Flat Optics based on Metasurfaces

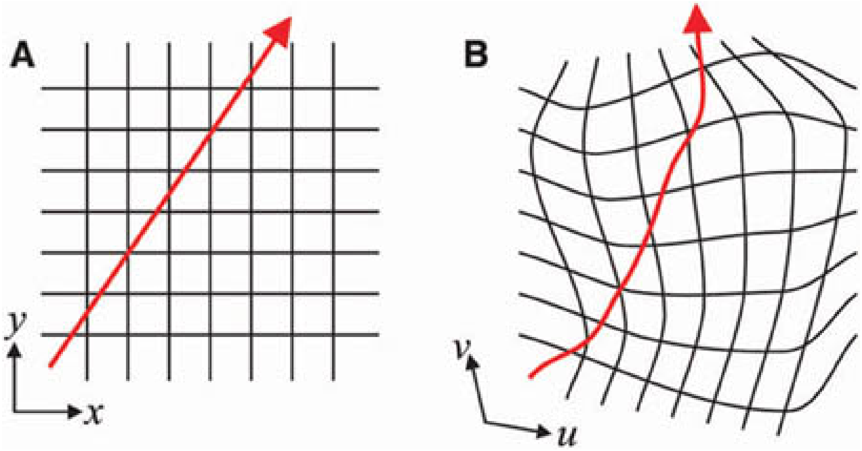
Federico Capasso
capasso@seas.harvard.edu
http://www.seas.harvard.edu/capasso/

School of Engineering and Applied Sciences
Harvard University

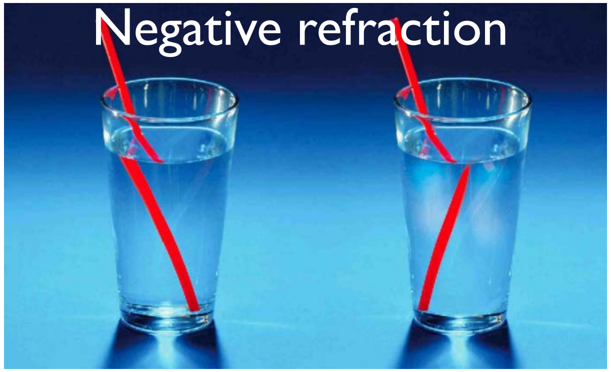
Review :
N. Yu and F. Capasso ,"Flat Optics with Designer Metasurfaces"
Nature Materials **13**, 139 (2014)

METAMATERIALS

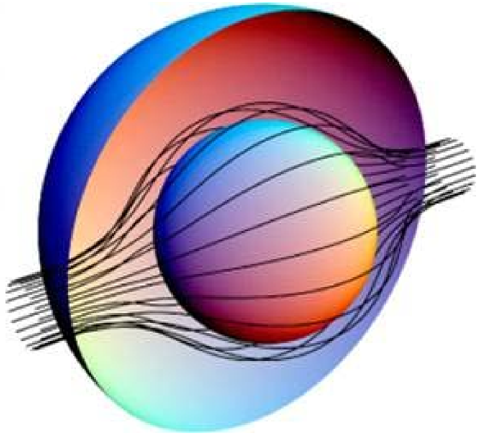
Metamaterials and Transformation Optics



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)



Negative refraction



Optical cloaking

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

What can we do in 2D ? "metasurfaces"

The Vision of Flat Optics

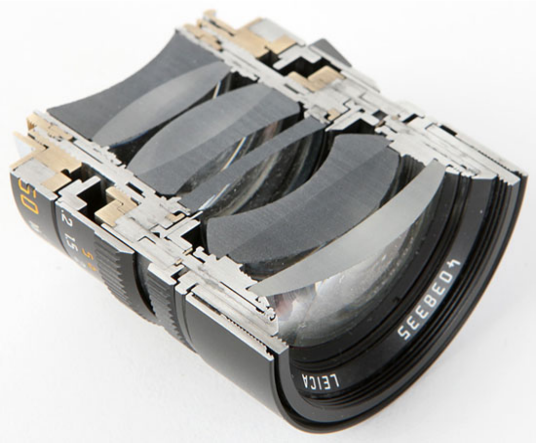
- Planar technology is central to Integrated Circuit technology ($ 300 B industry): Technology platform.
- Because of fabrication complexity 3D optical materials (metamaterials etc.) don't have a good chance of a major technology impact (large scale applications) at optical wavelengths.
- Ho do I know? From Photonic Crystals: exciting science but very limited technology penetration
- **So we should look at what we can do in 2D with metasurfaces**

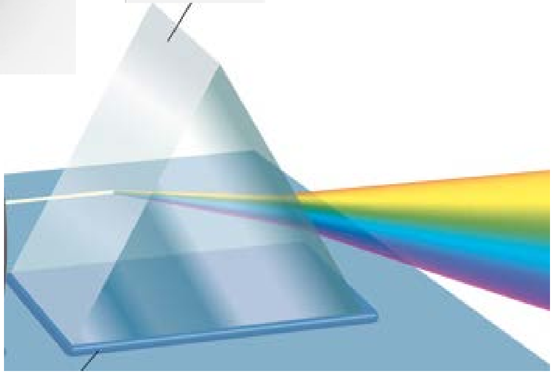
METASURFACES FOR FLAT OPTICS

- Optically thin engineered metasurfaces for Wave Front Engineering (phase control):
- Local phase, amplitude and polarization control of light along the surface using optical resonators
- New class of flat, compact and broadband components:(lenses, polarizers, etc.), beyond conventional diffractive optics
- Optical phased arrays for high speed wavefront control

Can we replace optical components with flat ones?

Conventional Optics





Diffractive Optics

Optically thin subwavelength structured interface (metasurface)

Metasurface: an optically thin (<<λ) array of sub-wavelength size (<<λ) , sub-wavelength (<<λ)   spaced optical elements (resonators, antennas)

Questions

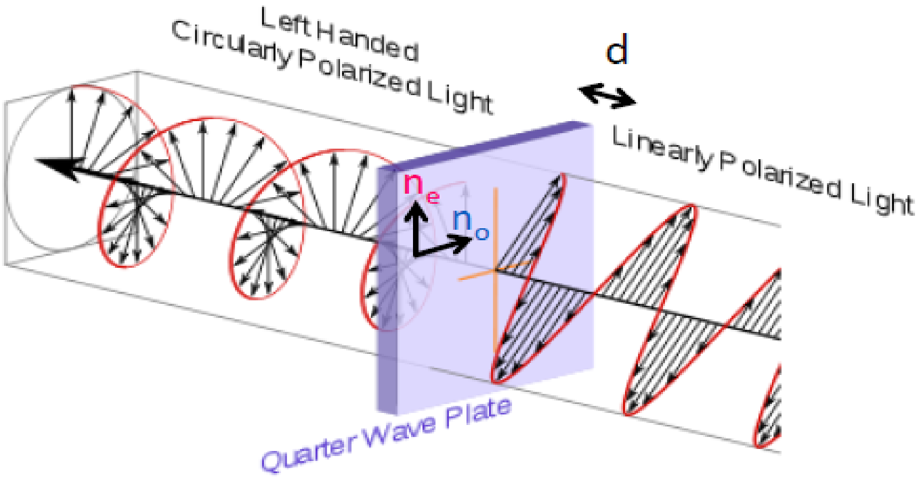
- Can we create metasurfaces that transform an incident beam into arbitrarily shaped (complex) beams (vortex, non-diffracting, etc. including vector beams) ?
- Can we make rapidly reconfigurable metasurfaces for fast wavefront control (nanosecond, many orders of magnitude faster than Spatial Light Modulators)?
- Can we make a high N.A. flat lens without aberrations (spherical, coma, etc.) and acromatic?
- Metasurface-based optical components : flat optics versus Fresnel Optics?
- Can we create metasurfaces that generate broadband vector beams (amplitude, phase and polarization vary from point to point)?
- Are strong optical interference effects possible in films much thinner than the wavelength (metafilms)?
- Physics and Technology of Disordered Metamaterials?
- What interesting physics and applications can emerge from embedding quantum effects into metasurfaces?
- Which large area lithographic technique?

CONVENTIONAL OPTICAL COMPONENTS

Conventional optical components rely on propagation effect

Camera lens (cross-section)

Quarter-wave plate



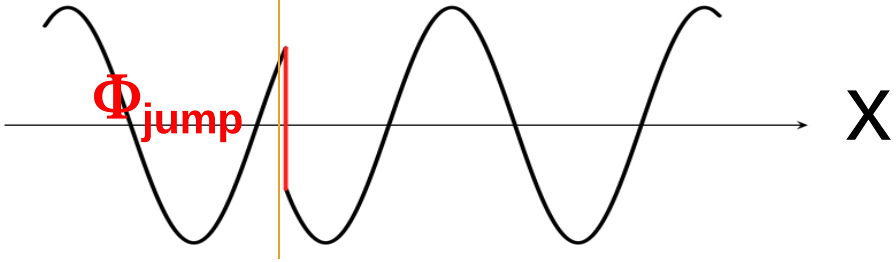
Propagation phase: $\int_A^B k_o n(r)\,dr$

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

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

Huyghens metasurfaces: phase “discontinuities”

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

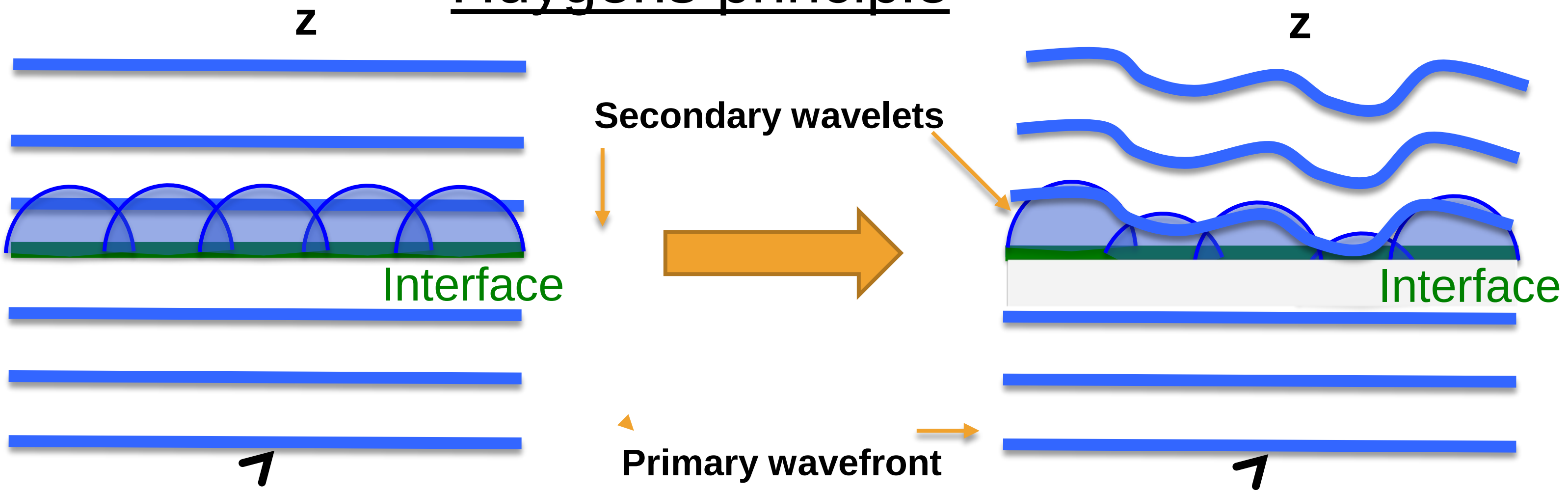


What if could have a spatial distribution of different phase discontinuities along the entire interface? → can make any desired wave front !

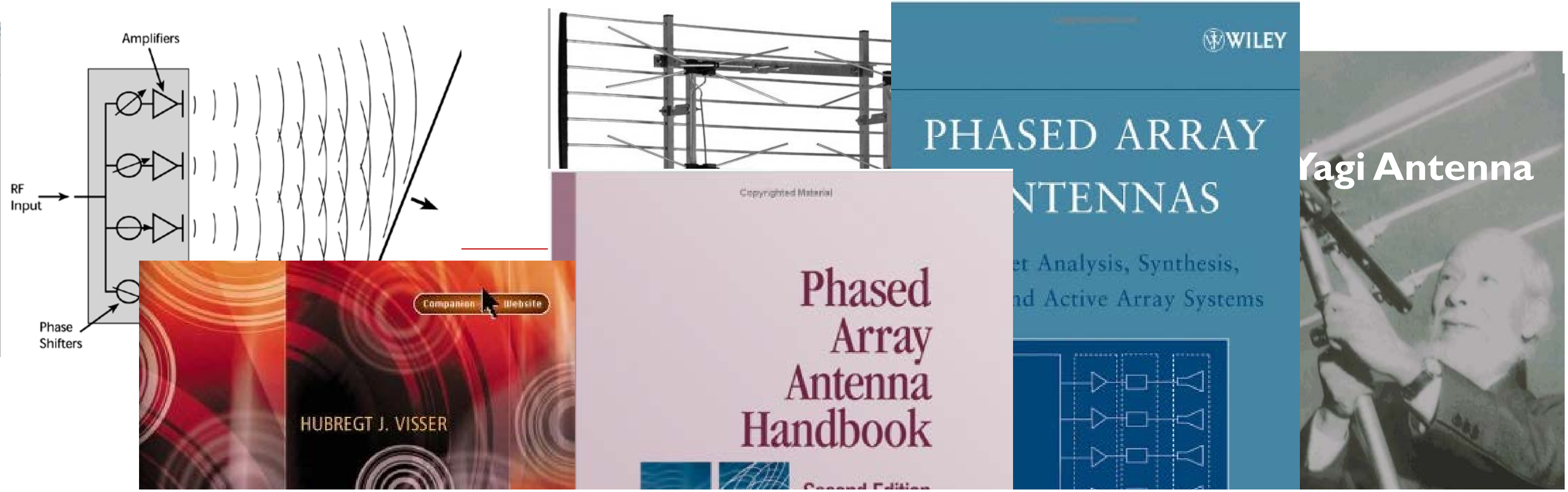
How? → Optically thin array of sub-wavelength spaced resonators

Any type of resonator: metallic (optical antenna), dielectric, fabry-perot, etc. will do

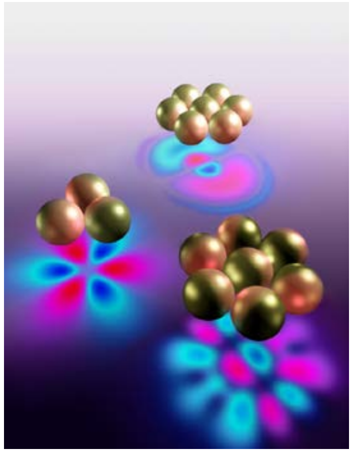
Huygens principle



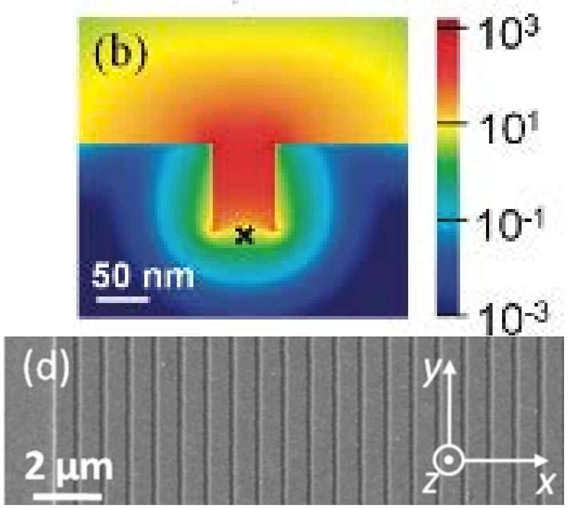
Phased-array antennas



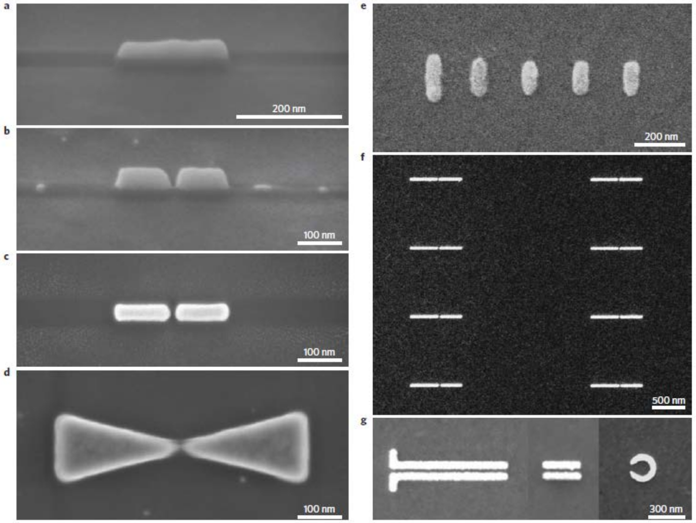
Phased-array antennas for light



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

Gradient Metasurfaces: broadband light bending

Assume a metasurface with a constant gradient of phase delay

$d\Phi/dx$

One can easily show that light can be bent in arbitrary ways; effect is broad band

Generalized Snell's law:

$$\sin(\theta_t)n_t - \sin(\theta_i)n_i = \frac{\lambda_o}{2\pi}\frac{d\Phi}{dx}$$

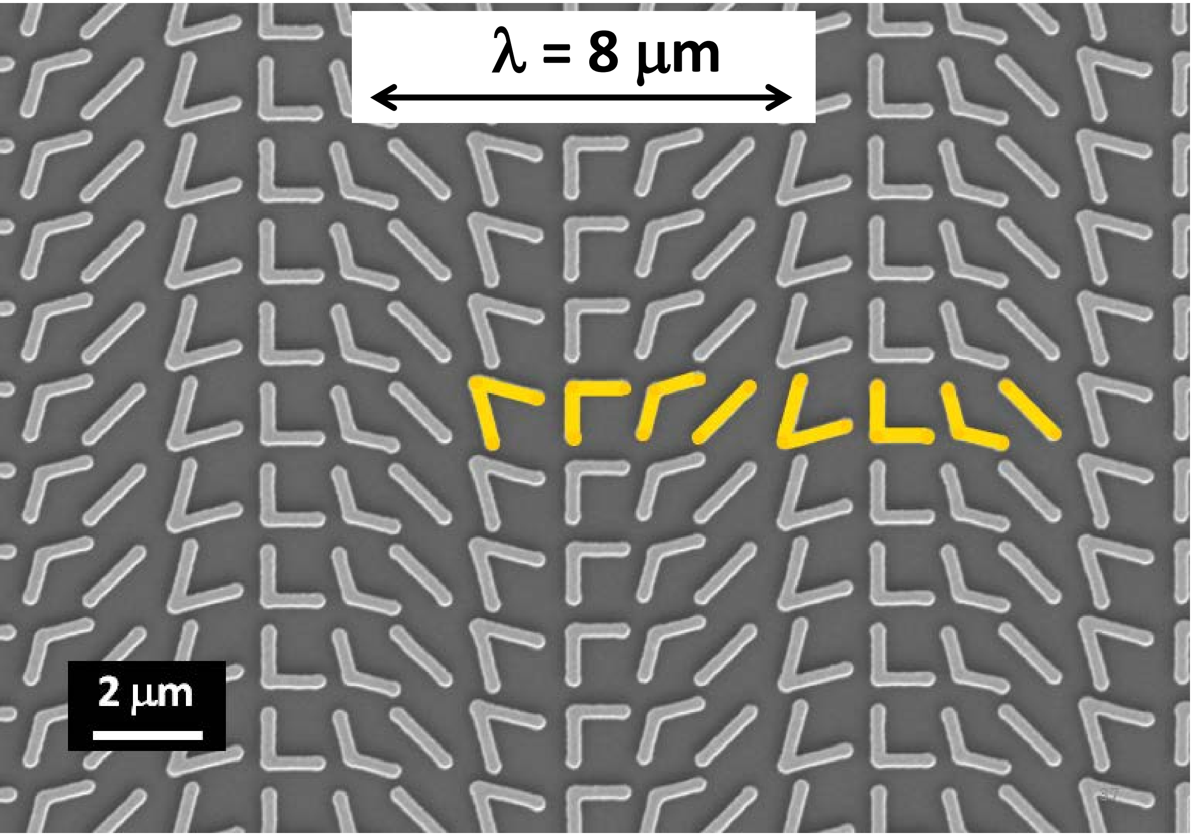
Negative refraction

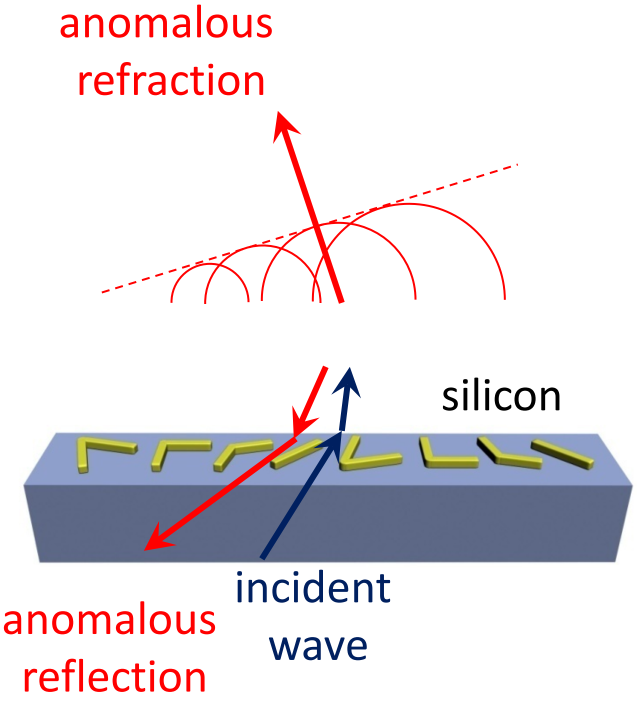
Generalized Law of reflection:

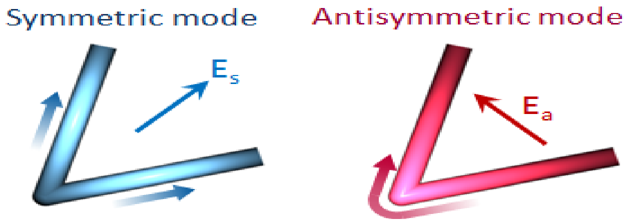
$$\sin(\theta_r) - \sin(\theta_i) = \frac{\lambda_o}{2\pi n_i}\frac{d\Phi}{dx}$$

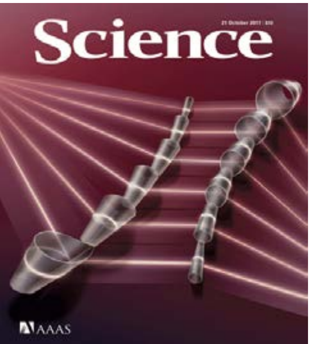
- Negative reflection
- Critical angle above which no reflection

Meta-interface for demonstrating generalized laws









☐ Optically thin: 50nm

☐ Subwavelength phase resolution: ~λ/5

☐ Instant imprinting of a linear phase distribution

☐ Broadband (5-11 microns)

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

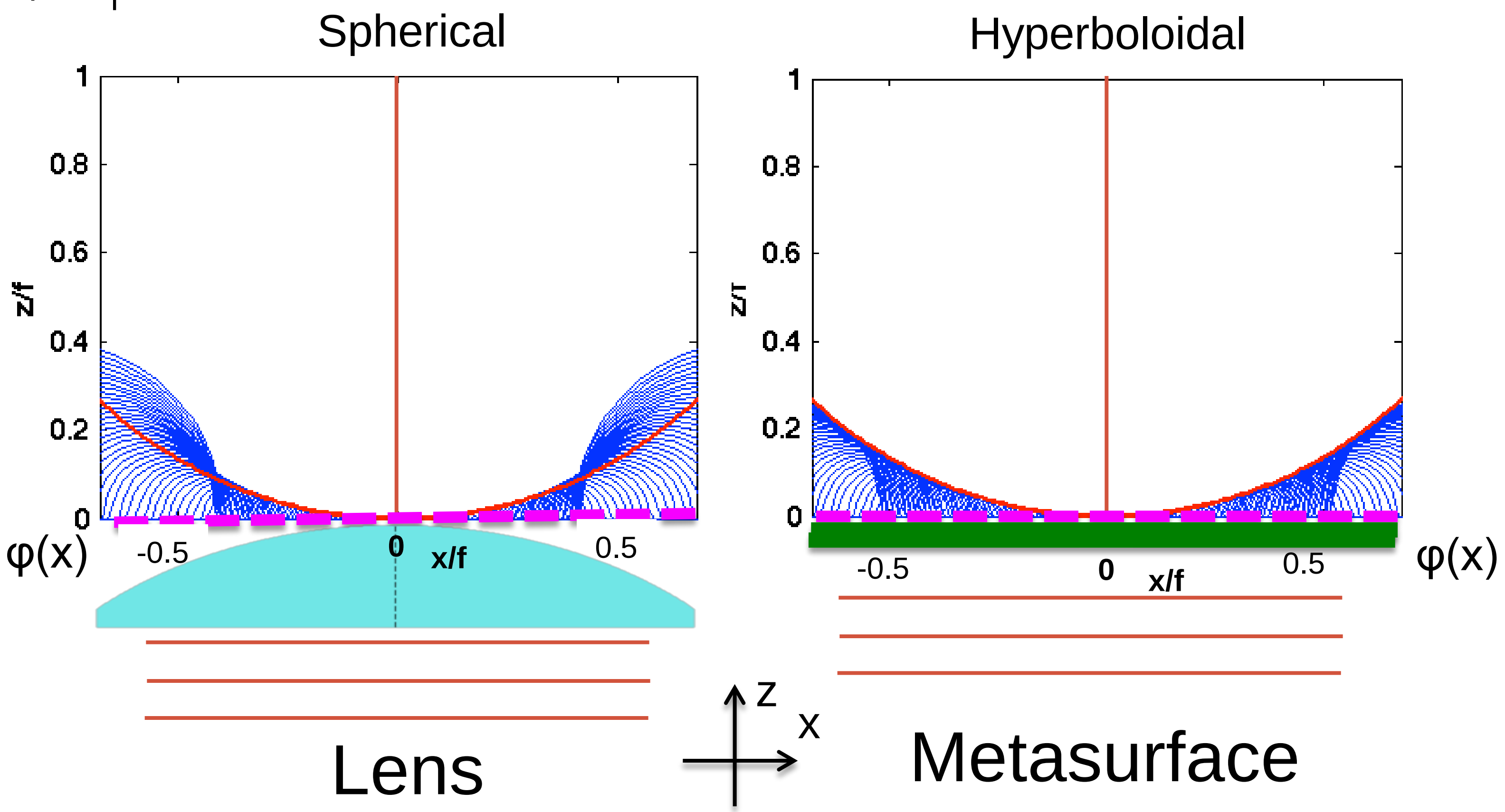
No Spherical Aberration for flat lens

Wavefront = Envelope of Secondary Waves with radii

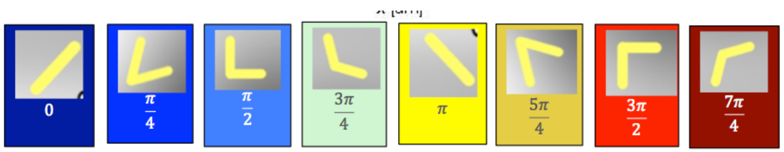
$$\mathbf{R(x) = \lambda/2\pi * \varphi(x)}$$

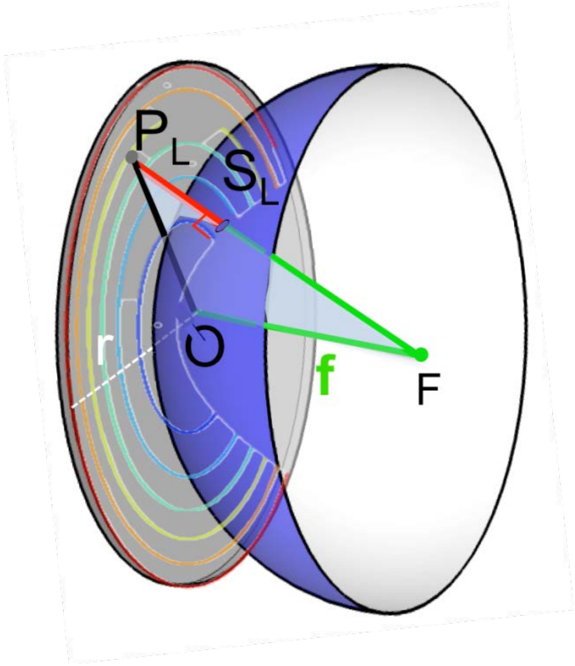
High N.A. = 0.8

$\sin\vartheta_i \neq \vartheta_i$



METALENS: Flat lens based on Metasurfaces





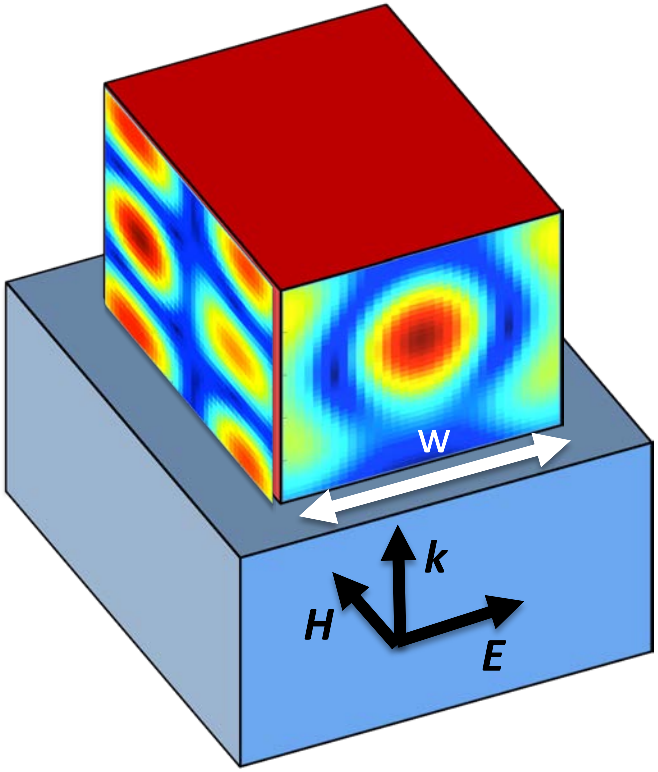
To focus at a certain focal f the interface must compensate for the distance of every point from a spherical surface centered in the focus and with radius f.

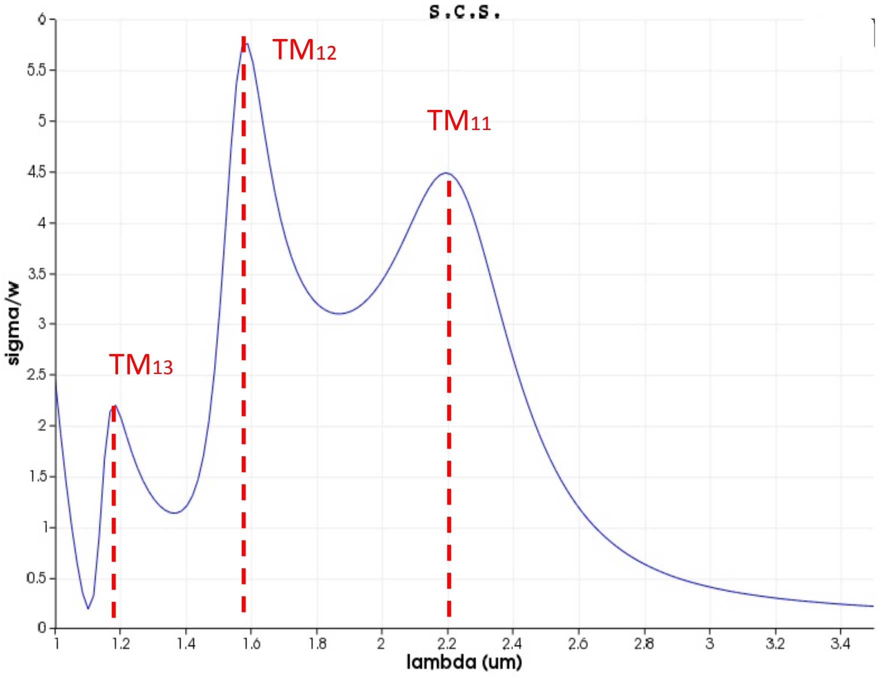
$$\varphi_L(x,y)=\frac{2\pi}{\lambda}\overline{P_L S_L}=\frac{2\pi}{\lambda}\left(\sqrt{(x^2+y^2)+f^2}-f\right)$$

No spherical aberration and large numerical aperture

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

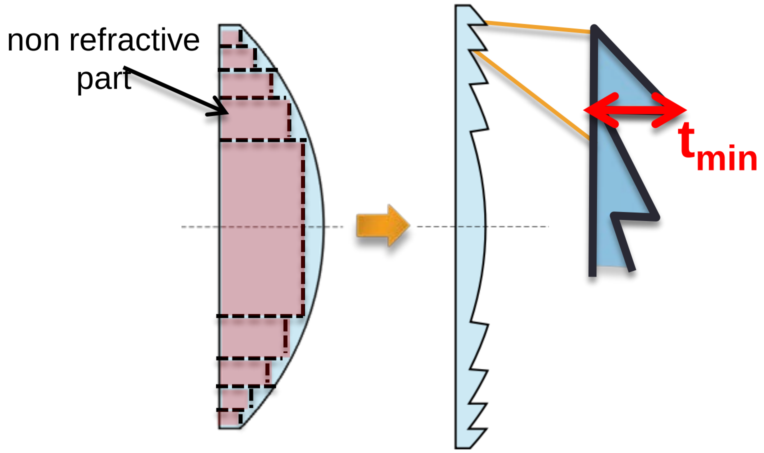
Dielectric resonators as new building block for tunable metasurfaces

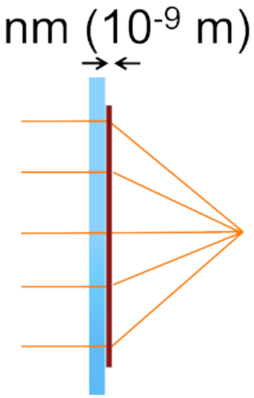




- A simple rectangular dielectric antenna supports multiple modes of resonance that can be used to introduce novel broadband functionalities
- When used at optical frequencies, dielectric materials do not suffer from parasitic optical losses present in metals.
- **High scattering efficiency ~ 90%. Scattering properties can be tuned by doping and gating standard dielectrics or combining them with phase change materials.**

Fresnel Optics vs Metasurface Based Optics

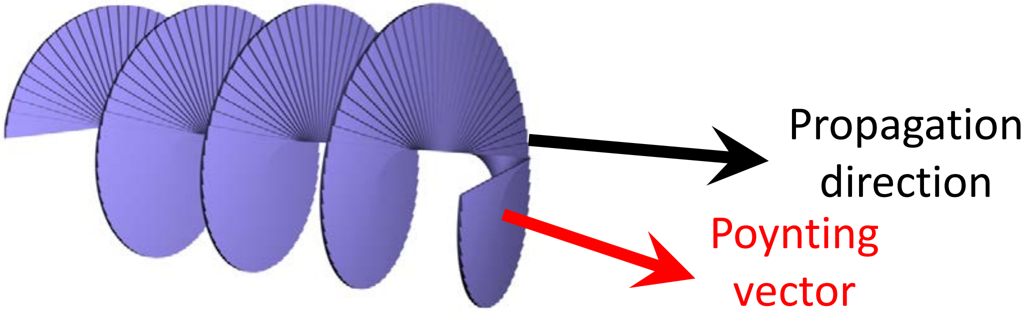


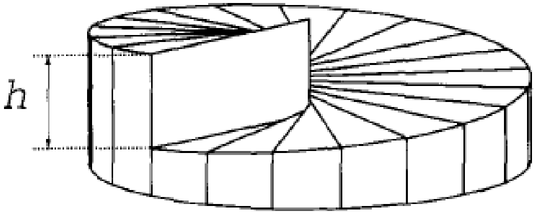


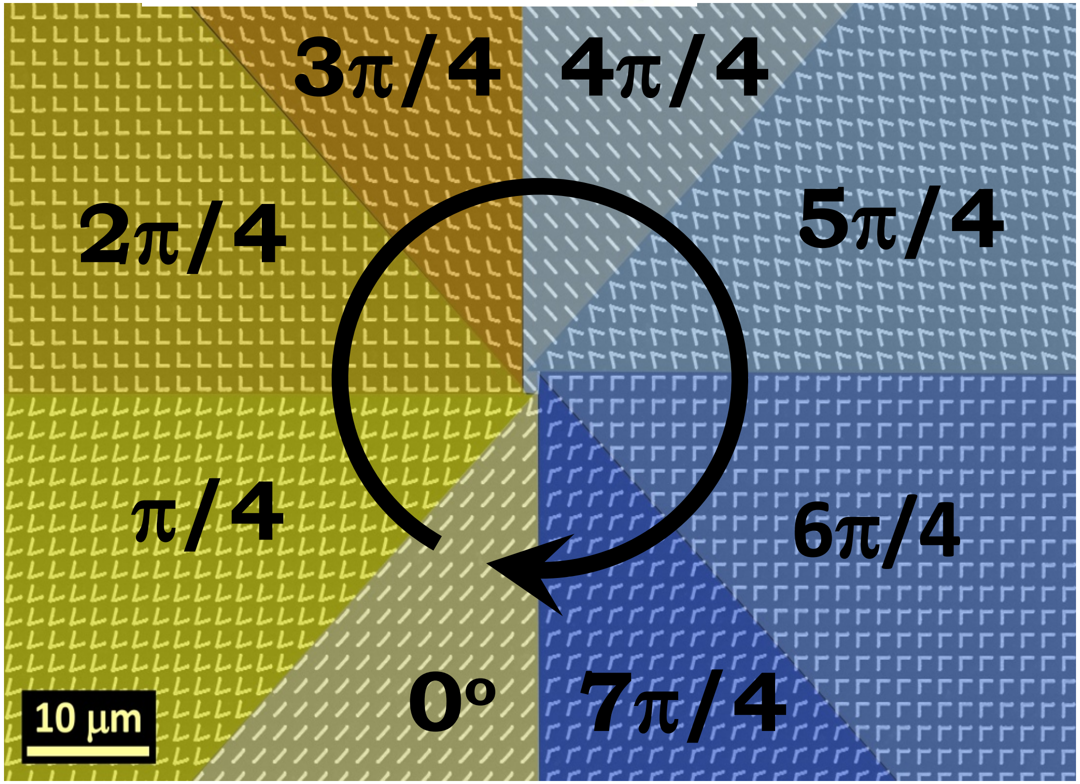
Fresnel Optics	Metasurface
thin but finite thickness	ultra - thin
finite lateral phase control	sub wavelength phase control
polarization insensitive	polarization control
diffractive: single wavelength operation	**controlled dispersion: achromatic**
multiple steps of lithography: N phase level→log$_2$ N steps	**single lithographic step**

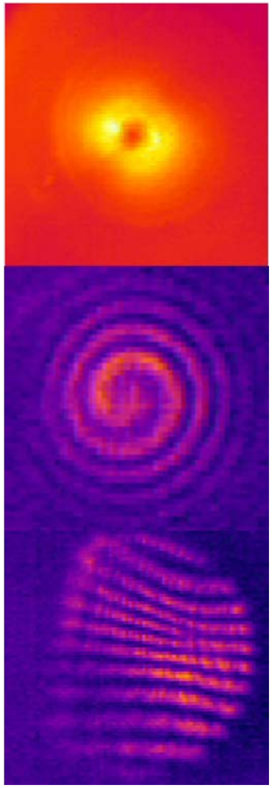
a single digital pattern (one mask level) creates arbitrary analog phase profile !

VORTEX PLATE









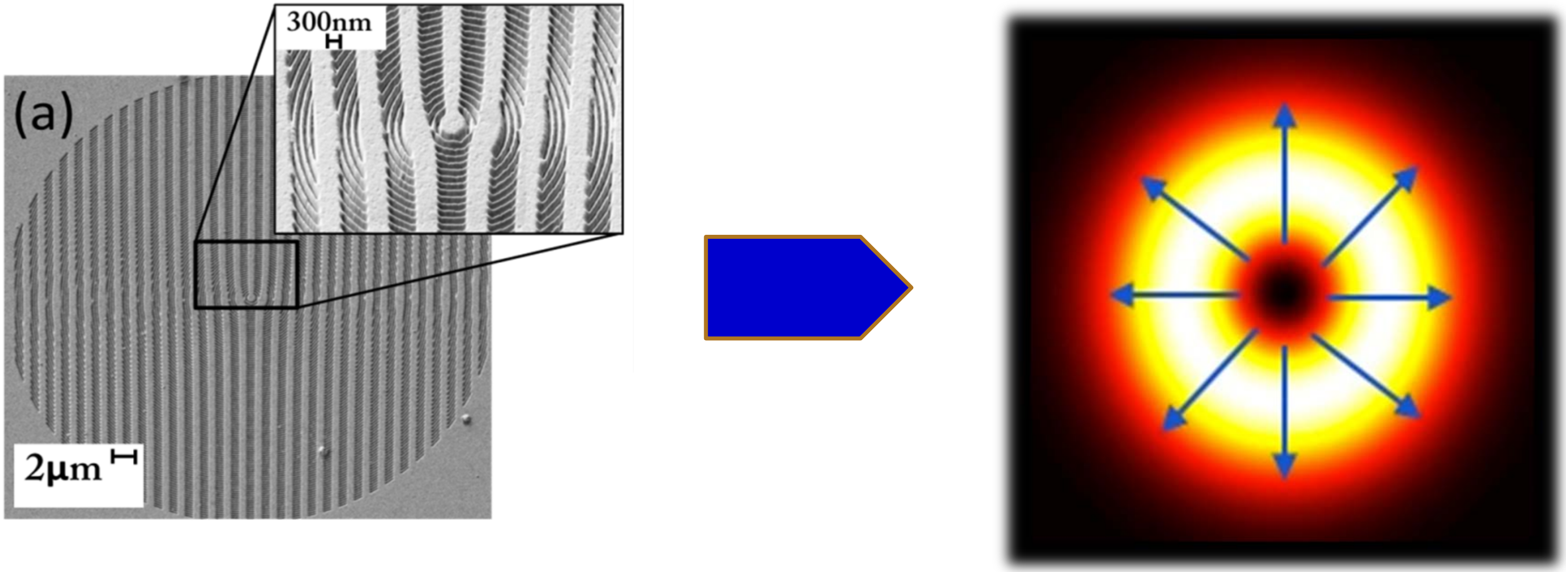
P. Genevet et al. Appl. Phys. Lett. 100, 13101 (2012

- Radial arrangements create flat lenses …
- Angular arrangements of antennas create optical vortices

Nanostructured Holograms for Vector Beam Generation

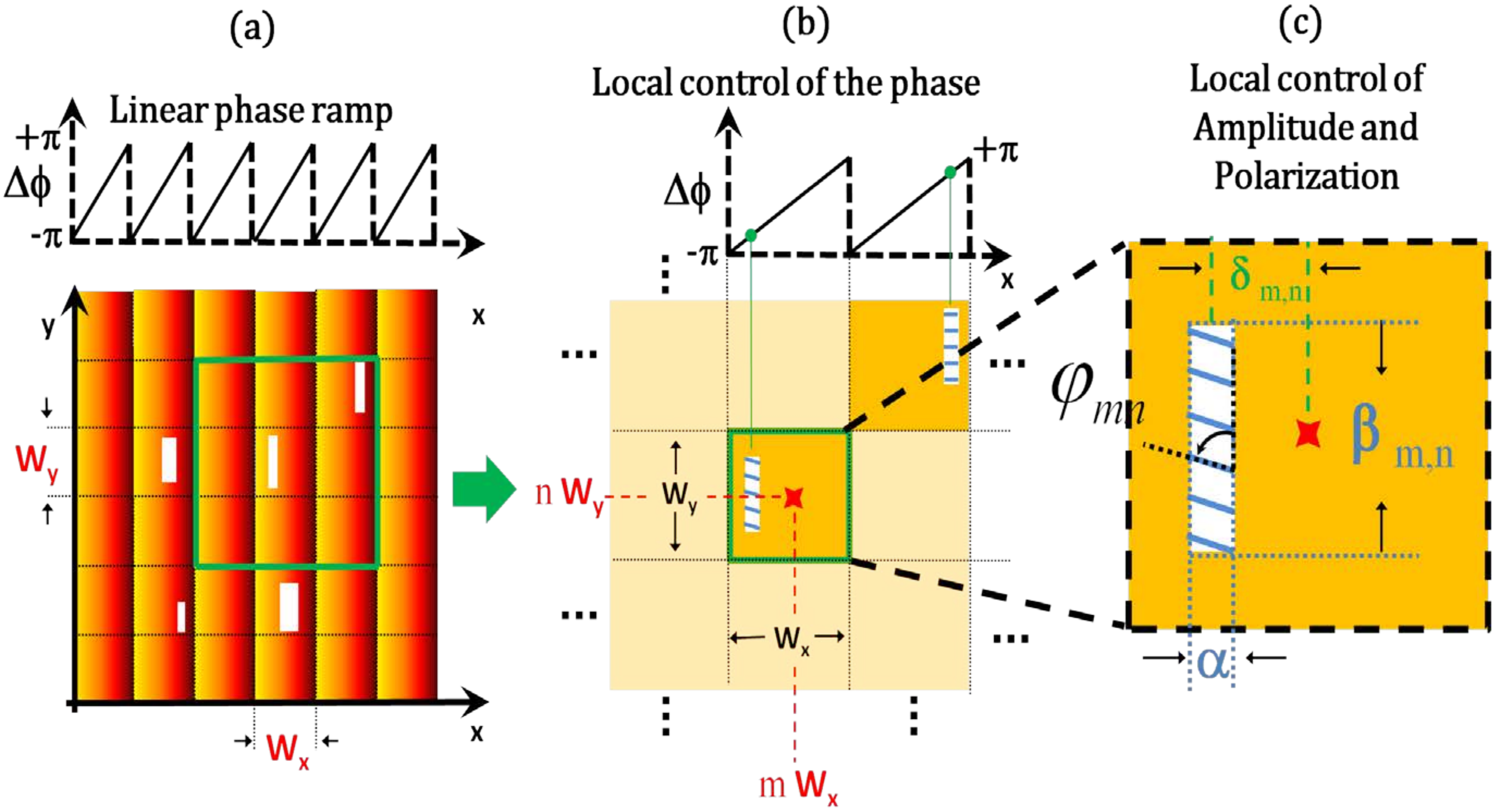
Computer Generated Holograms is the method of digitally generating holographic interference patterns.

A holographic image can be generated e.g. by digitally computing a holographic interference pattern and printing it onto a mask or film for subsequent illumination by suitable coherent light source.



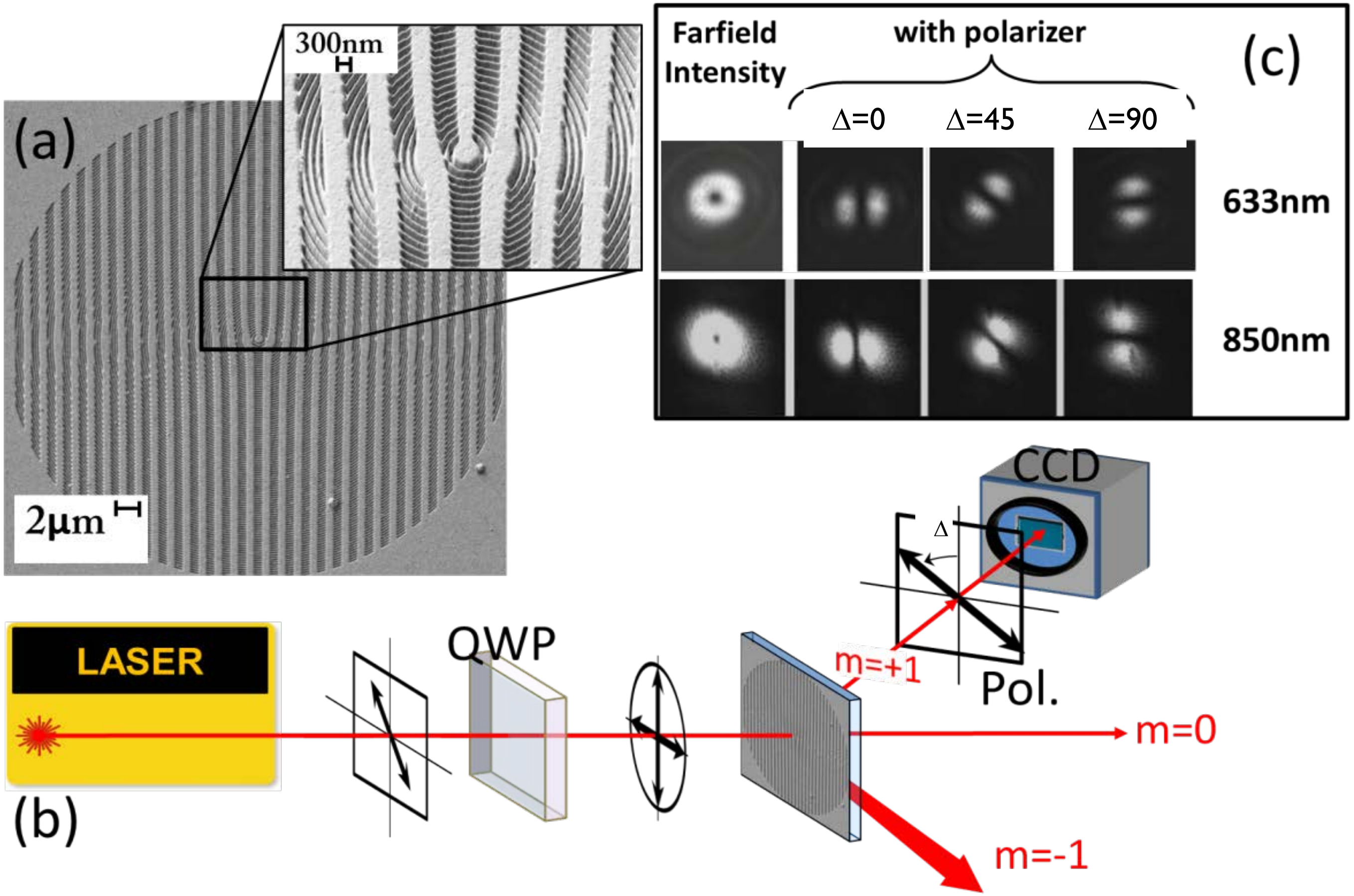
Nanostructured computer generated holograms for vector beam generation

Vector beam: wavefront with spatially varying polarization



the phase shift for a given wavelength (λ_1), will be observed at another wavelength (λ_2) at the angle θ_2 defined by

Nanostructured holograms for broadband manipulation of light

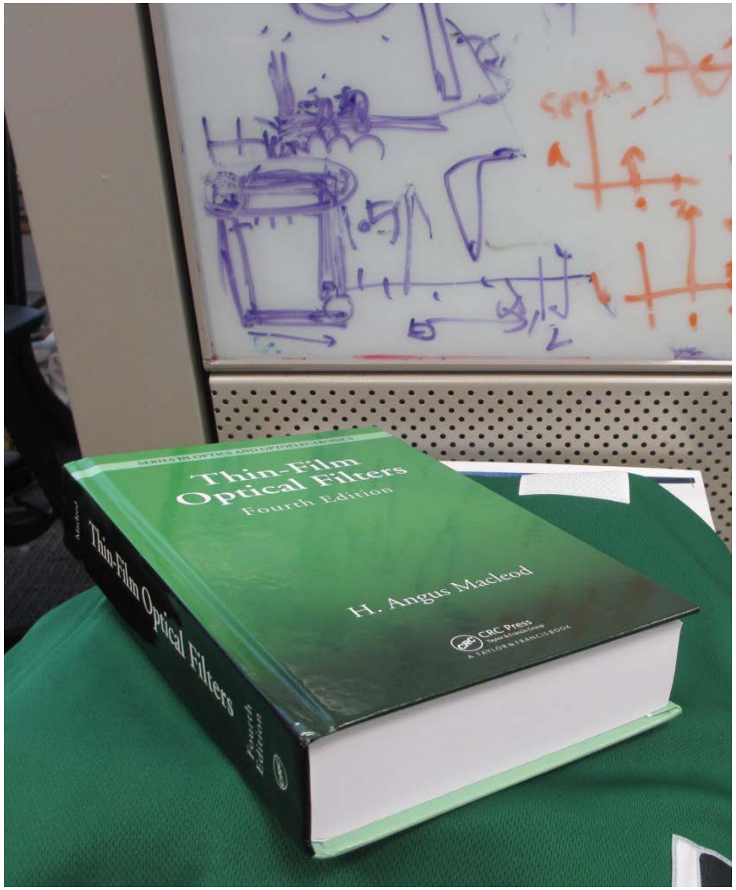


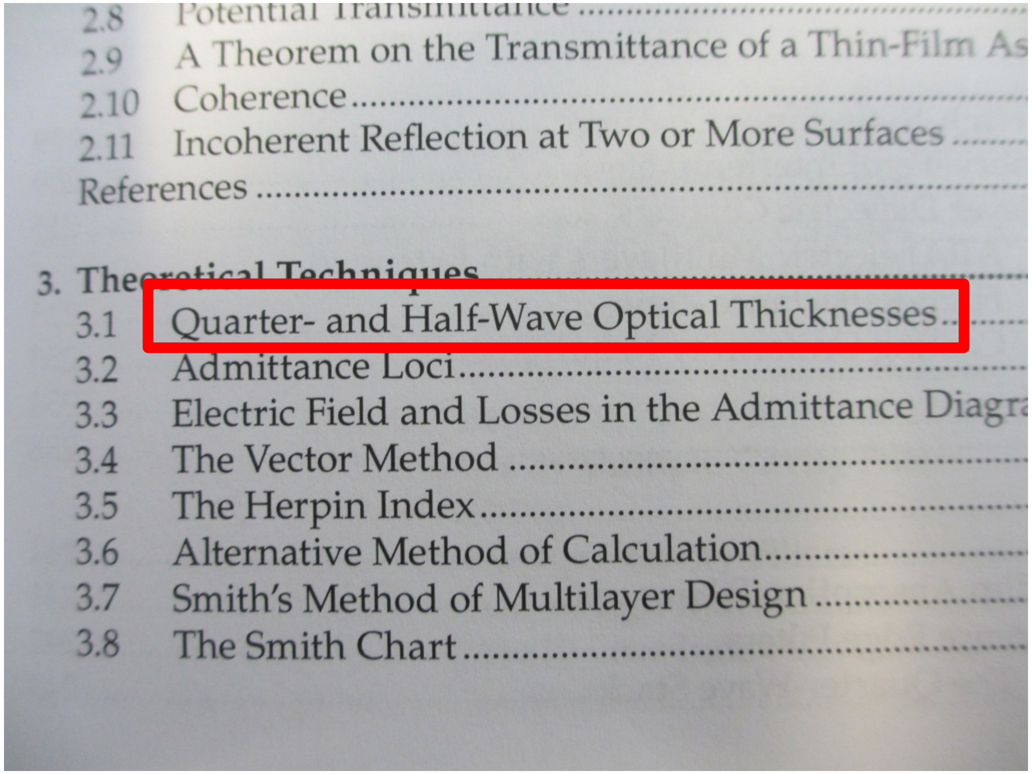
Questions

- Can we create metasurfaces that transform an incident beam into arbitrarily shaped (complex) beams (vortex, non-diffracting, etc. including vector beams) ?
- Can we make rapidly reconfigurable metasurfaces for fast wavefront control (nanosecond, many orders of magnitude faster than Spatial Light Modulators)?
- Can we make a high N.A. flat lens without aberrations (spherical, coma, etc.) and acromatic?
- Metasurface-based optical components : flat optics versus Fresnel Optics?
- Can we create metasurfaces that generate broadband vector beams (amplitude, phase and polarization vary from point to point)?
- Are strong optical interference effects possible in films much thinner than the wavelength (metafilms)?
- Physics and Technology of Disordered Metamaterials?
- What interesting physics and applications can emerge from embedding quantum effects into metasurfaces?
- Which large area lithographic technique?

Optical interference in films much thinner than wavelength

- Last half century: a lot of work on optical coatings and filters using thin film interference effects

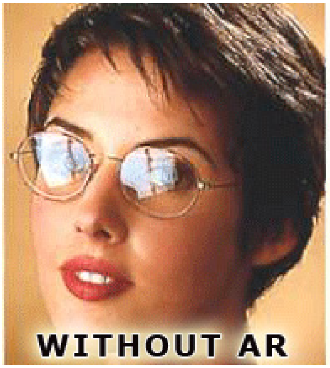


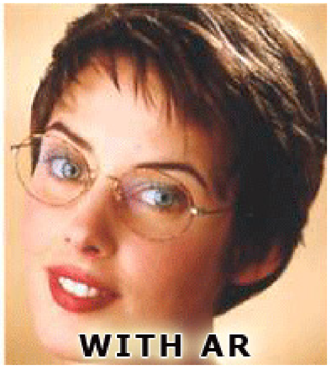


- Nearly all thin film optical coatings use dielectric layers with **low optical loss** and **thickness on the order of a wavelength**

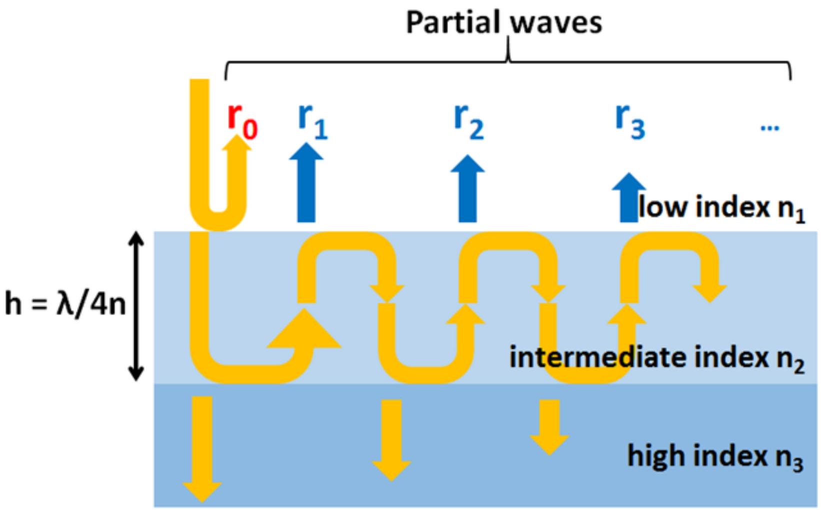
Anti-reflection (AR) coating

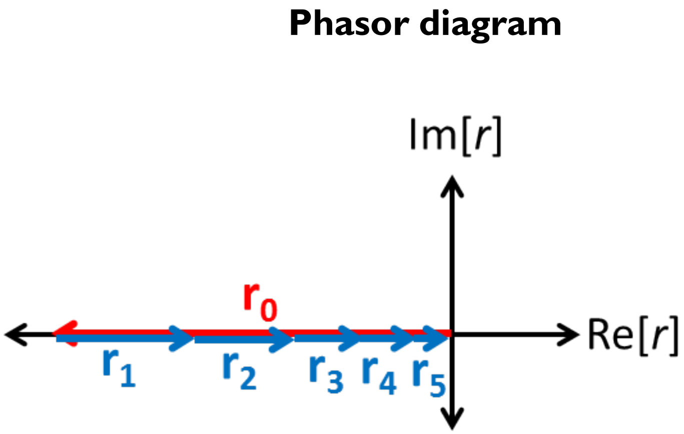
- A simple application: anti-reflective coatings





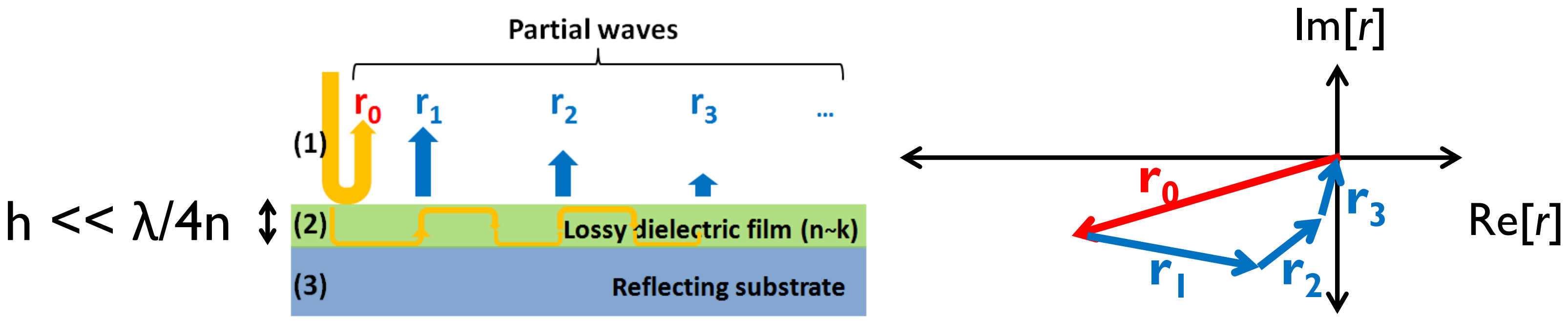
- Simplest/thinnest conventional AR coating: quarter-wave (~ 50 – 150 nm in the visible) film (optimized for a particular wavelength)





Lossy dielectrics and metals

- Metals with finite conductivity and lossy dielectrics have weird interface reflection phase shifts (i. e. not 0 or π)
  - Different interference condition compared to the lossless case: **“resonance” can exist for films significantly thinner than λ/4**

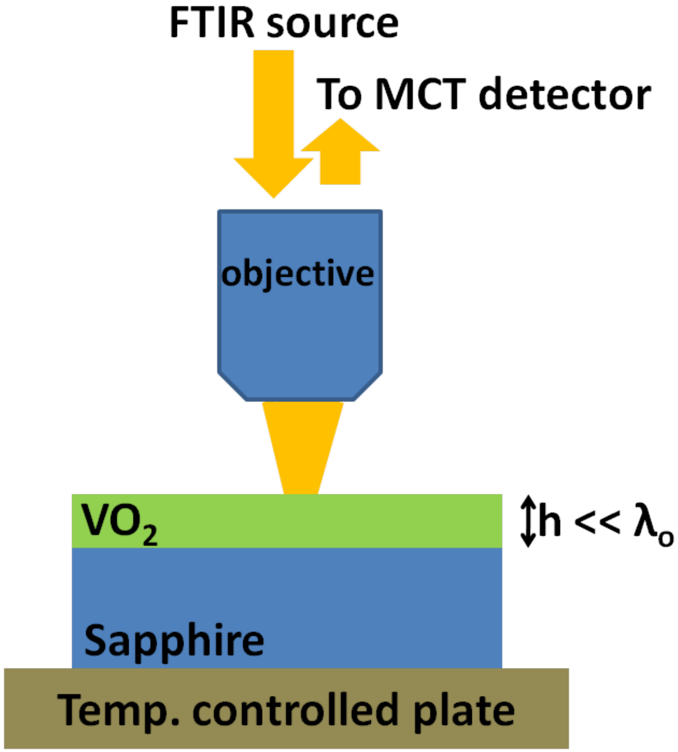


- Takeaway message: it is possible to **suppress reflection (perfect absorber)** by using **coherent effects** in a system involving an **ultra-thin, highly-lossy layer**

M.A. Kats et al, **APL** 101, 221101 (2012)

Making a perfect absorber

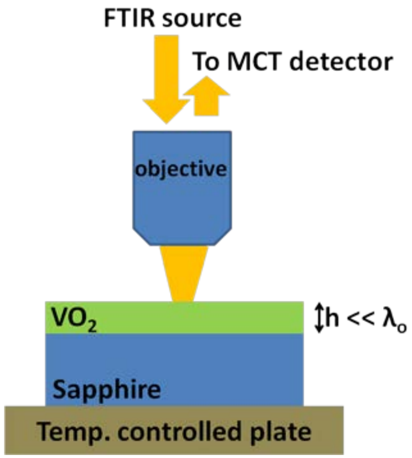
- Our experimental system comprises a thin (180 nm vs. λ ~ 5-15 µm) film of vanadium dioxide (VO_2) on sapphire
  - VO_2 serves as highly-absorbing layer (tunable)
  - Sapphire is highly-reflecting due to phonon activity in the IR

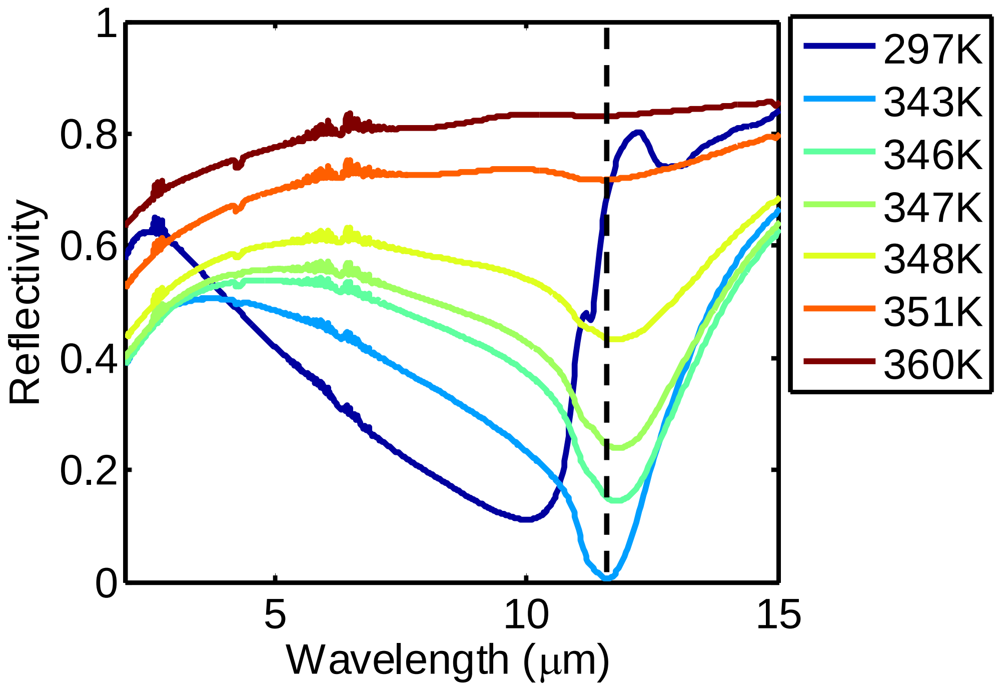


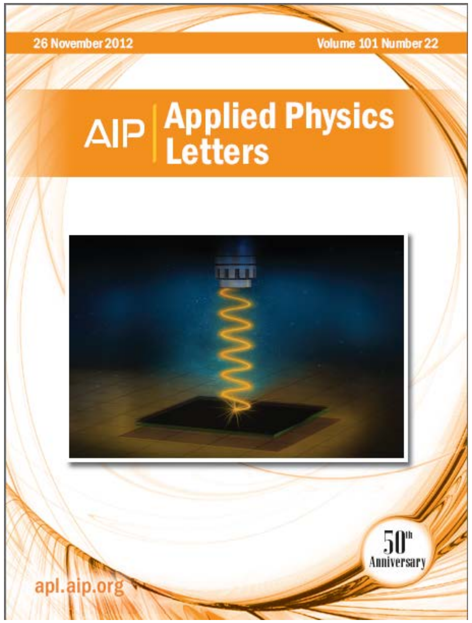
Perfect absorber

- Temperature control of VO_2 allows significant tuning of its refractive index, and hence the sample reflectivity

- Reflectivity tuning from ~80% to 0.25% at 11.6um
  → on/off ratio of more than 300
  → entire structure is simply 180nm of VO_2 on sapphire



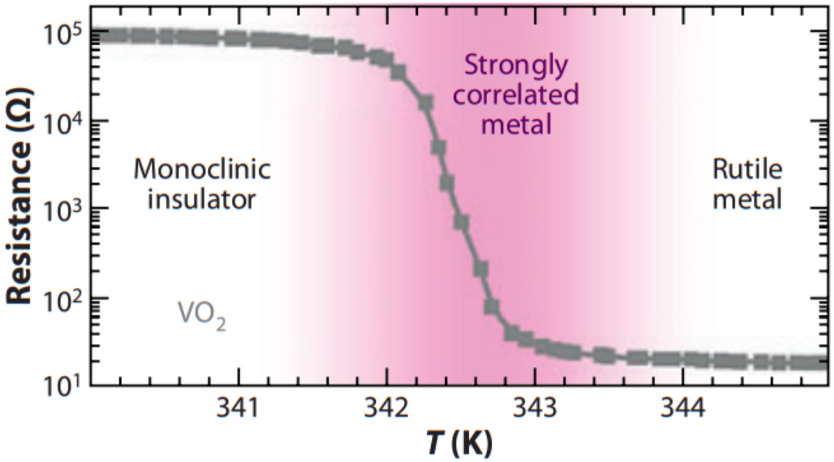


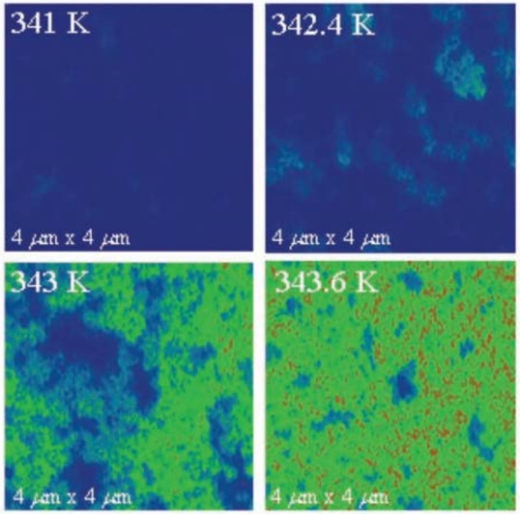

26 November 2012
Volume 101 Number 22
AIP Applied Physics Letters
50th Anniversary
apl.aip.org

M.A. Kats et al, **APL** 101, 221101 (2012)

VO_2 in the transition region

- What happens in the transition region of VO_2?



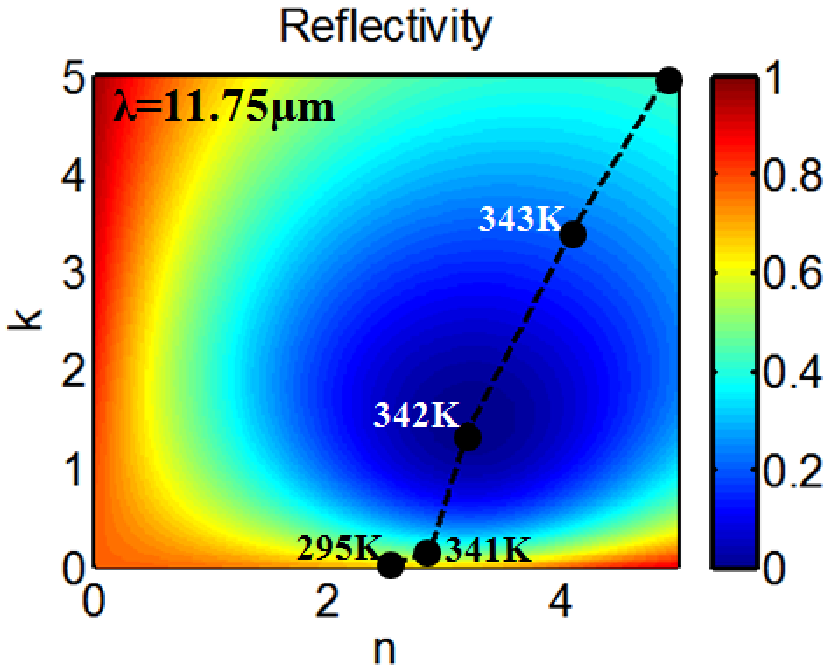


Qazilbash, Basov, et al, Science (2007)

- Nanoscale islands of metal-phase VO_2 begin to form within a background of dielectric-phase VO_2, which then grow and connect
  - The mixture can be viewed as a ***disordered, natural metamaterial***
  - The ratio of co-existing phases can be controlled → ***tunable medium***

Understanding the R = 0 condition

- Fix *h* = 180nm, λ = 11.75µm, sapphire substrate

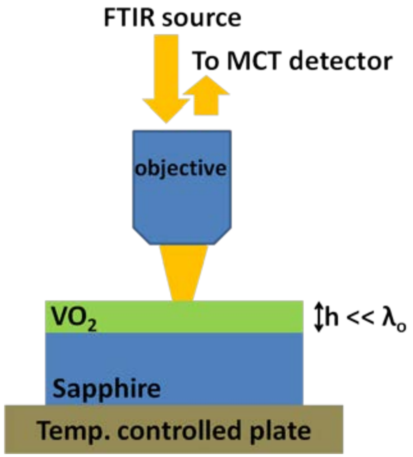


- VO2 complex-index trajectory as a function of temperature goes through perfect-absorption condition
- The minimum is very broad in *n*-*k* space, so the condition is insensitive to small changes in material composition, defects

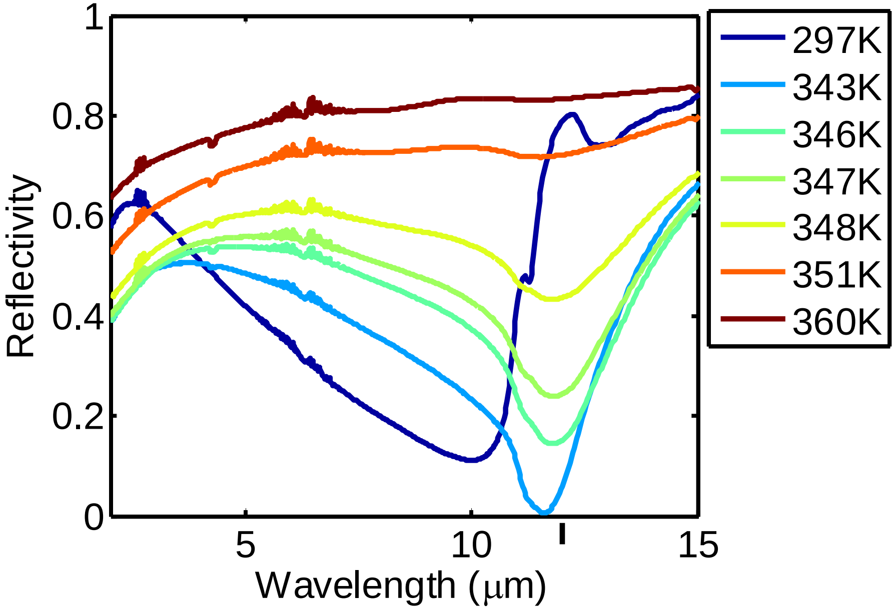
Perfect absorber

- Experiment matches analytical calculations
- Used VO_2 complex index data from Basov group (UCSD)

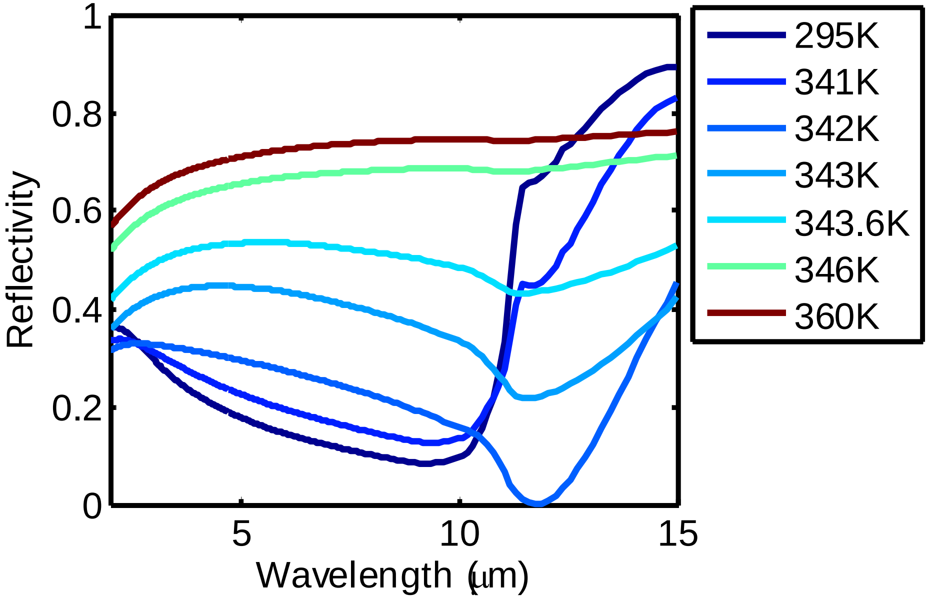
$$r = \sum_{m=0}^{\infty} r_m = \frac{r_{12} + r_{23}e^{2i\beta}}{1 + r_{12}r_{23}e^{2i\beta}}$$



Experiment



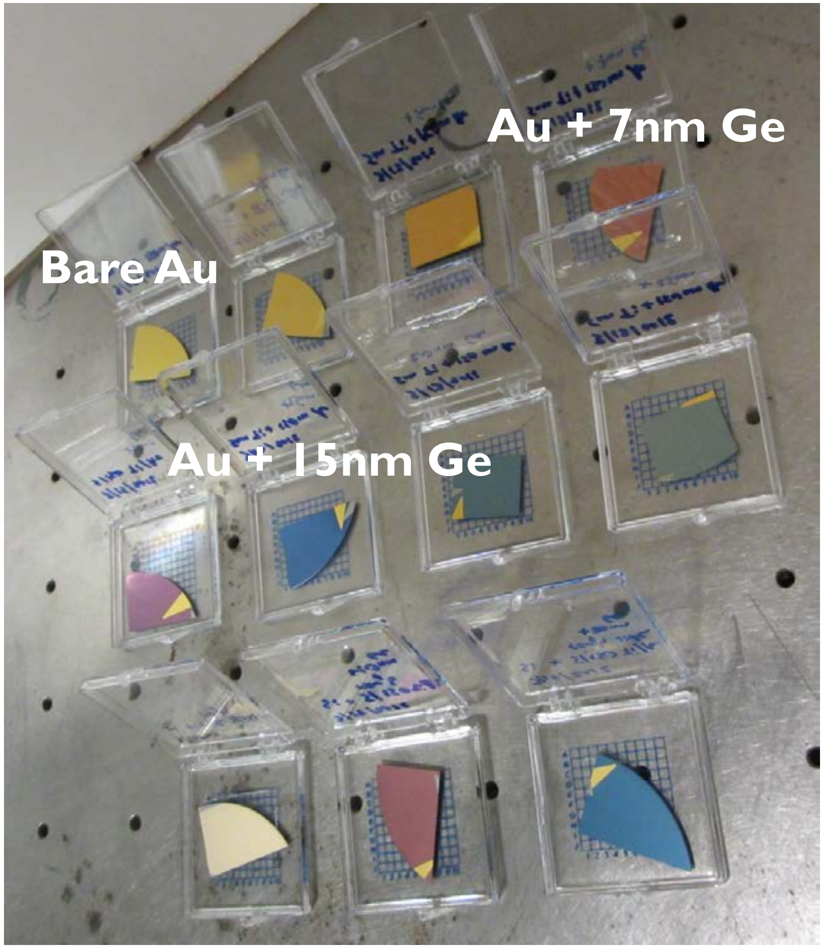
Calculation



M.A. Kats et al, **APL** 101, 221101 (2012)

Coloring gold

- “Colored” gold films by coating with 5-20 nm germanium films → much thinner than λ/4



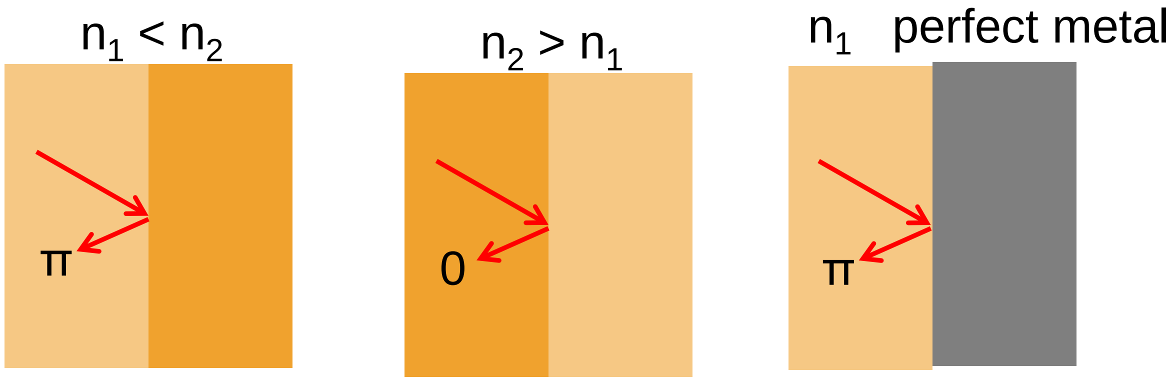
Polished substrate

Rough substrate (still works!)

M. A. Kats et al, **Nat. Materials** 12, 20 (2013)

Thin film interference in lossy media

- Thin film interference in highly-absorbing films is unexpected
  1. In the absence of optical loss reflection phase shifts are fixed to either 0 or π



- Lossy materials introduce nontrivial reflection phase shifts
  - → Resonant cavities can be made thinner than λ/4
  - → Short propagation lengths allow the use of highly absorbing media

Questions

- Can we create metasurfaces that transform an incident beam into arbitrarily shaped (complex) beams (vortex, non-diffracting, etc. including vector beams) ?
- Can we make rapidly reconfigurable metasurfaces for fast wavefront control (nanosecond, many orders of magnitude faster than Spatial Light Modulators)?
- Can we make a high N.A. flat lens without aberrations (spherical, coma, etc.) and acromatic?
- Metasurface-based optical components : flat optics versus Fresnel Optics?
- Can we create metasurfaces that generate broadband vector beams (amplitude, phase and polarization vary from point to point)?
- Are strong optical interference effects possible in films much thinner than the wavelength (metafilms)?
- Physics and Technology of Disordered Metamaterials?
- What interesting physics and applications can emerge from embedding quantum effects into metasurfaces? Decorating metasurfaces with single quantum emitters (e.g. NV centers in nanodiamonds)
- Which large area lithographic technique? Namoimprint, soft lithography, etc.

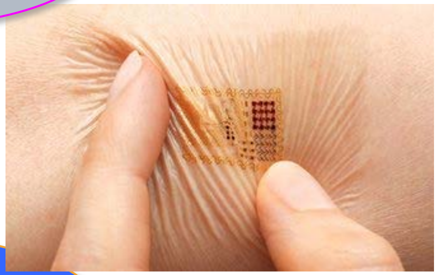
Flat optics

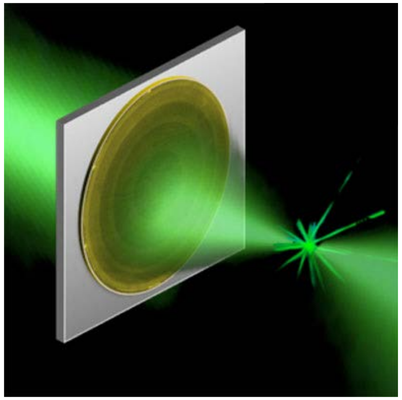
- New class of flat, compact and broadband components: lenses, polarizers., filters, etc.
- High speed tunable phased arrays for real-time wavefront control: role of phase change materials
- Lithography: from Optical to Nanoimprinting and Soft Lithography

High NA Objective

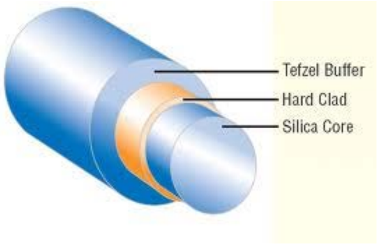
Strechable Materials

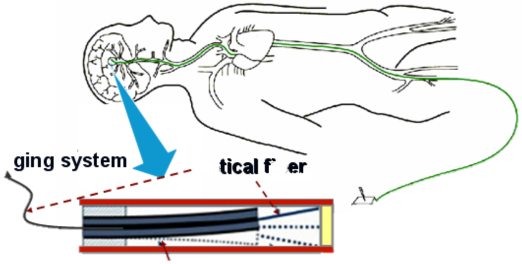
Smart Phones





Non-Invasive Imaging for Biomedical Application





Major opportunity in Midir due to poor refractory materials