Introduction to “Metasurfaces”

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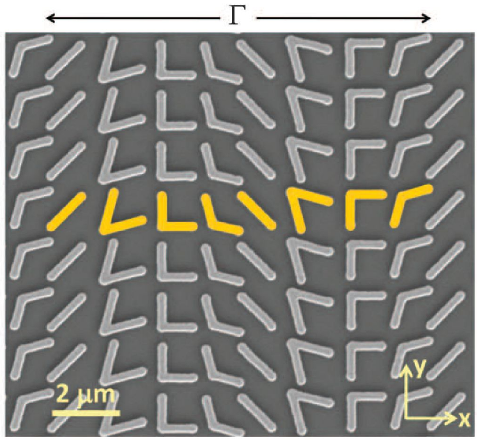
KISS Metasurfaces Workshop

Pasadena, CA, USA – September 23-28, 2024

Presentation Outline

1. What are metasurfaces? Broad overview.
2. Historical context.
3. Methods of imparting phase in diffractive optics.
4. Metasurface polarization optics.
5. Potential applications astronomy (incl. high-contrast imaging).

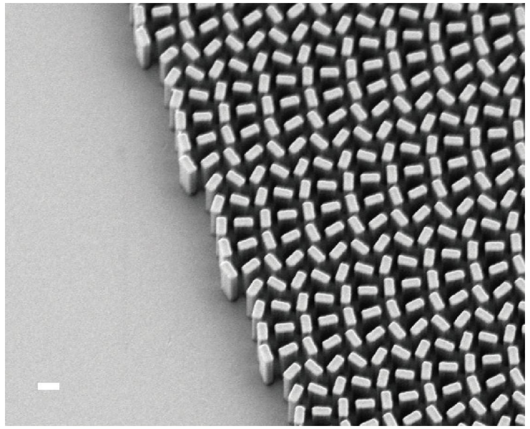
What is a "metasurface"?



N. Yu et al., *Science* **334** (6054), 2011

λ = 8 μm

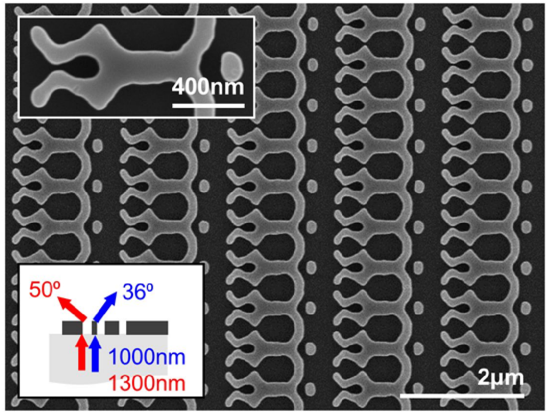
Au on Si



M. Khorasaninejad et al., *Science* **352** (6290), 2016

λ = 530 nm

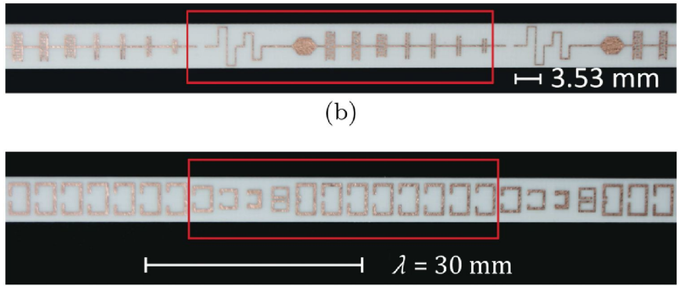
TiO_2 on SiO_2



J. Yang et al., *Nano Lett.* **17** 3742, 2017

λ = 1100 nm

Si on SiO_2



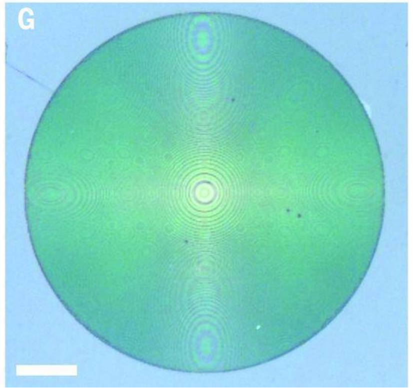
C. Pfeiffer and A. Grbic, *Phys. Rev. Lett.*. **110** (197401), 2013

Microwaves

Cu on RO4003

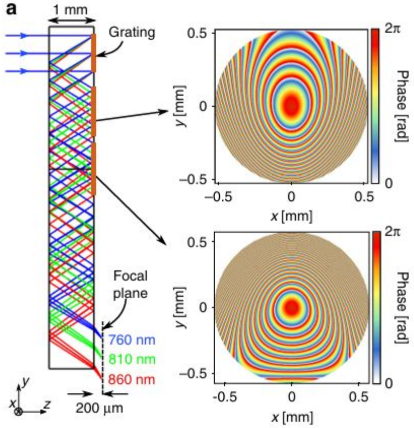
<u>One definition:</u> A **subwavelength-spaced array of phase-shifting elements intende**d to enact some desired behavior (either in reflection or transmission), generally in free-space. These elements – the "meta-atoms" – can be designed at-will and fabricated with standard semiconductor fabrication techniques.

Metasurface application areas



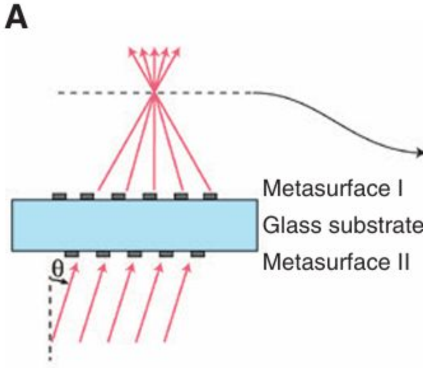
M. Khorasaninejad et al., *Science* **352** (2016)

Metalenses



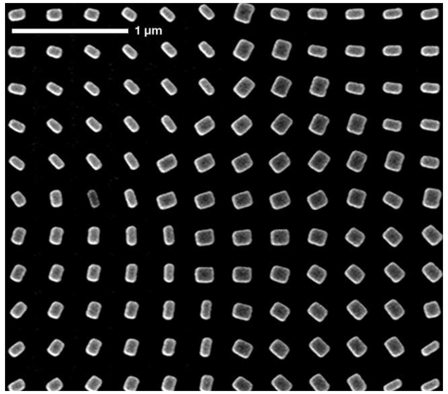
M. Faraji-Dana et al., *Nat. Comm.* (2018)

Spectroscopy



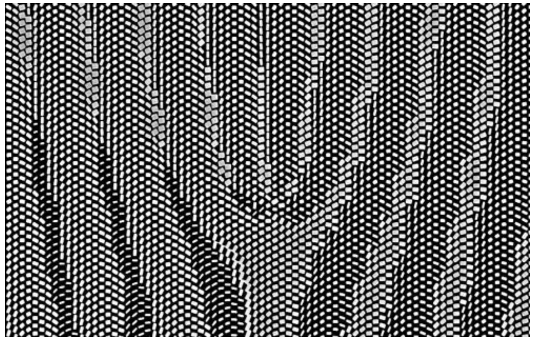
A. Arbabi et al., *Nat. Comm.* (2016)

Miniature Cameras



(own work)

Polarization optics/polarimetry



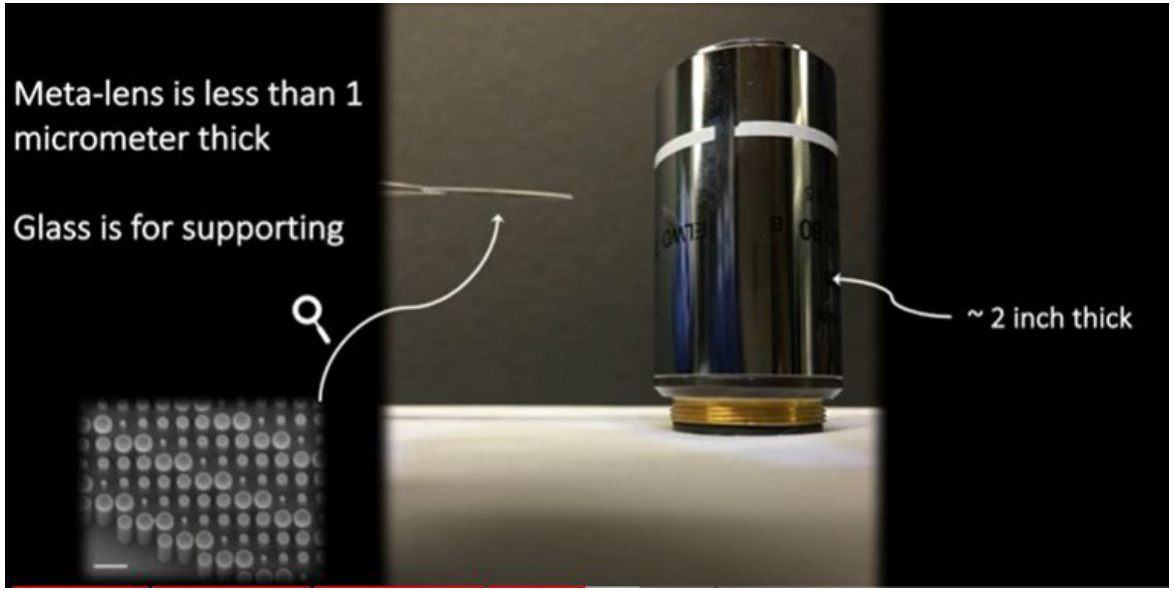
R.C. Devlin et al., *Science* **358** (2017)

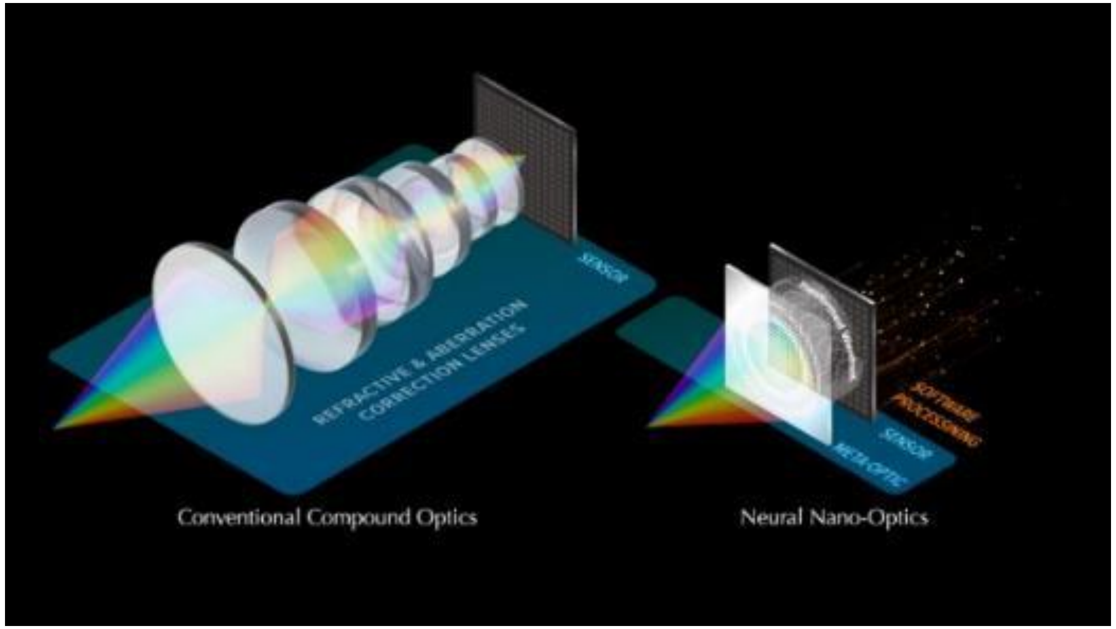
Vortex phase plates

This list is not exhaustive and this talk will be necessarily incomplete.

In some ways, any topic involving free space propagation can relate to metasurfaces, making this an impossibly broad field to cover.

Metasurfaces – the hype





TED Talk on metasurfaces

Nvidia Developer Technical Blog

- Metasurfaces are often billed as "2D metamaterials", fabricated on a plane. Sometimes also called *flat optics.*
- The scientific literature and even the popular press abound with claims surrounding metasurfaces' ability to remake free-space optical systems completely.

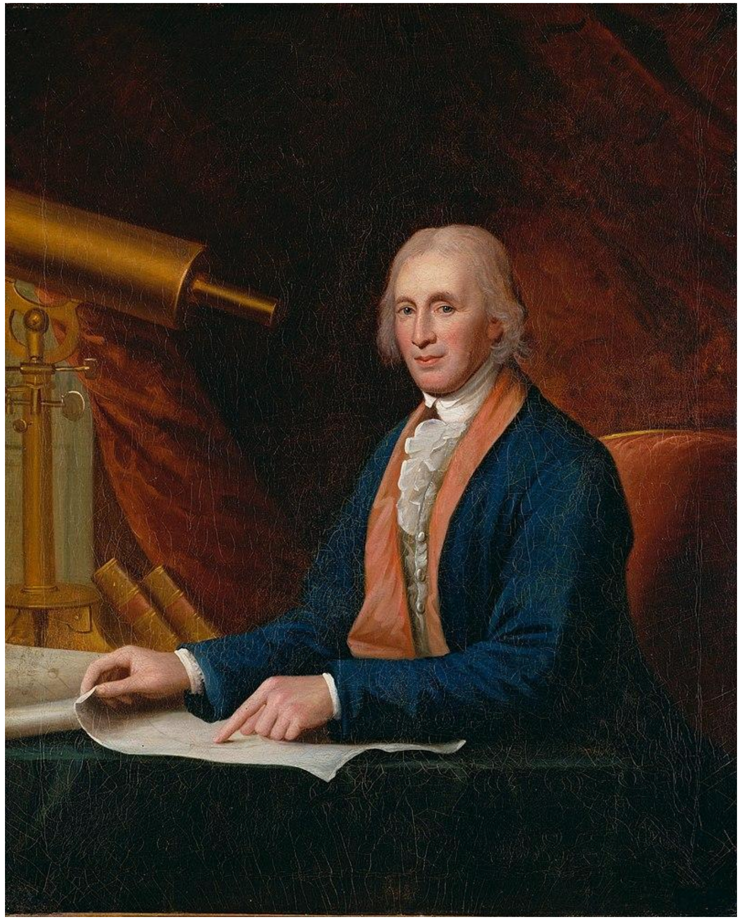
Focus of this talk

- The field of metasurfaces is reaching a point of maturity where we have to soberly consider where these may – and may not – hold relevance for real optical systems.
- All metasurface applications involve tradeoffs, sometimes significant.
- In this talk, I will (imperfectly) review what I find to be the essential physical principles – at a very high level.
- Only passive metasurfaces will be considered.

Historical context

Wherefore cometh thou, metasurface?

The first metasurface

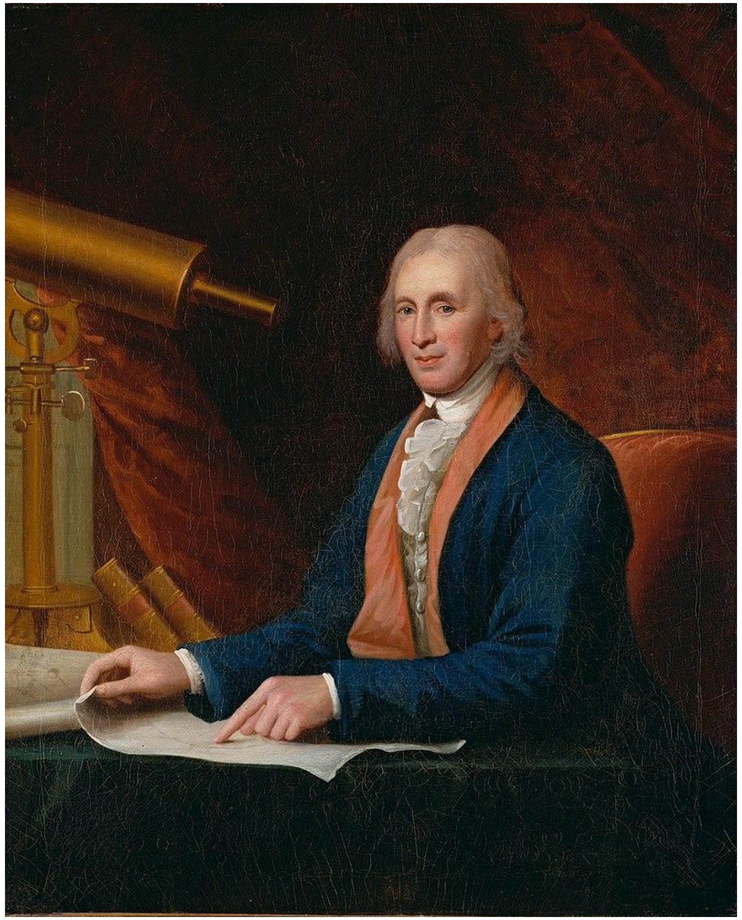


David Rittenhouse (1732-96)

"…I made a ſquare of parallel hairs about half an inch each way…I got a watchmaker to cut a very fine ſcrew on two pieces of ſmall braſ wire. In the threads of theſe ſcrews, 106 of which made one inch, the hairs were laid 50 or 60 in number."

F. Hopkinson and D. Rittenhouse, "An optical problem, proposed by Mr. Hopkinson, and solved by Mr. Rittenhouse". *Transactions of the American Philosophical Society*. **2**: 201–6, **1786**.

The first metasurface



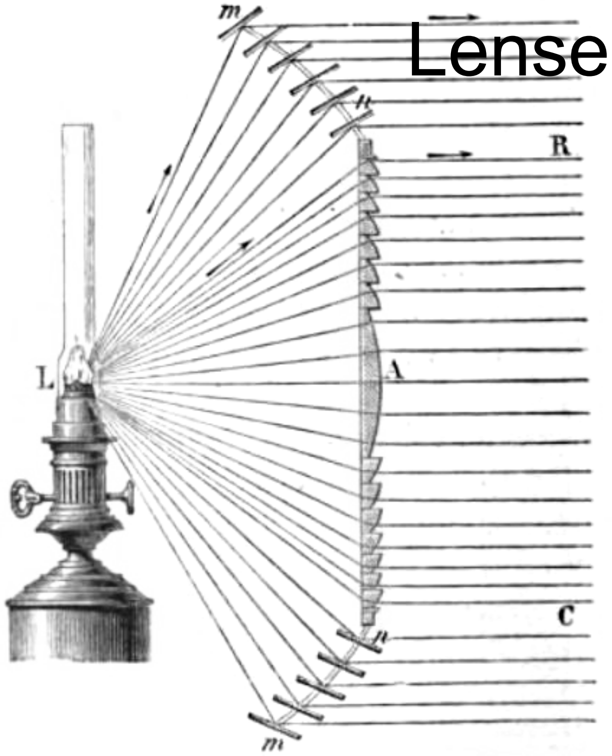
David Rittenhouse
(1732-96)

“Holding the hairs parallel to the ſlit, and looking towards the ſky, I saw three parallel lines, almost equal in brightness…I took out the hairs and put in others…of theſe 190 made one inch…the three middle lines of light were now not ſo bright as they had been before…”

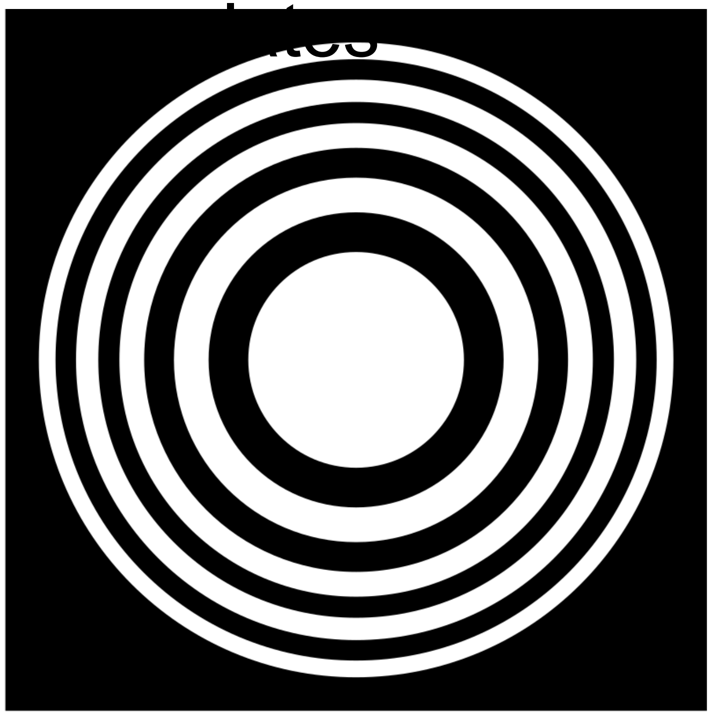
F. Hopkinson and D. Rittenhouse, "An optical problem, proposed by Mr. Hopkinson, and solved by Mr. Rittenhouse". *Transactions of the American Philosophical Society*. **2**: 201–6, **1786**.

The first metalenses

Fresnel Lenses

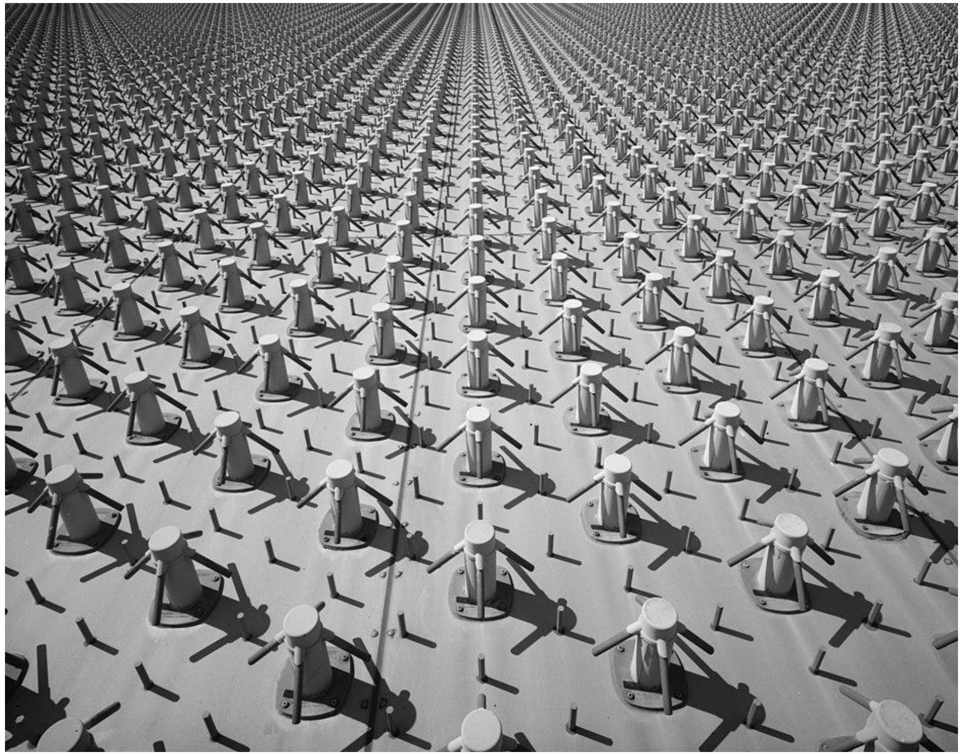


Zone

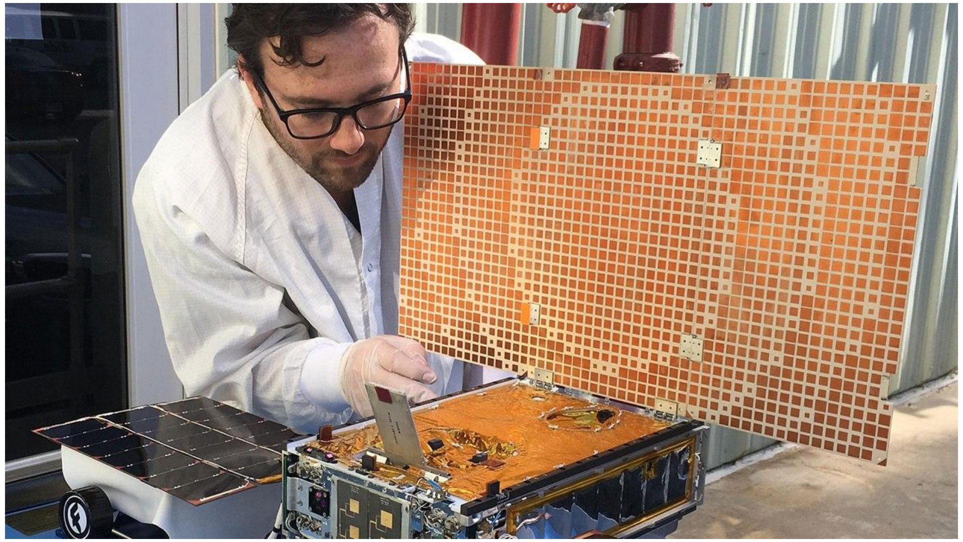


Both owed to Fresnel in the years ~1810-20

Anticipations in RF/microwaves



Radar phased array (f ~ 420 MHz, part of the US Cold War-era missile early warning system)



Reflectarrays – (example here from NASA JPL's MarCO cubesat, f ~ 420 MHz)

Many metasurface concepts have long histories at RF, where features can be macroscopic in size.

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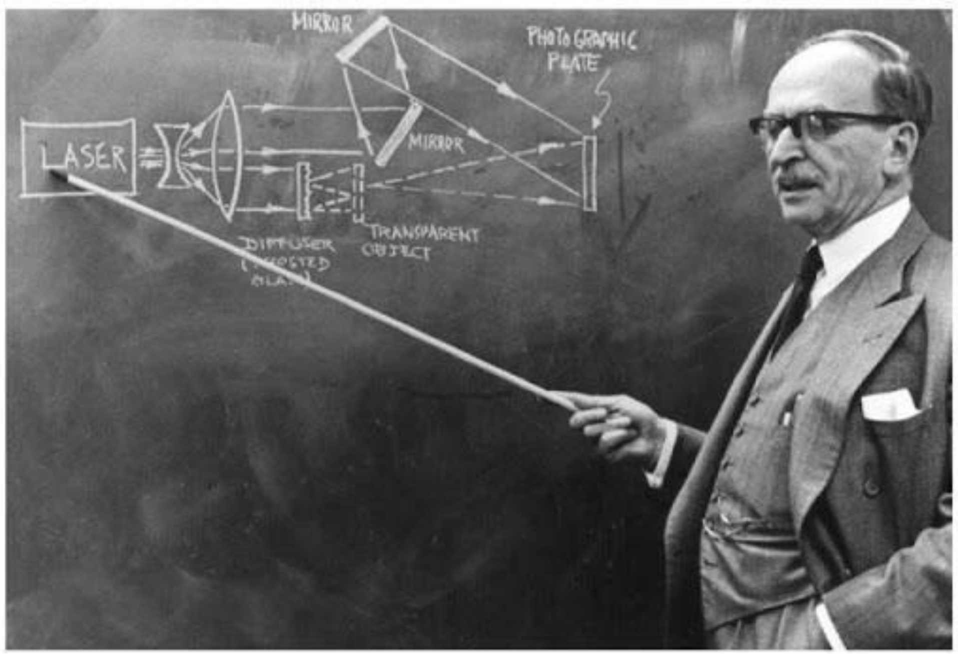
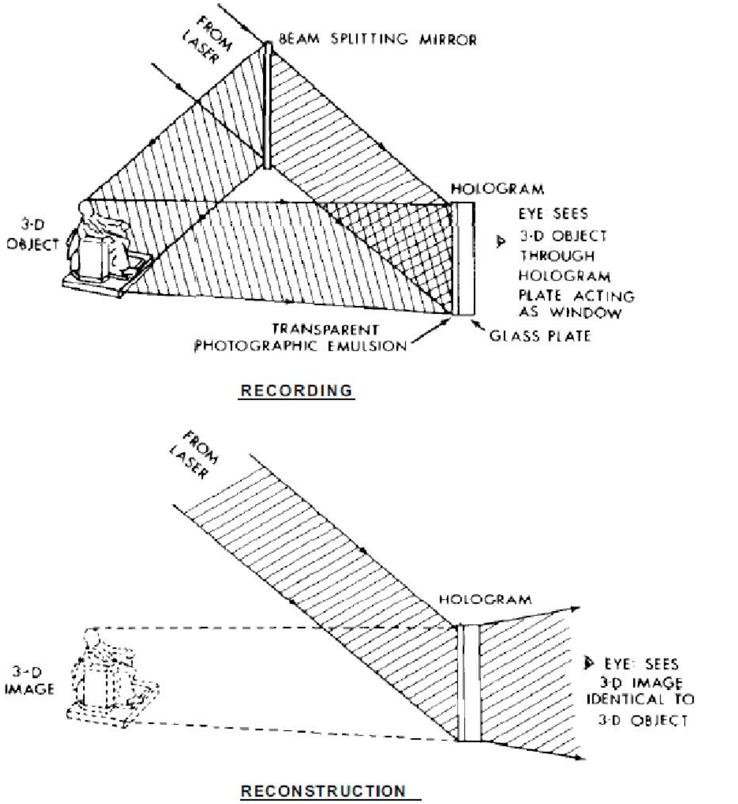
Holography



Dennis Gabor – 1971 Nobel Prize in Physics for Optical Holography

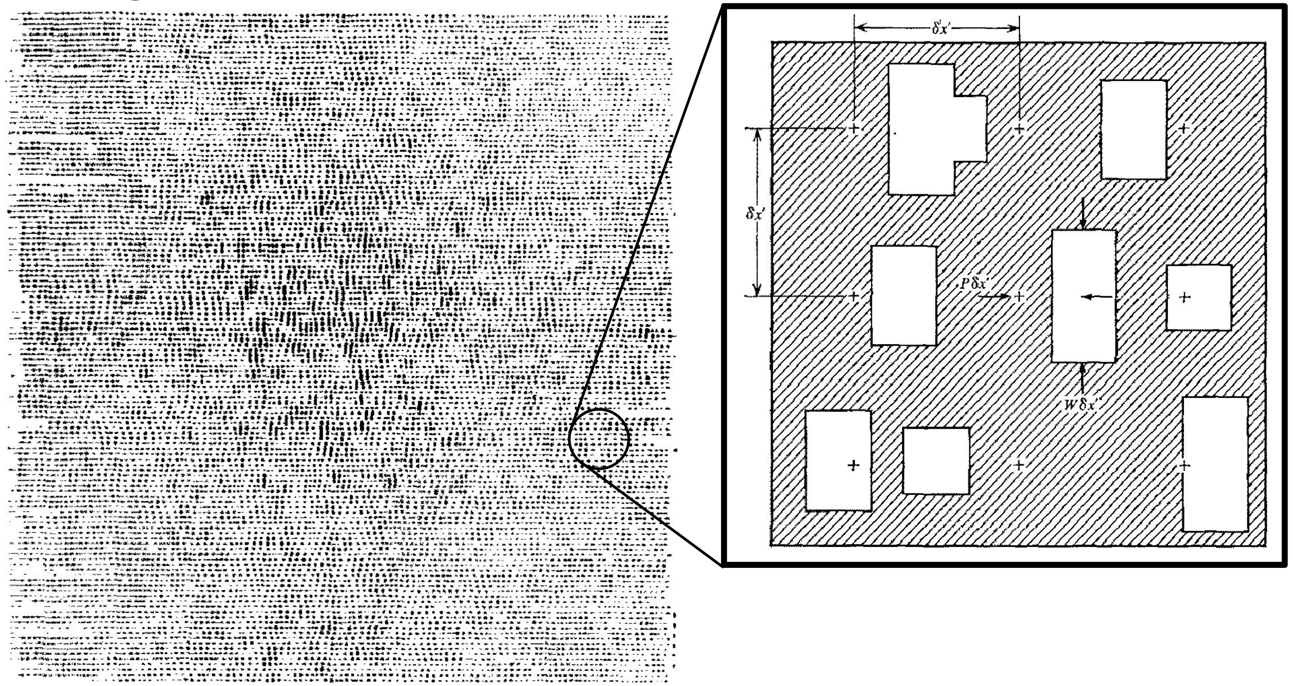
Recording and reconstructing the interference of waves.



D. Gabor – 1971 Nobel Lecture

Computer-generated holography

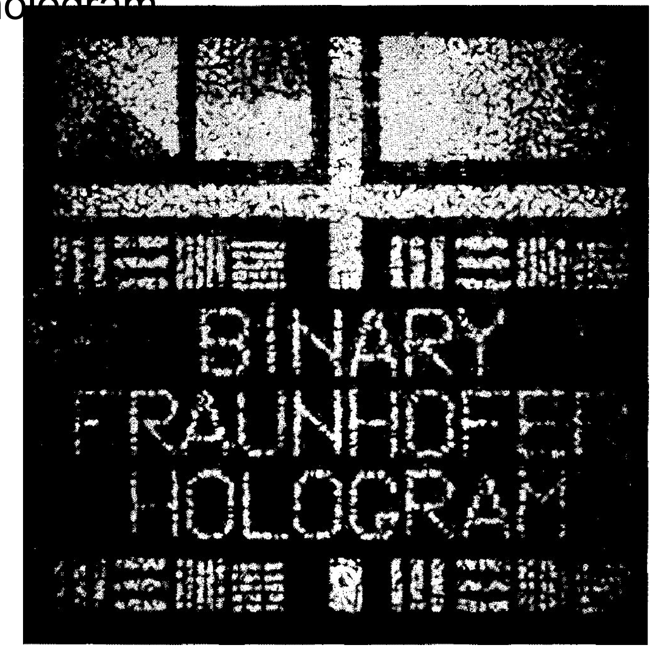
"Metasurfaces" are computer generated holograms



BR Brown and AW Lohmann, *Appl. Opt.* **5** (6), 1966

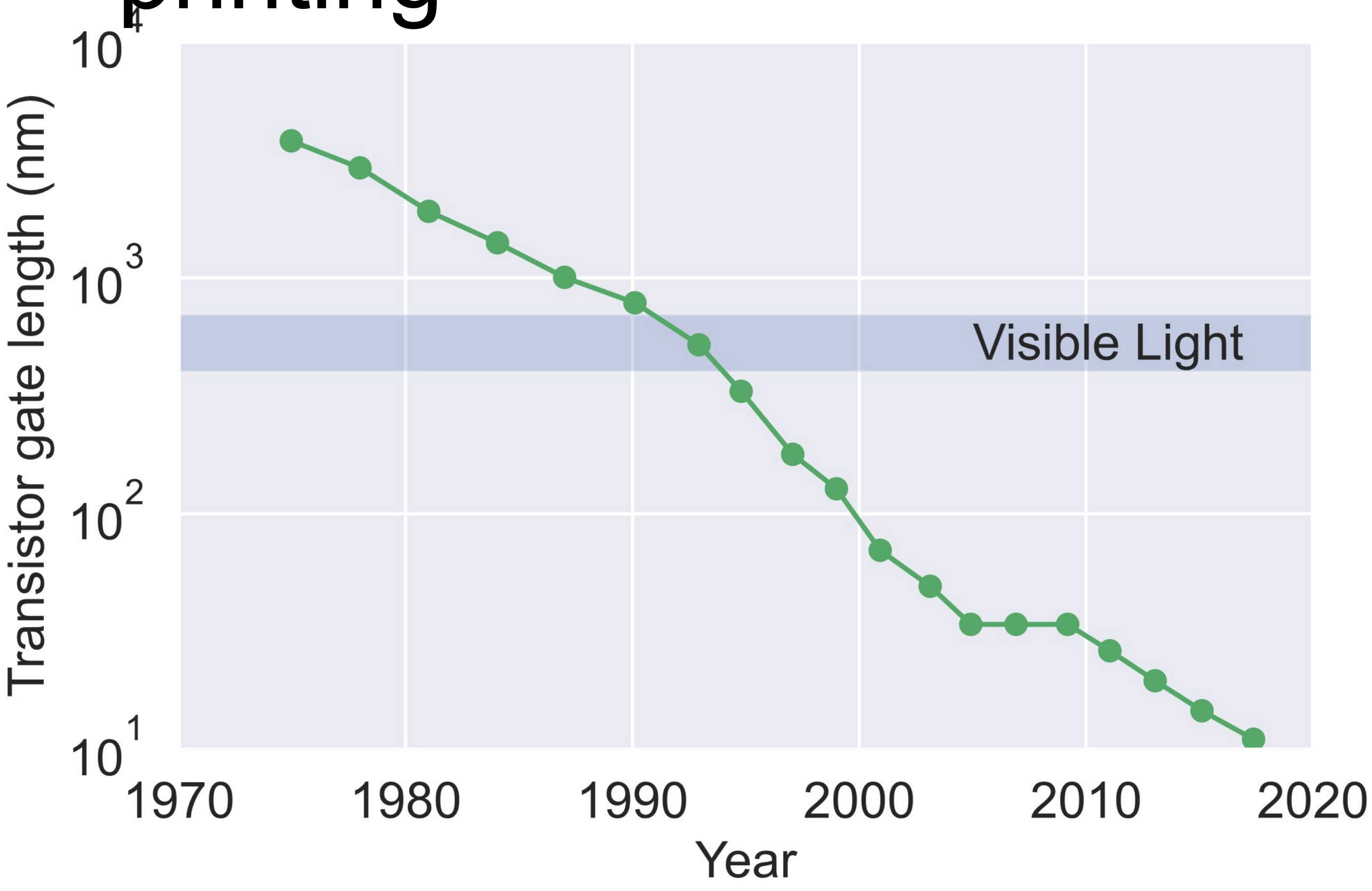
BR Brown and AW Lohmann, *IBM J. Res. Develop.* **13** (2), 1969

"Usually a hologram is produced by means of an interference experiment. Here, however, we let a computer-guided plotter draw the hologram…"



"The production of the filter or hologram was done first at large scale, and then photographically reduced…in one case the drawing was made by hand; in another case by a computer-guided plotter."

Needless to say, we have gotten *much* better at printing

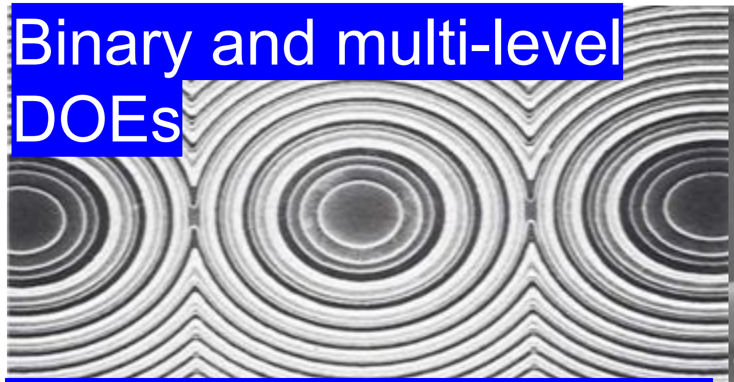


The inexorable march of Moore's Law

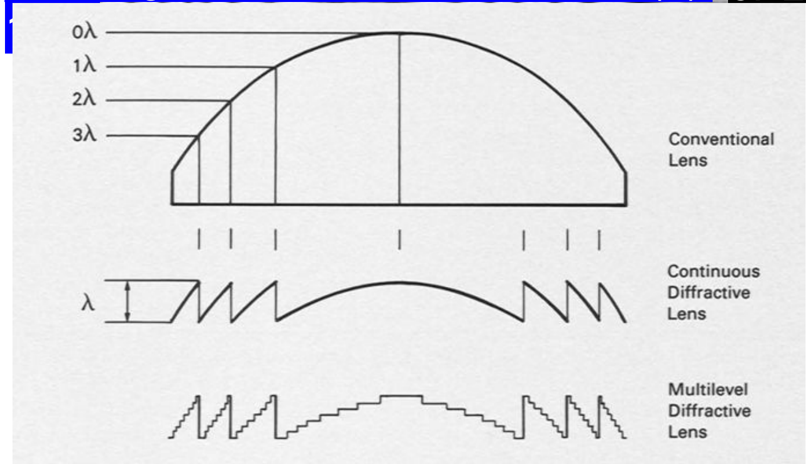
What has been possible with electron beam lithography has always been far ahead

Diffractive optical elements

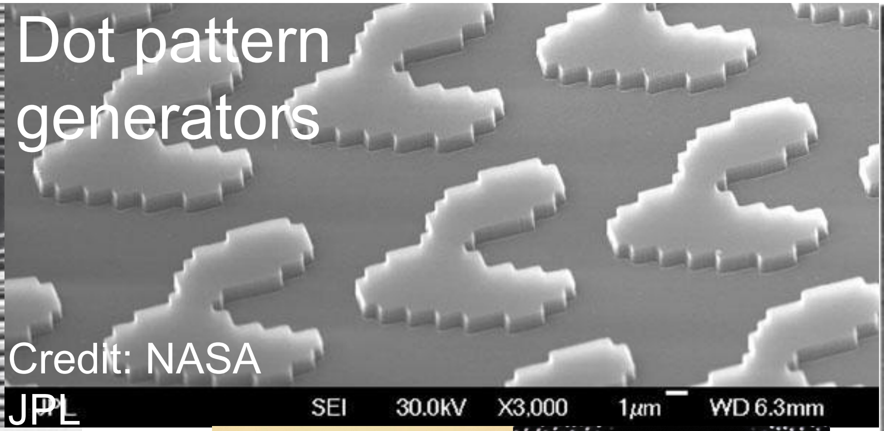
Binary and multi-level DOEs



J.R. Leger et al., *MIT LL Journal* **1**(2), 1



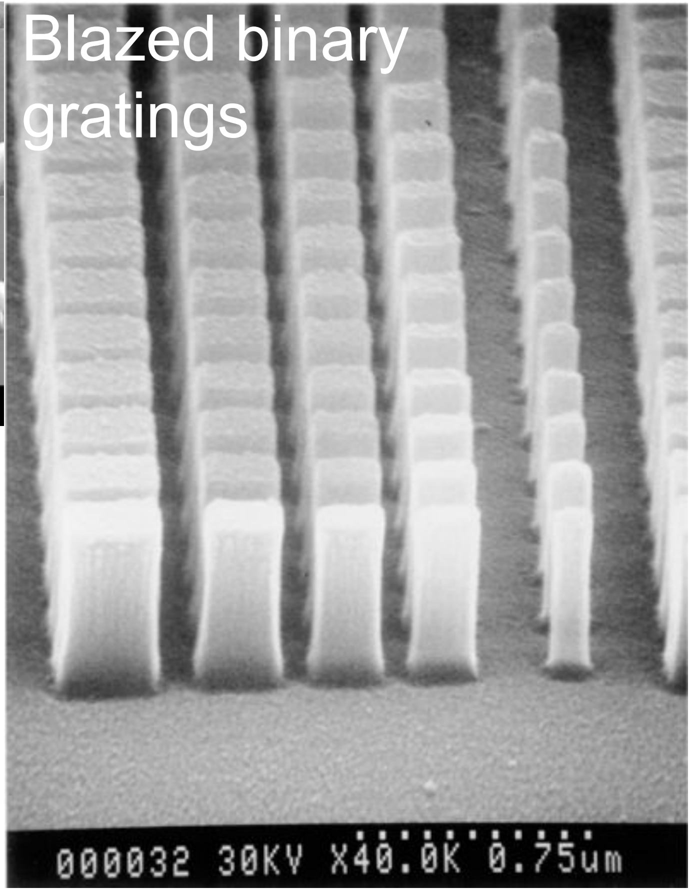
Dot pattern generators



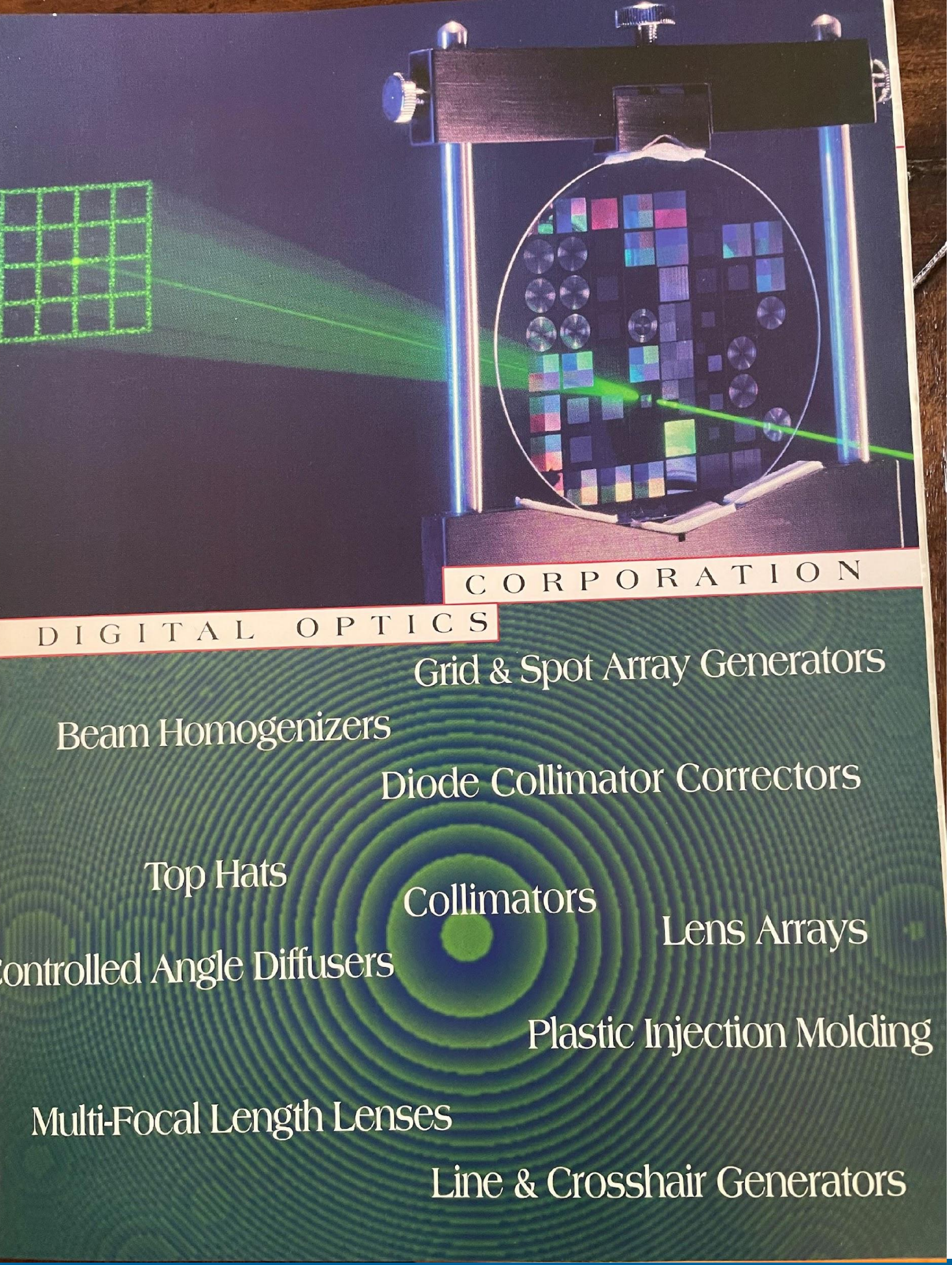
Credit: NASA JPL

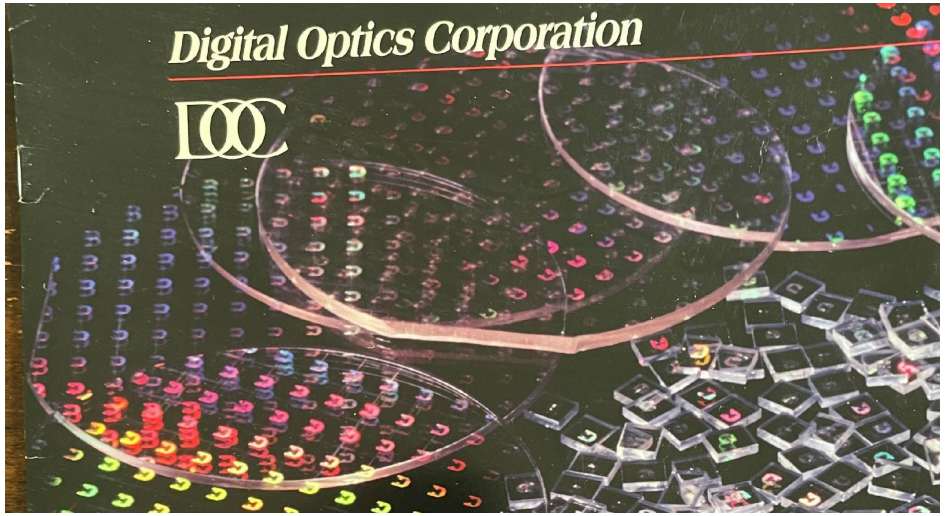
Credit:

Blazed binary gratings



P. Lalanne et al., *Opt. Lett.* **23** (14), 1999



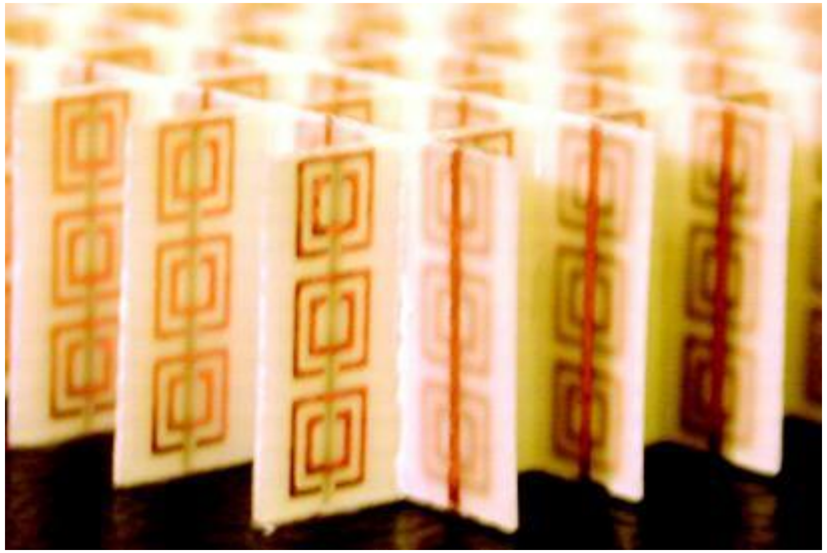


"We design and produce lenses with unique optical properties by creating microscopic patterns in substrates including glass, silicon, and plastic. Diffractives are not only lighter, smaller, and lower in cost than conventional refractive lenses, but can also perform functions that are impossible using conventional refractives."

Marketing material for Digital Optics Corporation (c. 1995)

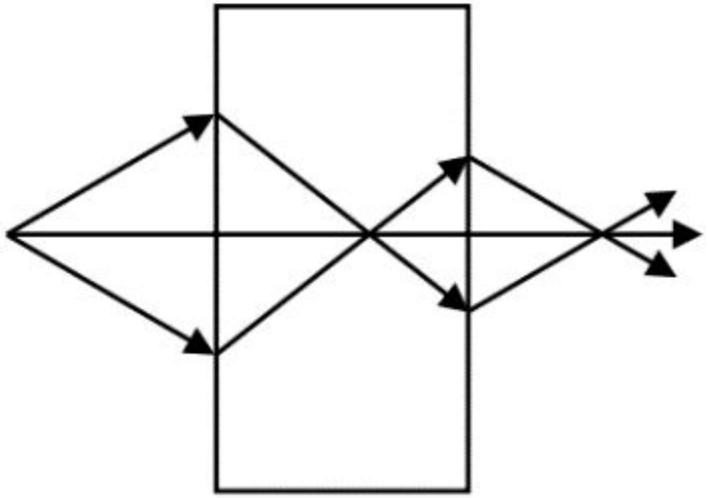
So why are metasurfaces regarded as a new/emerging field in 2024?

“Metamaterials”



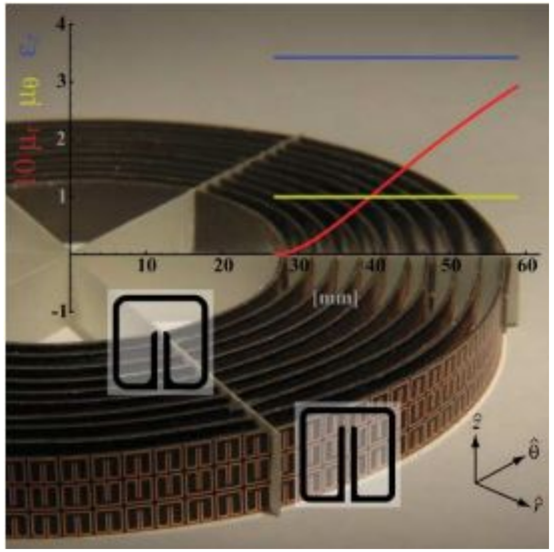
RA Shelby, DR Smith, and S Shultz, *Science* **292** (5514), 2001

Negative refractive index



JB Pendry, *Phys. Rev. Lett.* **85** (18), 2000

“Perfect” lensing

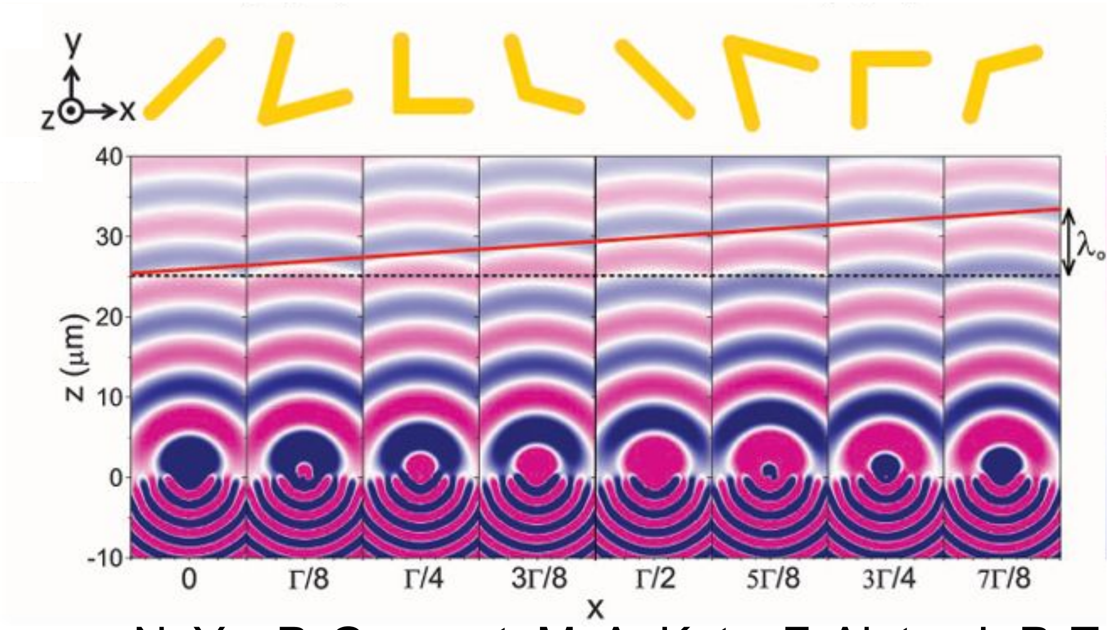


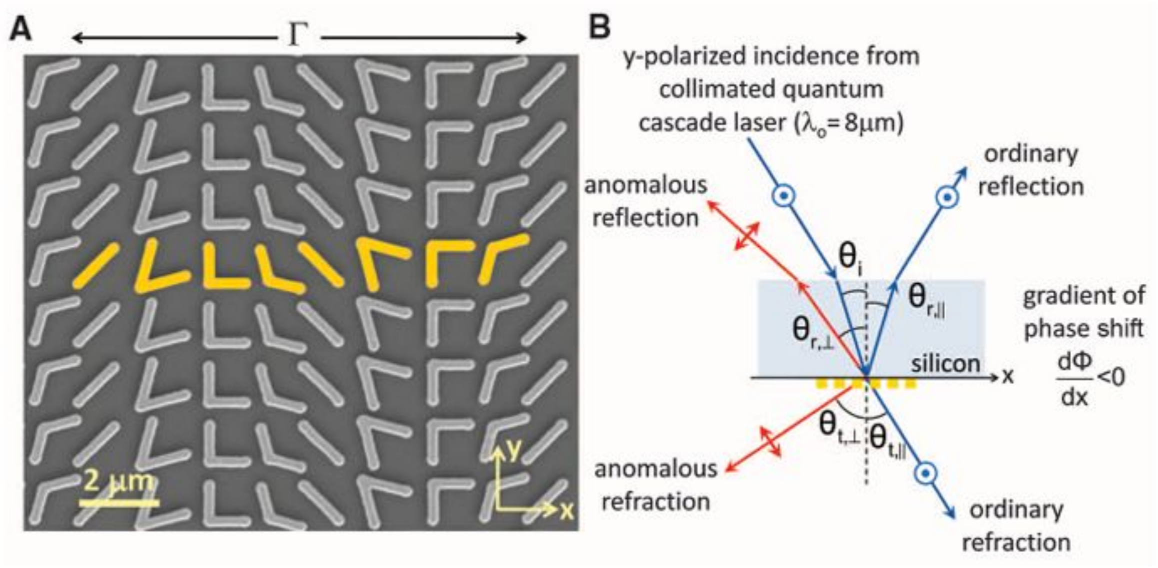
D Schurig, *Science* **314** (5801), 2006

Optical cloaking and “transformation optics”

The field of metamaterials sought to explore new devices and physics by controlling the constitutive parameters (ε, μ) of artificial electromagnetic media.

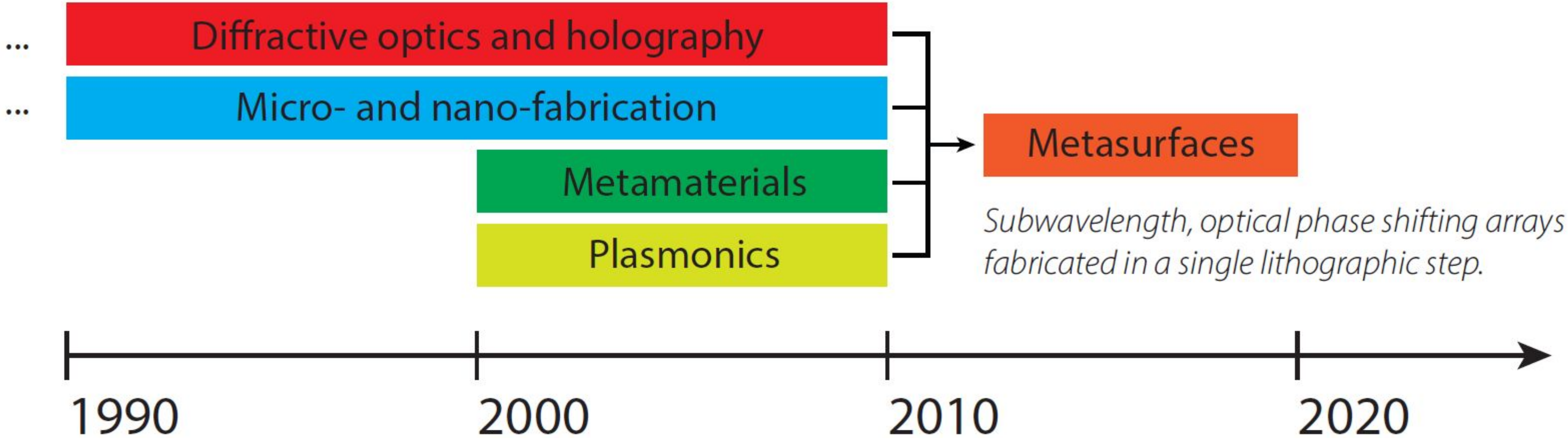
The genesis of metasurfaces
(from plasmonic metamaterials)





N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, and Z. Gaburro, *Science* **334** (6054), 2011.

"Generalized Laws of Reflection and Refraction" – reformulated principles of diffractive optics for the metamaterials community and set off a flurry of research in this direction that continues to this day.



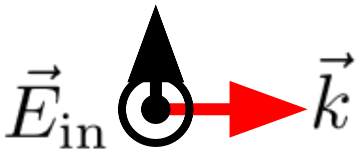
NA Rubin, Z Shi, and F Capasso, *Adv. Opt. Phot.* **13** (4), 2021

What we today call "metasurfaces" represent a convergence of multiple fields of knowledge with different histories and terminologies. In some ways, an evolution rather than a revolution.

<u>This has resulted in more people thinking about diffractive optics – with more widely distributed computational and fabrication resources – than ever before.</u>

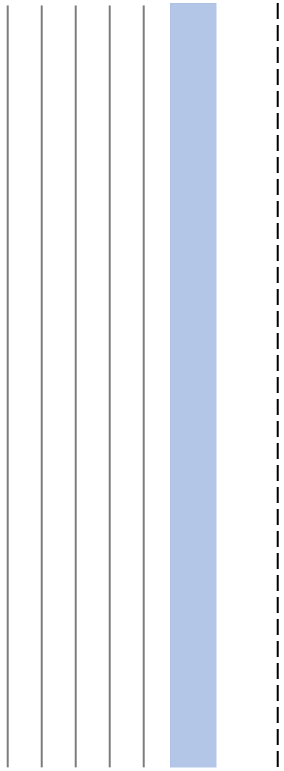
Basic design considerations

Central dogma of metasurfaces



1. <u>The illumination.</u>

Common assumptions:
- Plane wave with a fixed angle and polarization



2. <u>The metasurface.</u>
Common assumptions: Fixed height

3. <u>The near-field.</u>
The field just above the metasurface, as dictated by Maxwell's Equations

$\vec{E}_{\mathrm{out}}(x, y)$

4. <u>The propagator.</u>
Could be exact (e.g., plane wave expansion) or approximate (e.g., a Fourier transform in Fraunhofer regime)

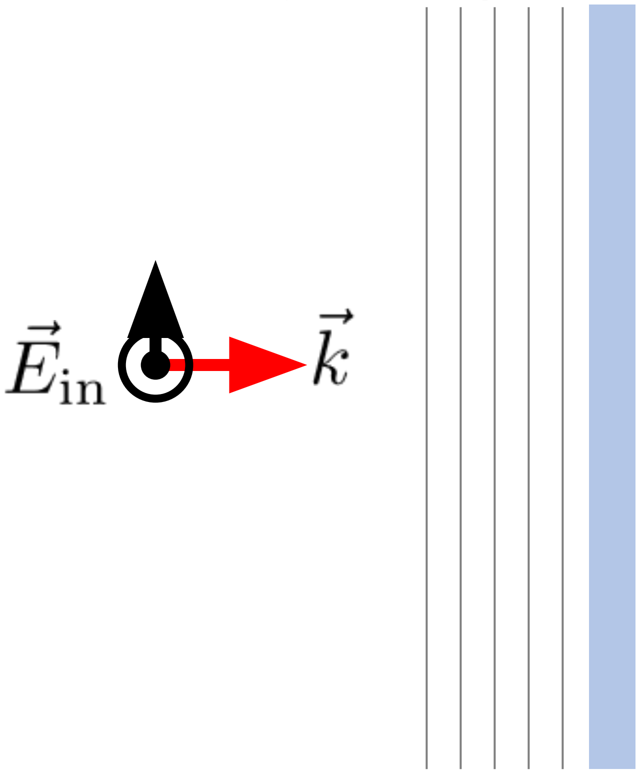
5. <u>The far-field.</u>
Some desired function the optic should enable. *The merit criterion.*

$$\mathcal{F}\{\vec{E}_{\mathrm{out}}(x, y)\}$$

In general, this requires solution of Maxwell's Equations over large, macroscopic areas.

Local approximations in metasurface optics

Local Approximation #1: Metasurface acts locally on the field (it is ***optically thin***)



$$E_{\mathrm{out}}(x,y) = t(x,y)E_{\mathrm{in}}$$

(scalar)

or

$$\vec{E}_{\mathrm{out}}(x,y) = J(x,y)\vec{E}_{\mathrm{in}}$$

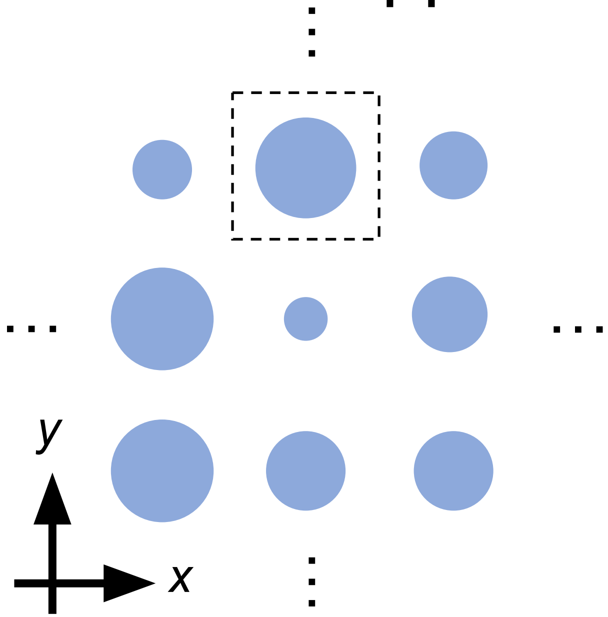
(with polarization)

In other words, a way of saying that light is not *redistributed* by propagation through the metasurface.

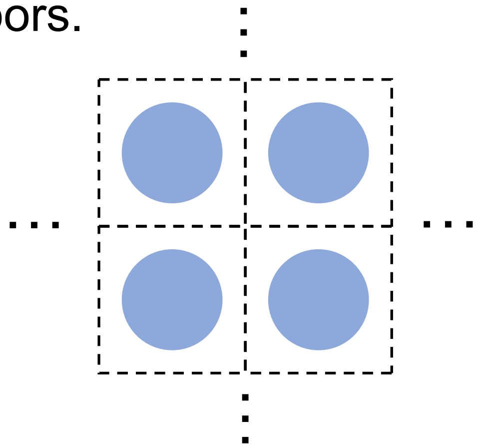
Very similar to the distinction between "thin" and "thick" holograms that is well-known in that field.

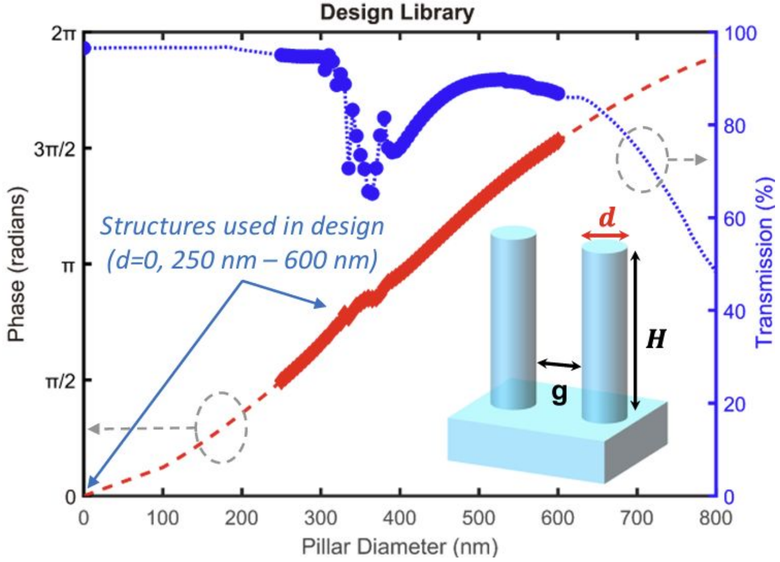
Local approximations in metasurface optics

Local Approximation #2: The “locally periodic” approximation



Assumption that the behavior of each element is independent of its neighbors.





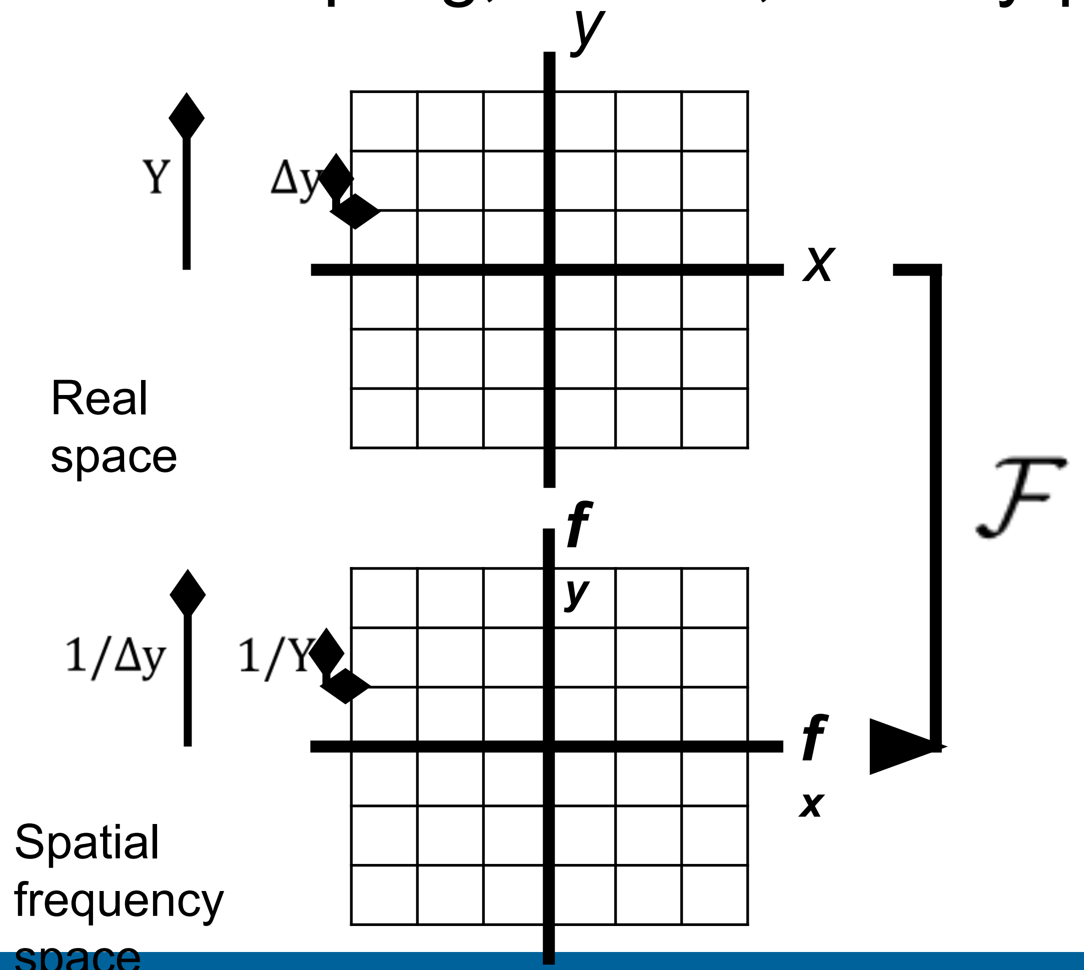
J.-S. Park et al., *ACS Nano* **18** (4), 2024

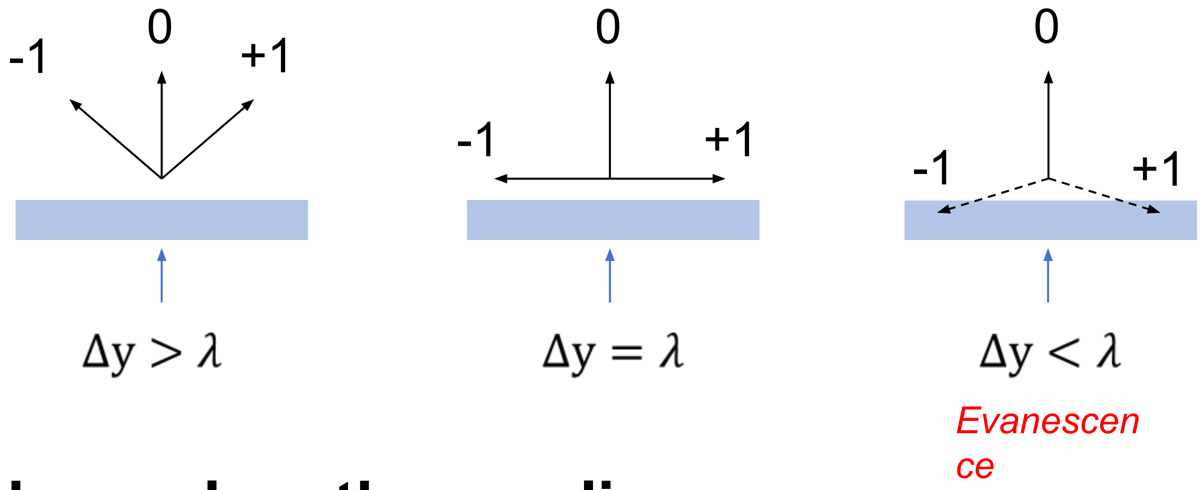
- Permits *library-based* metasurface design.
- Designs can be made abstracted one level from Maxwell’s Equations

<u>Both local approximations are ways of stating the paraxial (small angle) limit</u>

Why do we emphasize "subwavelength"?

Sampling, Fourier, and Nyquist.



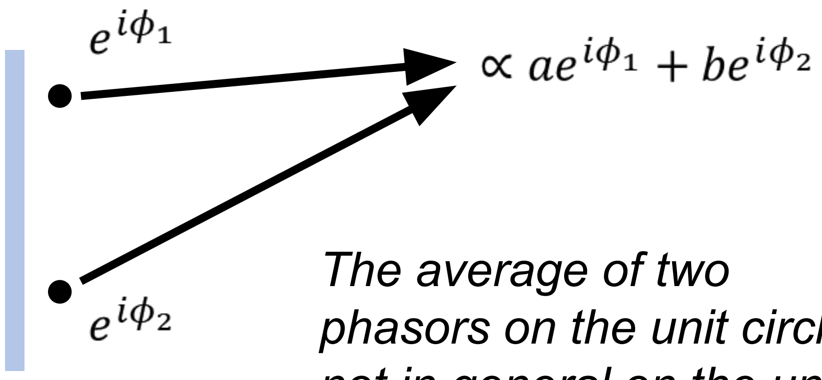


Subwavelength sampling suppresses higher-orders and permits control of the full angular half-space.

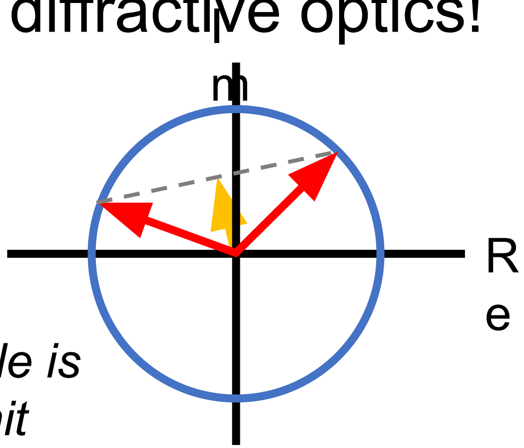
In other words, it avoids diffraction from "meta-atoms".

Why do we only talk about phase?

- Modulating amplitude usually means only *loss* (gain is hard to implement).
  - Control of amplitude then usually entails loss of photons.
- However, phase modulation + propagation can realize amplitude modulation! By *redistribution* of light, rather than absorption.
  - One of the essential features of diffractive optics!



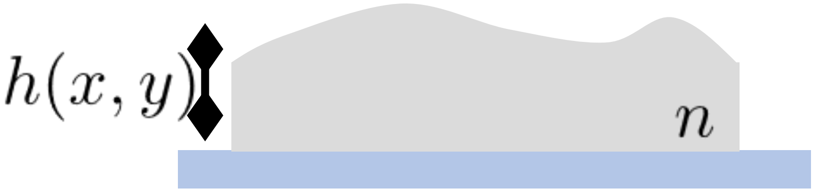
The average of two phasors on the unit circle is not in general on the unit circle



Closely related to the ideas of "phase retrieval"!

Methods of imparting phase: **Propagation**

<u>“Traditional” diffractive optics</u>



Continuous profile

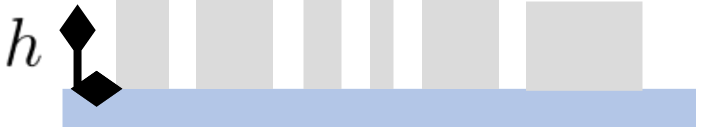
Hard to make over large areas (grayscale lithography)

Multi-level profile

For N levels, requires $\log_2 N$ aligned lithography/etching steps

$$\phi(x,y) = \frac{2\pi}{\lambda} \times n \times h(x,y)$$

<u>Metasurfaces</u>



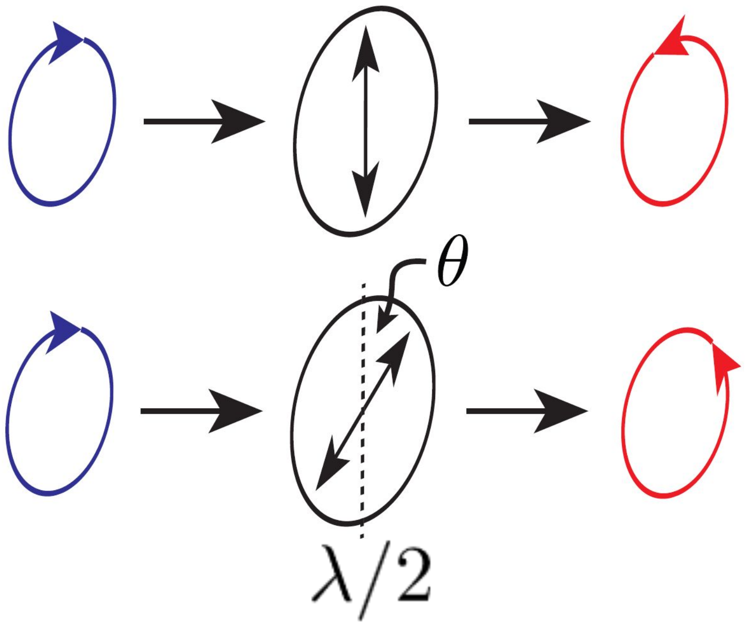
Simpler to make in a single lithographic step

- Modulation of transverse dimensions with constant height results in light feeling an **“effective index”**
- The dependence of this effective index on size parameters is usually modeled with full-wave simulation in the locally-periodic approximation.
- **High refractive index is desirable.**

$$\phi(x,y) = \frac{2\pi}{\lambda} \times n_{\text{eff}}(x,y) \times h$$

Methods of imparting phase: **Geometric phase**

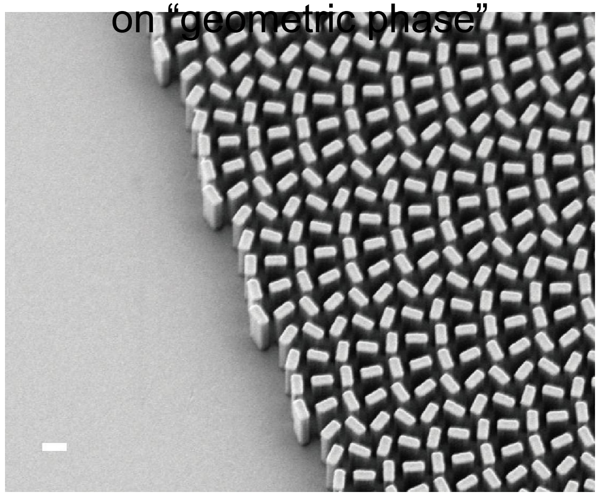
- Phase upon polarization conversion due to reference frame effects.
- Phase shift is achromatic.
  - …but efficiency is not.
- Basis of liquid crystal geometric phase optics used in coronagraphy today.



$$\phi(x, y) = 2\theta(x, y)$$

Form birefringent half-waveplates

Example of a device based on "geometric phase"



M. Khorasaninejad et al., *Science* **352** (6290), 2016

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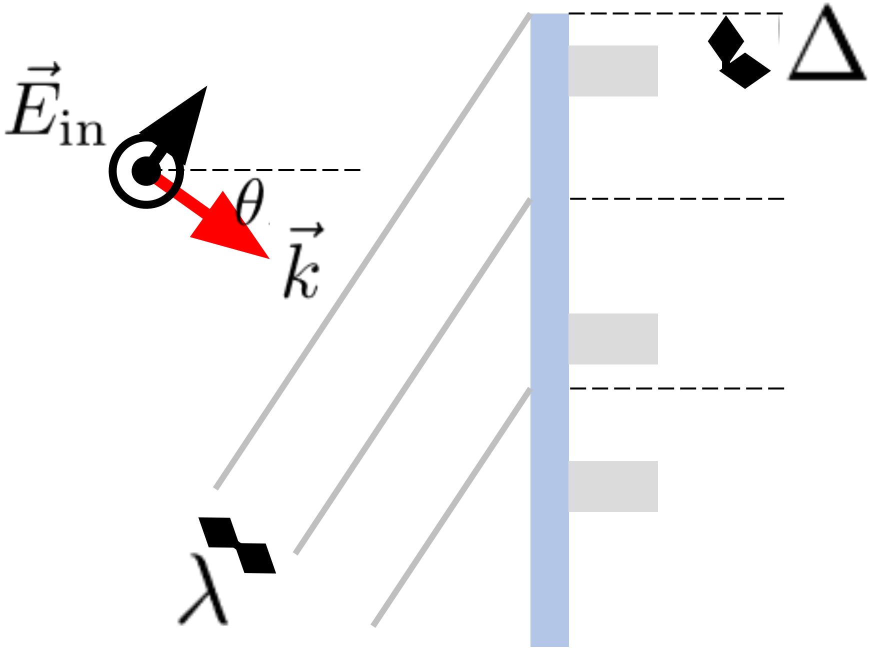
Methods of imparting phase: **Detour**



- Uses the phase dispersion inherent when operating at non-normal incidence.
- Technique used in first CGH demonstration in 1960s.

$$\phi(x,y) = \frac{2\pi \cos\theta \Delta(x,y)}{\lambda}$$

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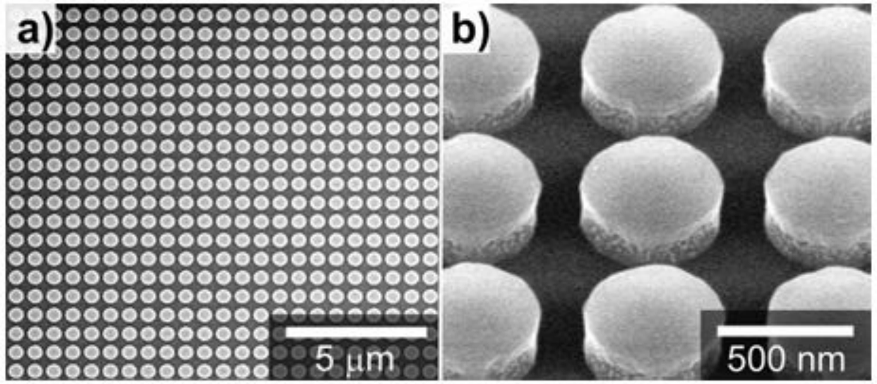
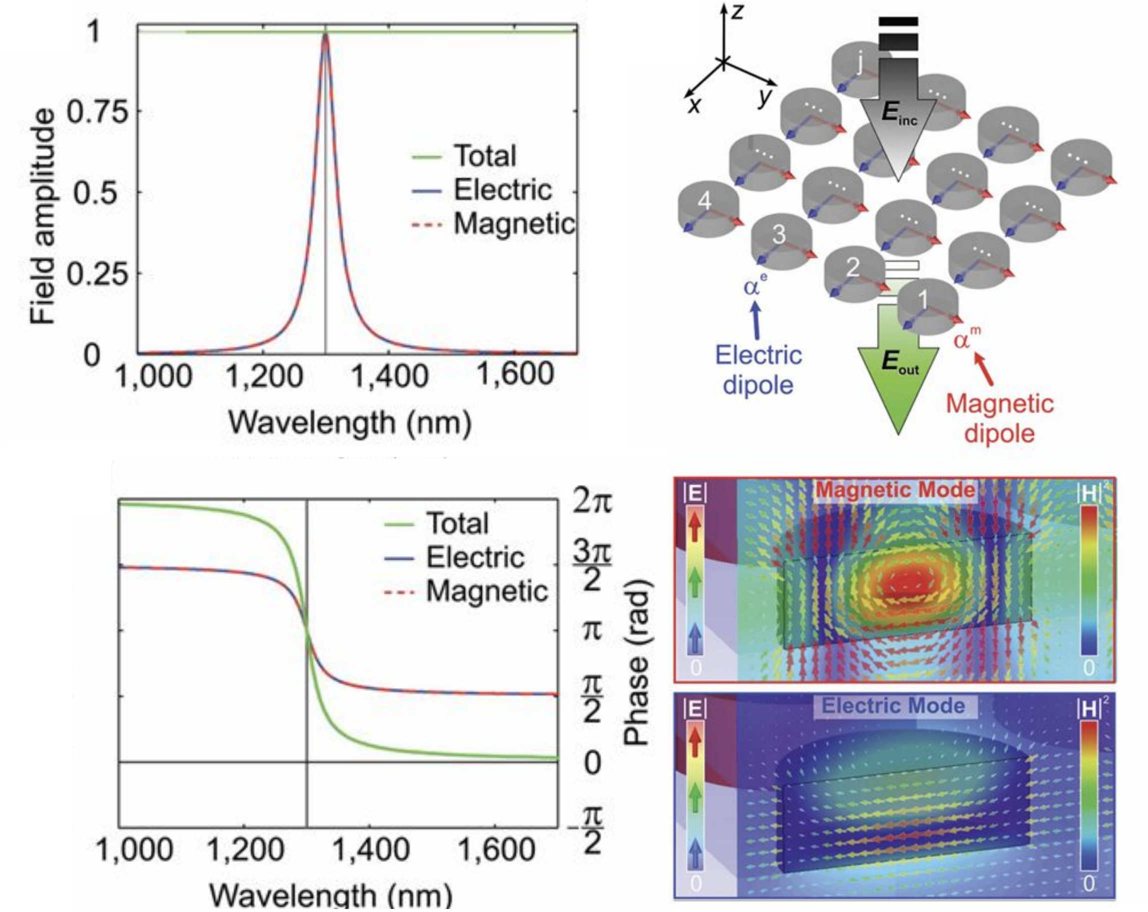
Methods of imparting phase: **Resonances**

Idea: Overlapping two resonances can result in rapid phase tuning between 0 and 2π. Q ~ 10. Also called “Huygens metasurfaces” or “Mie-tronics”.

Upsides: Lower aspect ratio structures.

Downsides: Everything is an order of magnitude more sensitive (dispersion of phase, fabrication tolerances, angle sensitivity).





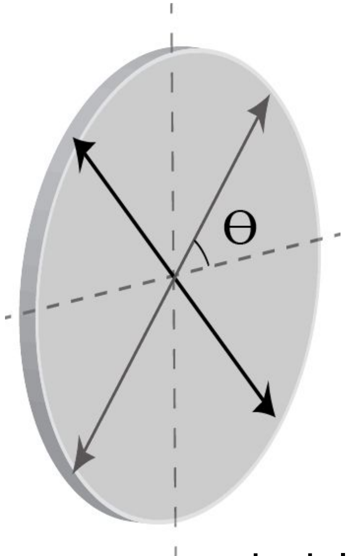
M. Decker et al., *Adv. Opt. Mat.* **3** (813-820), 2015.

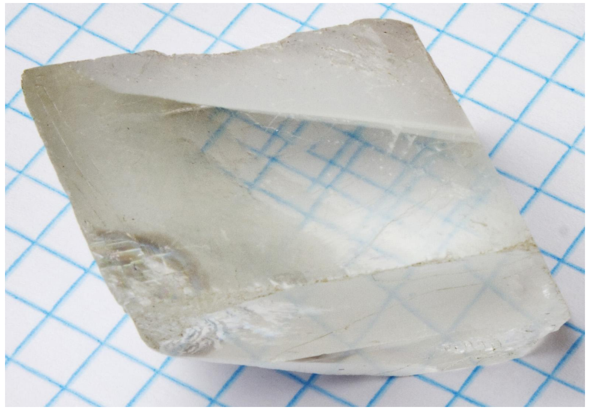
Metasurface polarization optics

Birefringence

Differential phase delay applied to orthogonal polarization states

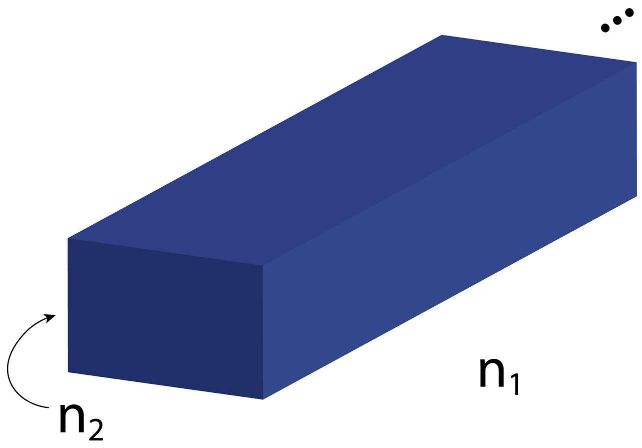
Material:





e.g., a uniaxial
crystal
waveplate

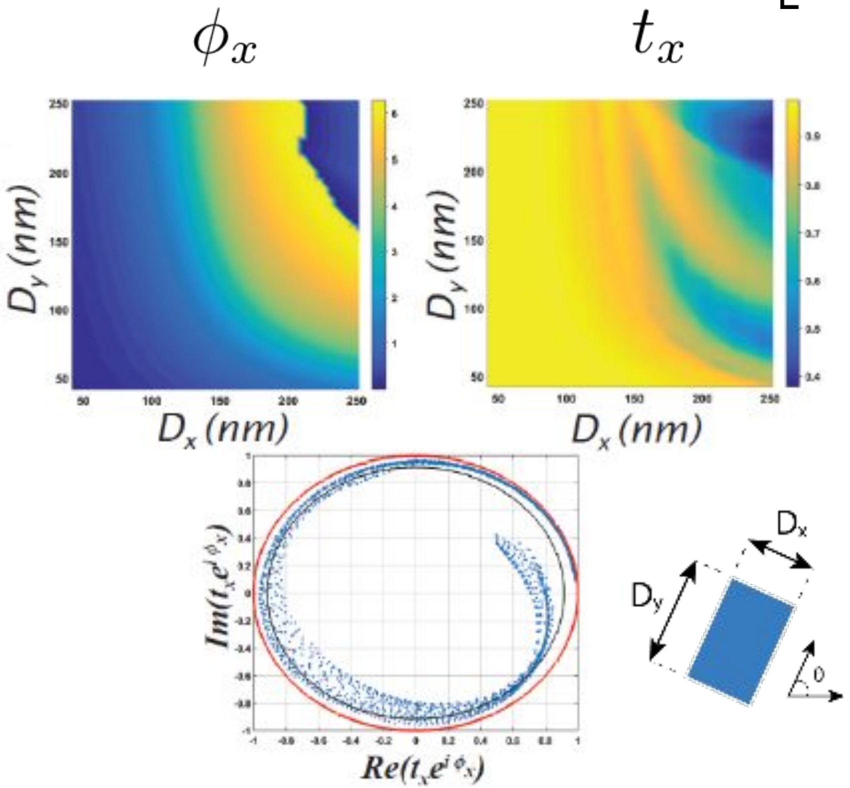
Shape:



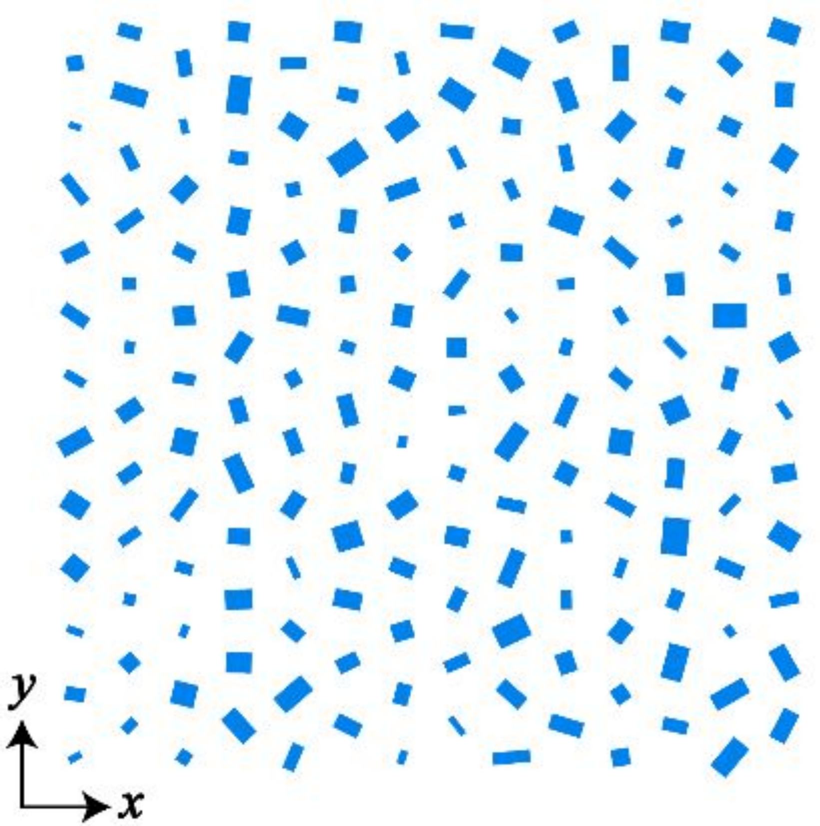
e.g., mode birefringence
in a waveguide

Metasurfaces and polarization

$$\boldsymbol{J}(x,y) = \boldsymbol{R}(-\theta)\begin{bmatrix} e^{i\phi_x} & 0 \\ 0 & e^{i\phi_y} \end{bmatrix}\boldsymbol{R}(\theta)$$



Simple pillar-like elements implement Jones matrix transformations that are approximately *unitary* and *symmetric.*



A Arbabi et al., *Nat. Nano.* **10,** 11 (2015)

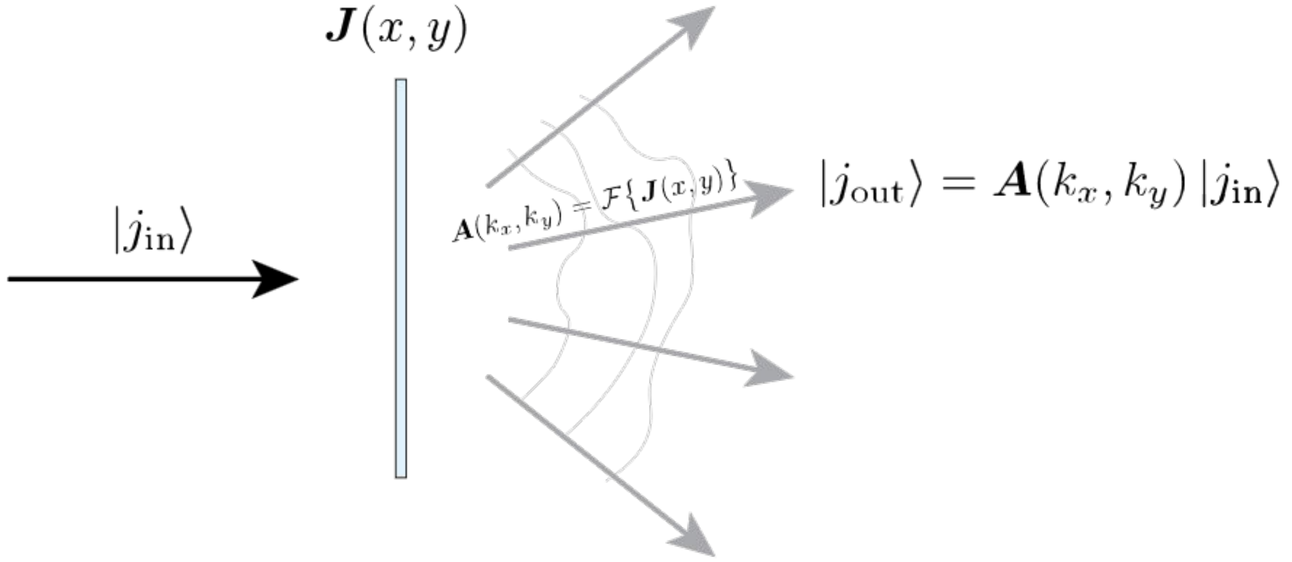
JPB Mueller, NA Rubin et al., *Phys. Rev. Lett.* **118,** 113901 (2017)

Jones matrix Fourier optics

$$\tilde{J}(x,y) = \begin{bmatrix} J_{11}(x,y) & J_{12}(x,y) \\ J_{21}(x,y) & J_{22}(x,y) \end{bmatrix}$$

$$\Big\downarrow \mathcal{F}$$

$$\tilde{A}(k_x,k_y) = \begin{bmatrix} A_{11}(k_x,k_y) & A_{12}(k_x,k_y) \\ A_{21}(k_x,k_y) & A_{22}(k_x,k_y) \end{bmatrix}$$



A metasurface is a parallel polarization device where every part of the far-field can implement a different polarization optical element.

NA Rubin et al., *Science* **365** (6448), 2019
NA Rubin, A Zaidi, AH Dorrah, Z Shi, and F Capasso, *Science Advances* **7** (33), 20
NA Rubin, Z Shi, and F Capasso, *Advances in Optics and Photonics* **13** (4), 2021

For more information on polarization aspects:

This presentation is a brief overview of an extensive subject. For more information, see review article:

NA Rubin, ZS Shi, and F Capasso, *Advances in Optics & Photonics* **13** (4), 2021.

Contains details on theory, history, and applications of polarization-sensitive metasurfaces.


836 Vol. 13, No. 4 / December 2021 / *Advances in Optics and Photonics* **Review**

Advances in Optics and Photonics

Polarization in diffractive optics and metasurfaces

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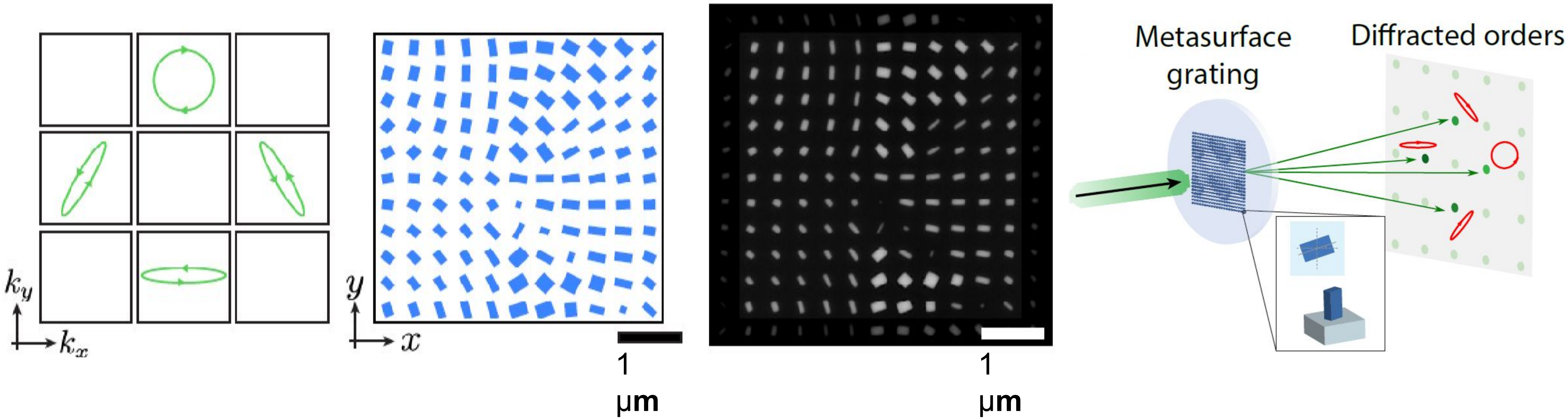
Emerging applications in astronomy

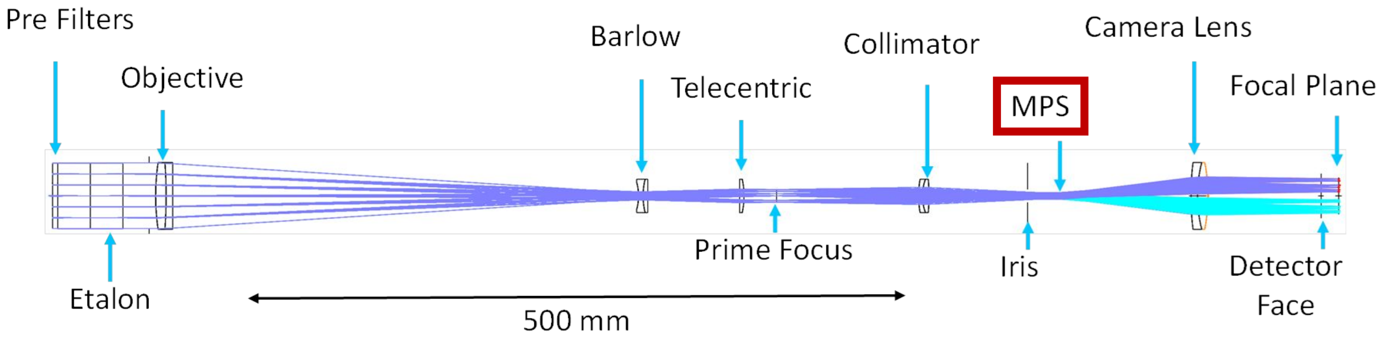
Metasurface polarization splitters



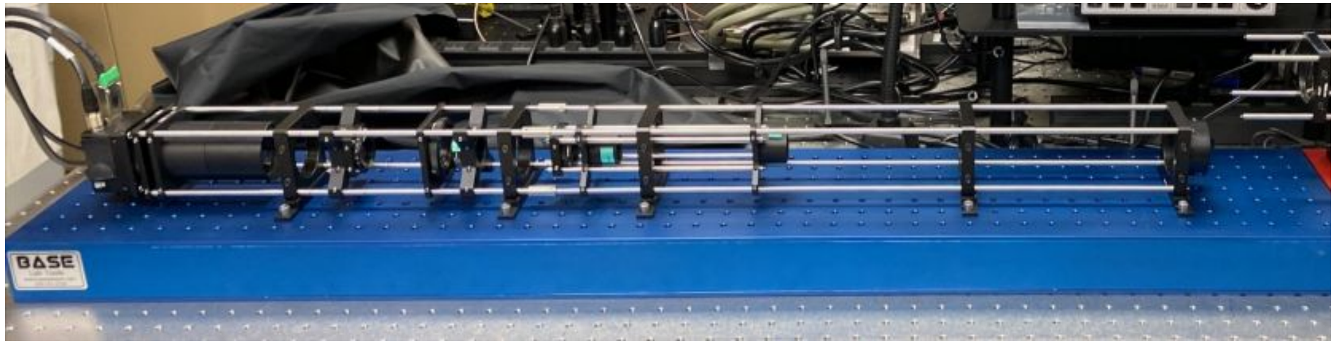
A grating formed from many of the above unit cells **diffracts light into four inner diffraction orders that act as polarizers**.

NA Rubin et al., *Science* **365** (6448), 2019

Astrophysical polarimetry



MPS: "Metasurface Polarization Splitter"



In collaboration with:

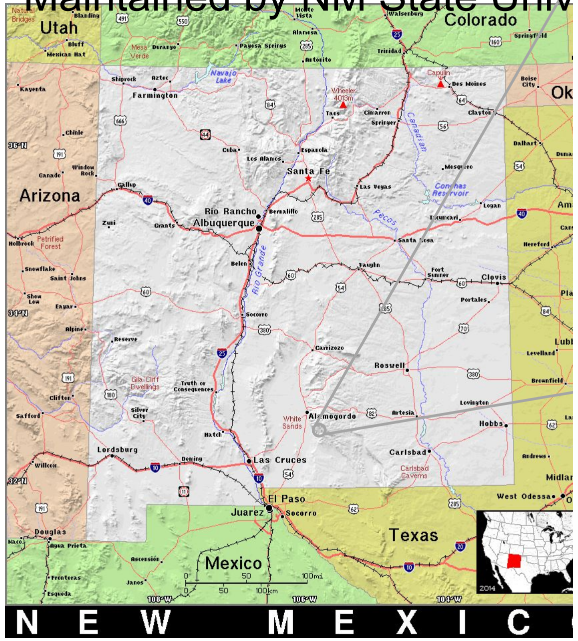
Ball NCAR

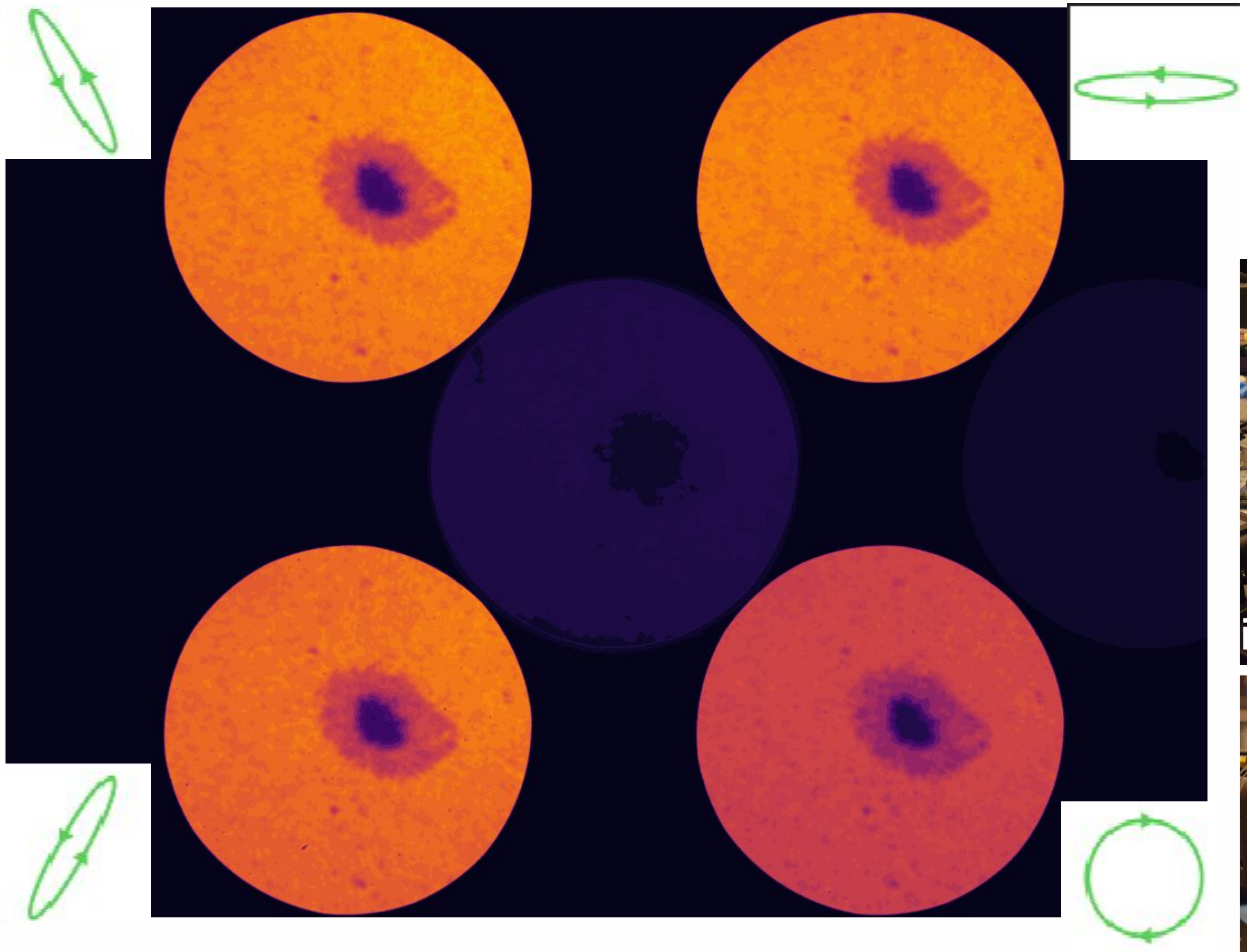
- A **telescope** with a metasurface polarization-analyzing grating in its pupil plane.
- Enables **simultaneous and passive** acquisition of the full-Stokes vector across the solar disk.
- Integrated across a 0.1Å spectral line (corresponding to the Sr-I line at **460.7 nm**).

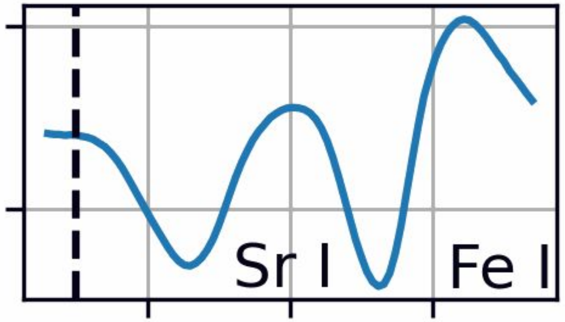
Field ca

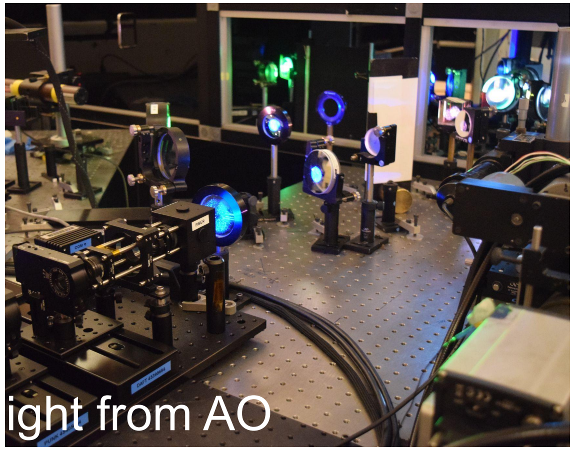
Dunn Solar Telescope o Sacramento Peak, Suns NM

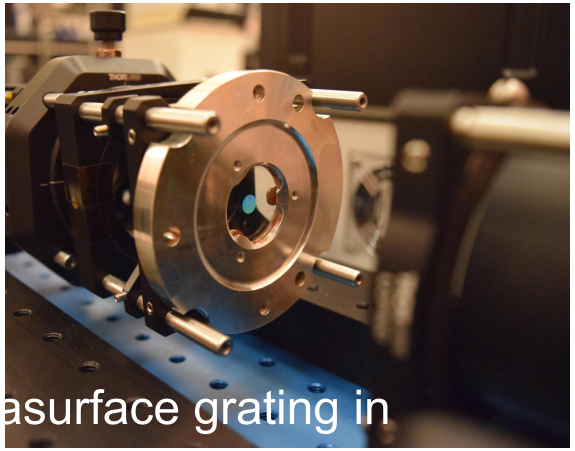
Maintained by NM State Univ











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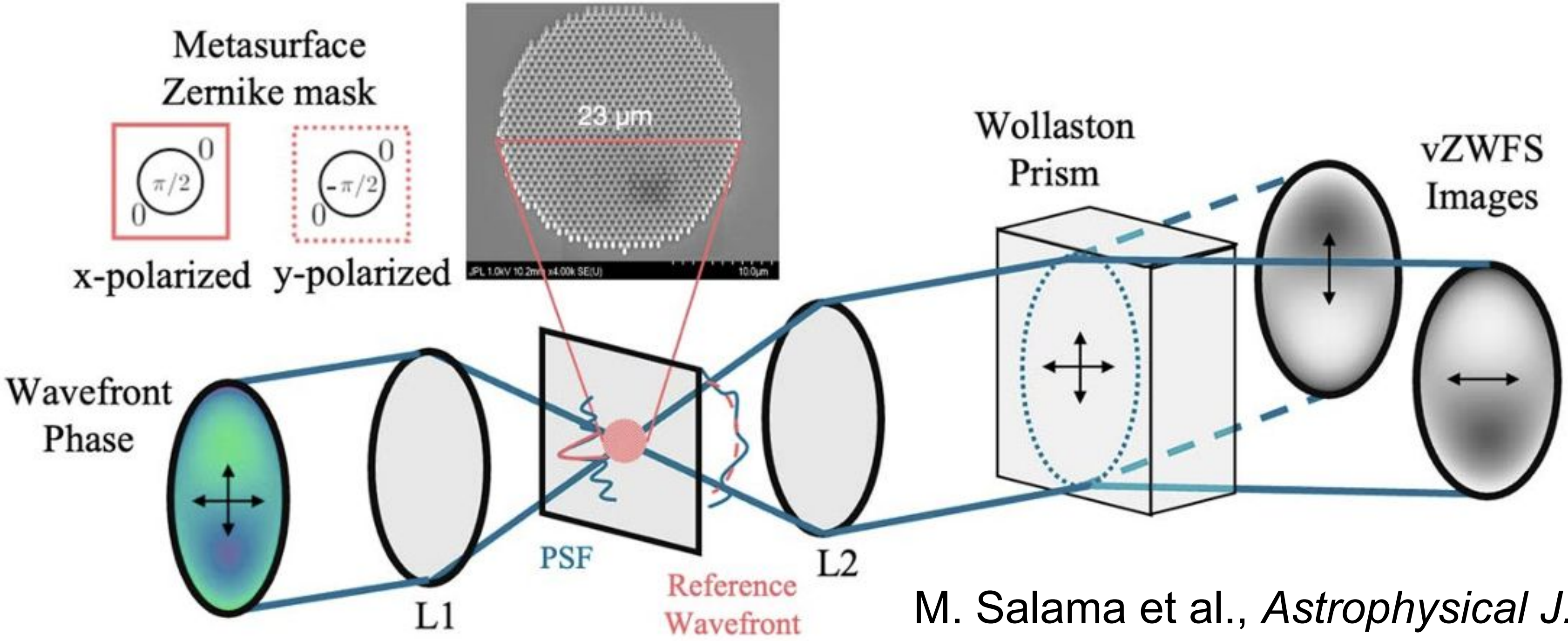
Zernike wavefront sensors



M. Salama et al., *Astrophysical J.* **967** (2), 2024.

- Zernike Wavefront Sensing (ZWS): Essentially the same as Zernike's phase-contrast microscope.
- *Vector* ZWS: Expanding to a full 2π dynamic range with polarization multiplexing.
- Demonstrated on Keck Planet Imager.
- Very similar in concept to quantitative phase imaging.

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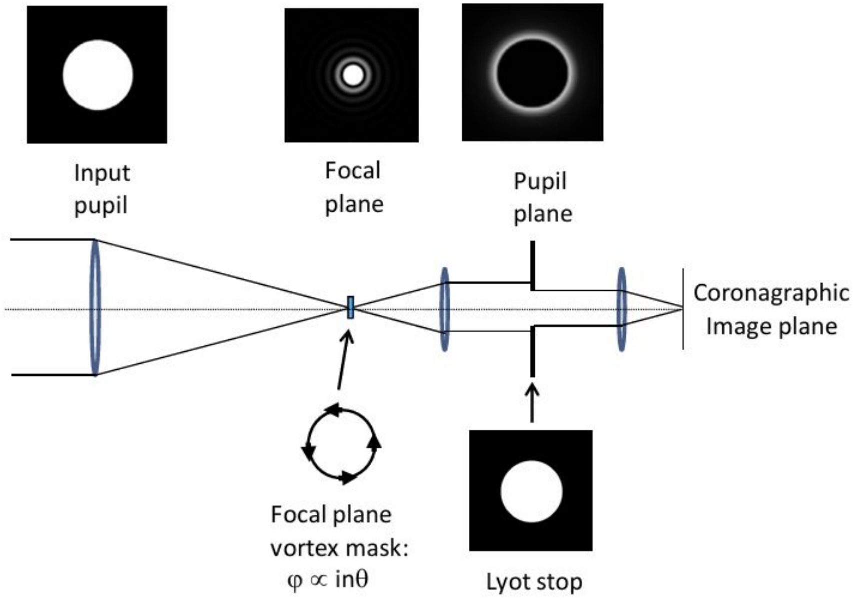
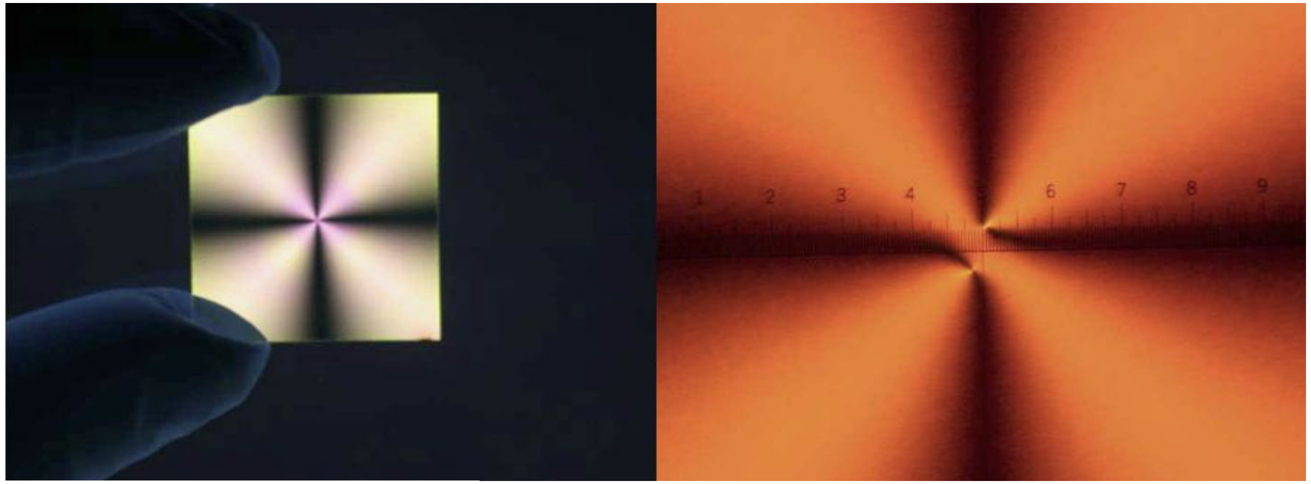
Vortex phase plates for coronagraphy

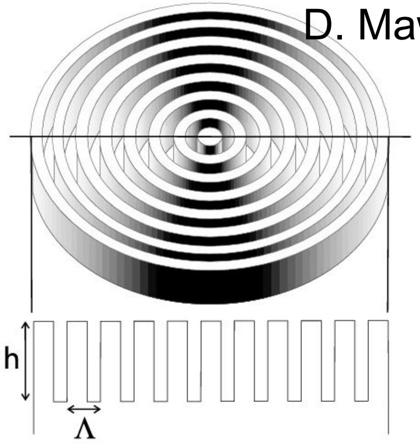
$$\phi(x,y) = e^{i\ell\phi}$$



E. Serabyn, D. Mawet, et al., *Nature* **464**, 2010



D. Mawet, E. Serabyn, et al., *Opt. Exp.* **17** (3), 2009



D. Mawet et al., *Astrophys. J.* **633**, 2005

- Vortex phase profile acts as an angle-selective filter to distinguish off-axis from on-axis light.
- Requires high degree of achromaticity.

Liquid crystal comparison

Geometric phase liquid crystal optics*:

- Can be patterned easily over large areas.
- Self-alignment and spin coating allow for many layers enhancing achromatism.
- Reliance on self-alignment prone to defects at smallest size scales
- Limited polarization control.
- Necessarily polarization-sensitive.
- Polymers.

*in my opinion these are also "metasurfaces"

Dielectric metasurfaces:

- Challenging fabrication.
- Even more challenging to make multi-layer.
- Highest spatial resolution
- Enhanced control over polarization.
- Either polarization sensitive or insensitive.
- Space-compatible optical materials.