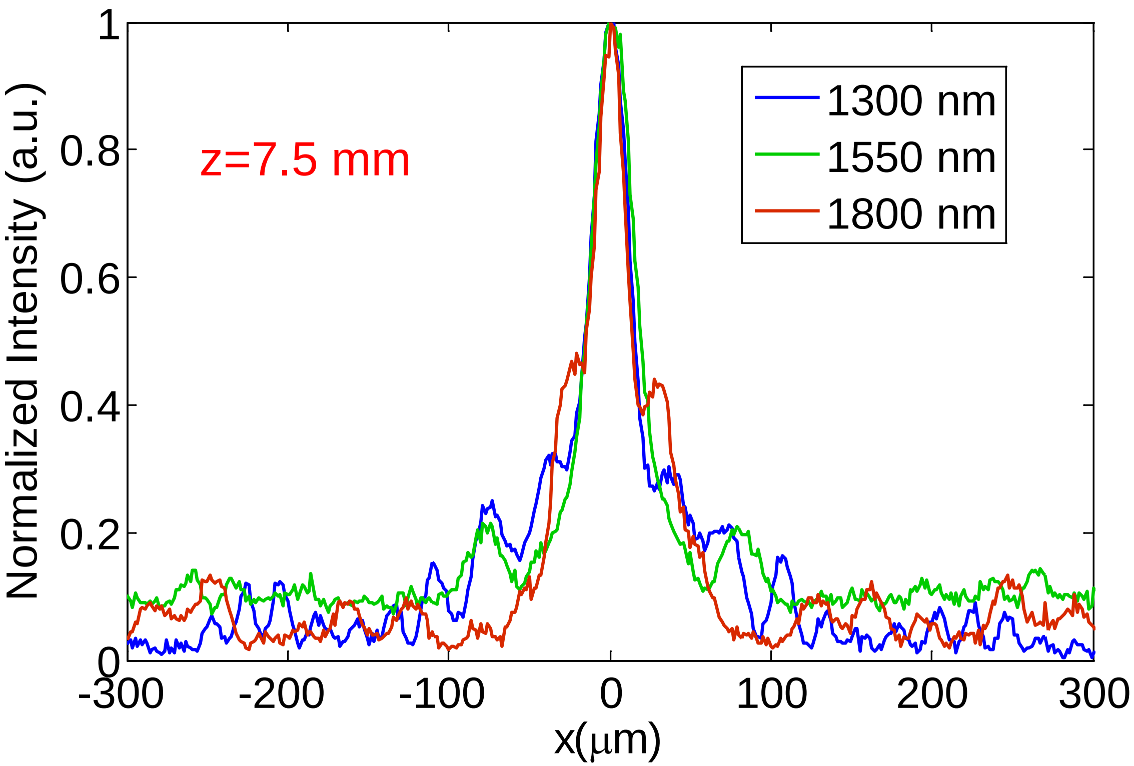
λ=1300 nm λ=1550 nm λ=1800 nm



Top: Experiments
Bottom: Simulations

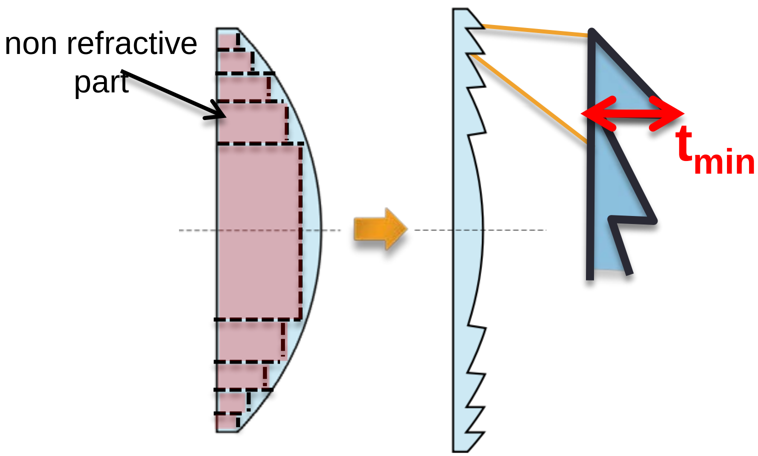
Reza Khorasaninejad et al. Unpublished (2015)

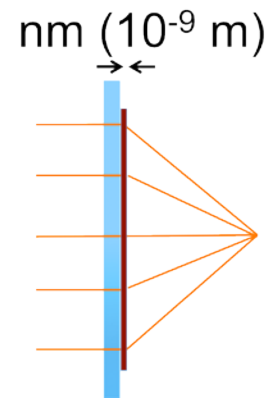
Intensity distribution in the focal plane



unpublished (2015)

Fresnel Optics vs Metasurface Based Optics





Fresnel Optics	Metasurface
finite lateral phase control	sub wavelength phase control
polarization insensitive	polarization control
multi wavelength operation hard	**controlled dispersion: achromatic**
multiple steps of lithography: N phase level→$\log_2$ N steps	**single lithographic step**

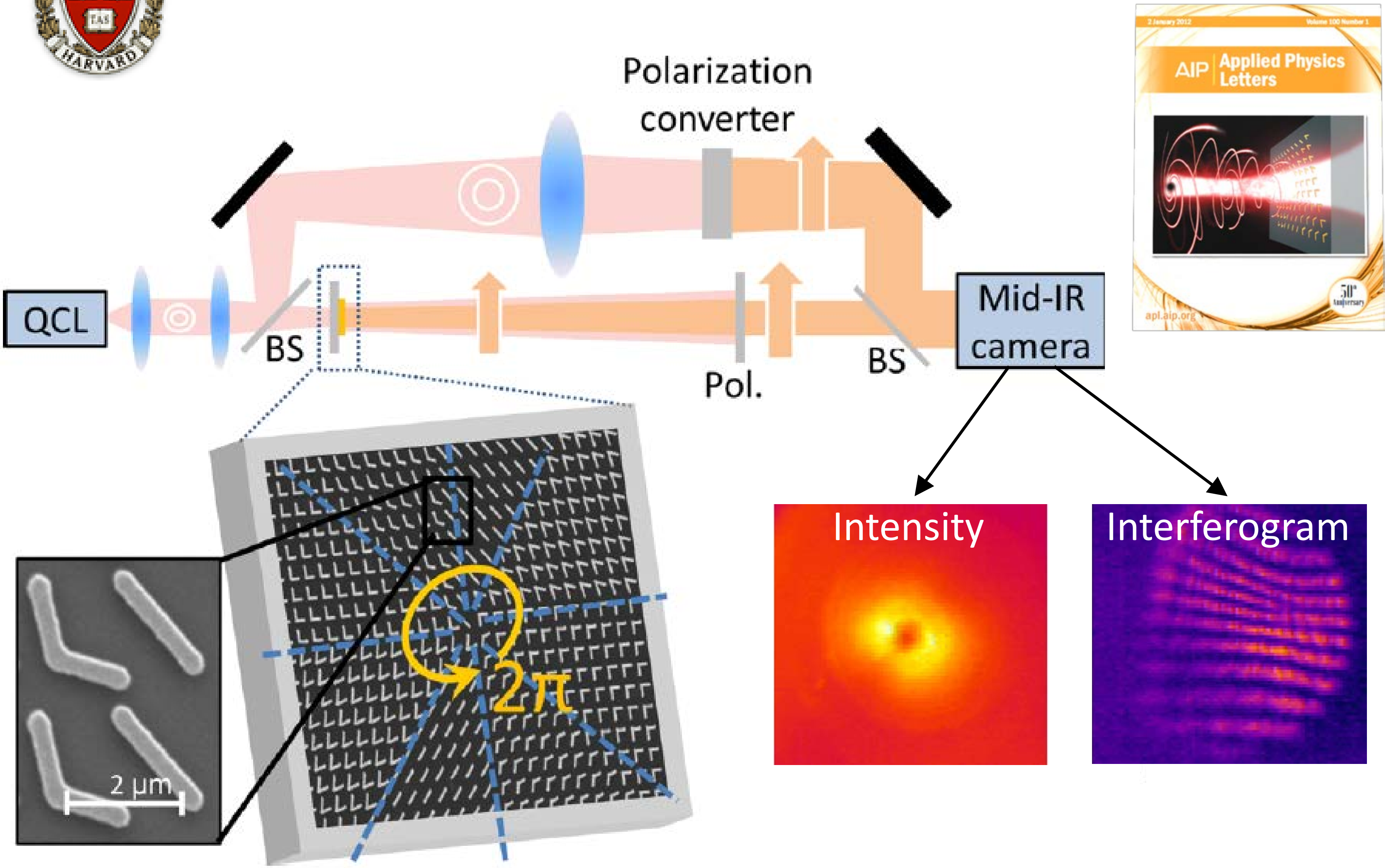
Diffractive optics based on metasurfaces

- Technology simplification:
  Bernard Kress (Google) “a single digital pattern (one mask level) can create an arbitrary analog phase profile”

Topics

- Wavefront Control: amplitude, phase, polarization (transmittarrays & reflectarrays)
- Gradient and Huyghens metasurfaces
- Flat optical components
- Graphene (VdW Heterostructures)metasurfaces
- Aberrations and Achromatic metasurfaces
- **Structured Light: vector beam generation**
- **Holographic metasurfaces**
- Active (Nonlinear Optical) Metasurfaces
- Waveguide control: guided and frees space mode conversion
- Polarization controlled routing
- Materials

Vortex plates based on metasurfaces



P. Genevet et al., *Appl. Phys. Lett.* **100**, 13101 (2012)

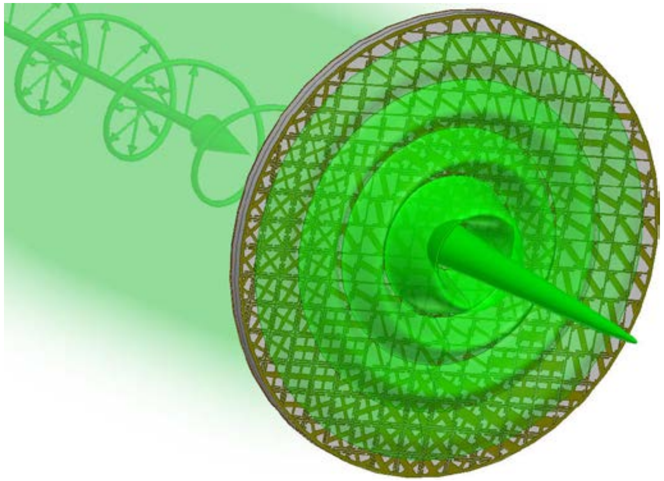
Gaussian-to-Bessel transformer

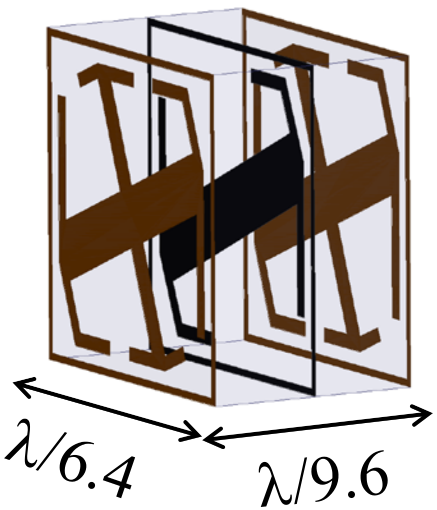
C. Pfeiffer, A. Grbic, *Physical Review Applied*, 2, 044012, 2014.

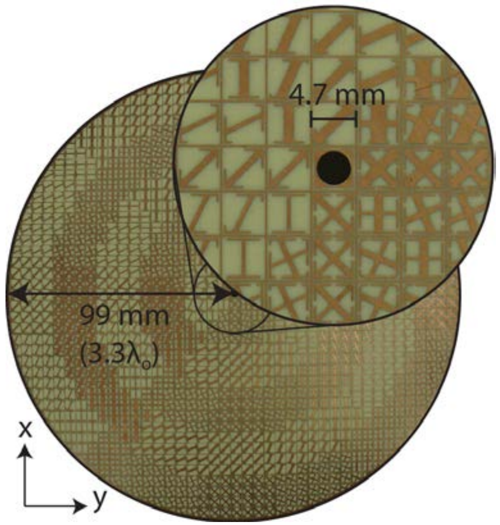
- Anisotropic and inhomogeneous metasurfaces allow for simultaneous control of the wavefront and its polarization.

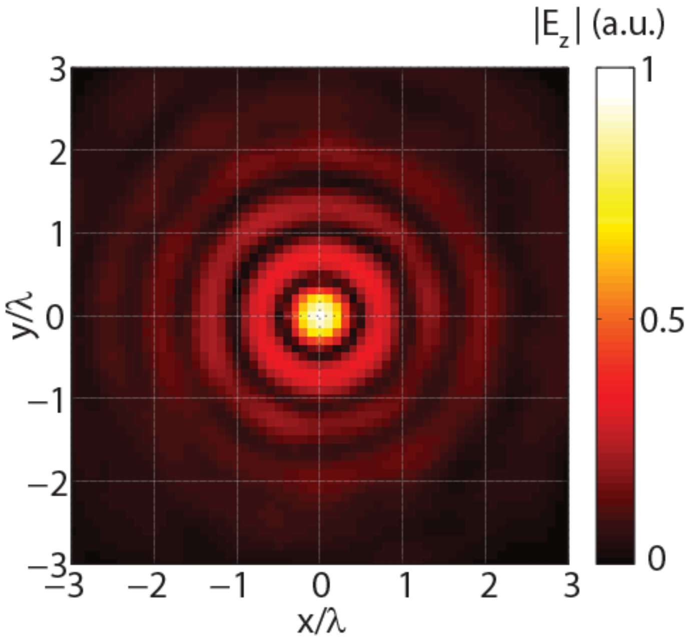
- Metasurface was designed to transform an incident Gaussian beam into a radially polarized Bessel beam.

- Each unit cell provides 360º phase coverage for wavefront control and acts as a waveplate for polarization control

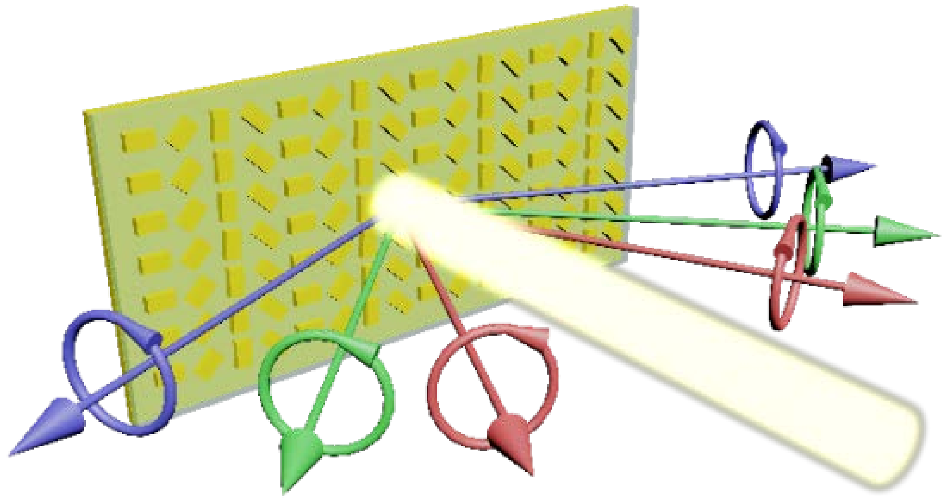








Circular Dichroism Spectrometer



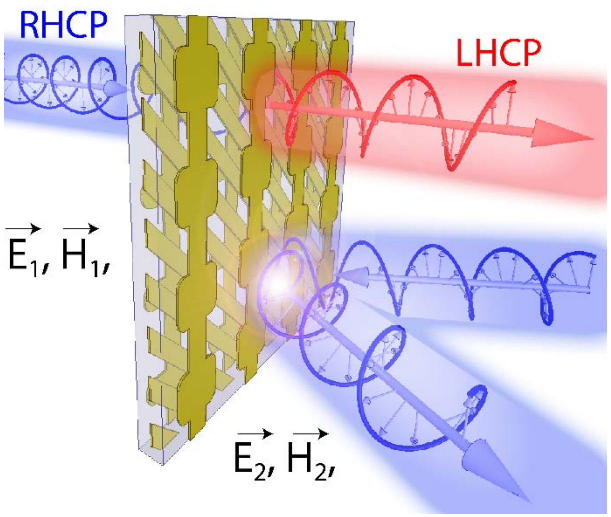
- Circular Dichroism (CD) spectrometer measures the differential absorption between circular polarizations (LCP and RCP), important in bio-sensing of chiral molecules. CD spectrometers typically obtain LCP and RCP spectra "sequentially". They are very large and complicated because of the hardware required to switch the circular polarization of the laser and to manage sequential data collection.

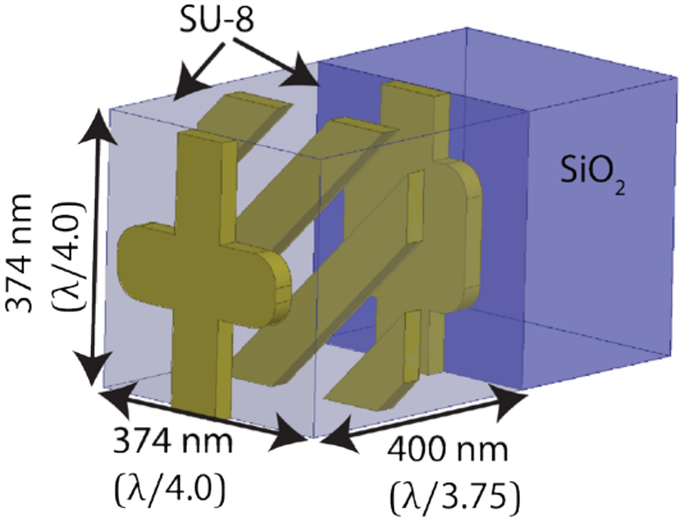
- The metasurface separates CP and RCP spectra "spatially".   UsesnPhotonic Spin Hall Effect in Gap-plasmon metasurface to reflect different optical spins (circular polarization) in opposite sides at wavelength dependent angle.

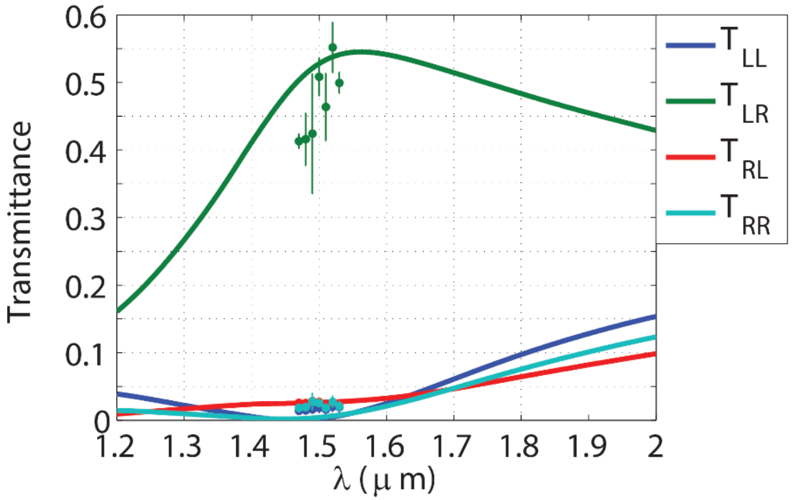
V. Shalaev, A. Boltasseva, A. Kildishev, Purdue 2015

Bianisotropic metasurfaces

- Systematic design procedure for realizing complete polarization control using cascaded anisotropic sheets was developed.
- Asymmetric circular polarizer provides high transmission for RHCP when propagating in the +z direction.
- RHCP is reflected when propagating in –z direction.
- Performance is an order of magnitude improvement over previous optical structures providing asymmetric transmission.

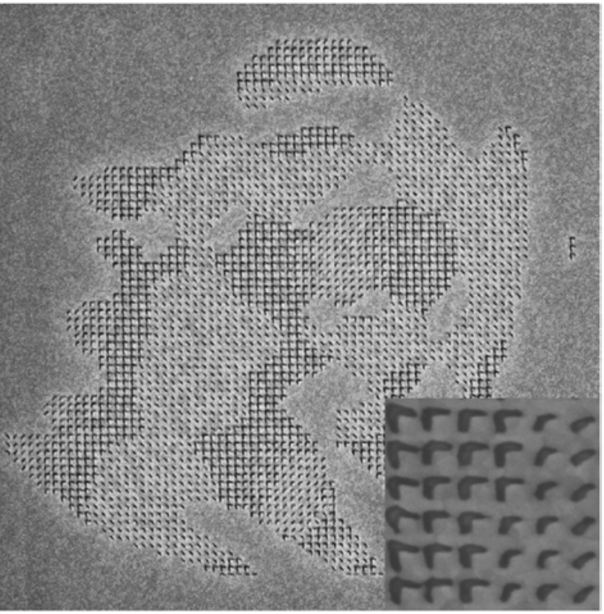






C. Pfeiffer, C. Zhang, V. Ray, L. J. Guo, A. Grbic, *Phys. Rev. Lett.*, vol. 113, 023902, 2014

Ultrathin Metasurface Holograms

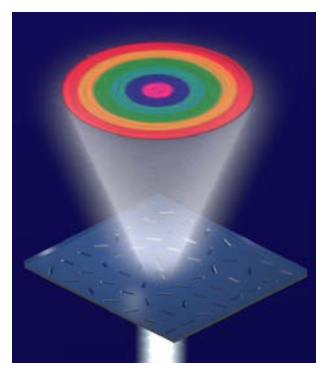


Hologram of Letter P

X. Ni et al. NATURE COMMUNICATIONS | DOI: 10.1038/ncomms3807 (shalaev group)

676-nm Kr/Ar laser

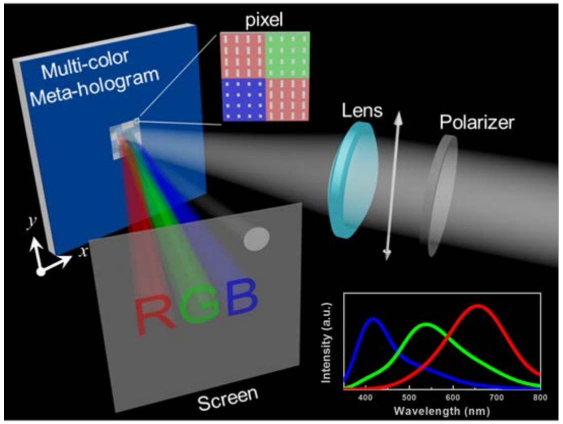
<u>Polychromatic Phase Hologram</u>



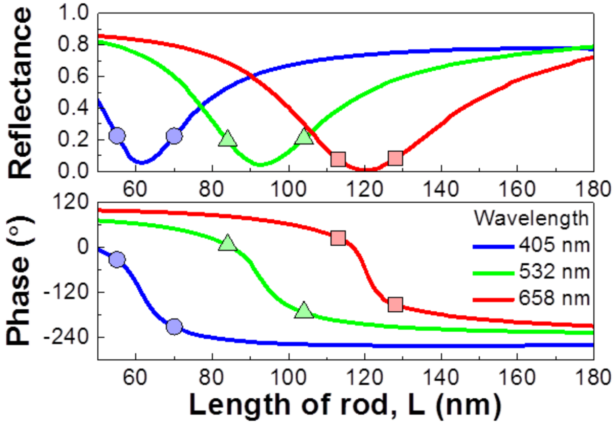
Sajid Choudhury, et al,"*Color Hologram Generation Using a Pancharatnam-Berry Phase Manipulating Metasurface* ", *CLEO* (2015)

Aluminum Plasmonic Multicolor Meta-Hologram

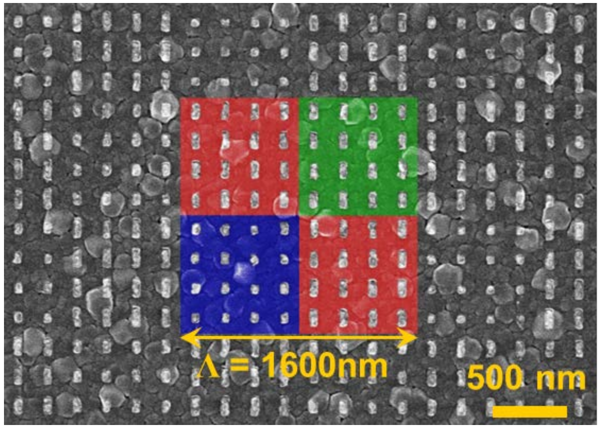
Illustration for the device



Reflective phase / amplitude



SEM image



- Sandwich structure: Al-nanorod/SiO_2/Al-mirror
- Aluminum plasmonics: Visible plasmon resonances, low-cost, mass-producible
- Narrow resonances & 2-level phase modulation scheme: Color multiplexing
- Conserved linear polarization, polarization-dependent images
- 180 × 180 pixels, each made of 4 sub-pixels; one for blue, one for green, and two for red to compensate for the lower reflectance in red.

Phase-modulated full-color meta-hologram. The reconstructed image is polarization-dependent, achieved by using Al nanorods with resonances covering whole visible range.

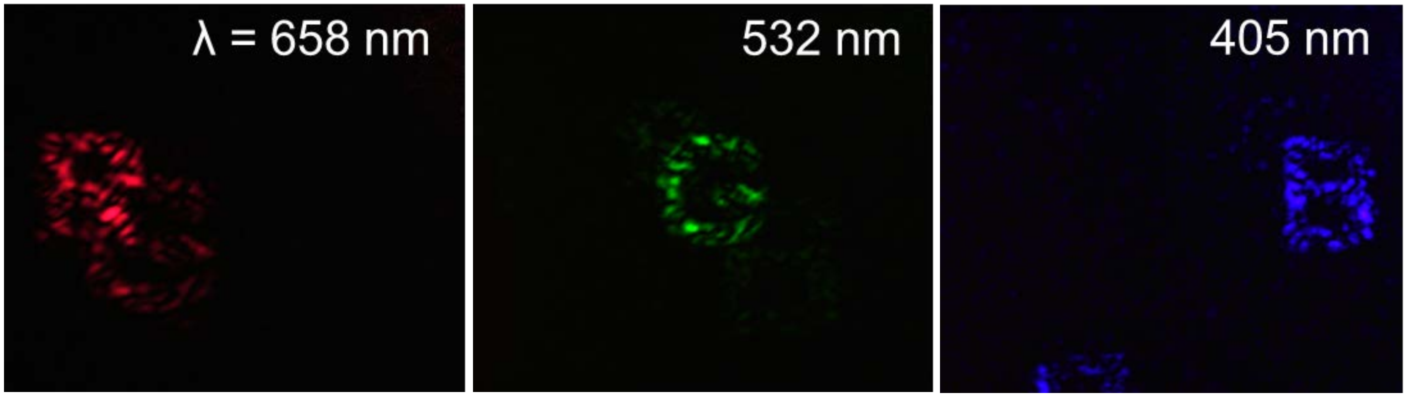
D. P. Tsai, *et al., Nano Letters*, ASAP (DOI:10.1021/acs.nanolett.5b00184)

D. P. Tsai Group

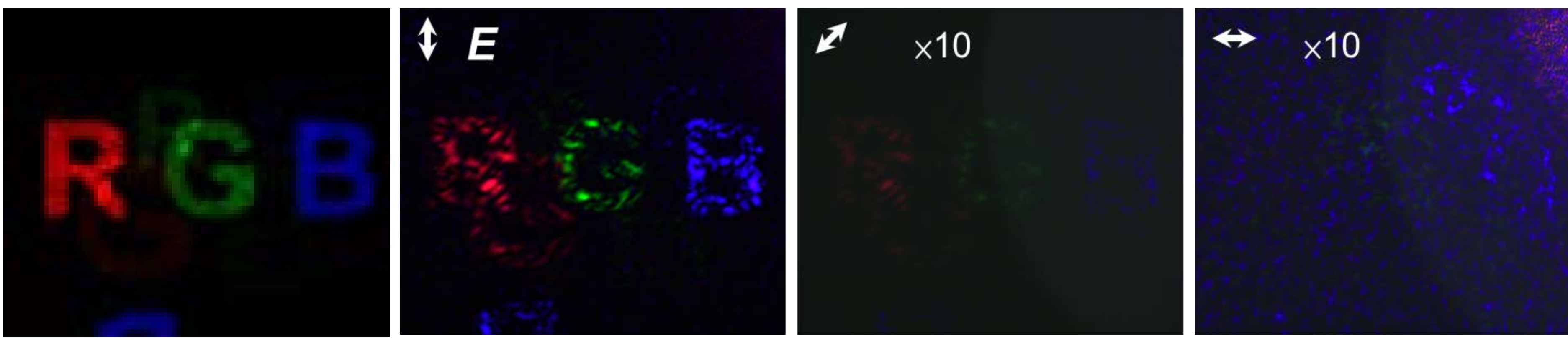
Wavelength and polarization-dependent images

Sandia National Laboratories

Color multiplexing



Simulated image   Polarization-dependent reconstructed images

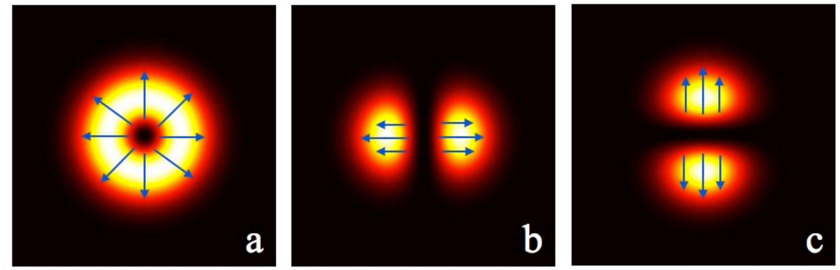


D. P. Tsai, *et al., Nano Letters*, ASAP (DOI:10.1021/acs.nanolett.5b00184)

Nanostructured holograms with local Polarization engineering

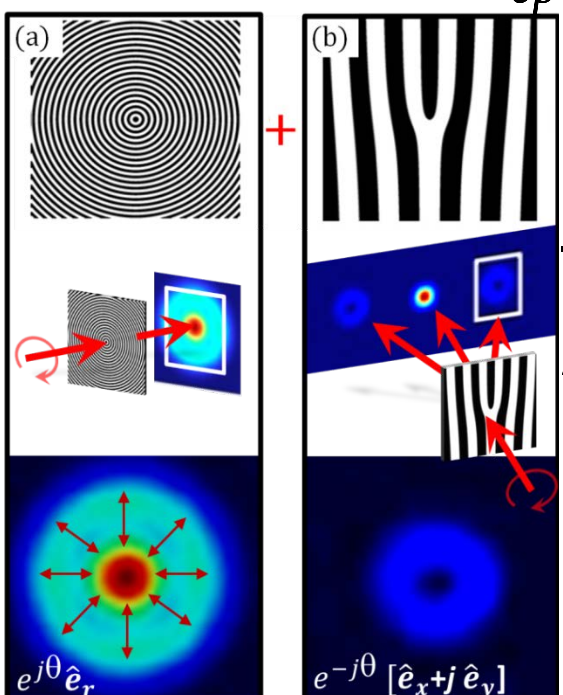
Radially polarized light: an example of vector beams

J. Lin, P. Genevet, et. Al. *Nano Lett.*,*13*, **4269** (**2013**)



Suppose an incident circularly polarized Gaussian beam

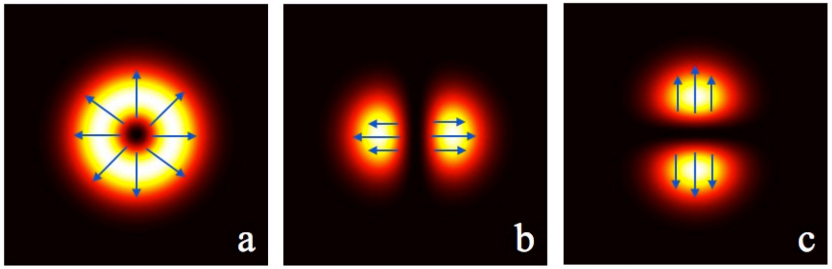
$$\overrightarrow{E_{cp}} = \overrightarrow{e_x} + j\overrightarrow{e_y} = e^{j\theta}\left(\overrightarrow{e_r} + j\overrightarrow{e_\theta}\right)$$



$$\overrightarrow{E_{out}} = (e^{j\theta}\overrightarrow{e_r})e^{-j\theta}$$

Nanostructured holograms for vector beam generation

Radially polarized light:



Suppose an incident circularly polarized Gaussian beam

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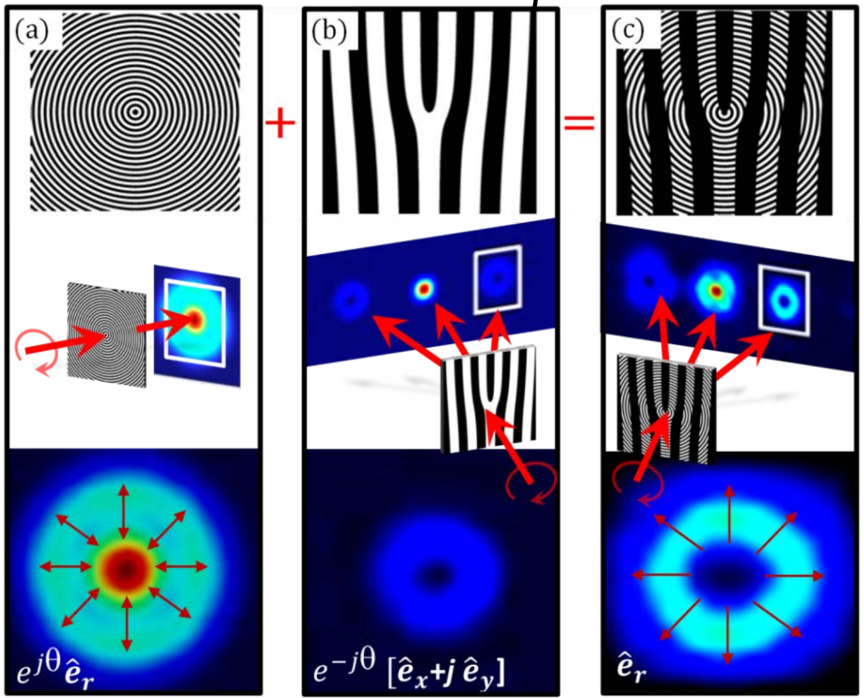
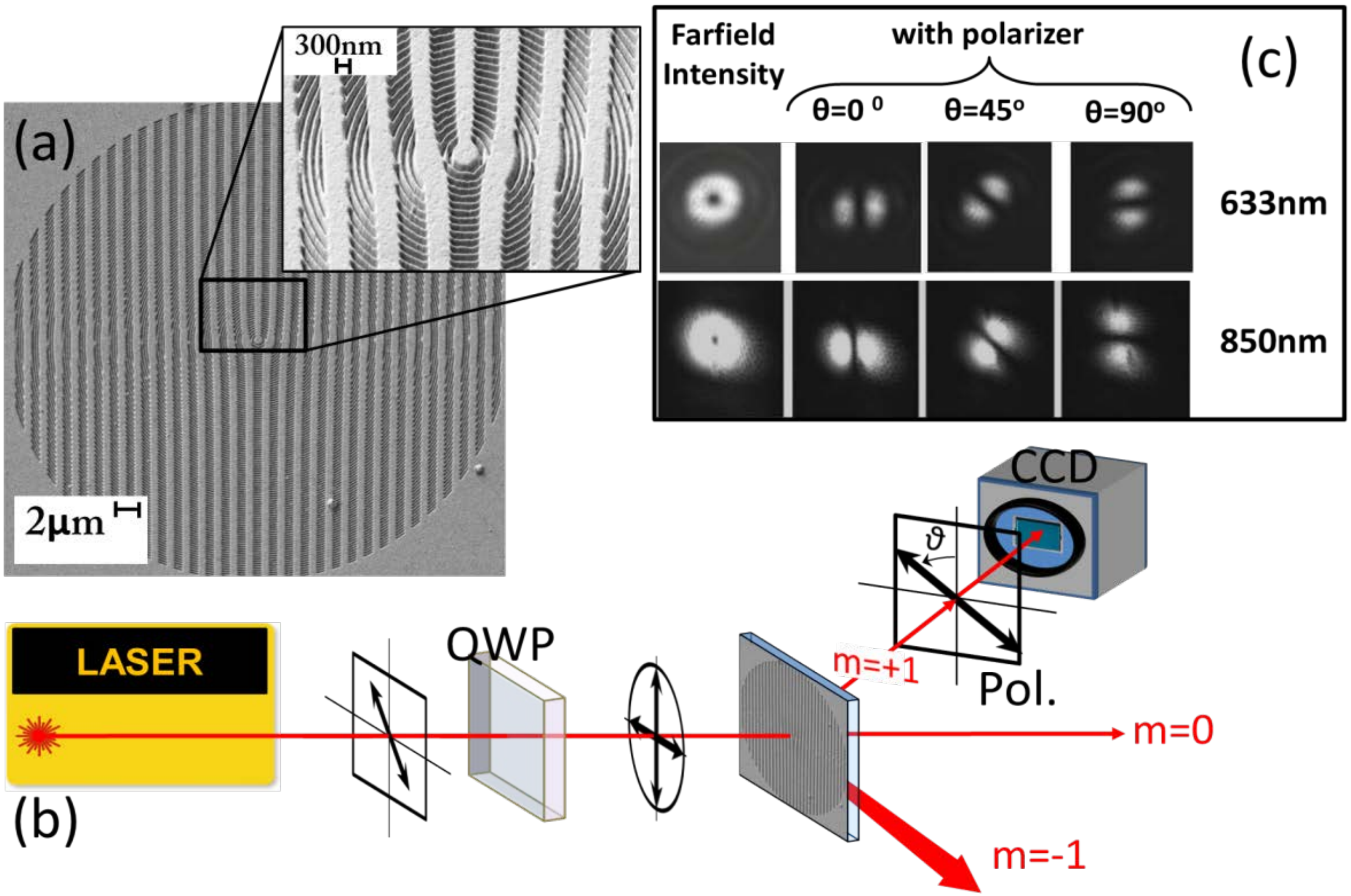


$$\overrightarrow{E_{out}} = \overrightarrow{e_r}$$

Nanostructured holograms for broadband manipulation of light



Broadband property is a consequence of the shift theorem of Fourier optics

Constructive interference for a given wavelength (λ_1) is controlled by $2j\pi\delta \frac{\sin(\theta)}{\lambda}$

It will be observed at another wavelength (λ_2) at the angle θ_2 defined by: $\theta_2 = \sin^{-1}\left[\frac{\lambda_1}{\lambda_2}\sin\theta_1\right]$

Topics

- Wavefront Control: amplitude, phase, polarization (transmittarrays & reflectarrays)
- Gradient and Huyghens metasurfaces
- Flat optical components
- Graphene (VdW Heterostructures)metasurfaces
- Aberrations and Achromatic metasurfaces
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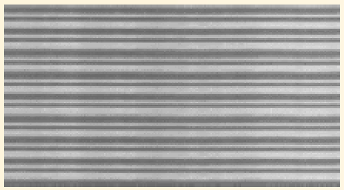
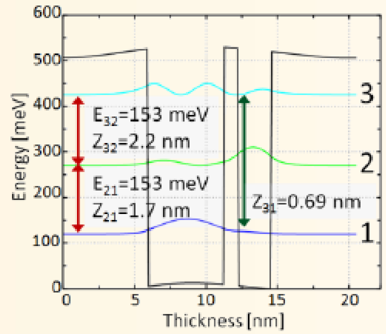
- Holographic metasurfaces
- **Active (Nonlinear Optical) Metasurfaces**
- Waveguide control: guided and frees space mode conversion
- Polarization controlled routing
- Materials

Efficient Second-Harmonic Generation over a Surface

Quantum engineering of nonlinear coefficients with intersubband transitions

N-doped multiple quantum wells (MQW)





$$\chi_{zzz}^{(2)}(\omega \rightarrow 2\omega) \approx N_e \frac{e^3}{\hbar^2 \varepsilon_0} \frac{z_{12} z_{23} z_{31}}{(\omega_{31} - 2\omega - i\gamma_{31})(\omega_{21} - \omega - i\gamma_{21})} \sim 10^5 \ pm/V$$

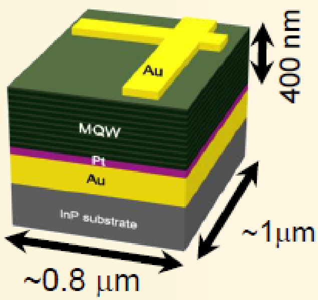
10^3-10^4 times larger than in traditional materials

Similar approach for giant coefficients for:

- Electro-optic effect
- Difference- and sum-frequency generation
- Phase conjugation, all-optical control

+ Electromagnetic engineering of plasmonic resonators

M. Belkin Group, UT Texas
A. Alu' Group



Design considerations:

- Strong coupling of impingent field to z-polarized intersubband transitions
- Resonances and strong field enhancement at both input and output frequencies
- Maximizing overlap integral for optical modes at input and output frequencies, e.g. for ω → 2ω:

$$\chi_{ijk}^{(2)eff} = \chi_{zzz}^{(2)} \frac{\int_{Unit\ cell} E_{z(k)}^{\omega}(x,y,z) E_{z(j)}^{\omega}(x,y,z) E_{z(i)}^{2\omega}(x,y,z) dV}{E_{k(inc)}^{\omega} E_{j(inc)}^{\omega} E_{i(inc)}^{2\omega} V_{Unit\ cell}}$$

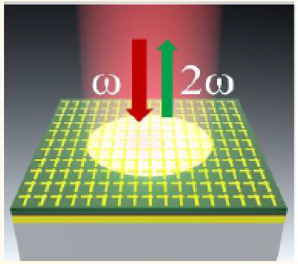
= Ultrathin highly-nonlinear and electrically/optically reconfigurable metasurfaces

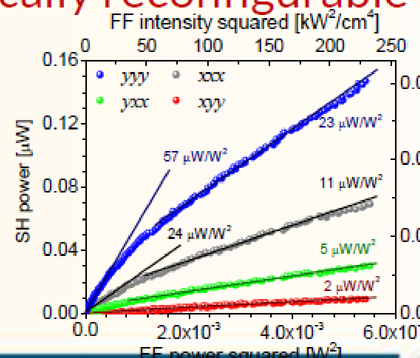
Proof-of-concept demonstration:

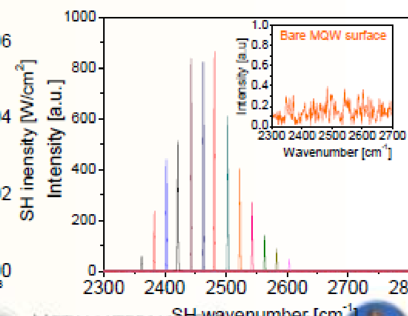
Ultrathin mid-IR second-harmonic metasurface*

- Automatic phase matching in reflection
- 2×10^{-4} % conv. eff. for only 15 kW/cm^2 intensity
- ~10^8 improvement over traditional materials

J. Lee et al., *Nature* **511**, 65 (2014)

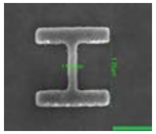


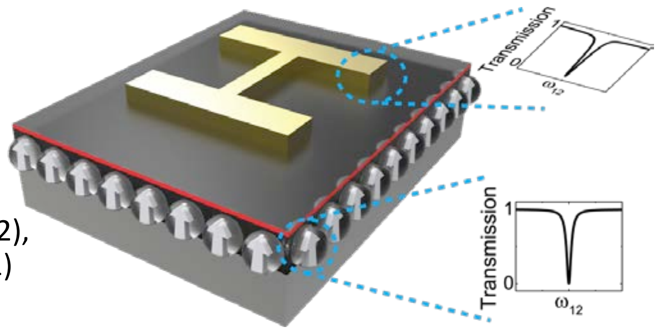




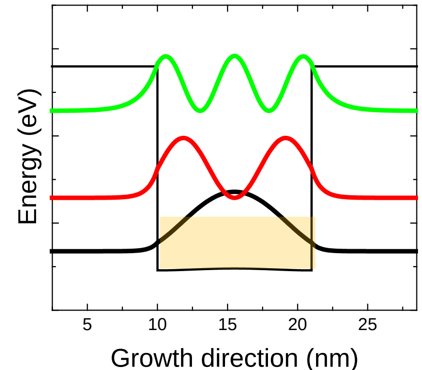
Strong Coupling Between Metamaterials to Intersubband Transitions in Quantum Wells

Igal Brener Group

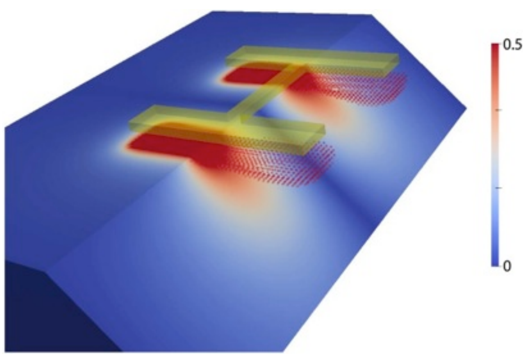




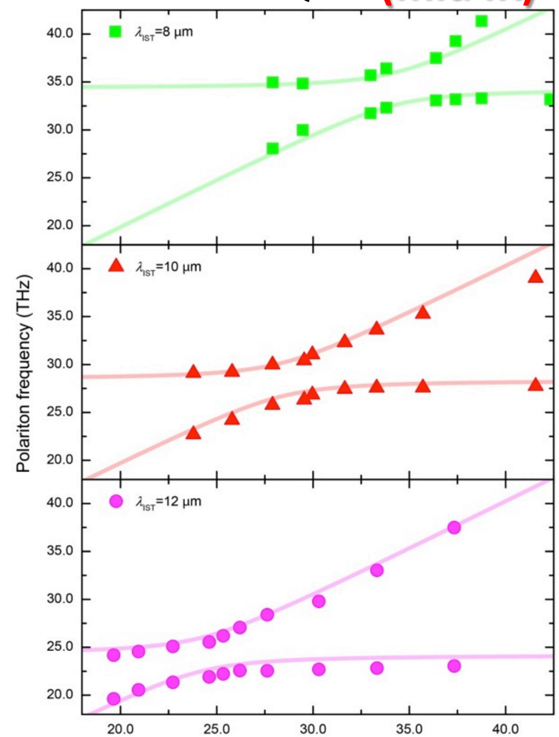
Opt. Express 20, 6584 (2012),
APL 98, 203103 (2011)



Very Strong Mode Confinement

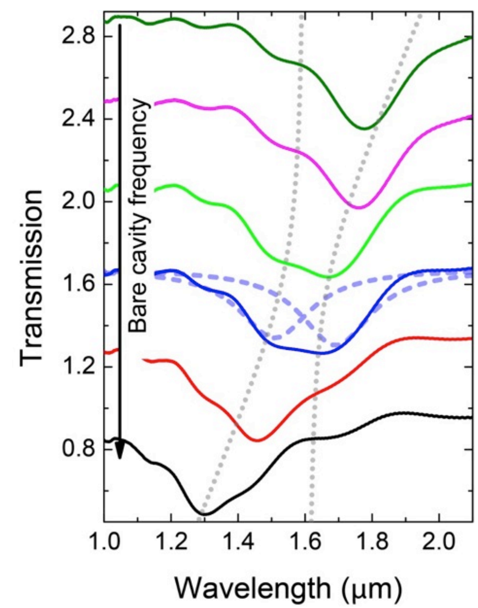


InGaAs QWs **(mid IR)**



Nat. Comm.4, (2013)

GaN QWs **(near IR)**



ACS Photonics (2014)

These strongly coupled systems can be used to enhance second harmonic generation, voltage tunable coupling, etc

Topics

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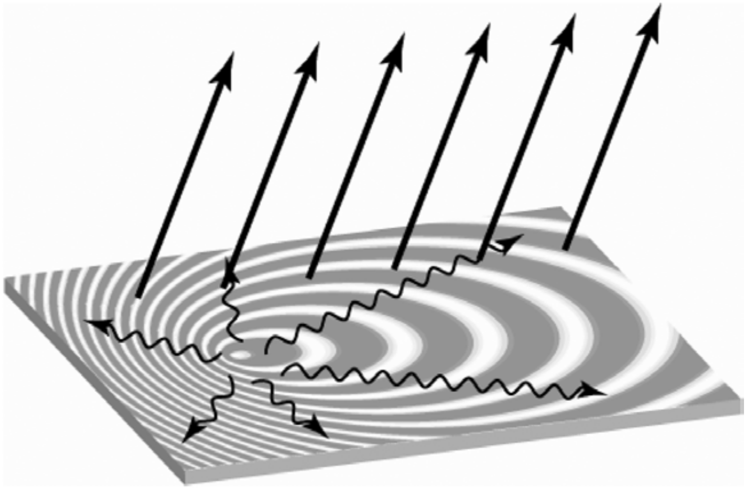
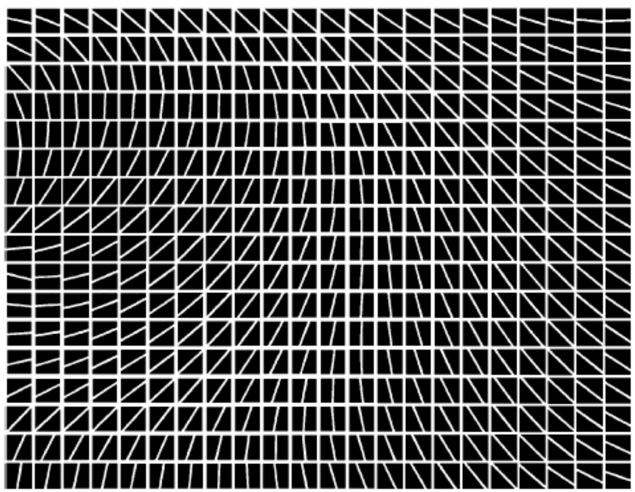
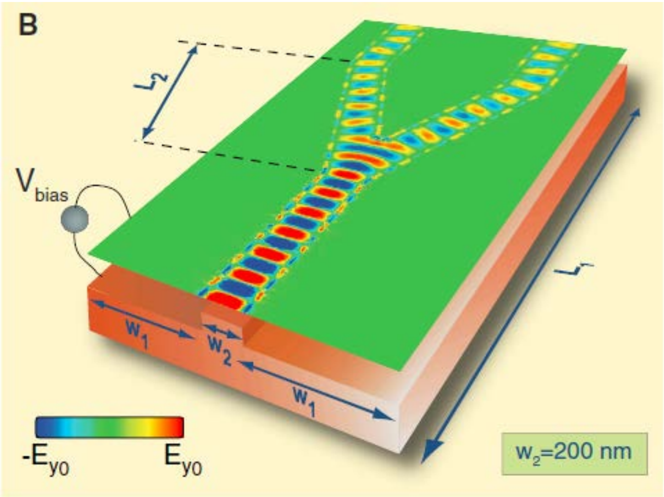
- Materials

Controlling guided EM waves using metasurfaces

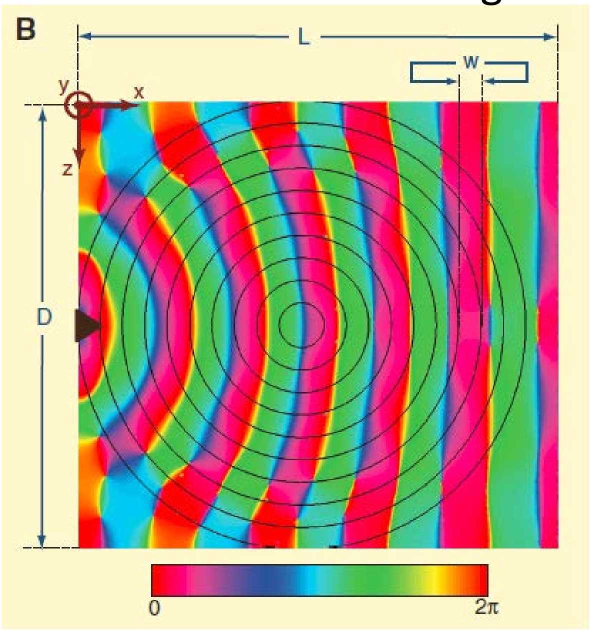




Tensor holographic impedance for converting surface wave into circularly polarized wave in the far-field



Graphene metasurface waveguides



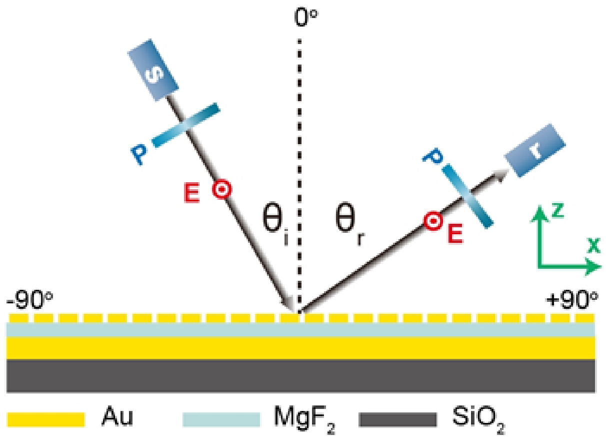
Metasurface Luneburg lens

Fong, *et al., IEEE Trans Antennas Propag* **58**, 3212 (2010)

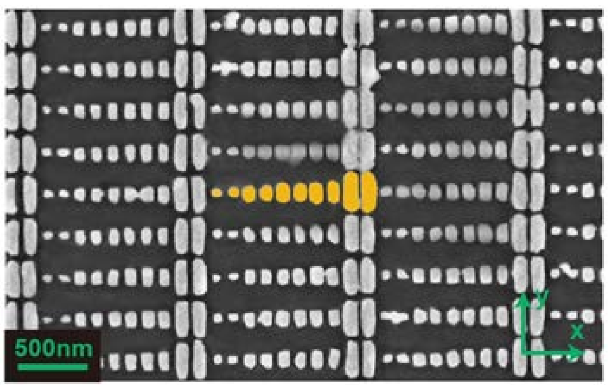
Vakil and Engheta, *Science* 332, 1291 (2011)

Far-Field Demonstrations

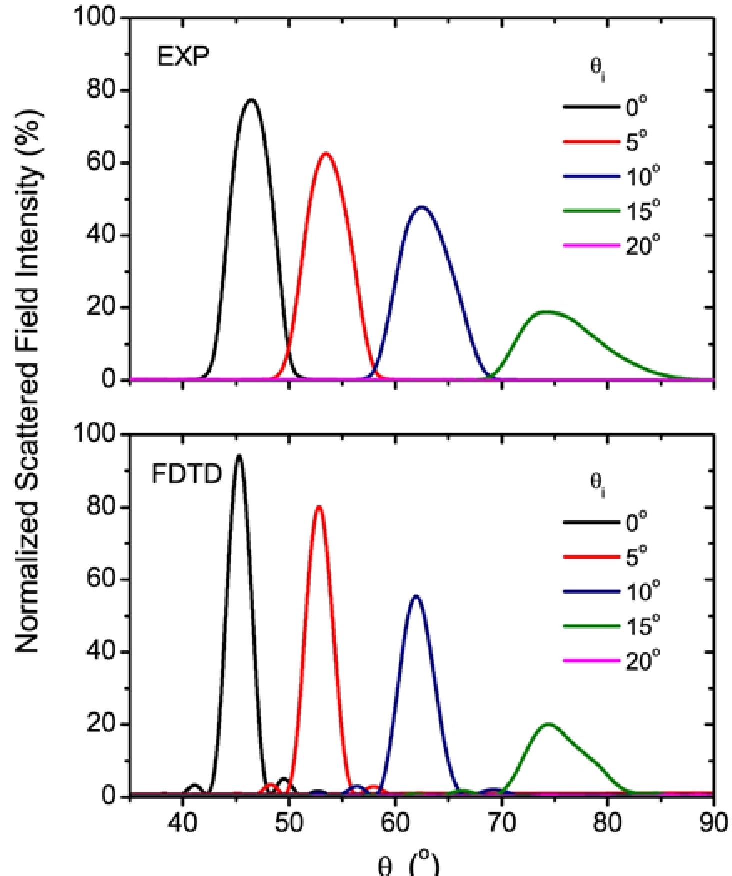
❑ Experimental setup



❑ SEM image of meta-surface



❑ Measured and simulated normalized scattered electric field intensity



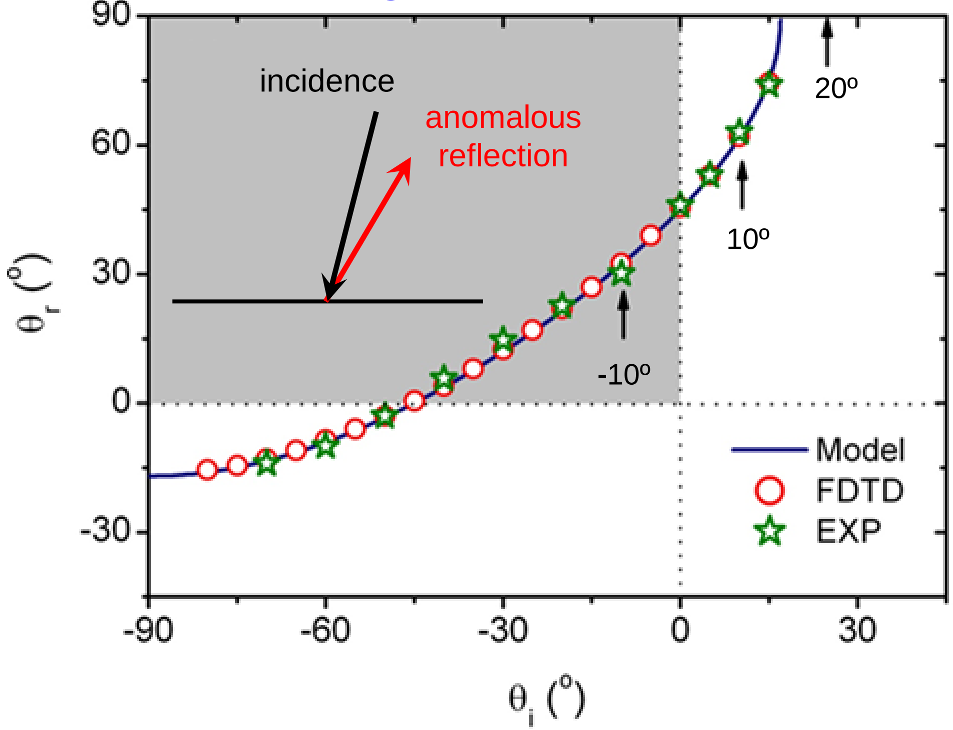
- Normalized scattered field peak of anomalous reflection mode is up to 80%.
- Experimental results match well with FDTD simulations

S. Sun *et al.*, *Nano Lett.* **12**(12), 6223-6229 (2012).

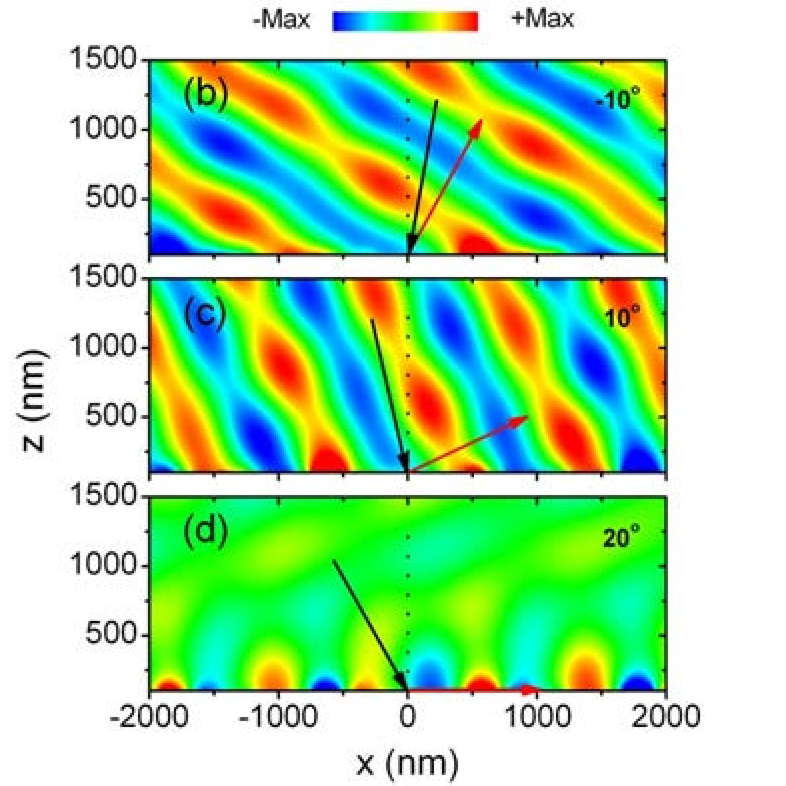
- Lei Zhou (Fudan U) and Din Ping Tsai (Acad. Sinica, Taiwan) Groups

Generalized Snell's Law & New Surface Waves

- **Anomalous reflections at different incident angles**



- **E_y Field patterns on the *x-z* plane**



- The momentum conservations of scattered field:

$$k_0 \sin\theta_r = k_0 \sin\theta_i + \zeta, \quad \zeta = 0.7\, k_0$$

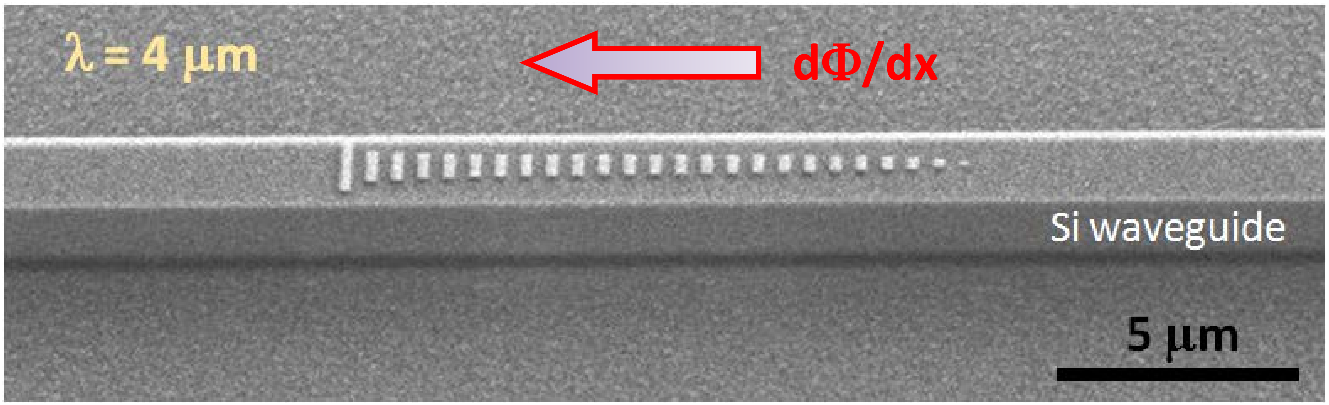
S. Sun *et al.*, *Nano Lett.* **12**(12), 6223-6229 (2012).

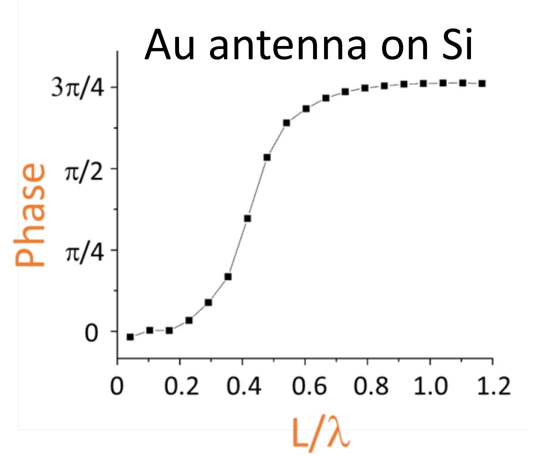
- Negative reflection, positive reflection, and surface wave generation are demonstrated
- Beyond critical incident angle $\theta_c = -17^o$ (plane wave → surface wave)

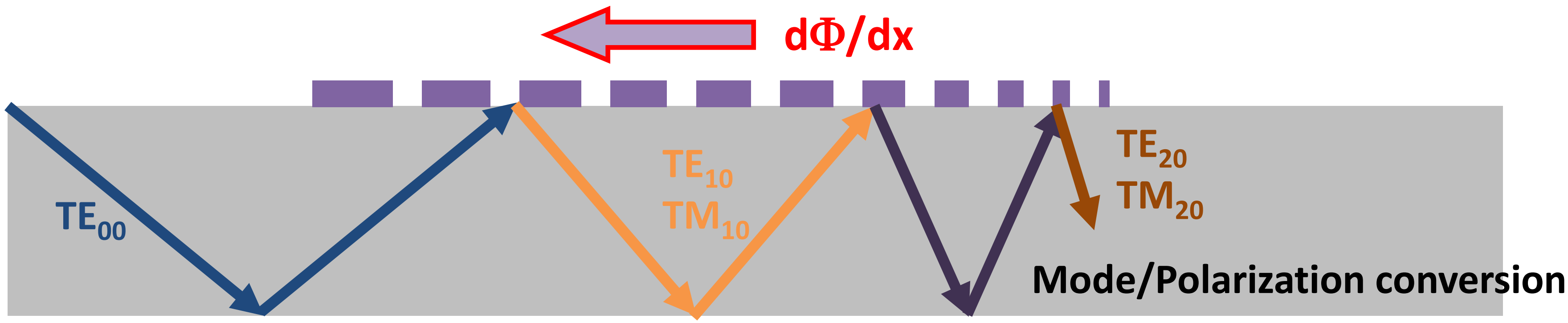
- Lei Zhou (Fudan U) and Din Ping Tsai (Acad. Sinica, Taiwan) Groups

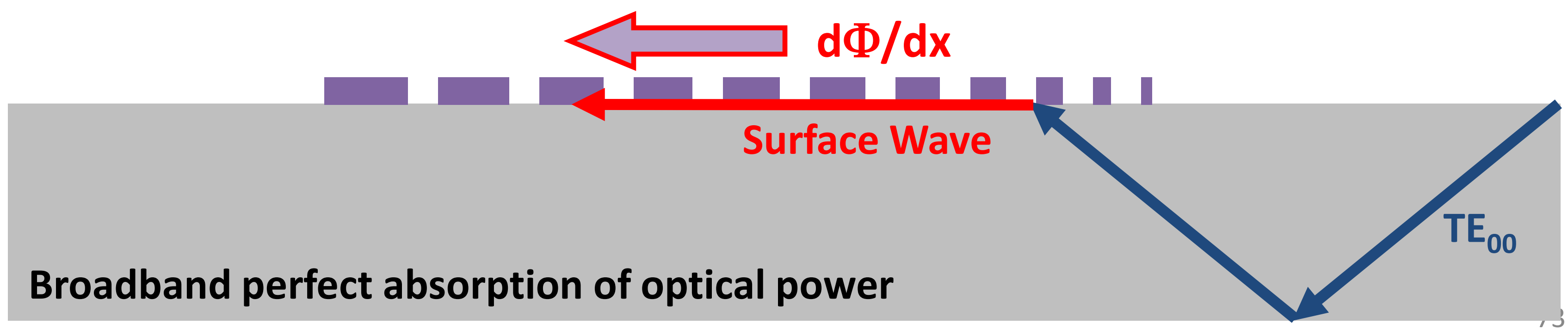
Using metasurfaces to control waveguide mode conversion

Nanfang Yu group



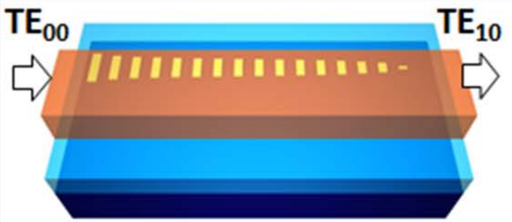
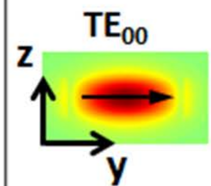
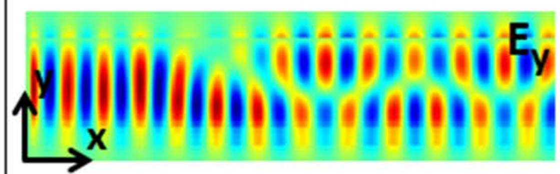
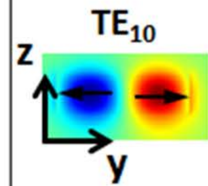
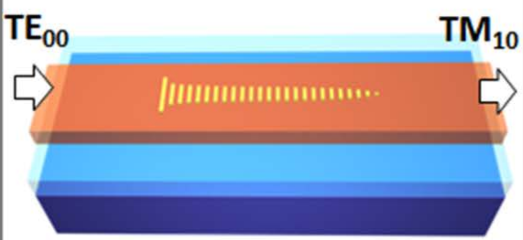
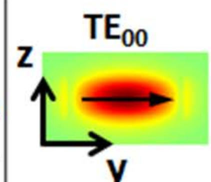
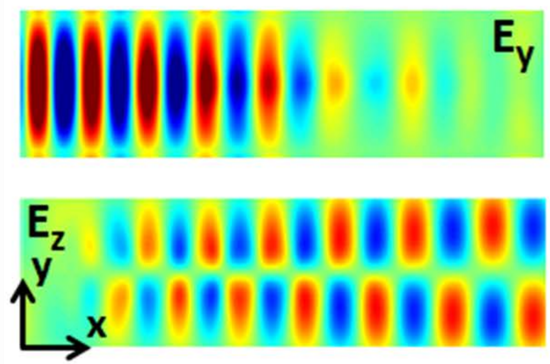
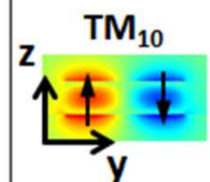
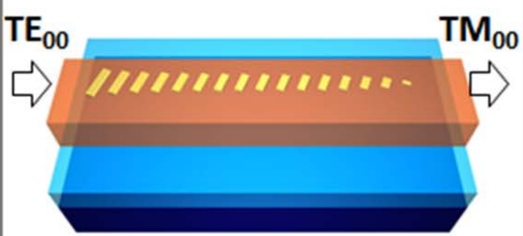
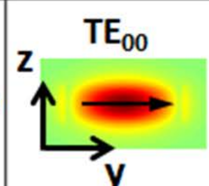
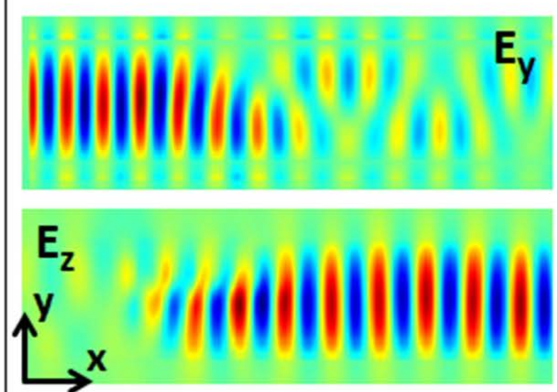
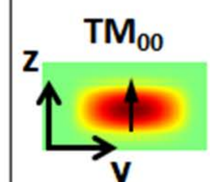






Waveguide mode converters and polarization rotators (λ = 4 μm)

Nanfang Yu Group

Schematic	Input	Mode evolution	Output	T	η
				71%	81%
				36%	95%
				65%	76%

T = transmission, η = mode conversion efficiency

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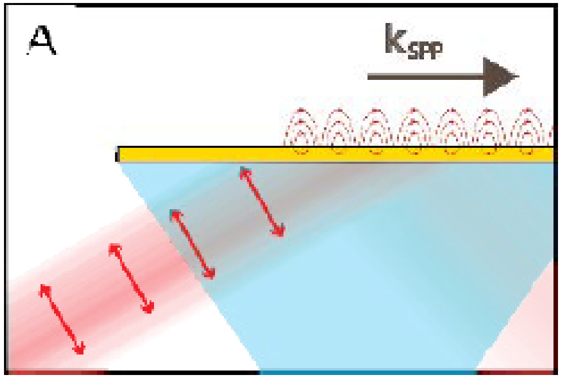
Surface Plasmon Polaritons: Coupling to Free Space Photons

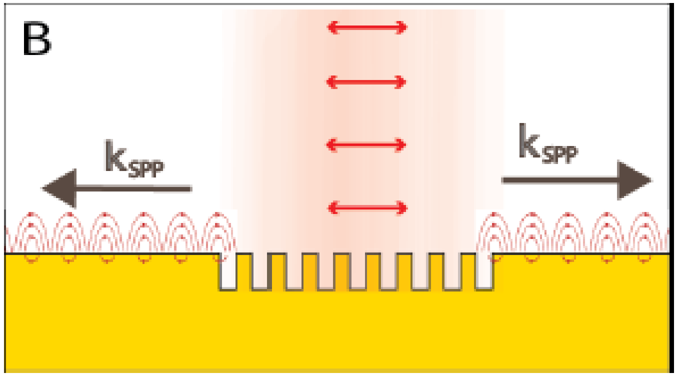
Common Coupling Methods: Limitations



(A) Prism Coupling

The generated SPPs propagate along the direction of the incident field.

Only p-polarized incident light is coupled.



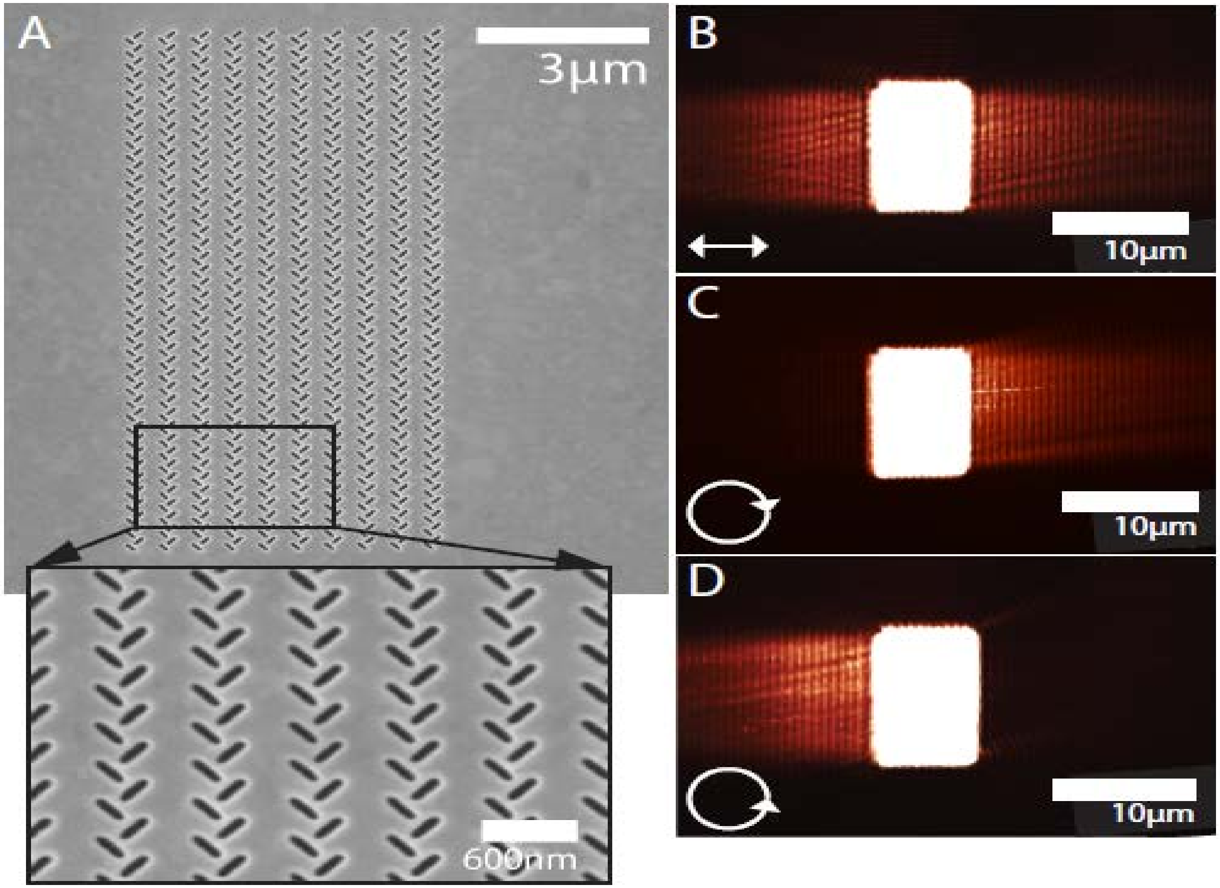
(B) Grating Coupling

Direction fixed by momentum matching condition given by wavelength, angle of incidence and the grating period.

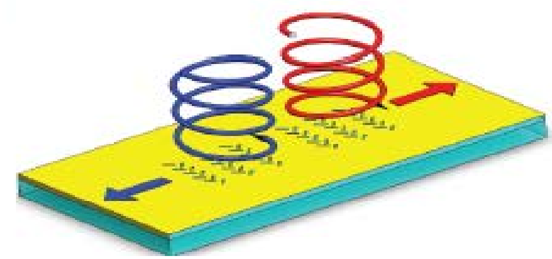
For normal angle of incidence, SPPs are launched towards both sides.

Grating-like structures can only convert incident light that is polarized perpendicular to groove- or ridge-like features to SPPs.

"Fishbone" Gratings



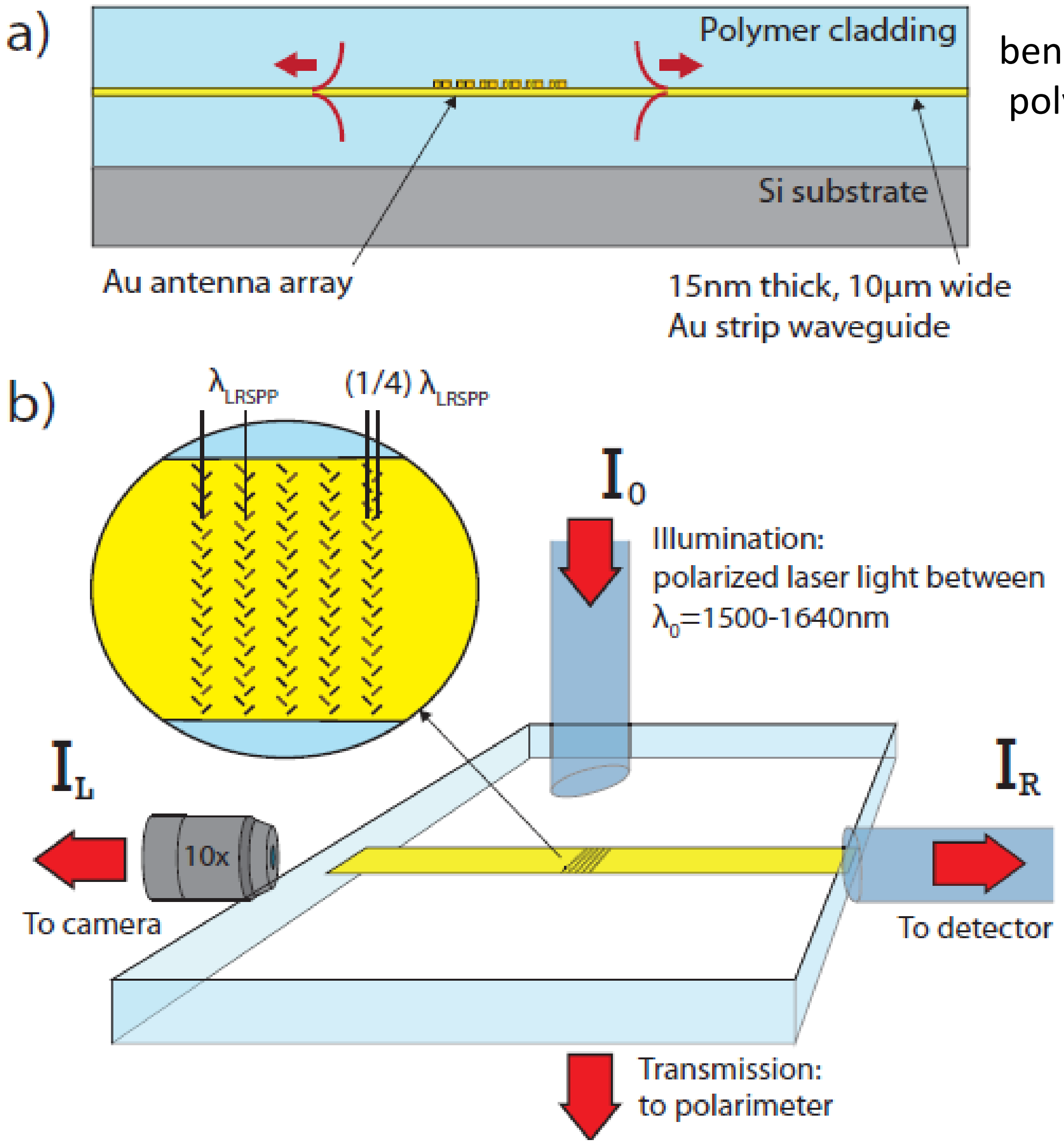
Interference between transmitted beam through film and SPP. Period equal λ_{SPP} = 606 nm



- λ = 633 nm, λ_{SPP} = 606 nm.
- Geometrical parameters : S =150 nm, Vertical antenna separation D= 300 nm, Antenna width & length: W=40 nm and L = 200 nm. Column pairs spacing: 600 nm; thickness of the Au film = 150 nm.

Jiao Lin et al. *Science* **340**, 331 (2013)

Polarization controlled coupling to a long range surface plasmon waveguide



benzocyclobutene (BCB) polymer

The polymer has a refractive index of n = 1:535 at 1550 nm. This geometry supports a single TM-polarized mode at C and L band frequencies (l0 = 1530 nm to 1625 nm),

*J. B. Mueller et all. Nano Lett.*14, 5524 (2014)

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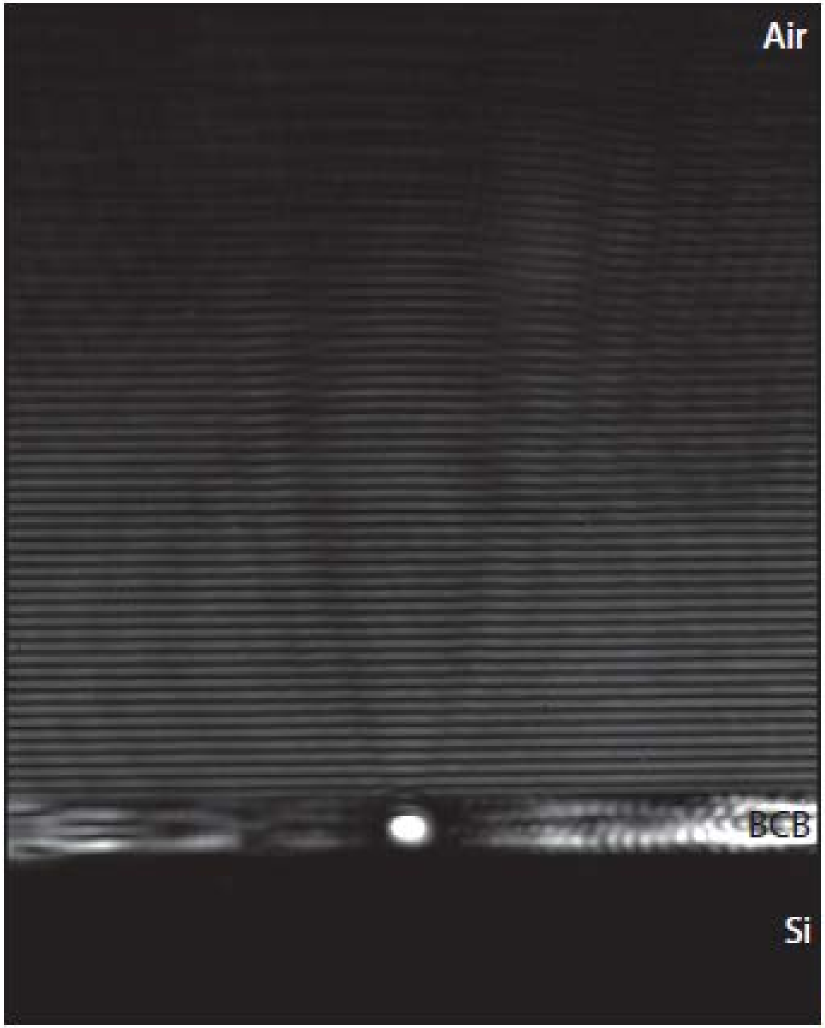
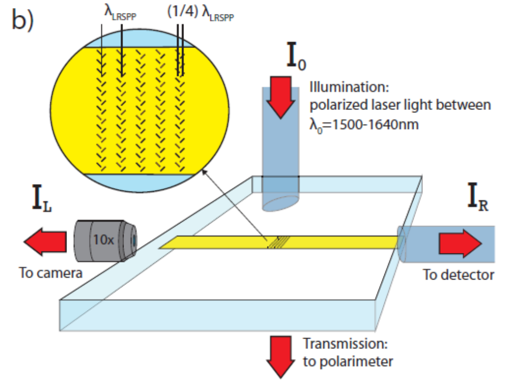
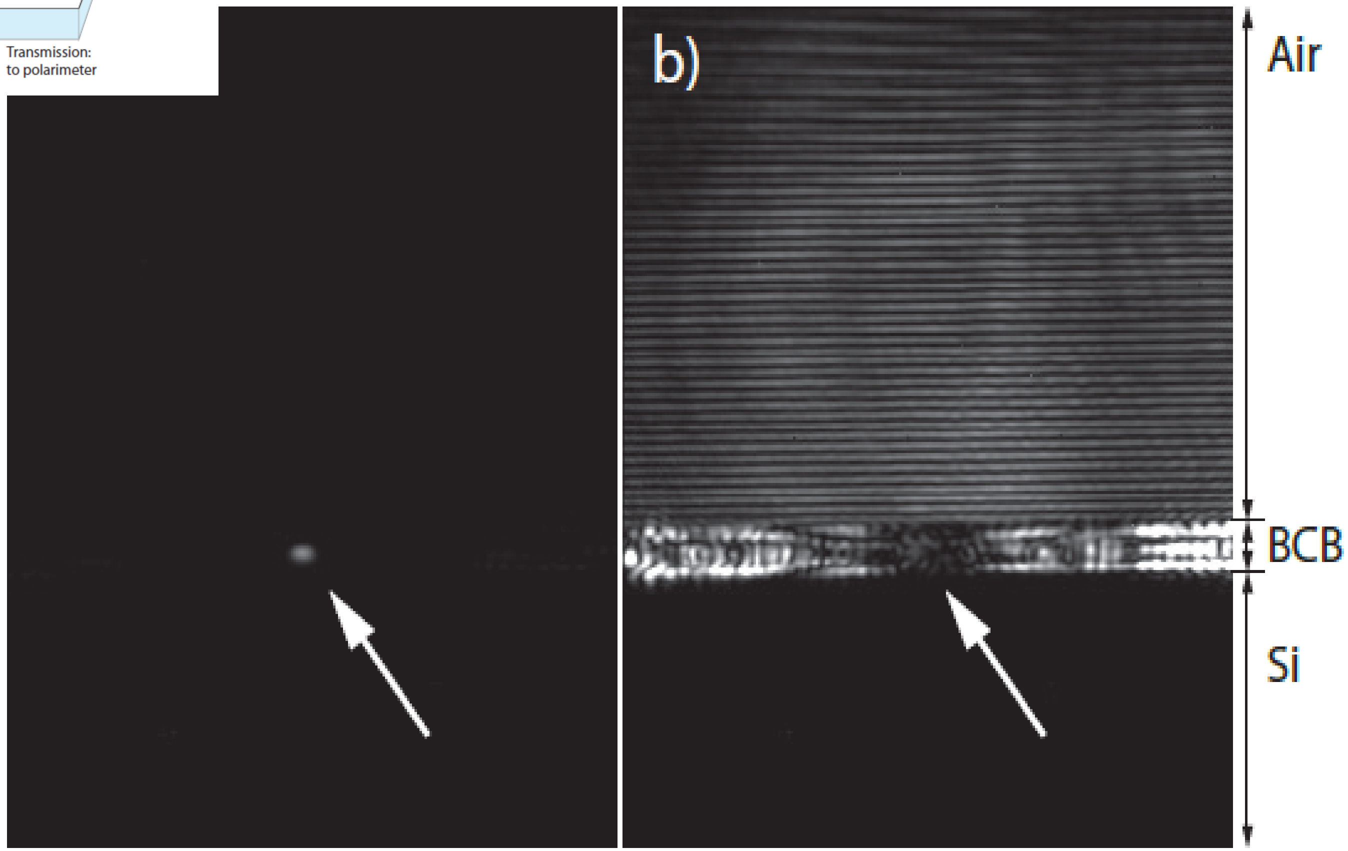
Single Mode Operation



InGaAs Camera Image (saturated)

Polarization-dependent switching





Polarization-dependent switching. (>30dB Extinction)

*Note the difference in camera settings.

Towards new polarimeters ! (J. P. Balthasar Mueller)

Flat optics

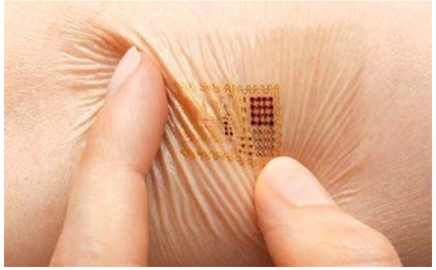
- New class of flat, compact and broadband components: lenses, polarizers., filters, high speed tunable phased array for real-time wavefront control. Add quantum effects: actives metasurfaces

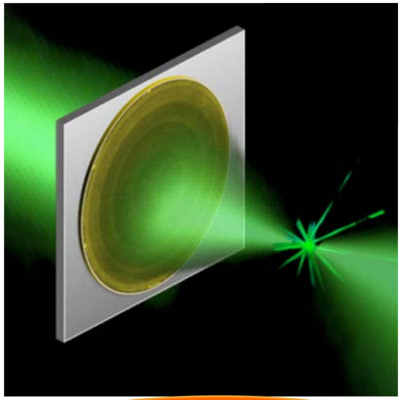
- Lithography: from Deep UV to Nanoimprinting and Soft Lithography
- Ultimate frontier: Inverse optical design. **Given the wavefront what is the metasurface ?**

StrechableM aterials

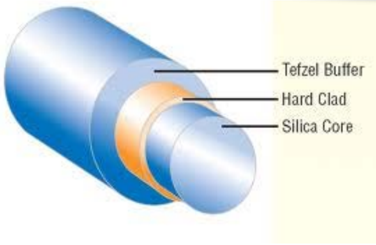
High NA Objectiv

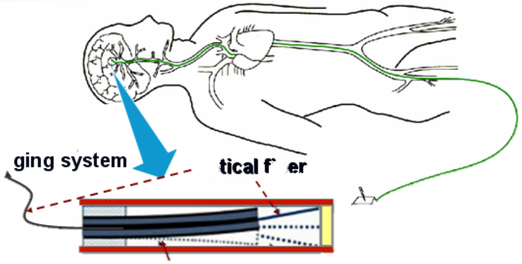
Smart Phones





Non-Invasive Imaging for Biomedical Application

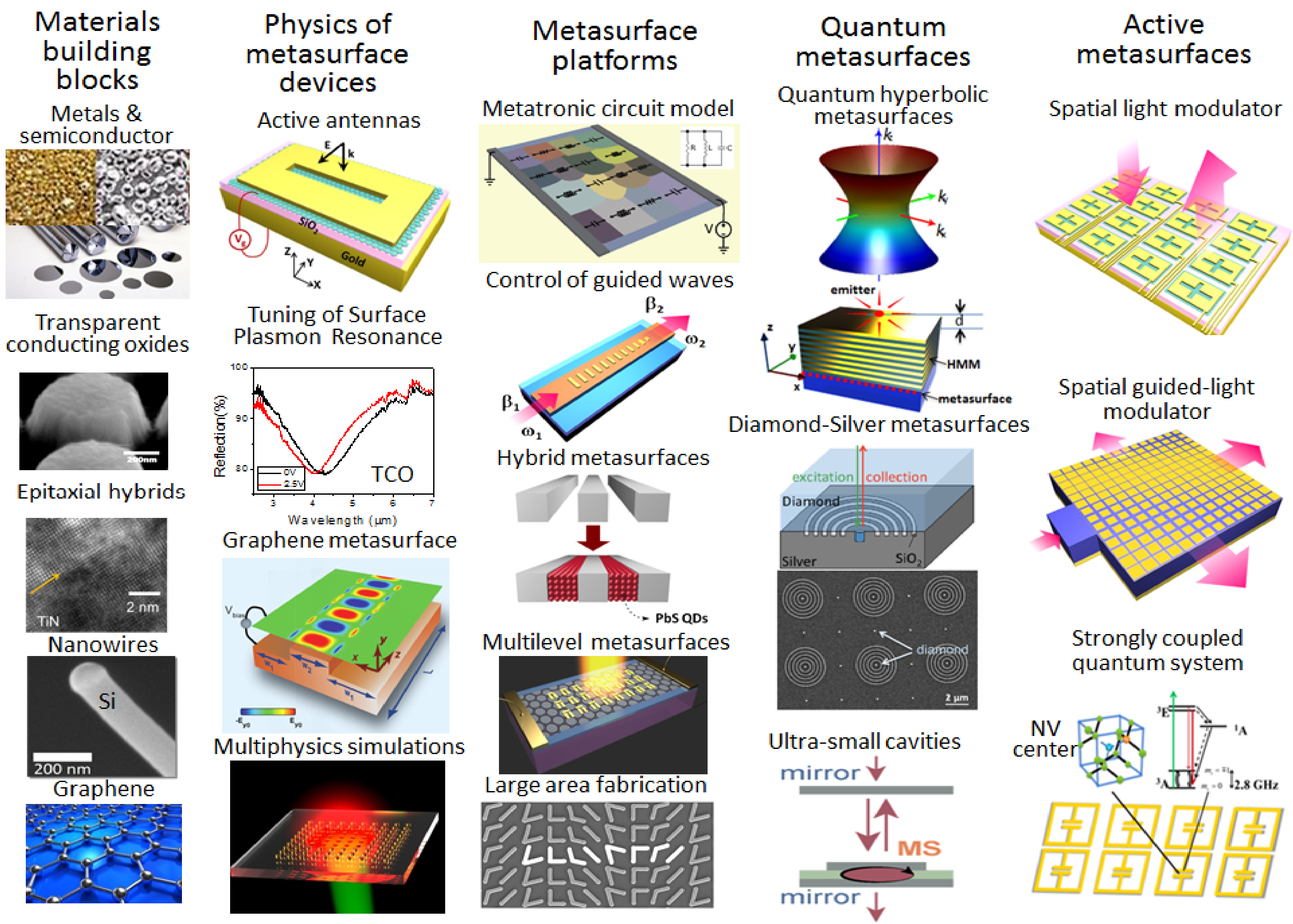




Major opportunity in Midir due to poor refractory materials

Science and Technology: Vision and Impact

Explore new metasurfaces and their breakthrough applications in photonics, in particular active metasurfaces that are reconfigurable and/or tunable in real time with external control of their optical characteristics
Metasurfaces can be used to design new optical forces on nanoparticles, surfaces: wide open frontier!



ALTERNATIVE MATERIALS

21 JANUARY 2011 VOL 331 SCIENCE

MATERIALS SCIENCE

Low-Loss Plasmonic Metamaterials

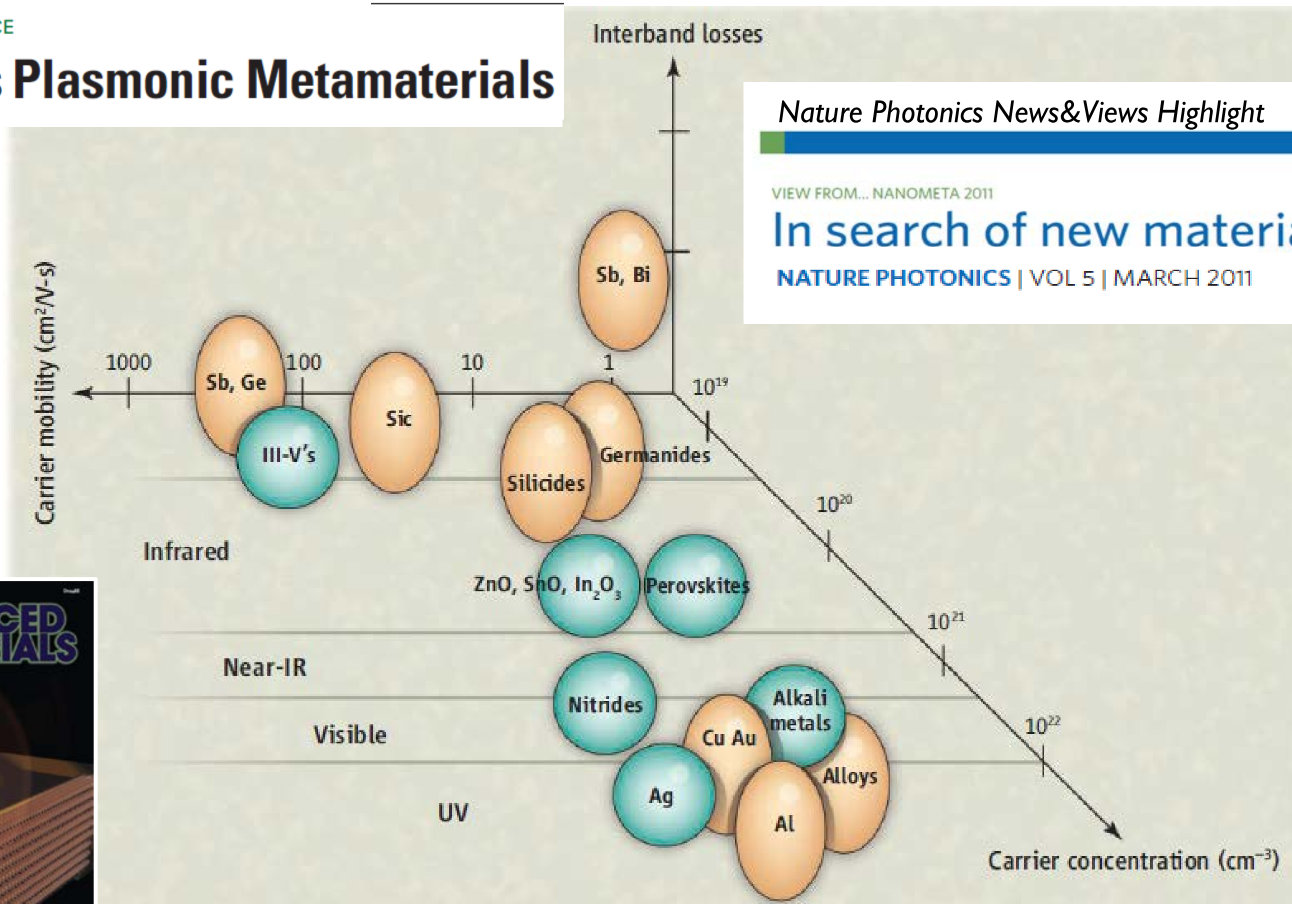
Nature Photonics News&Views Highlight

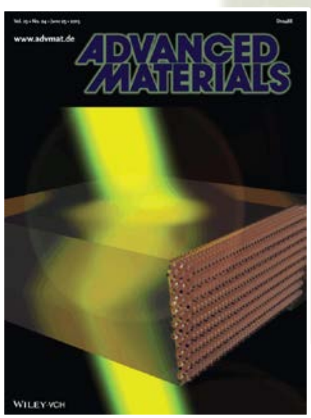
news & views

VIEW FROM... NANOMETA 2011

In search of new materials

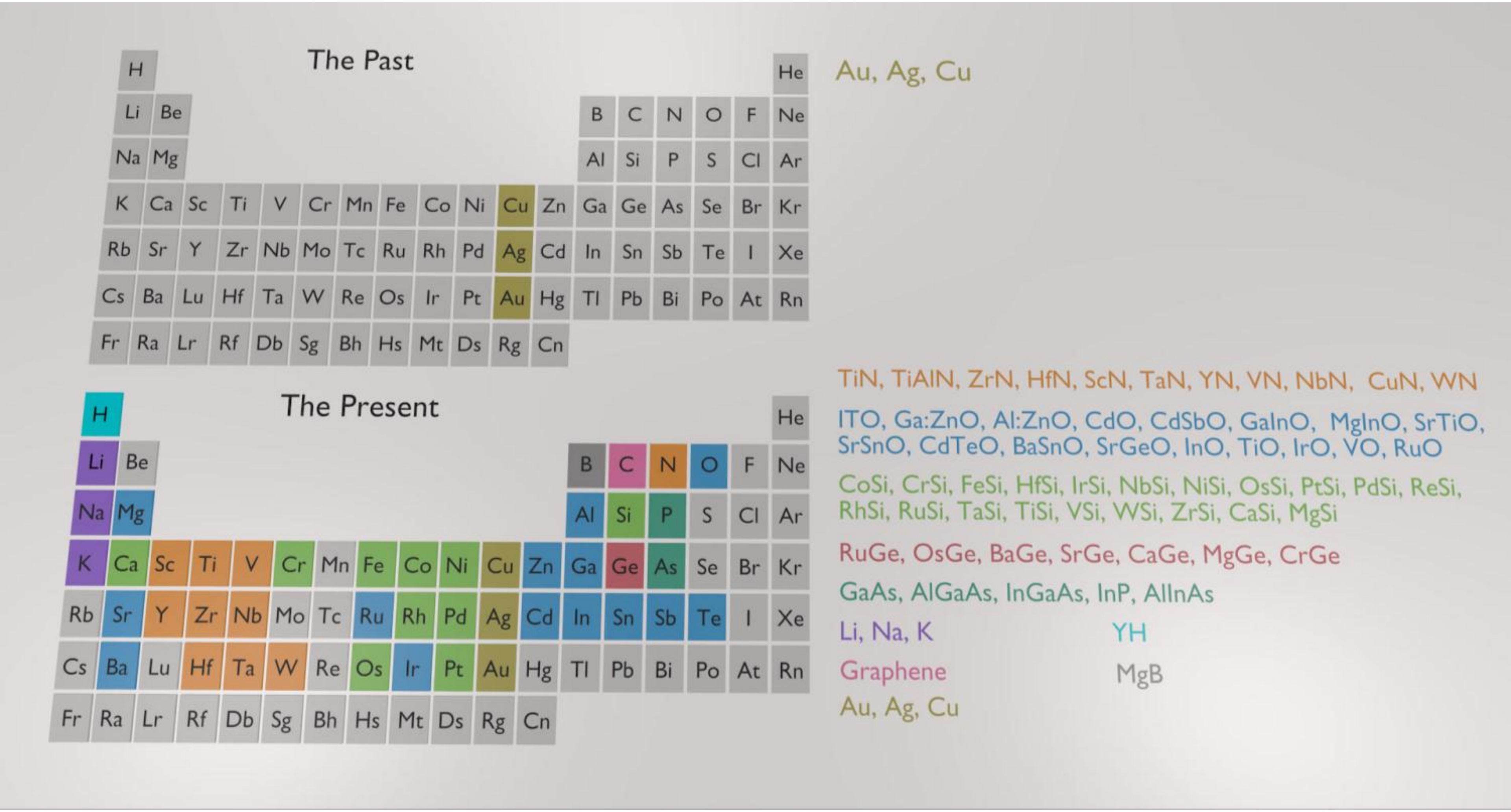
NATURE PHOTONICS | VOL 5 | MARCH 2011





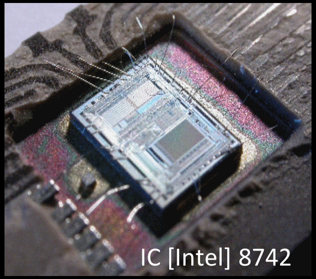
THE PAST AND PRESENT

Looking for intermediate carrier density materials



TITANIUM NITRIDE

- Metallic/Plasmonic: Golden luster
- Hard & tough: high speed drill-bits, coatings
- CMOS-compatible (silicon ICs):
    - Gate metal
    - Barrier layer
- Deposition: CVD, sputtering, evaporation…
- Epitaxial growth on c-sapphire, MgO, and silicon *(2nm layer)*
- Mechanically, chemically stable
- BIOCOMPATIBLE high biostability
    - BioMEMS
    - Medical implant
- REFRACTORY (melting point 2900C)



Capasso Group