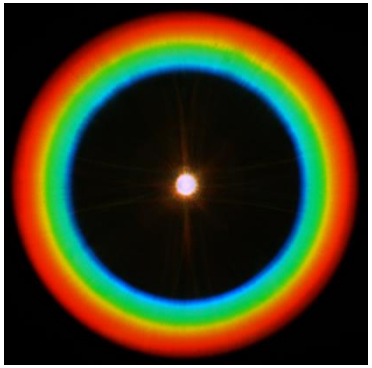
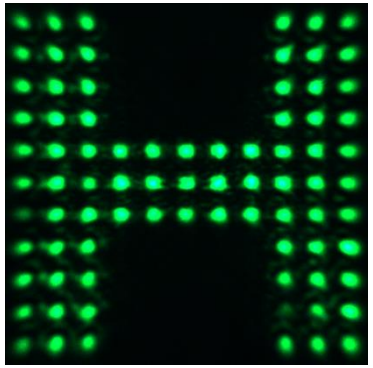
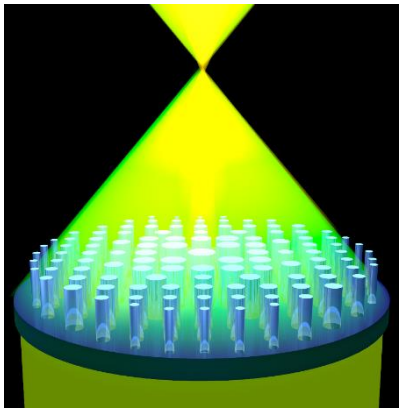
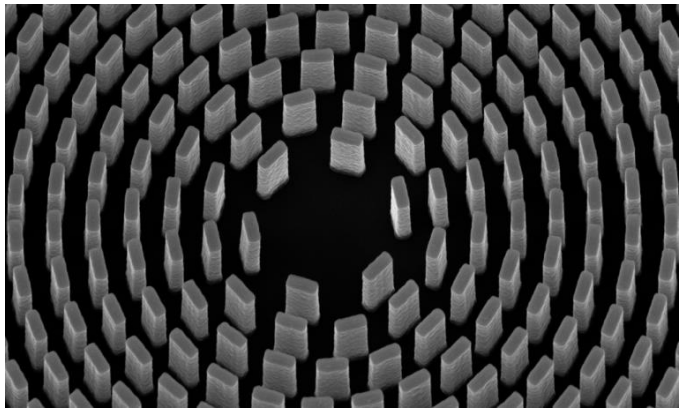
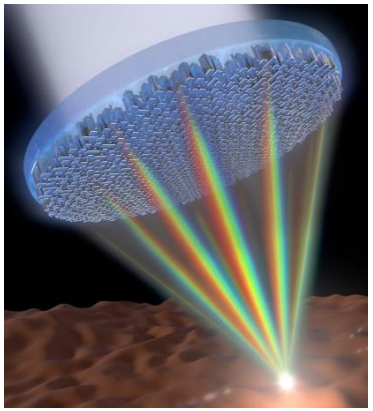
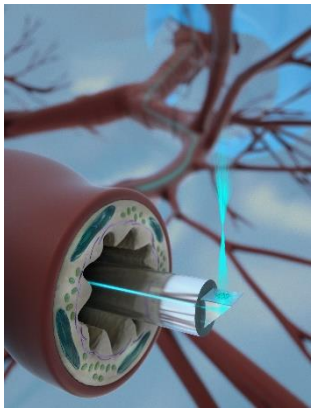
# Optics with Metasurfaces: From Spectroscopy to Medical Imaging



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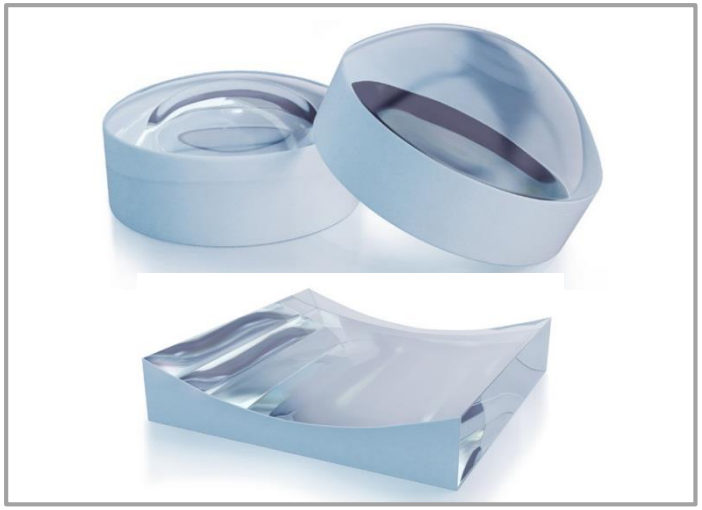
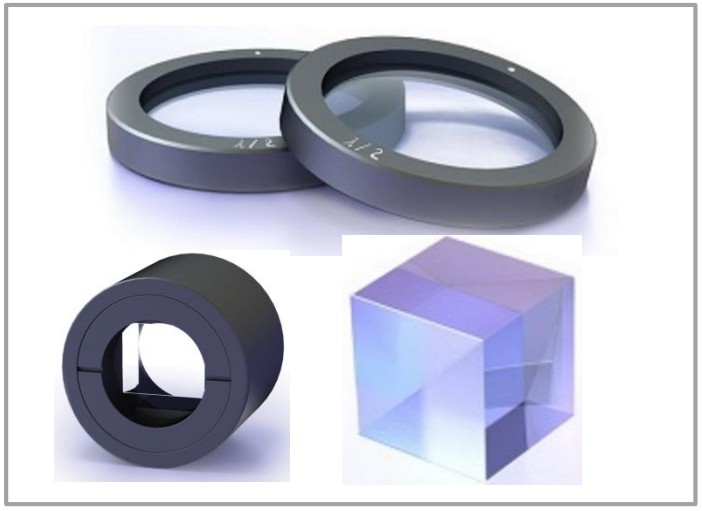
# Motivation for Flat Optics

Lenses

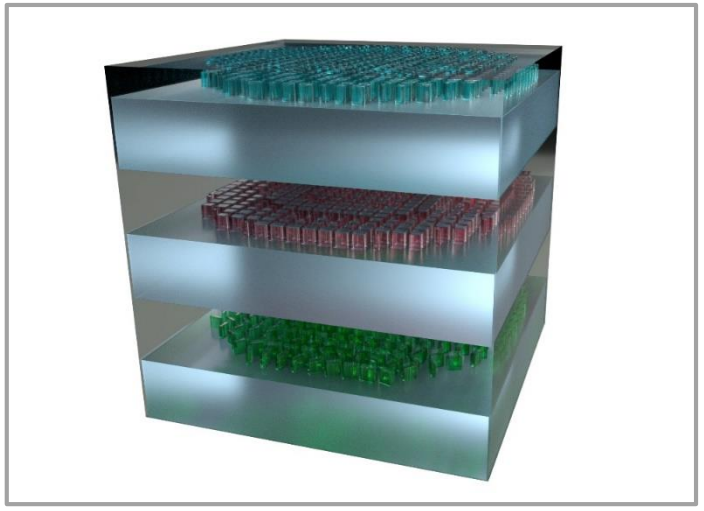


Gratings and Filters


Wave-plates and Polarizers



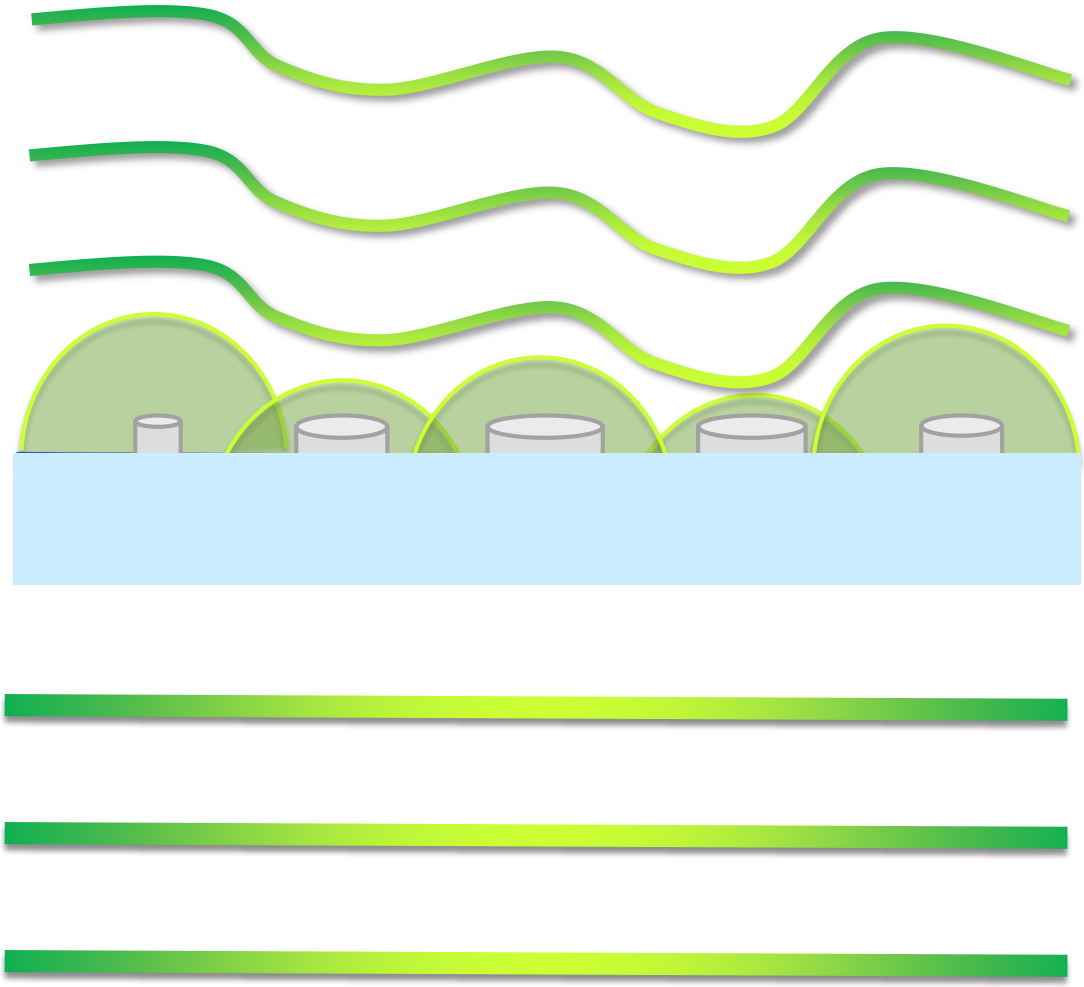
Vertical Integration



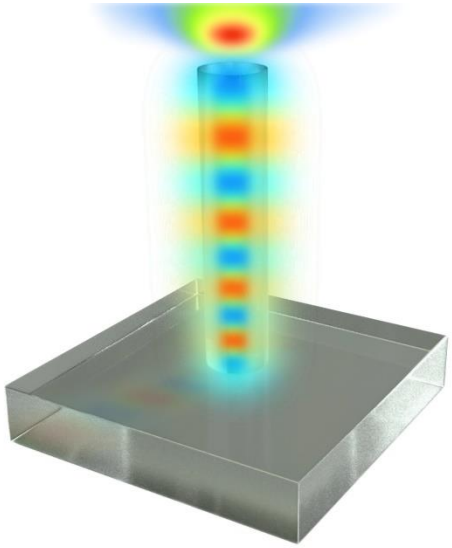
# Benefits

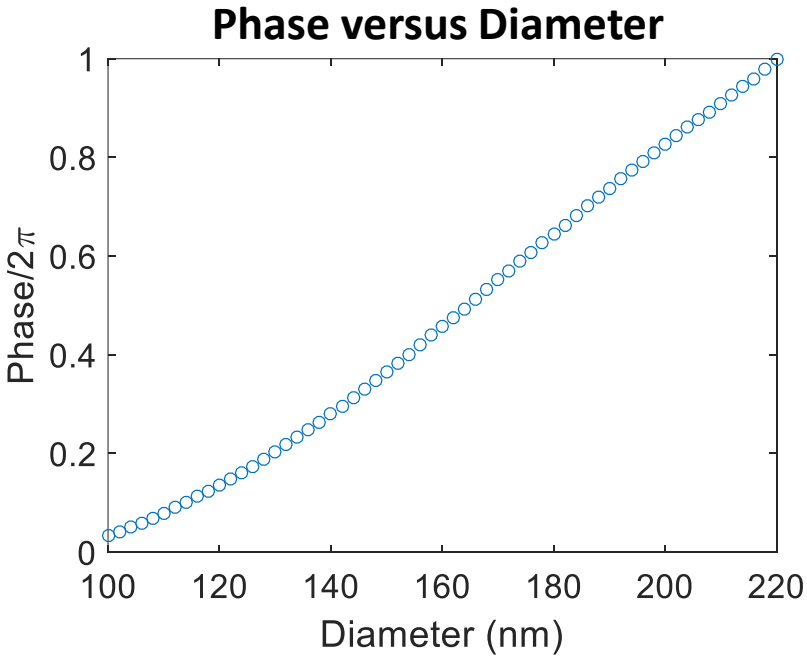
- **Straight-Forward Fabrication**
  - One mask level, cost effective
- **Vertical Integration Capability**
  - Light weight, compact
- **Overcome Limitations of Conventional Optics**
  - Aberrations, multifunctionality

# Metasurfaces Concept

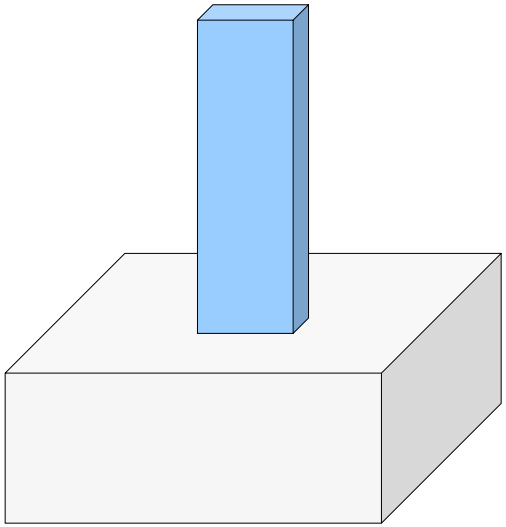


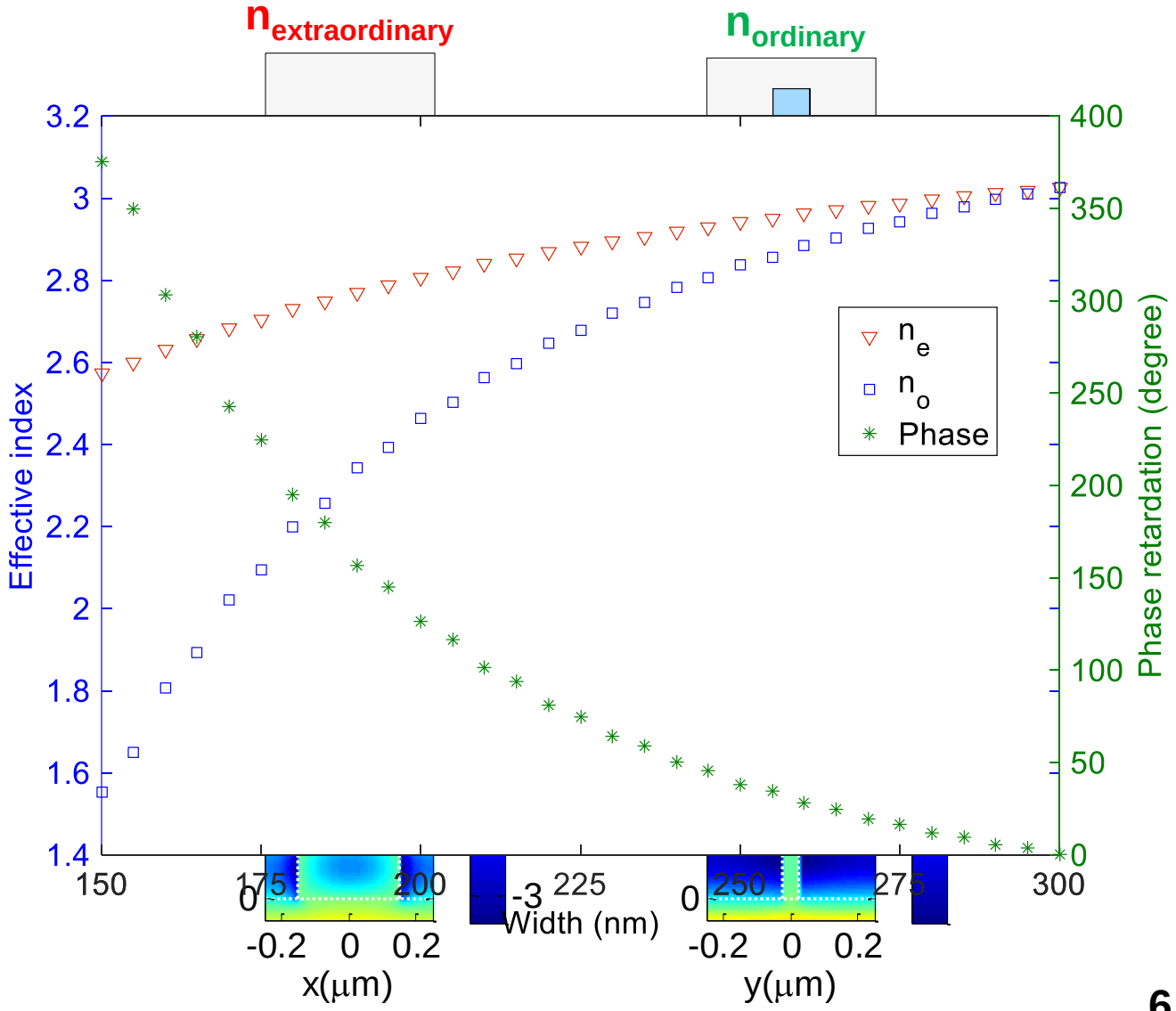
# Building Block: Waveguiding Effect



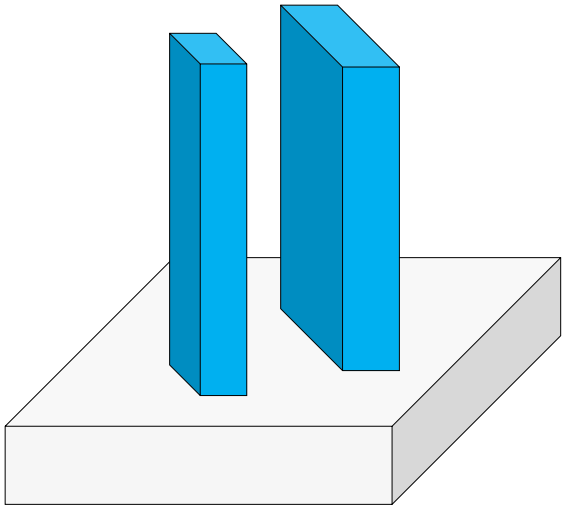


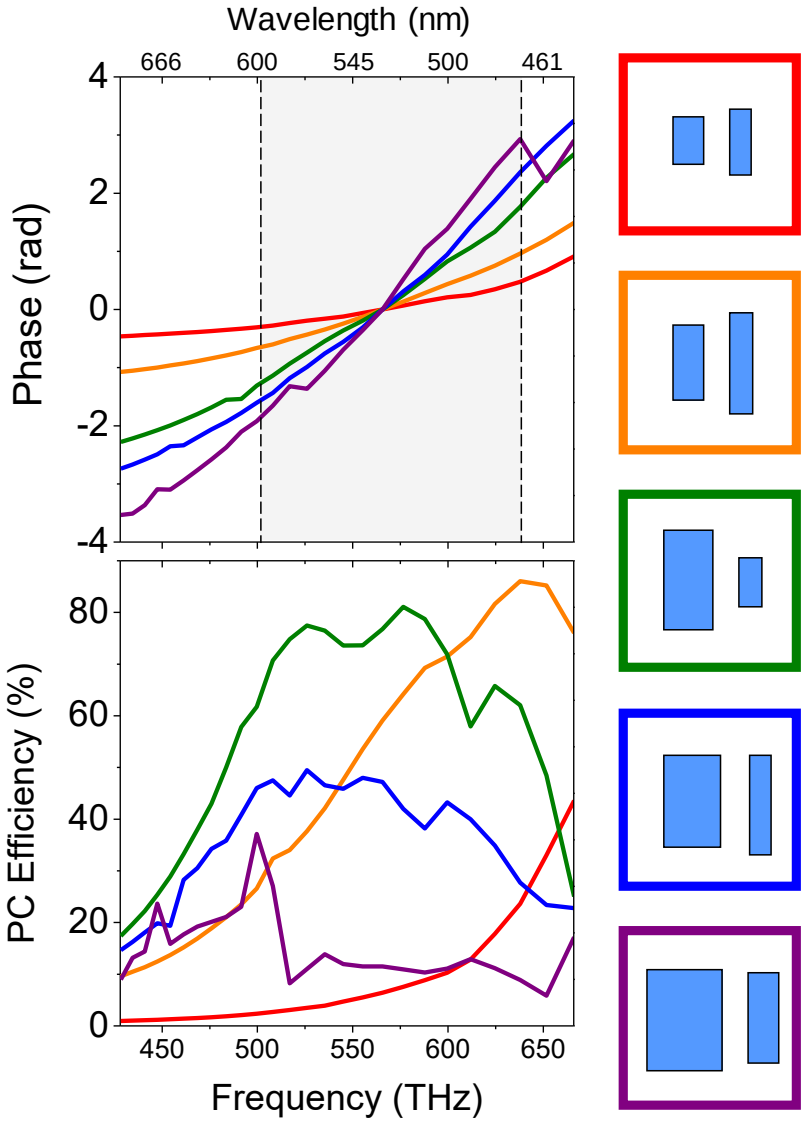
# Building Block: Polarization Sensitive



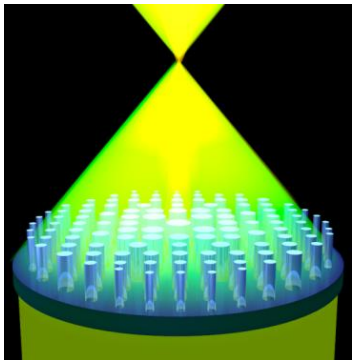
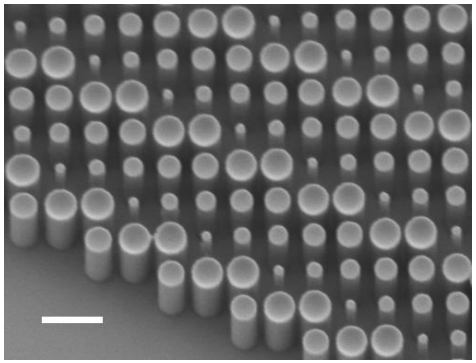
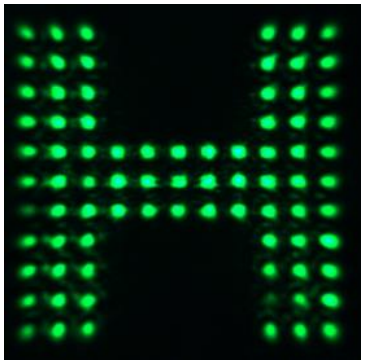
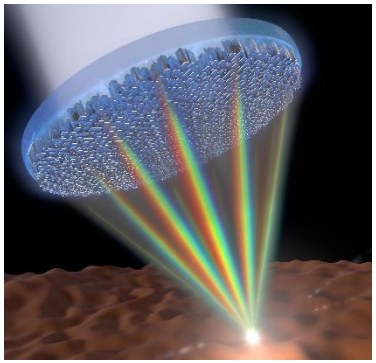
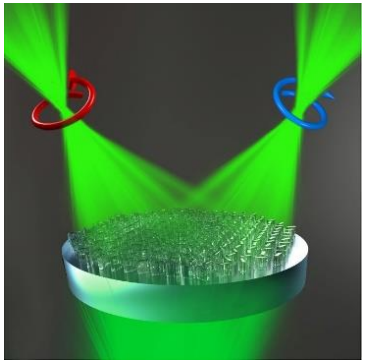


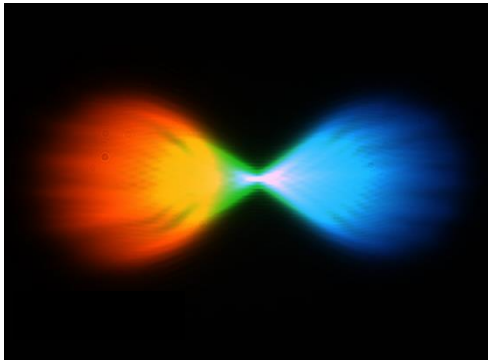
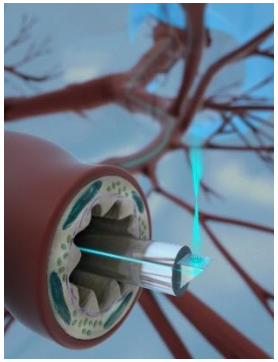
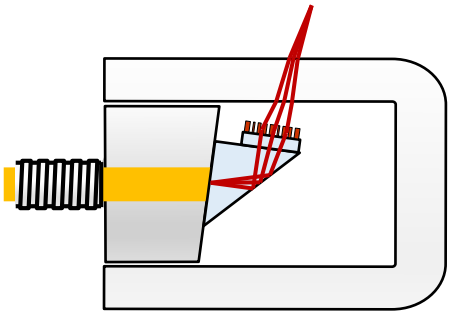
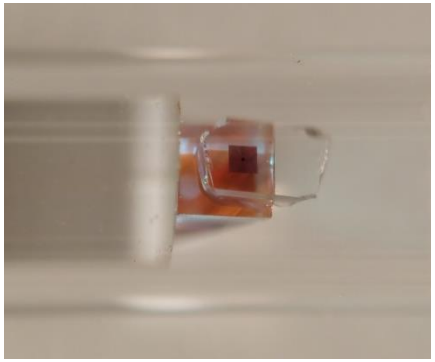
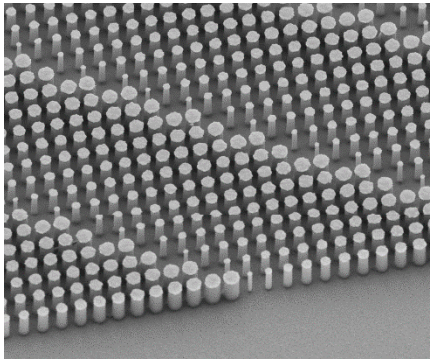
# Building Block: Dispersion Engineering



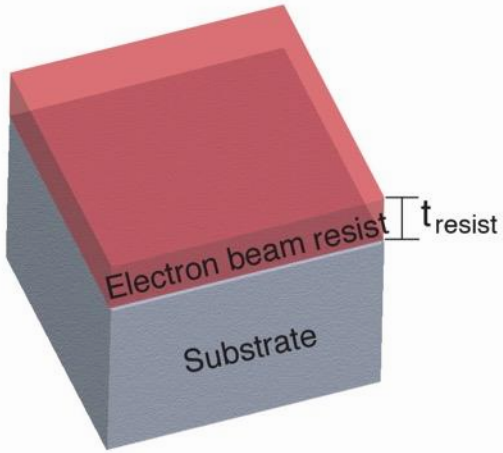


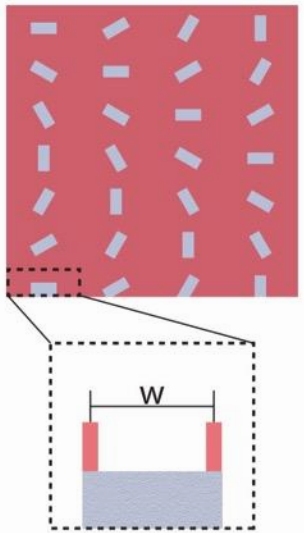
# Summary

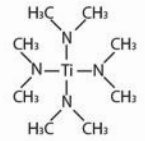






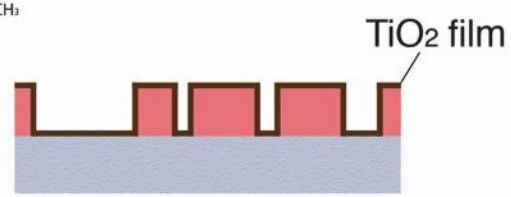






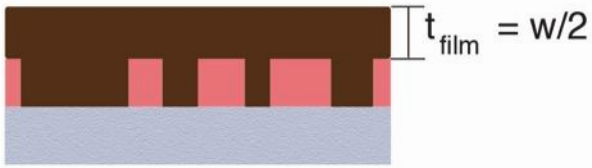
# Fabrication Steps of $TiO_2$ Metasurfaces

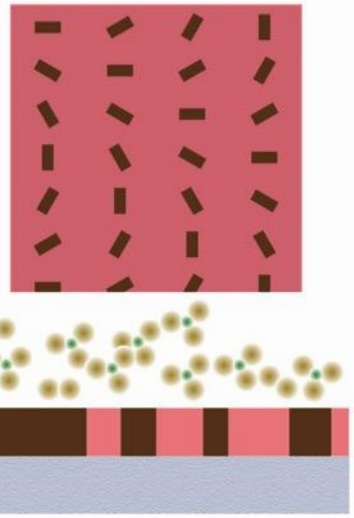


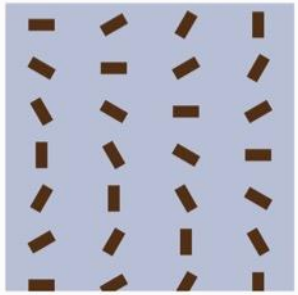



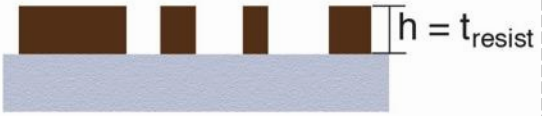





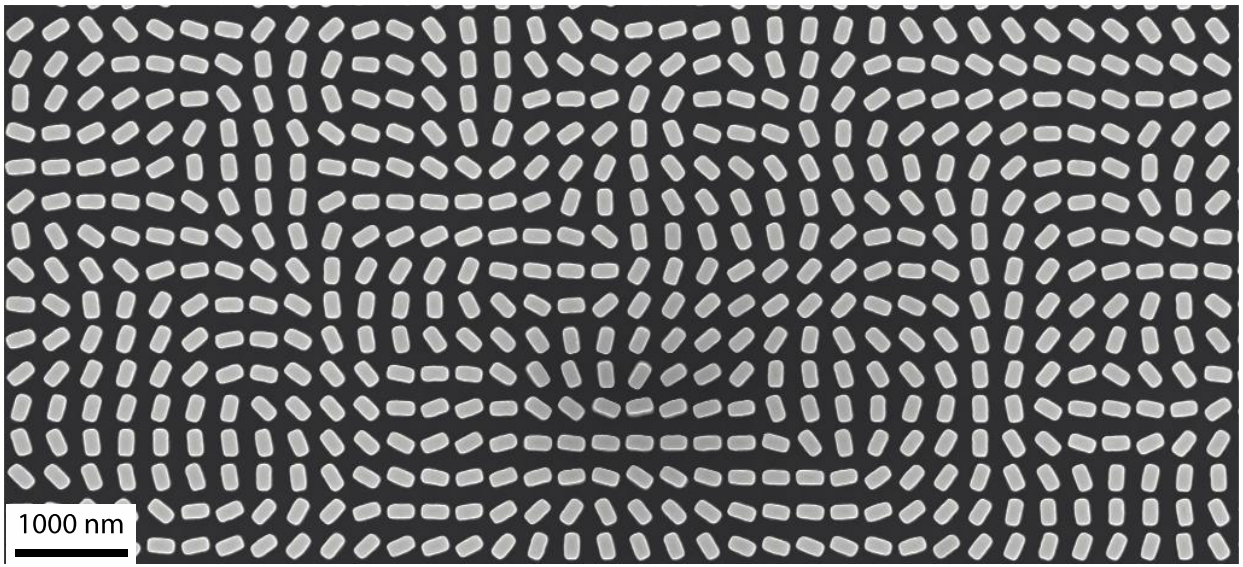



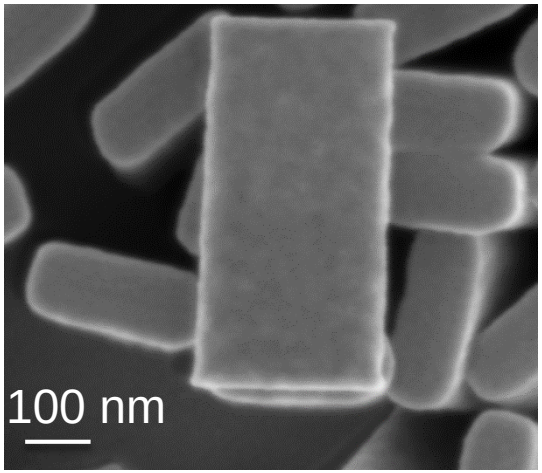


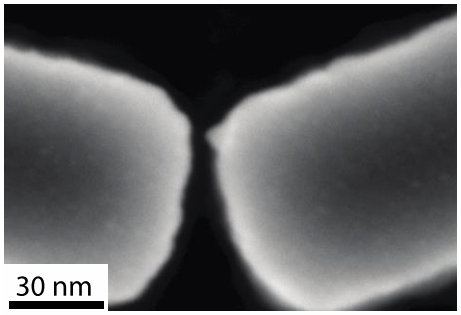


# Example of Fabricated Metasurfaces

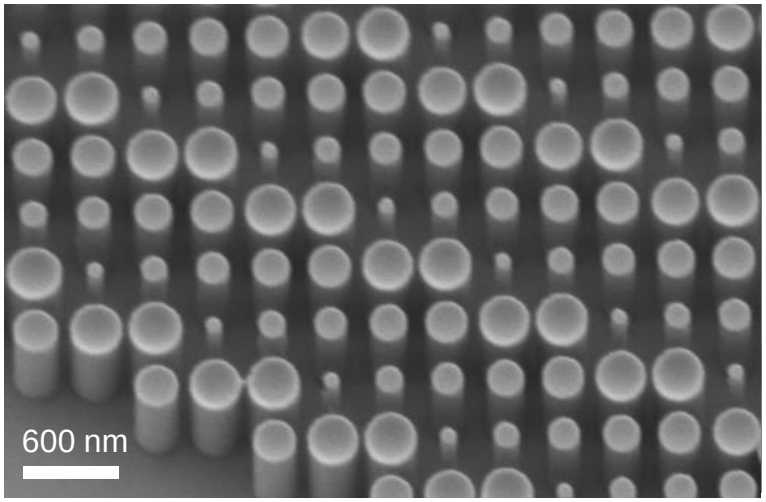


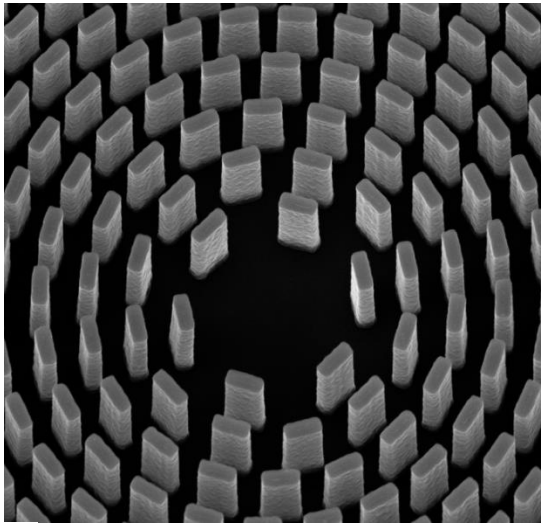

Side view



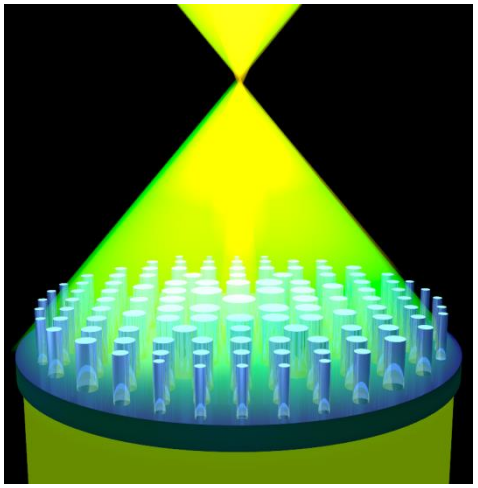


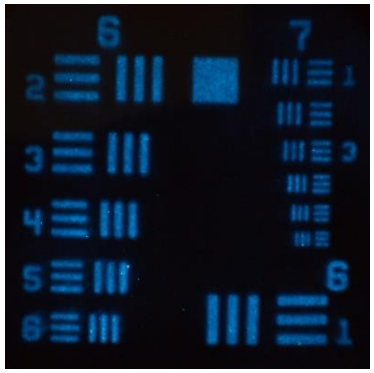
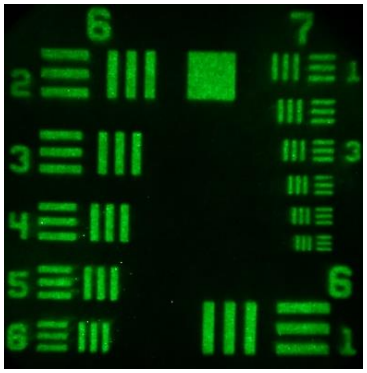
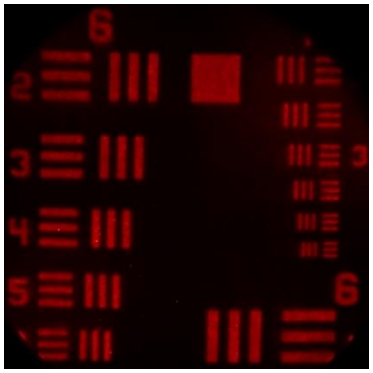
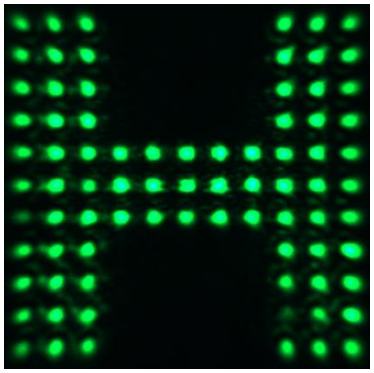
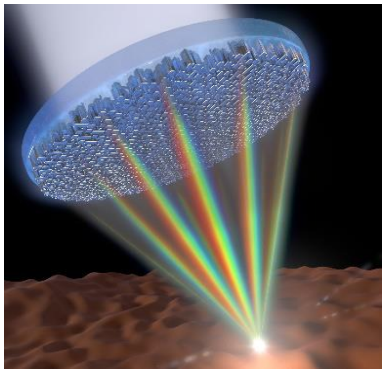


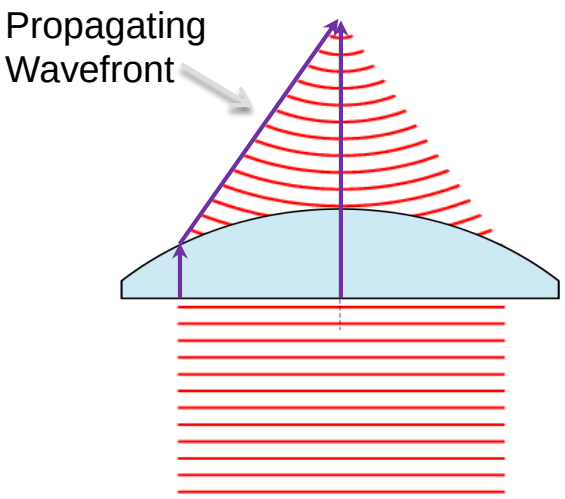
# Flat Lenses

- **Flat Lenses (Meta-lens)**
  - Ultra-Thin Lenses, High Numerical Aperture
  - Diffraction-Limited Focusing
  - Sub-Wavelength Imaging Resolution
  - Dispersion Engineering

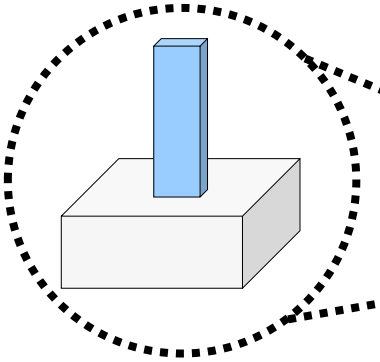


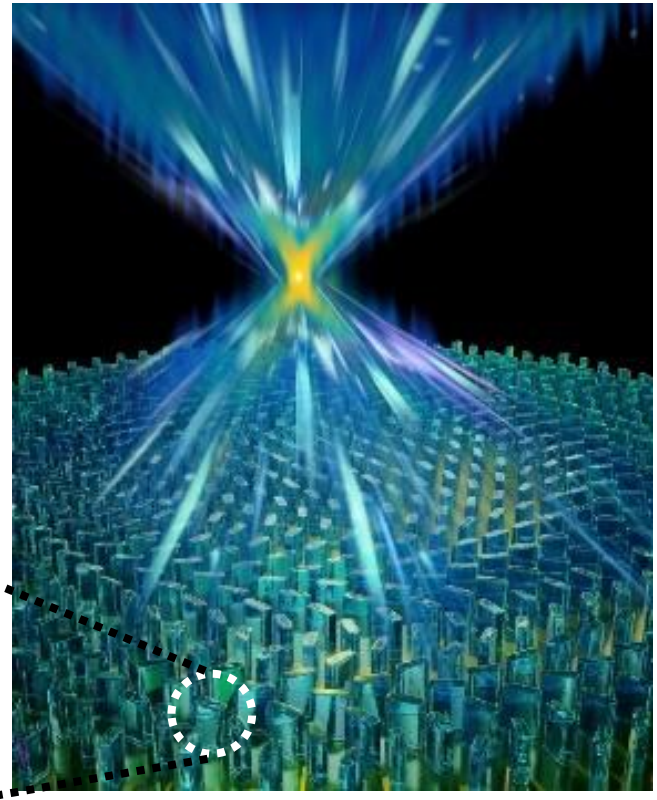






# Design of Flat Lens




www.wikipedia.org



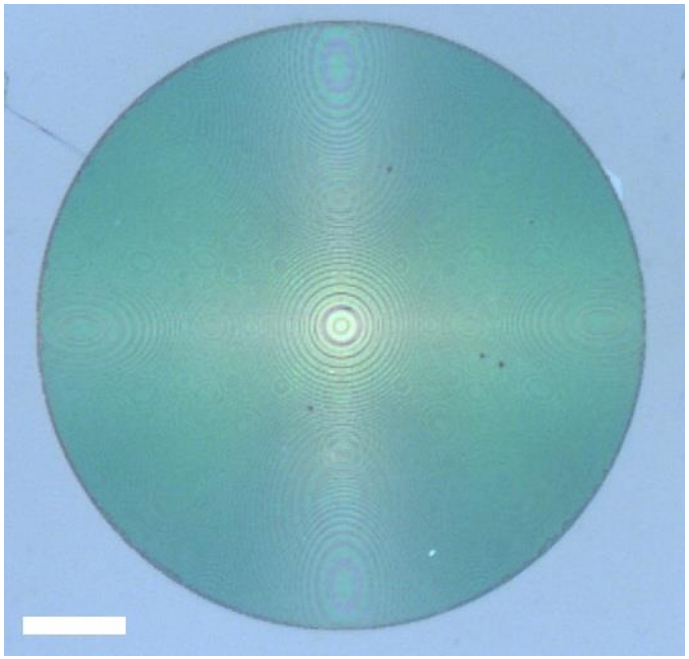


Science, 2, pp. 1190-1194 (2016).

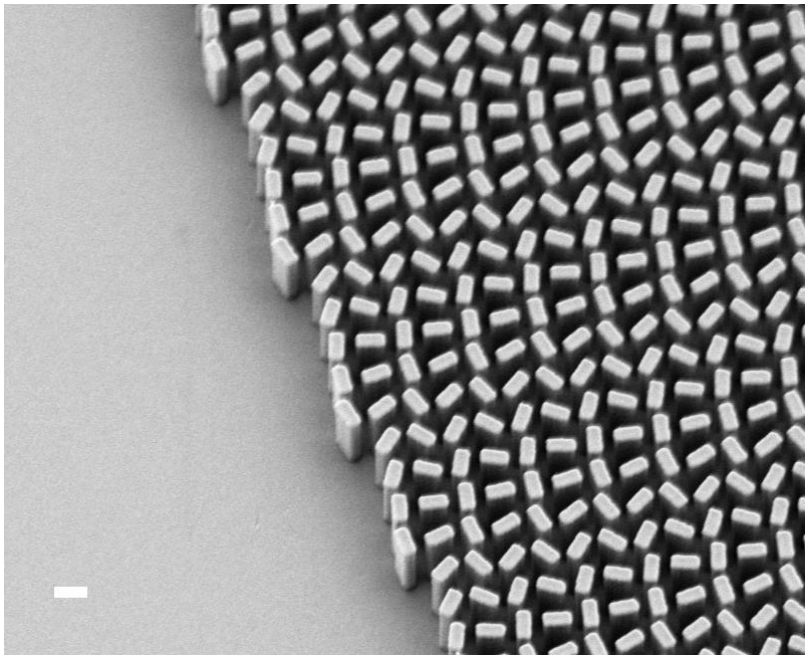
- ✓ **Uniform amplitude**
- ✓ **Geometric Phase, 2π phase coverage**

# Flat Lens based on Geometric Phase

- **Optical and SEM images of fabricated flat lens**



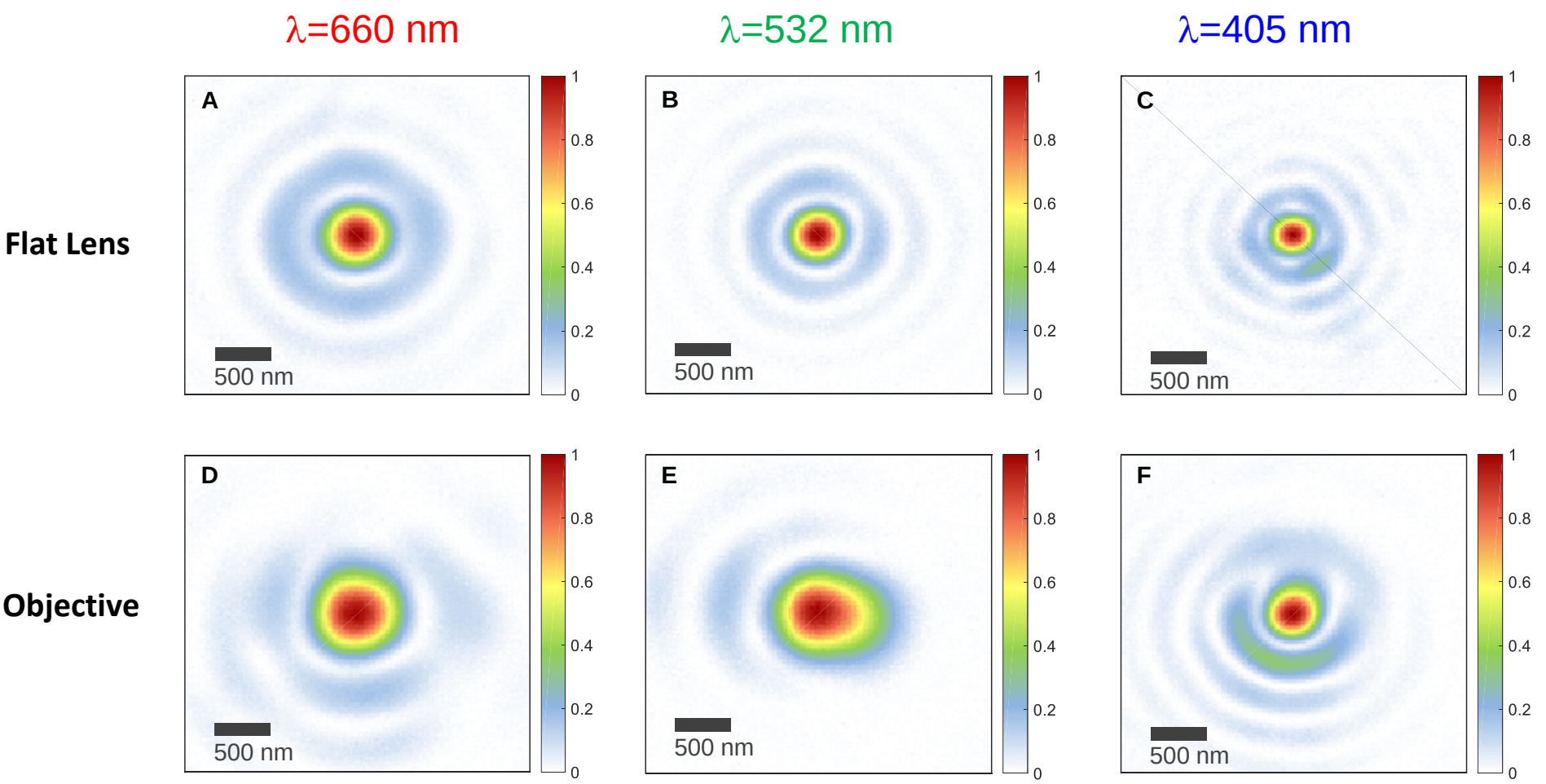
Scale bar: 40 μm



Scale bar: 300 nm

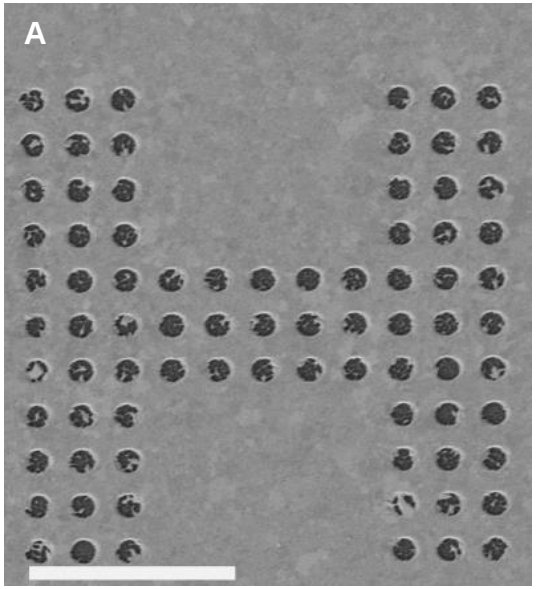
# Diffraction Limited Focusing (NA=0.8)

- **Measured Focal Spots (Diameter= 240 μm, Focal length=90 μm, NA=0.8)**

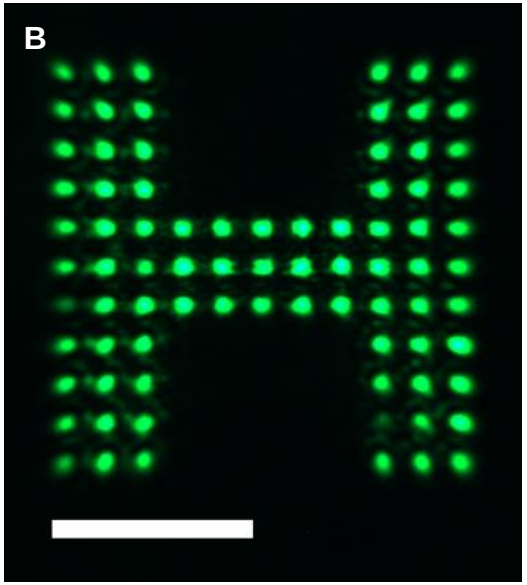



Science, 2, pp. 1190-1194 (2016).

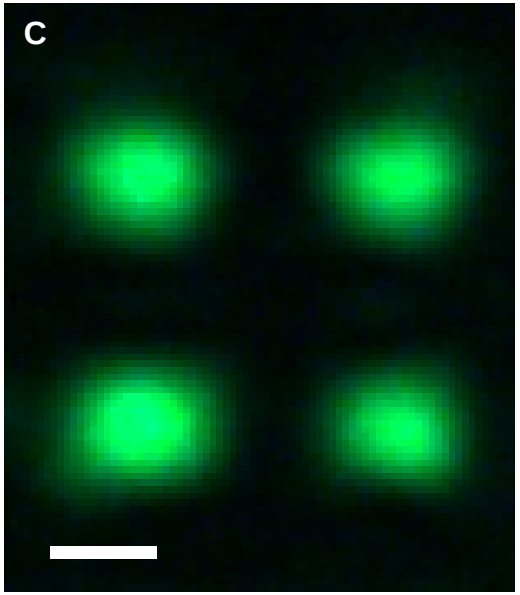
# Sub-Wavelength Resolution Imaging




Scale bar: 10 μm



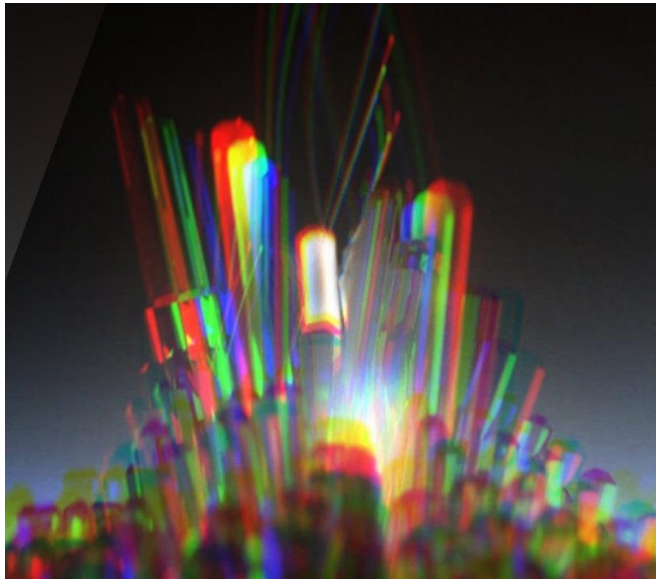

Scale bar: 10 μm



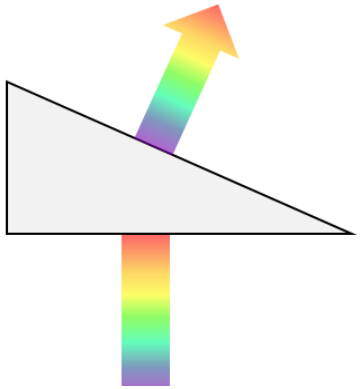

Scale bar: 500 nm

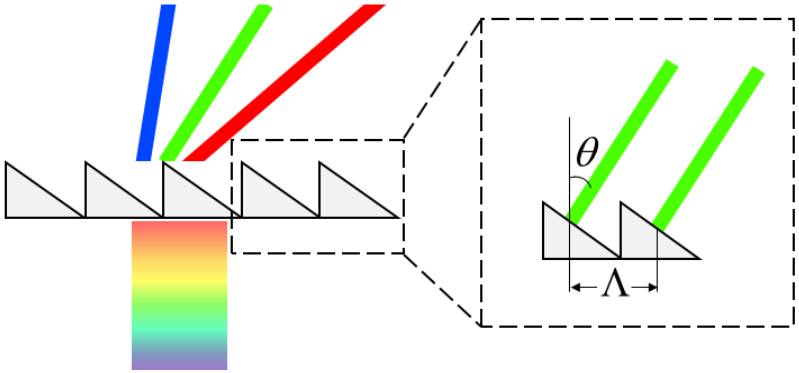
Science, 2, pp. 1190-1194 (2016).

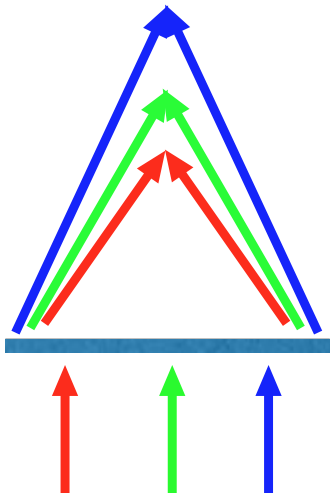
# Chromatic Dispersion



www.gettyimages.com



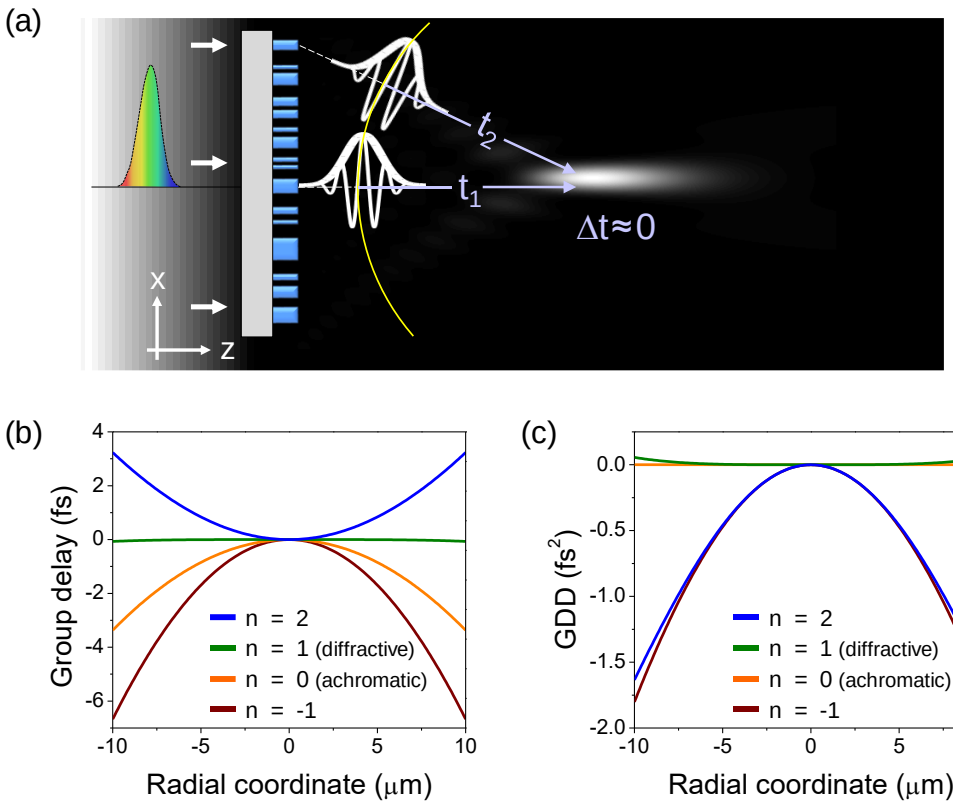


# Dispersion Engineering

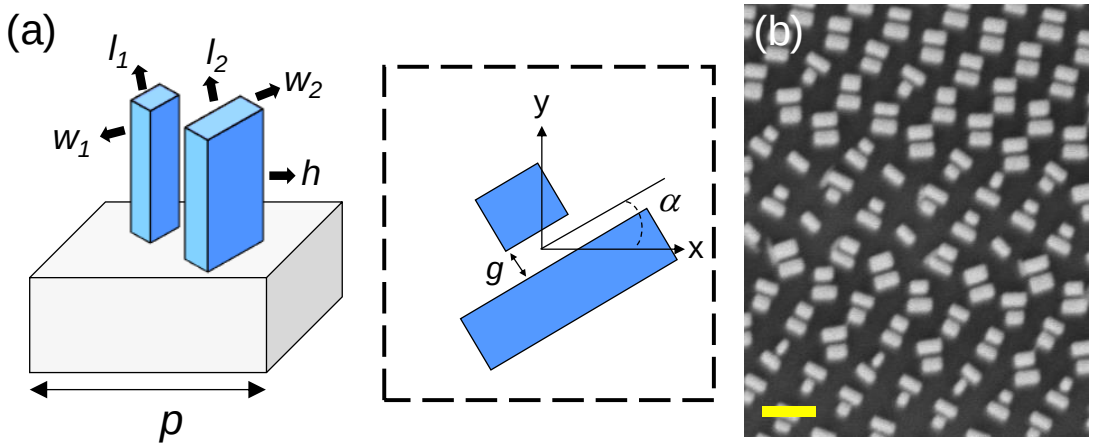
$$\varphi(r,\omega) = -\frac{\omega}{c}\left(\sqrt{r^2 + F^2} - F\right)$$

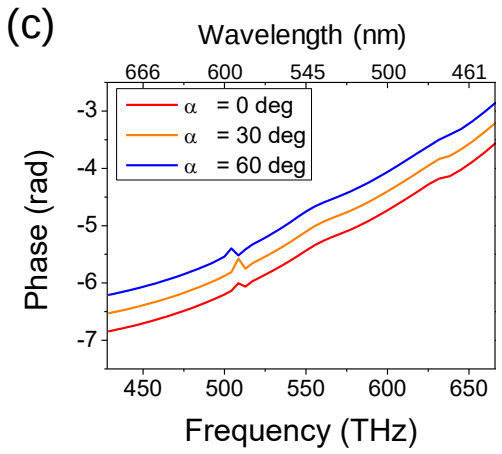
$$F = k \times \omega^n$$

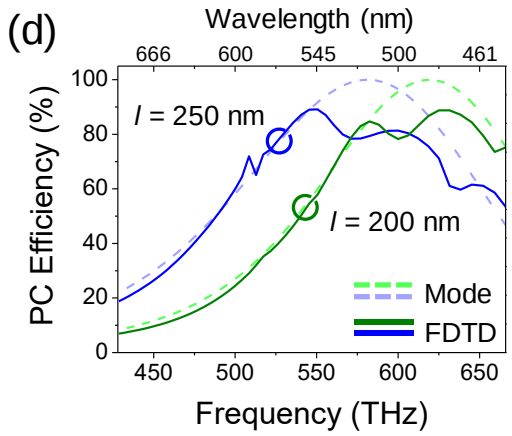


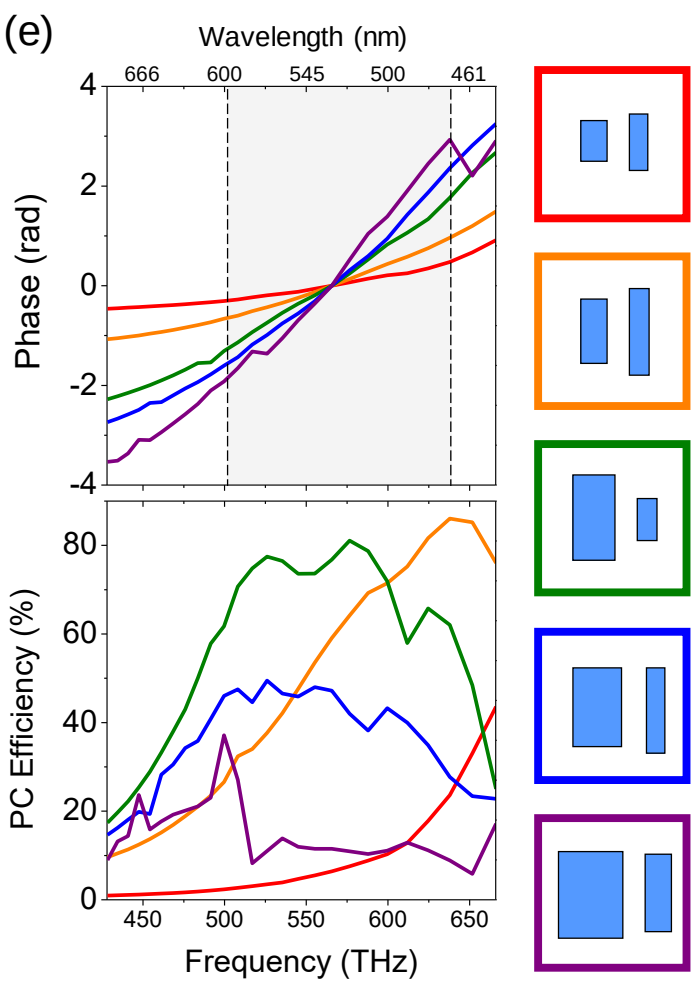

$$\varphi(r,\omega) = \varphi(r,\omega_d) + \left.\frac{\partial\varphi(r,\omega)}{\partial\omega}\right|_{\omega=\omega_d}(\omega-\omega_d) + \left.\frac{\partial^2\varphi(r,\omega)}{\partial\omega^2}\right|_{\omega=\omega_d}(\omega-\omega_d)^2 + \ldots$$

# Dispersion Engineering

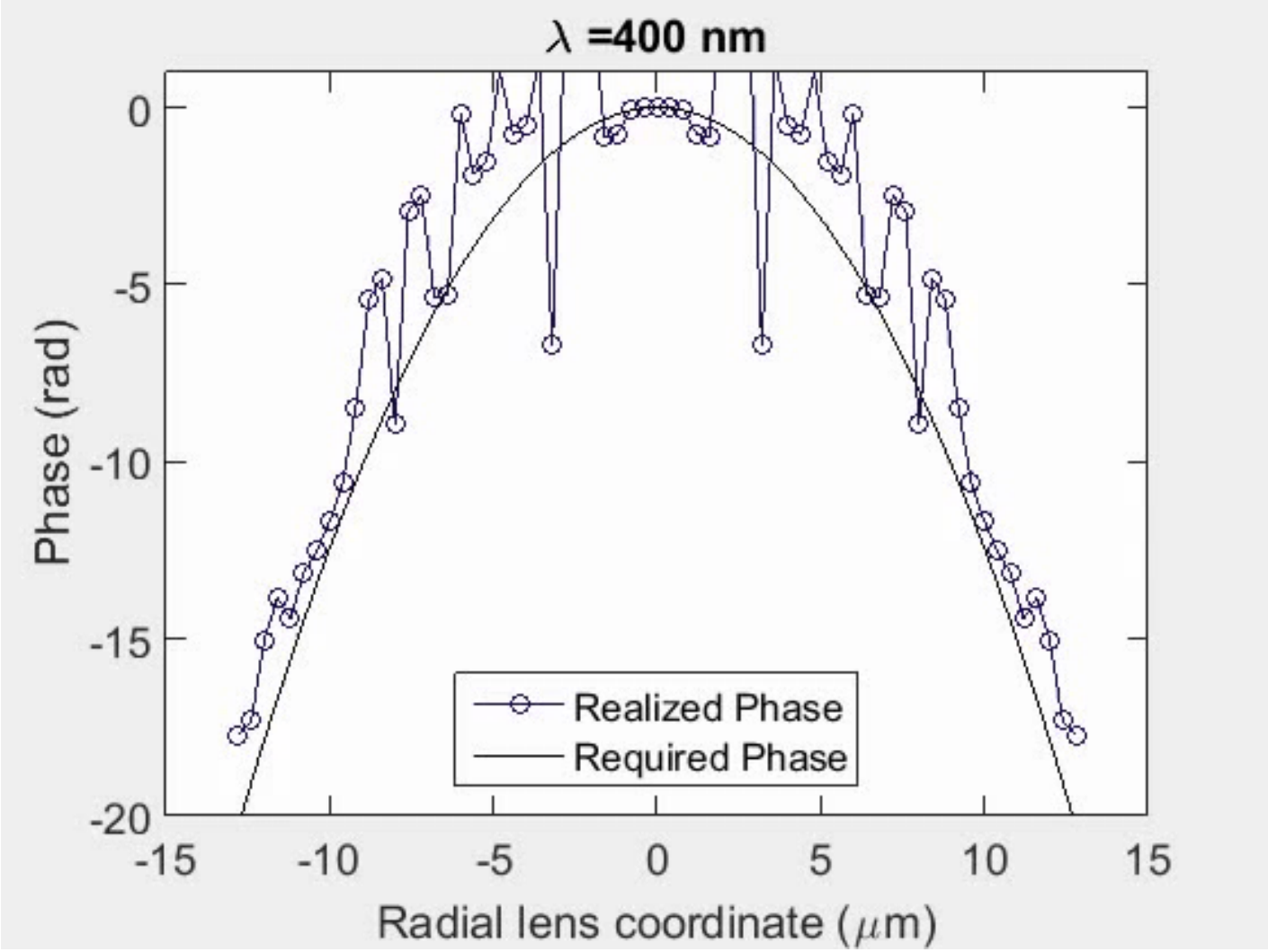


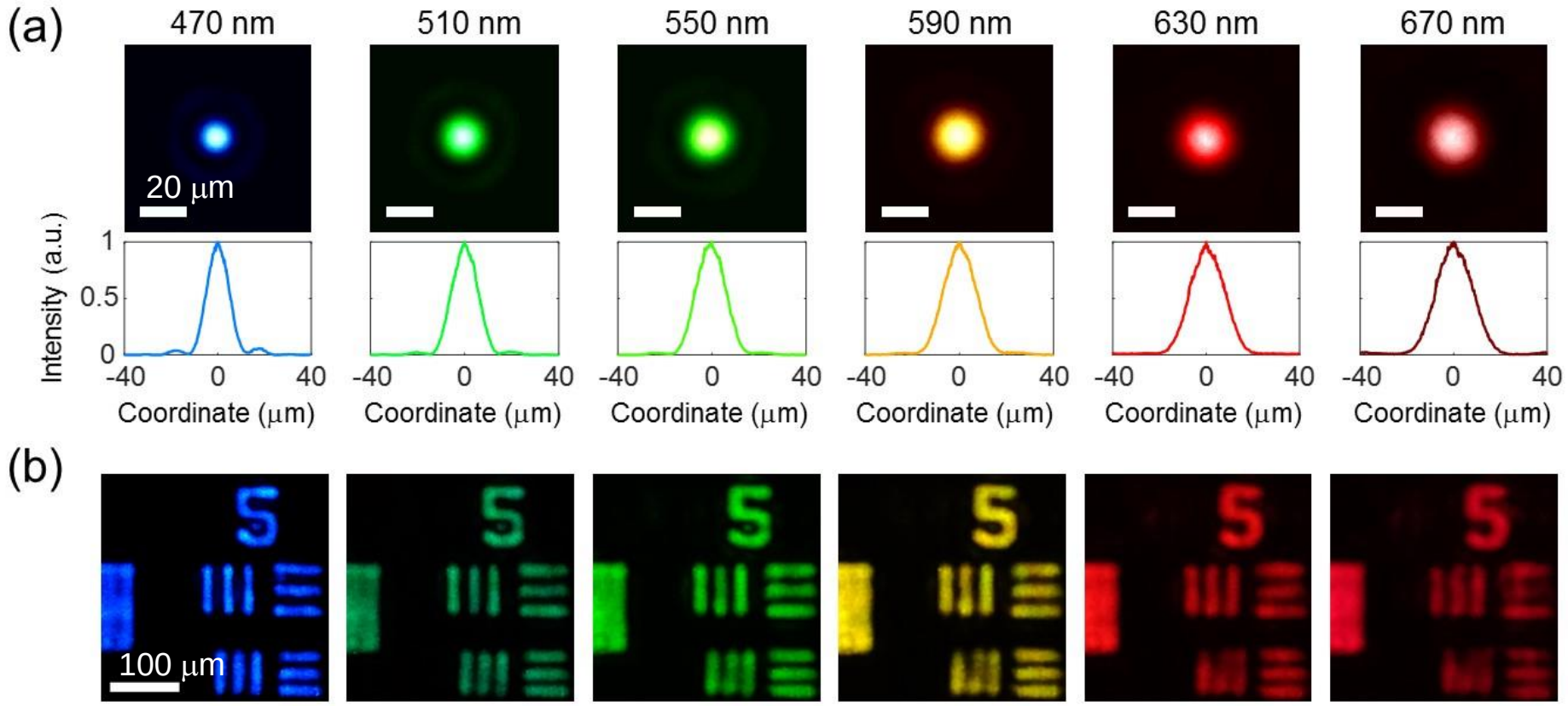



# Phase Profile of Achromatic Flat Lens



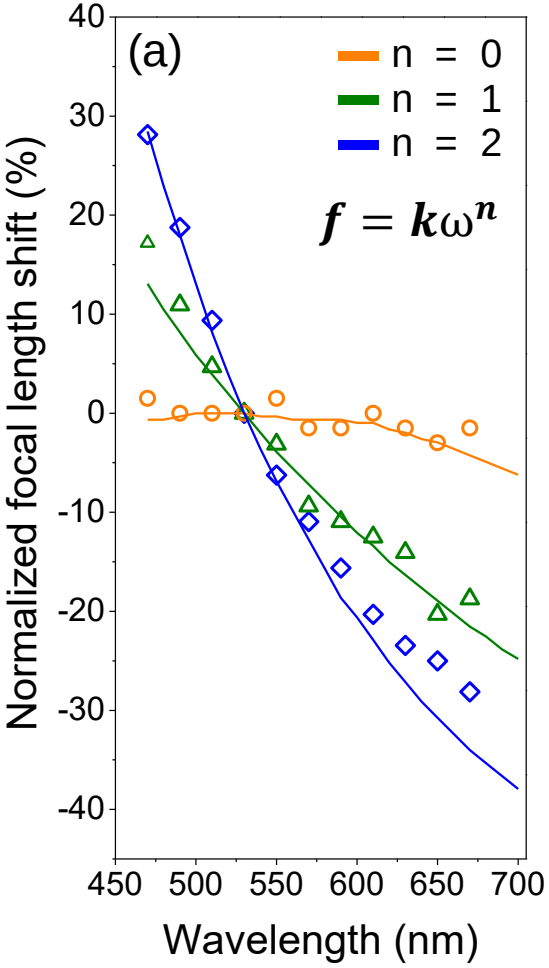
# Focusing and Imaging with Achromatic Flat Lens

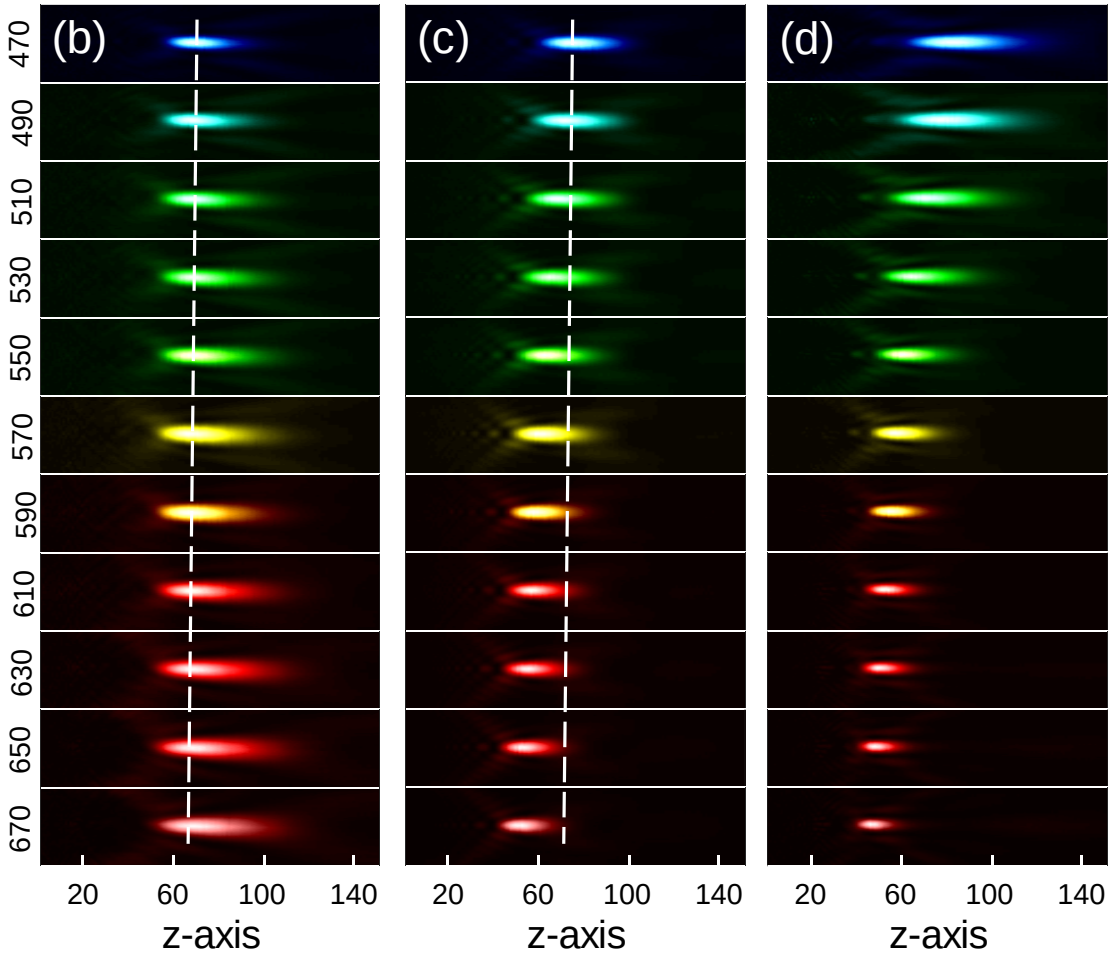



Nature Nanotechnology13 (3), 220 (2018)

**NA=0.02, f=5.5 mm, $\lambda_d$=530 nm**

# Tailoring Chromatic Dispersion



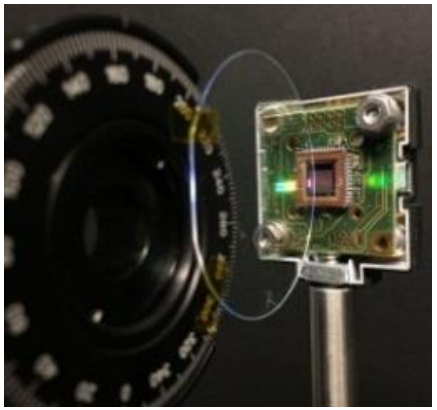

Nature Nanotechnology13 (3), 220 (2018)

**NA=0.2, f=63 μm, $\lambda_d$=530 nm**

# Multifunctional Flat Lenses

- **Multispectral Chiral Imaging**
  - Multifunctional Metasurface
  - Resolving Chirality
  - Resolving Spectral Information

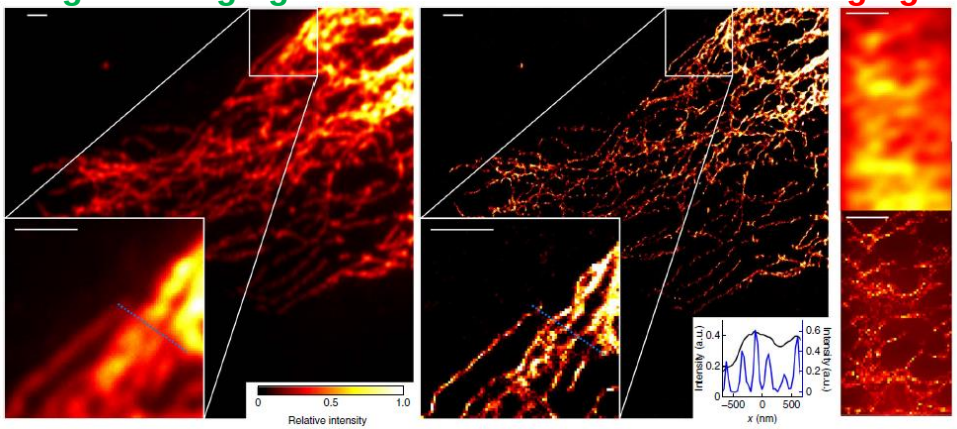
- **Meta-spectrometer**
  - Multiple Meta-gratings on the Same Flat Substrate
  - Ultra-compact, Variable Resolution and Spectral Range
  - Simultaneous Polarization Measurement Capabilities



# Polarization Resolved Imaging

Regular imaging

Polarization-resolved imaging



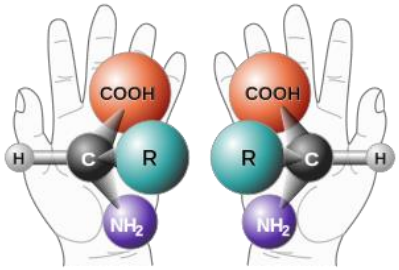

Hafi et al. Nature Methods 11, 579–584 (2014).

Regular imaging

Polarization-resolved imaging

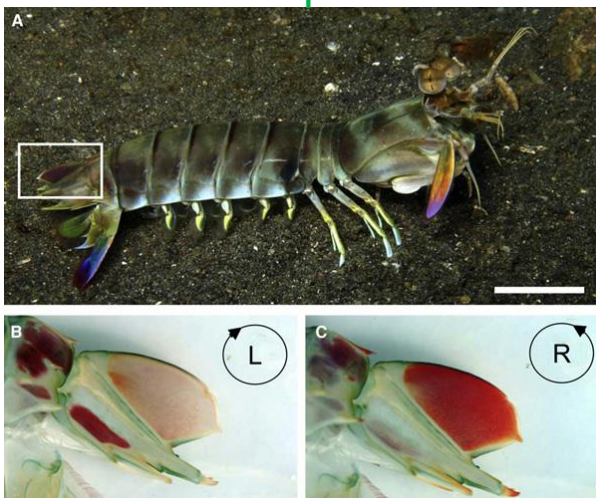

Gruev, et al., *Opt. Express* 18, (2010).

- **Reflection/Transmission**
  - Degree of Polarization (DOP)
- **Atomic/molecular transitions**
  - Fluorescence, Luminescence



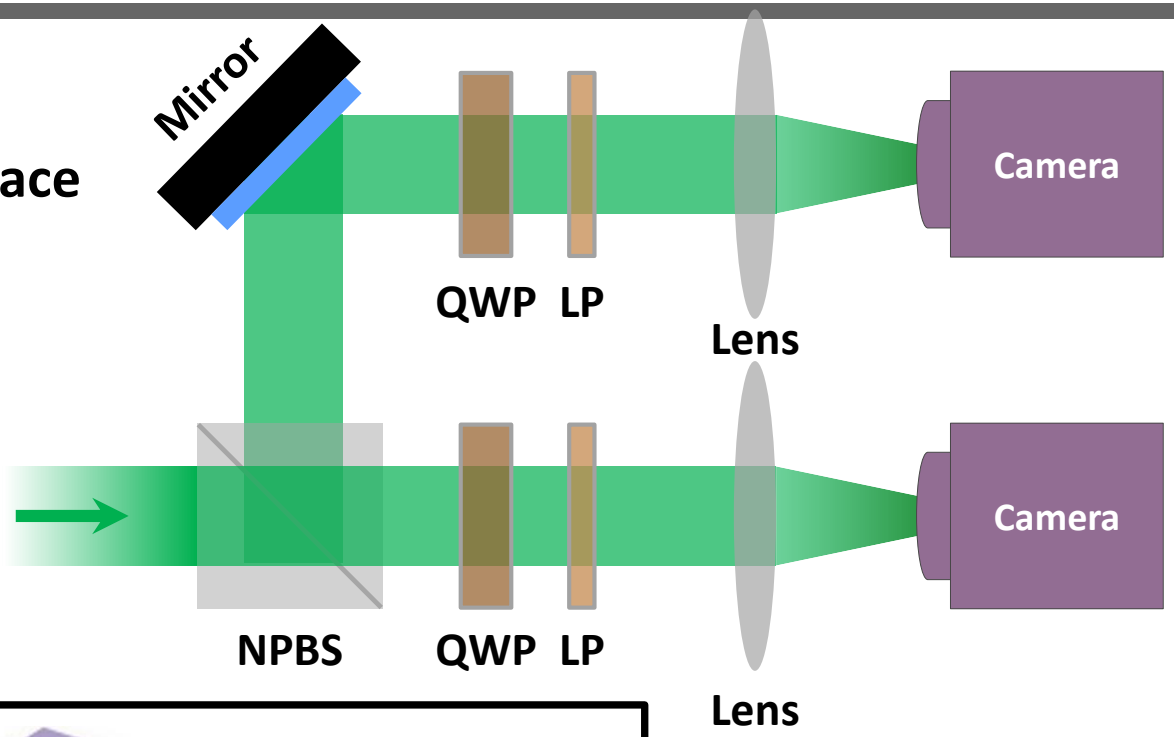


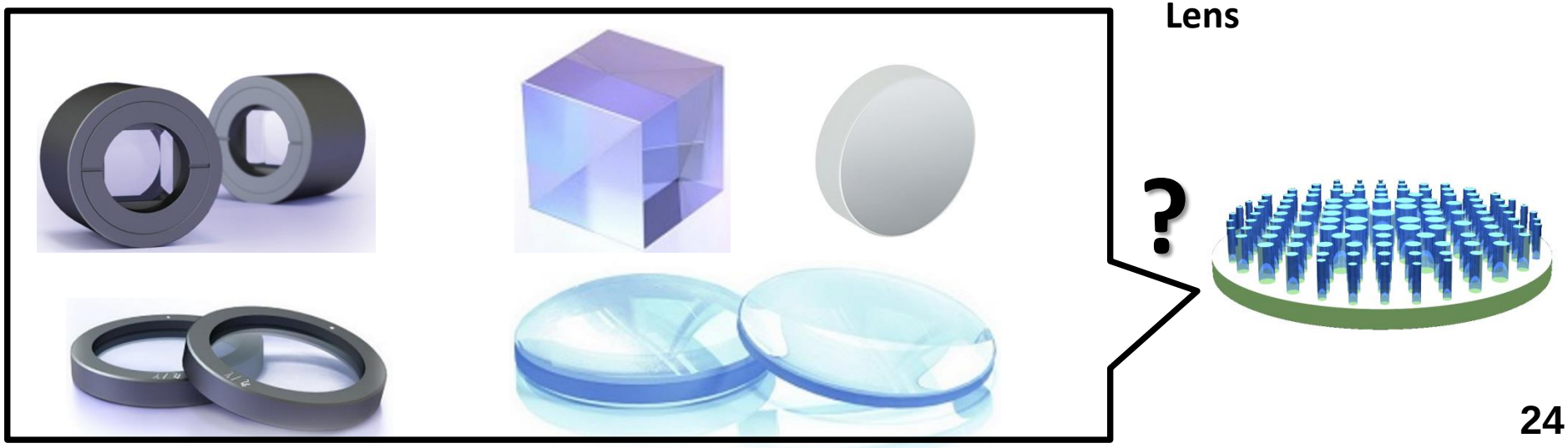
Mantis Shrimp



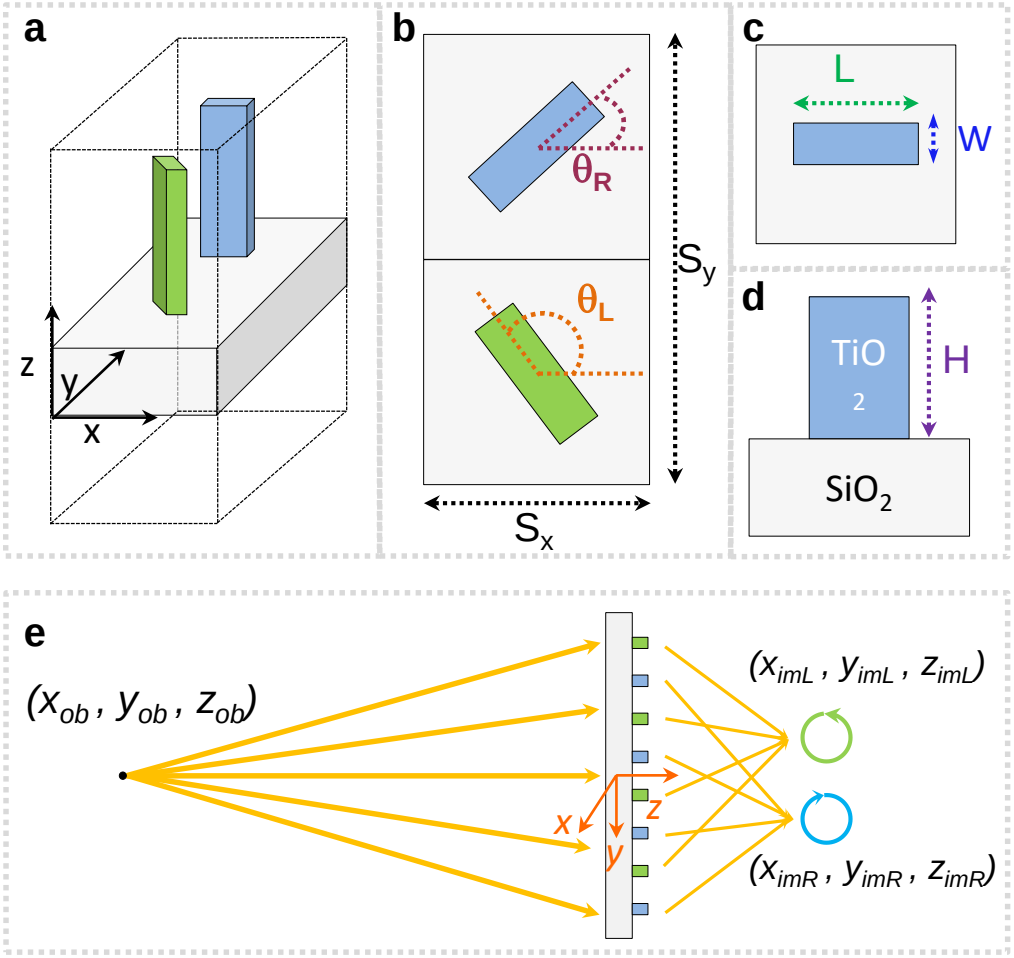
# Multispectral Chiral Imaging

- Multifunctional Metasurface
- Resolving Chirality



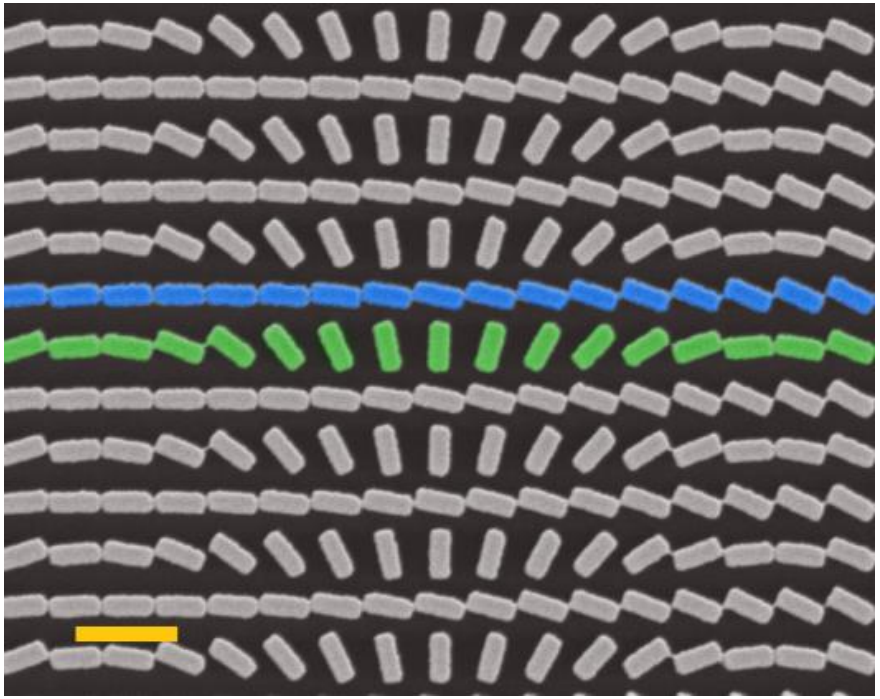



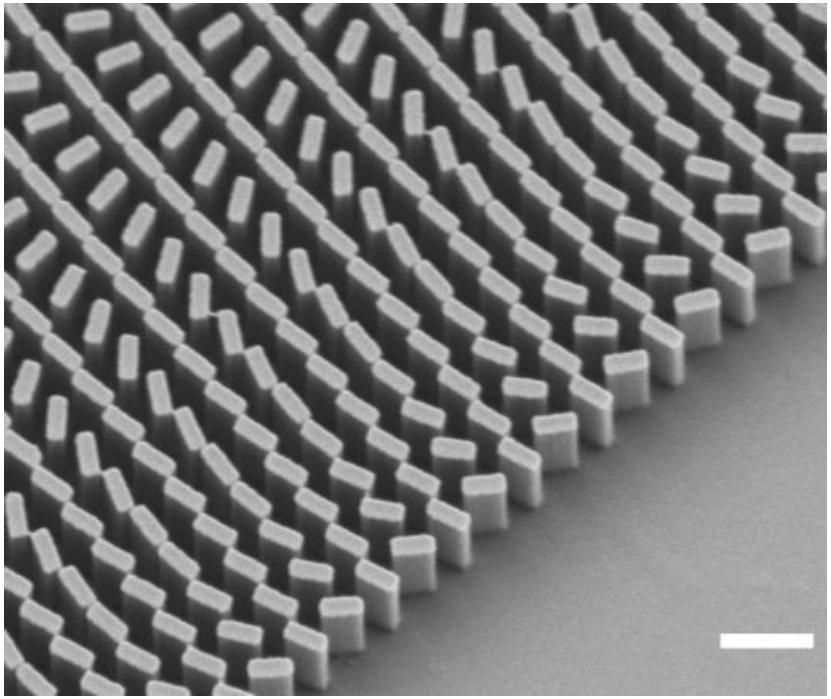
# Design of Multispectral Chiral Lens (MCHL)




*Nano Lett., 16 , 4595–4600* (2016).

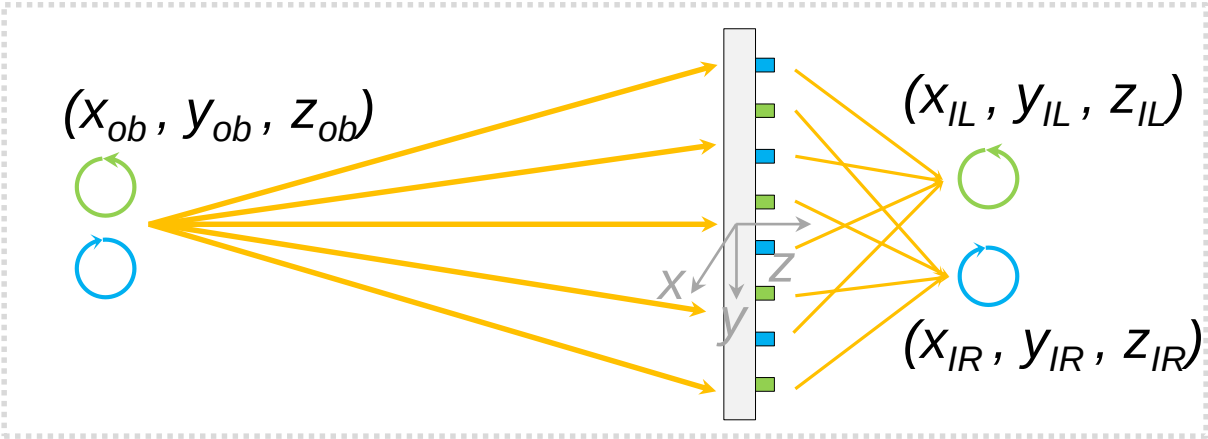
# SEMs of Fabricated MCHL



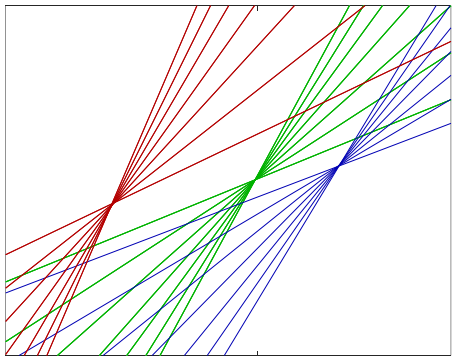


Scale bar: 600 nm

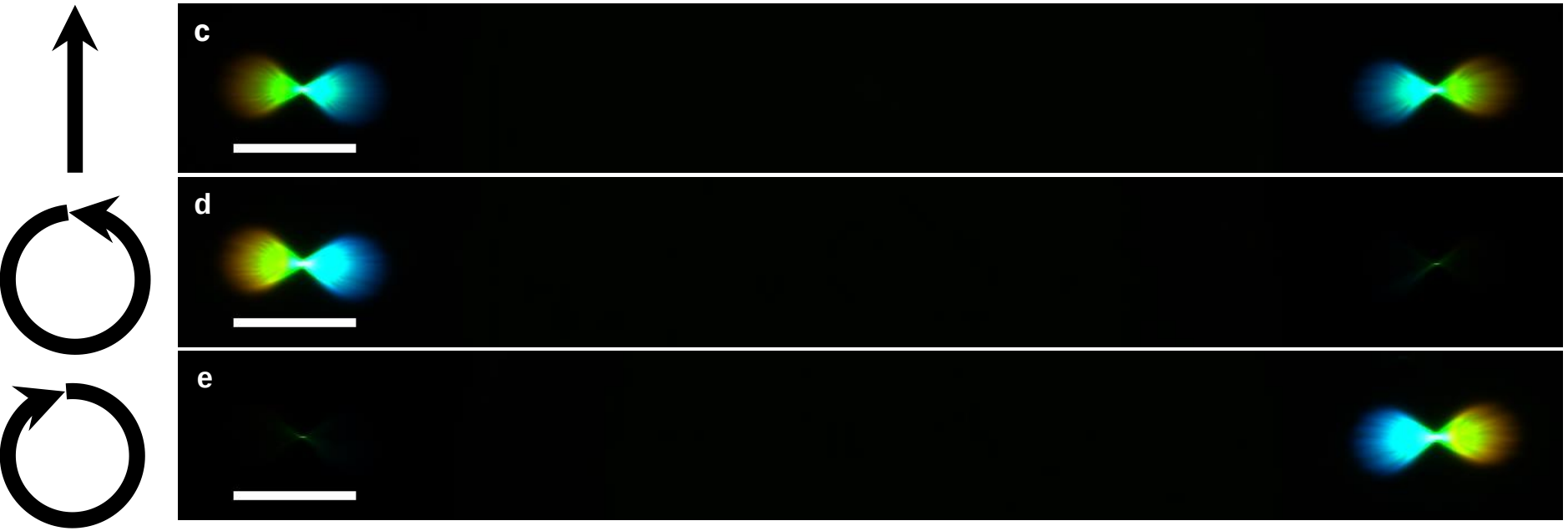
# Imaging a Facet of Single Mode Fiber: Linear Polarization

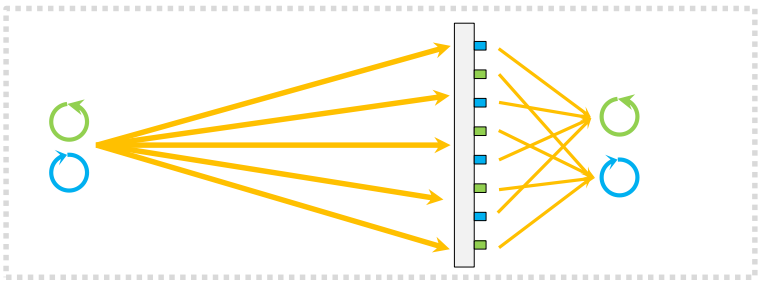



Scale bar 0.5 mm

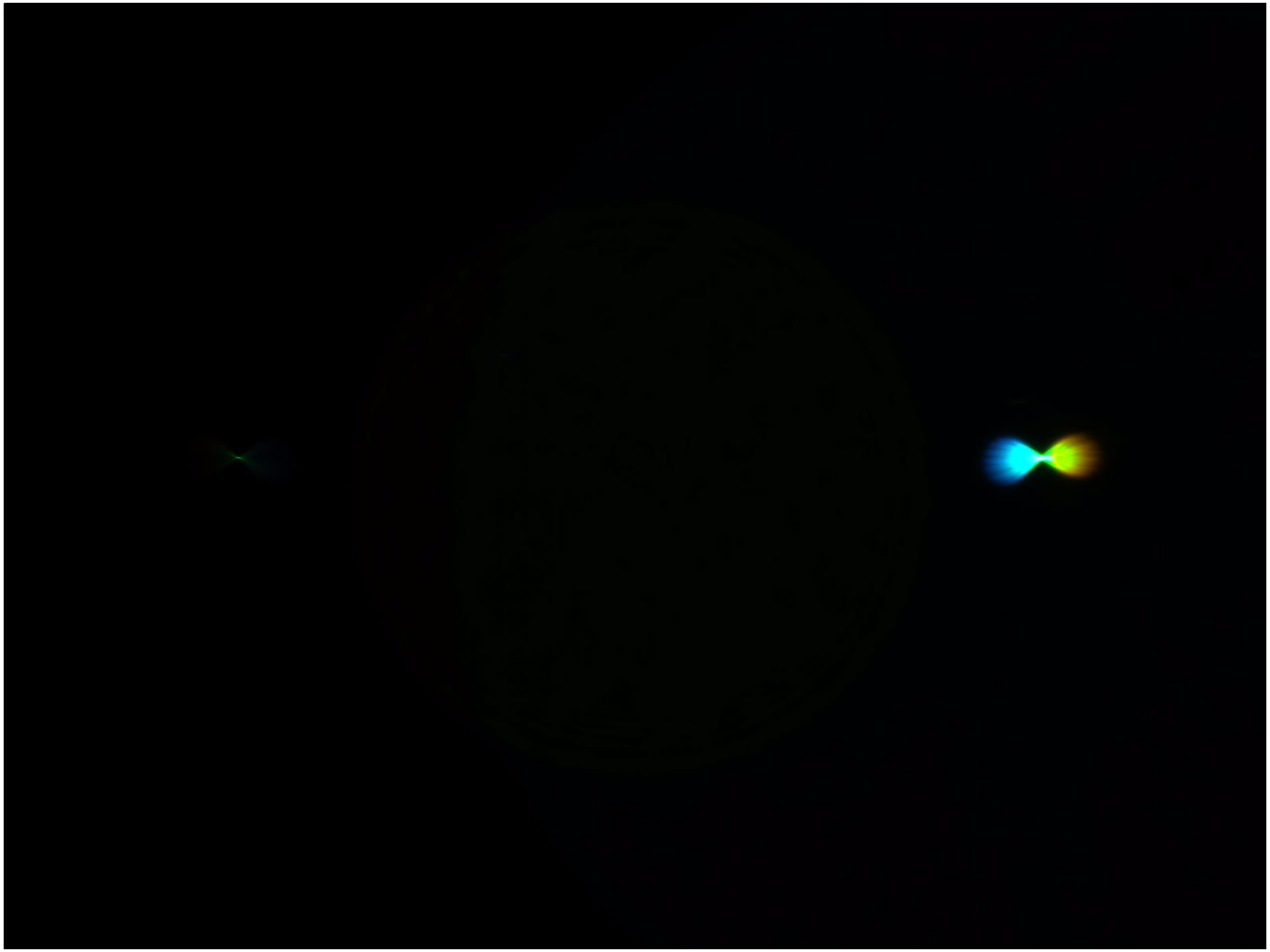


# Chiral Response



# Chiral Response

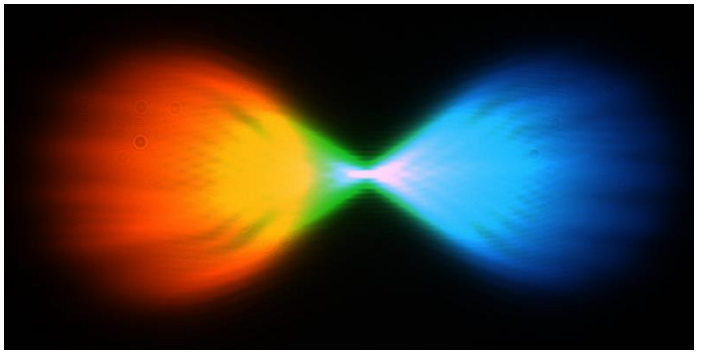


# Chiral Imaging: Chiral Object

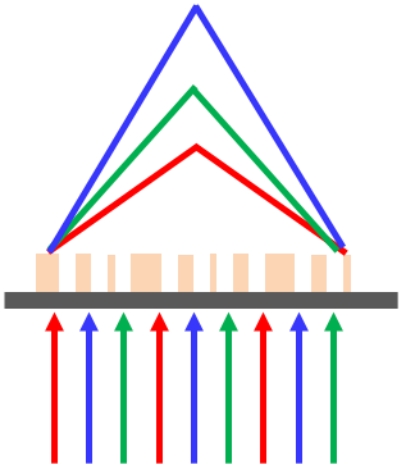
# Chiral Imaging: Non-Chiral Object

# Engineered Dispersive Response

- **Utilizing Chromatic Dispersion**

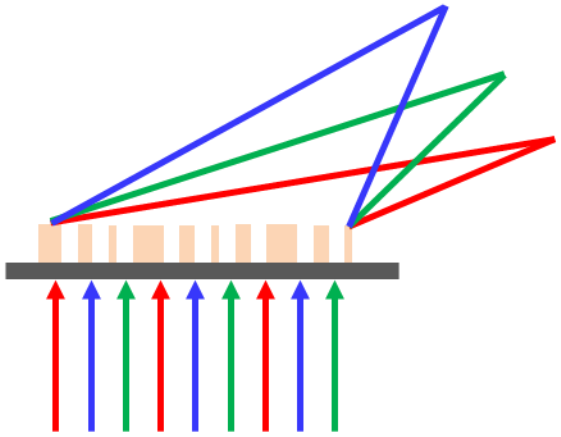


- On-axis focusing



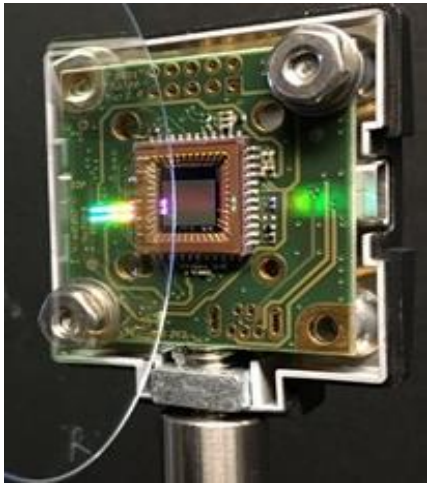
Chromatic incidence

- Off-axis focusing



# Meta-spectrometer

- Diffraction limited focal spots at design wavelength (532 nm)
- Spectral resolutions as high as 0.05 nm (NA=0.1) and spectral range up to ~200 nm (NA=0.02)
- Comparable values to some of the best commercial systems with ~ meter propagation lengths
- Reduced cost and size, with also polarization resolving functionality




Operating Grating Angle: **17.609 degrees**

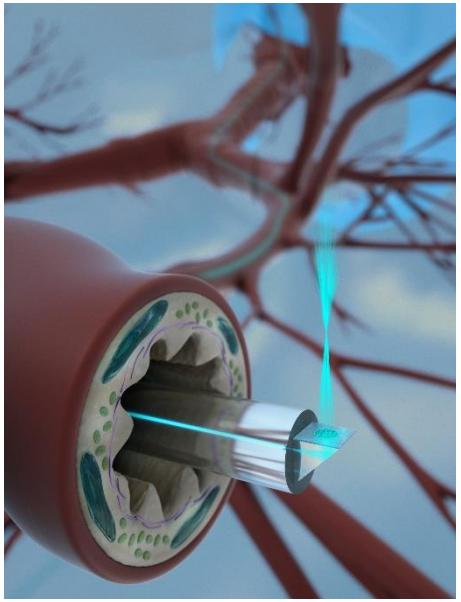
| | nm | eV | Raman Shift $cm^{-1}$ |
|---|---|---|---|
| Center Wavelength | 500 | 2.48 | |
| Range Start | 487.14 | 2.55 | |
| Range End | 512.86 | 2.42 | |
| Bandpass | 25.71 | 0.13 | |
| **Spectrum Resolution** | **0.051** | **0.000248** | A laser wavelength is required for Raman Shift calculations<br>Please enter above. |
| Maximum Wavelength | 1431.39 | 0.87 | |
| Nominal Dispersion | 1 nm/mm | - | |

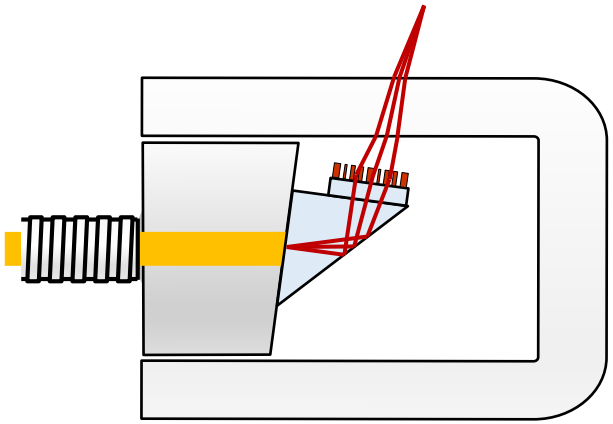
| SYSTEM SUMMARY | Newton 970 EMCCD<br>16µm - 1600 x 200 | Shamrock 750mm<br>f/9.8 - 68mm grating | Grating<br>1200 lines/mm |
|---|---|---|---|

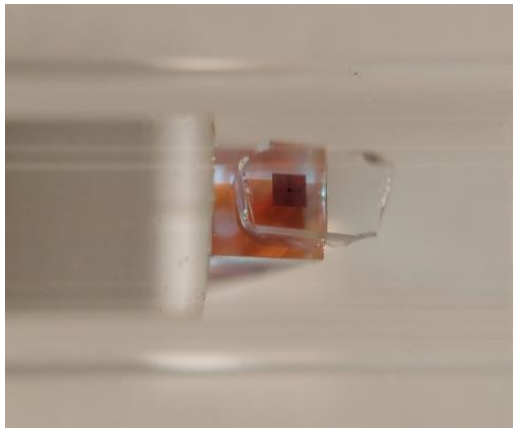

Nano Letters, 16 (2016).
APL Photonics, 2, (2017).

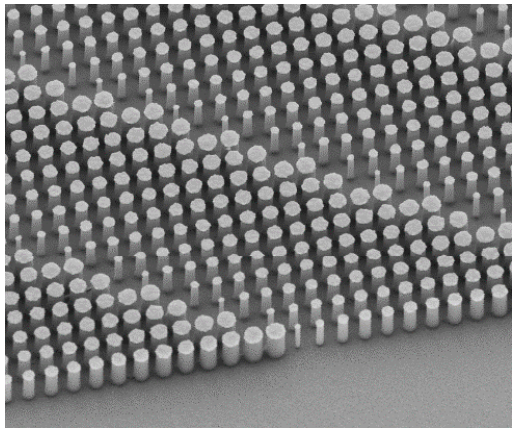
# Nano-optic Endoscope Optical Coherence Tomography

- **Use of Flat Lens**
  - Free of Spherical Aberration
  - Free of Astigmatism
  - Enhanced Depth Resolution

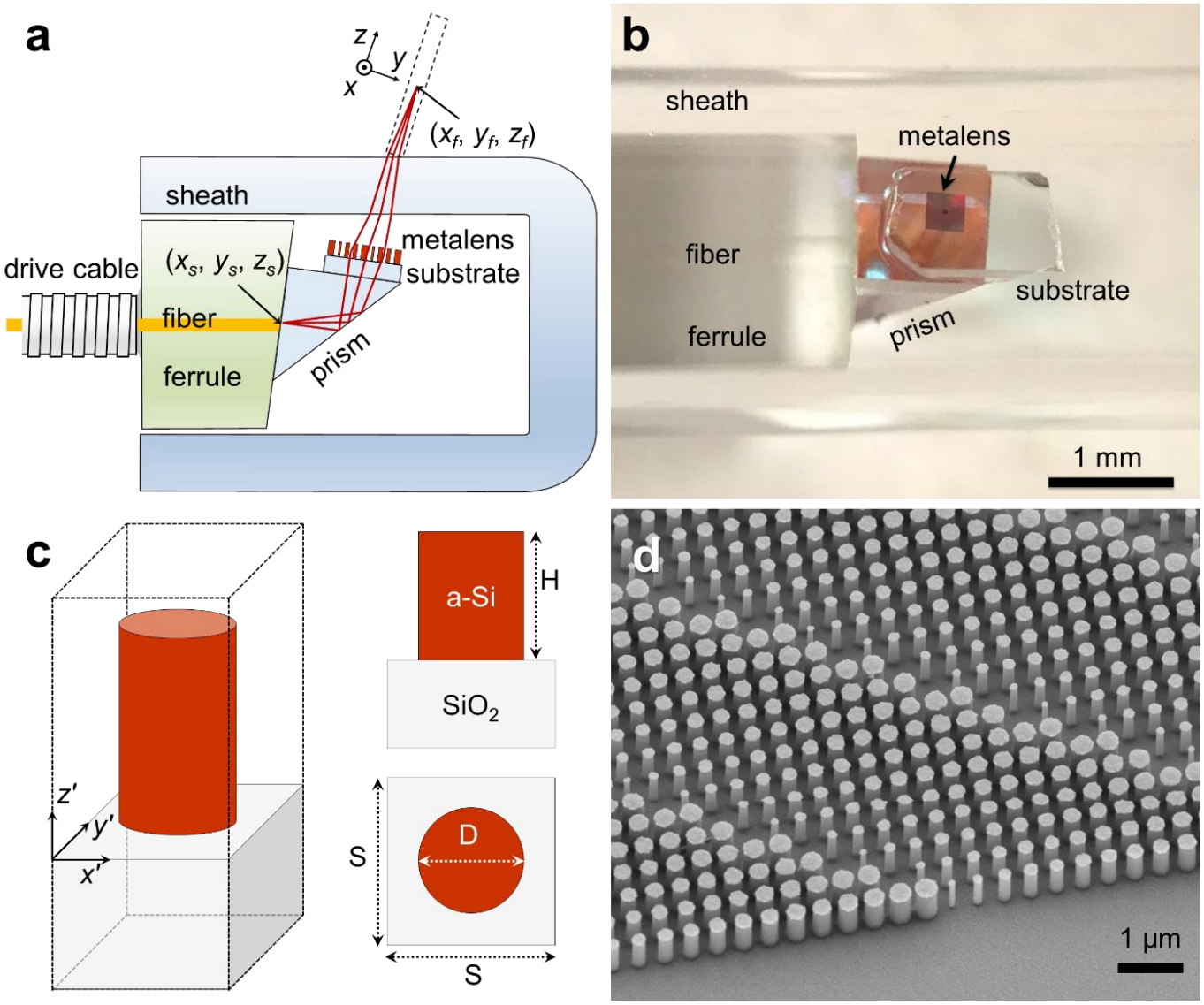






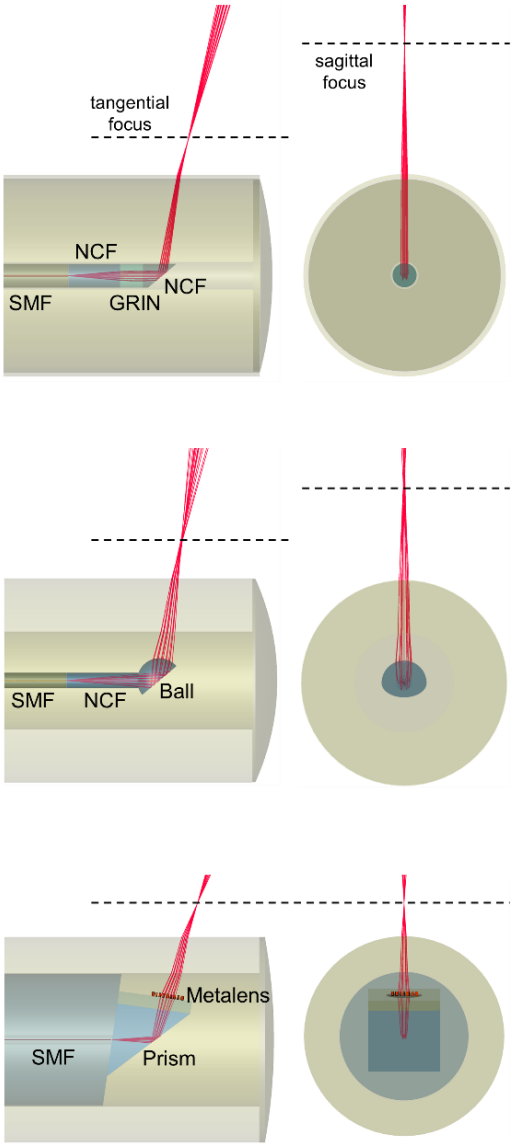


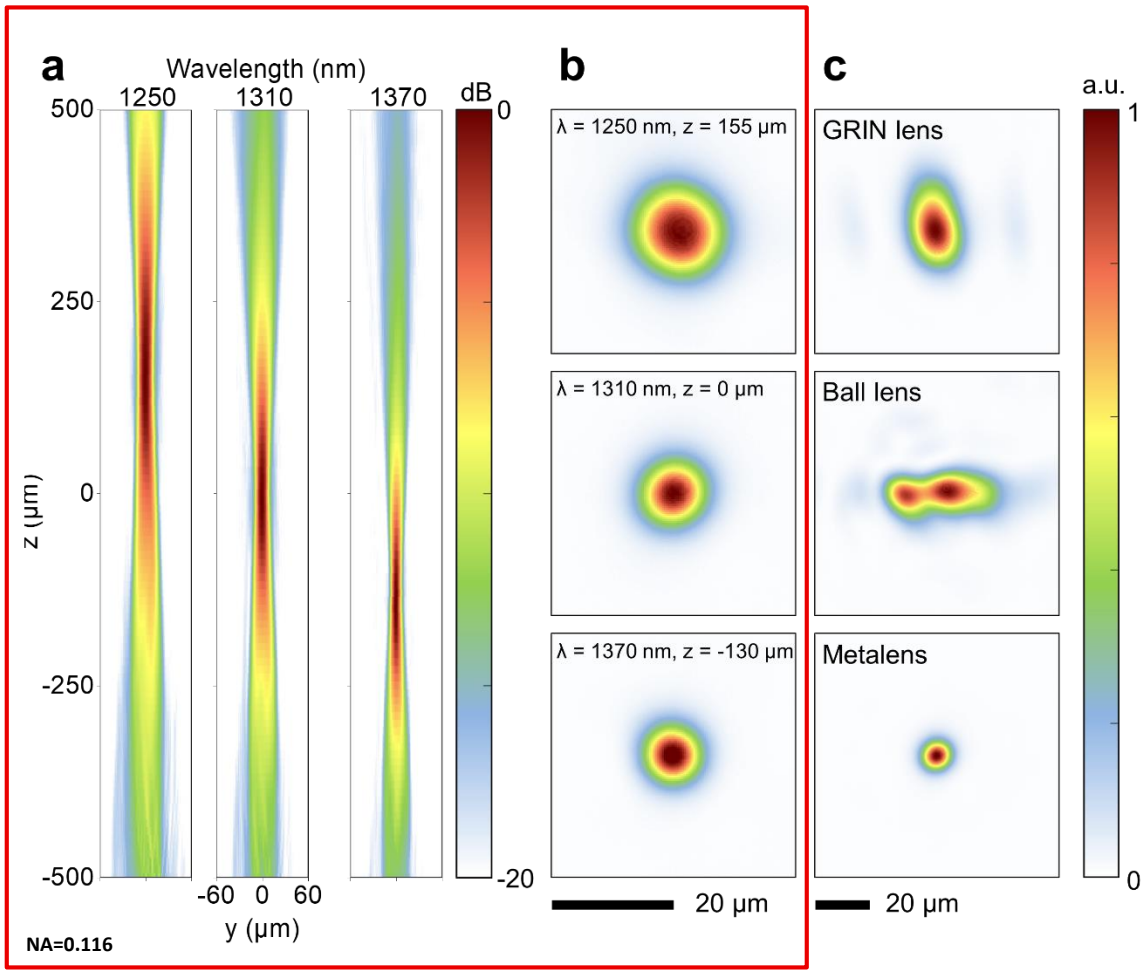
# Catheter based on Flat Lens




Nature Photonics, 12, 540 (2018).

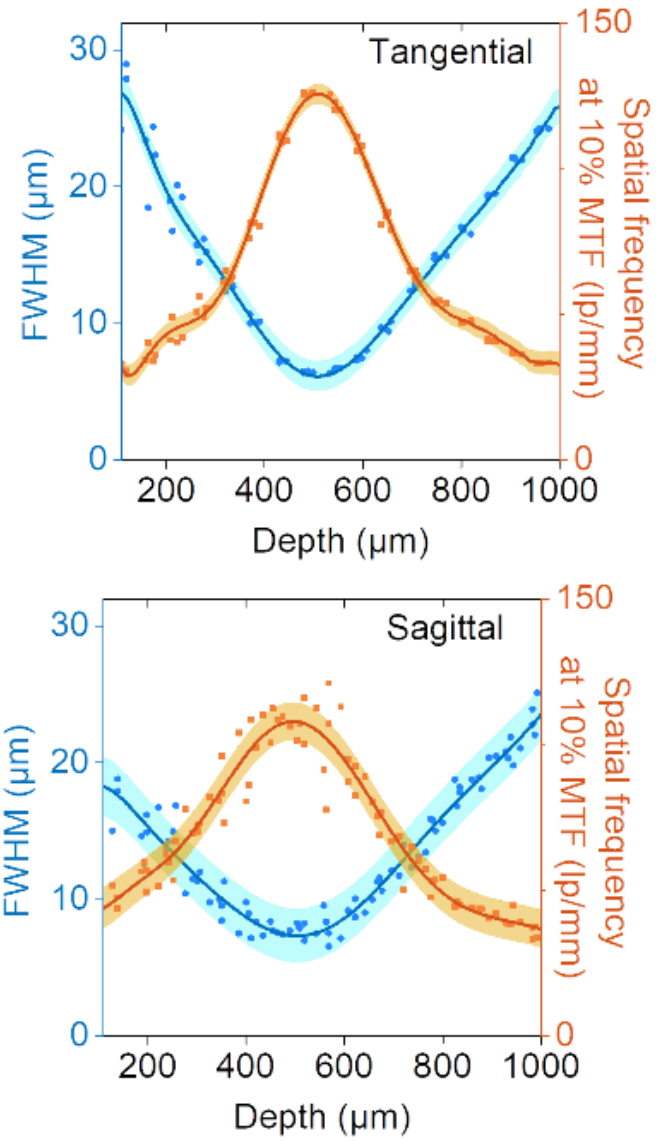
# Comparison with the State-of-Art

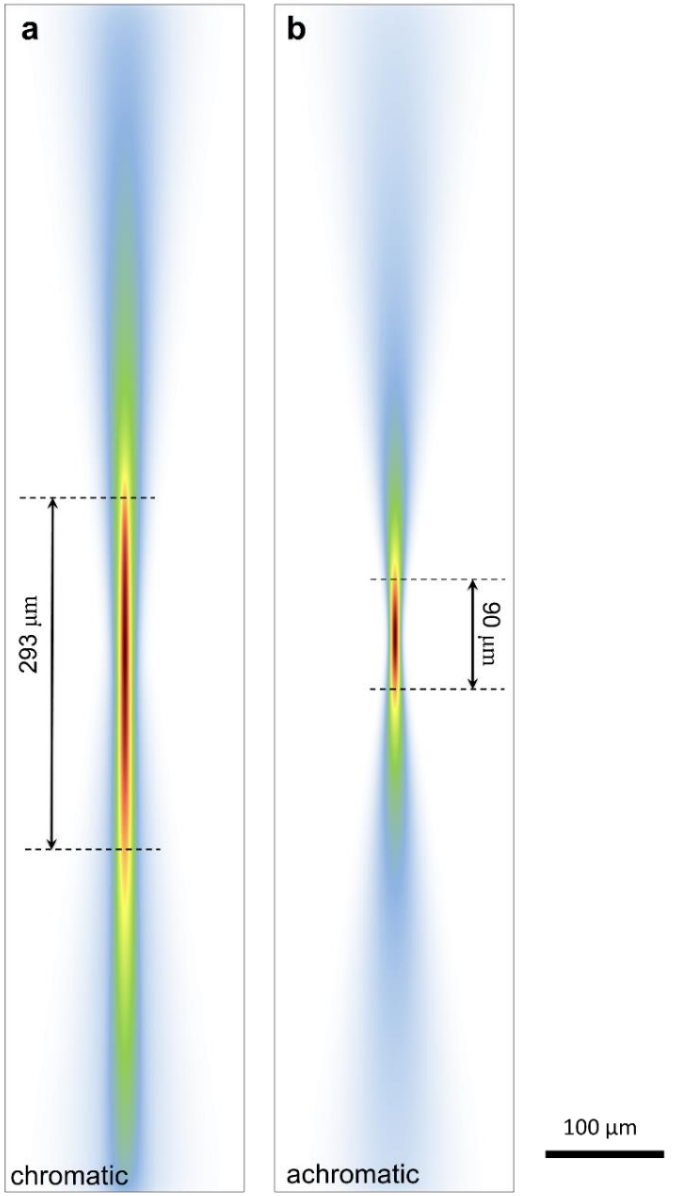



Nature Photonics, 12, 540 (2018).

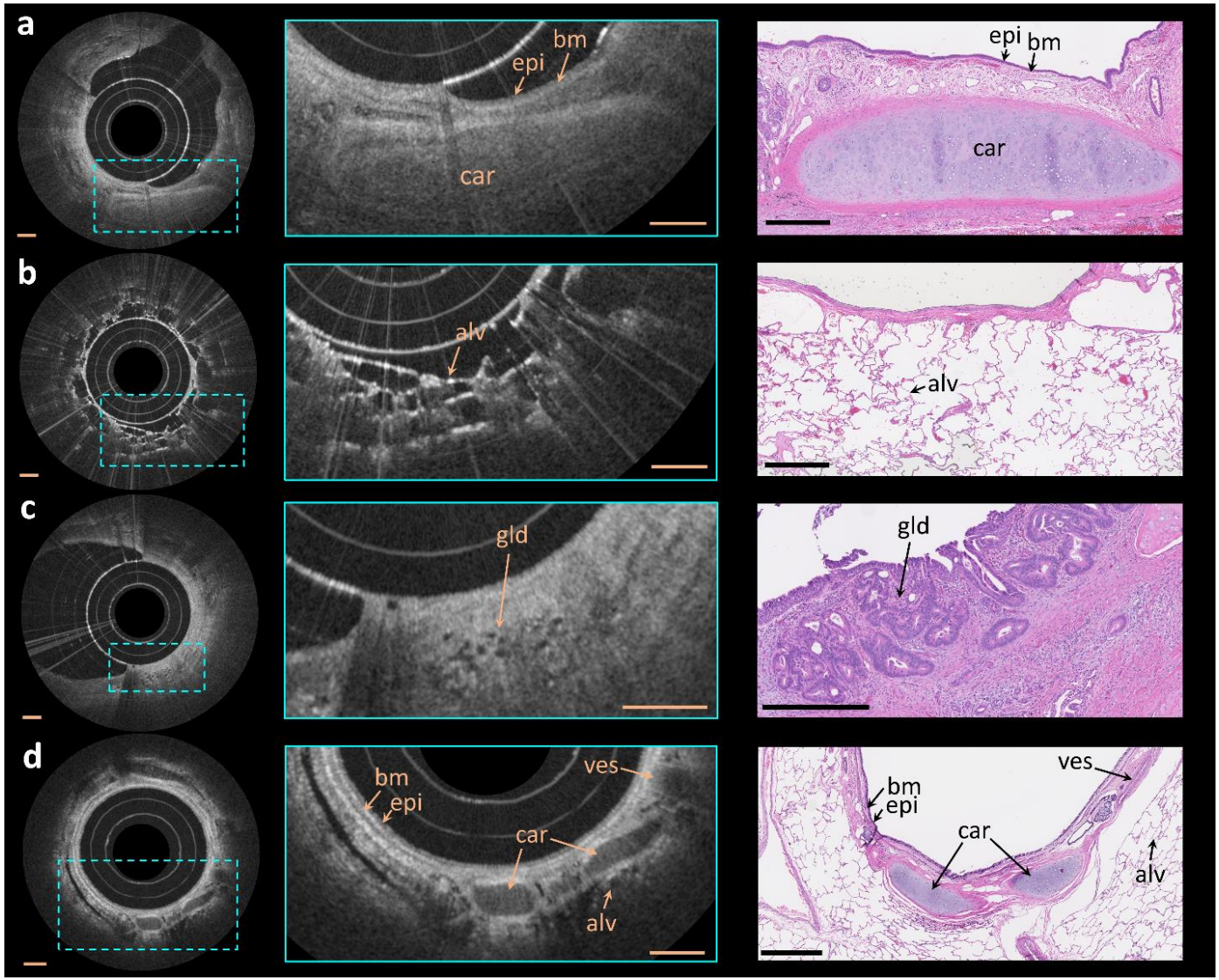
# Resolution Measurements




Nature Photonics, 12, 540 (2018).

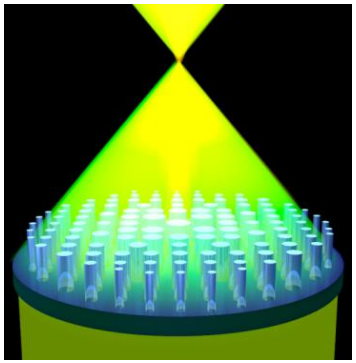
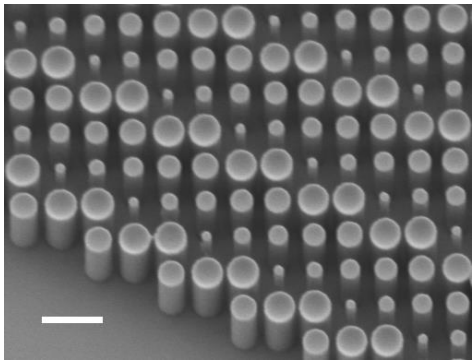
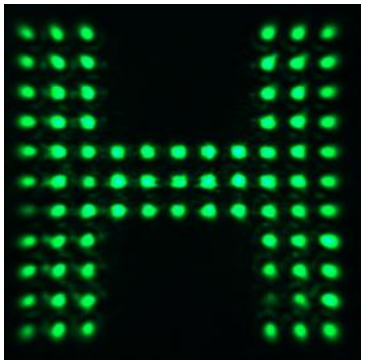
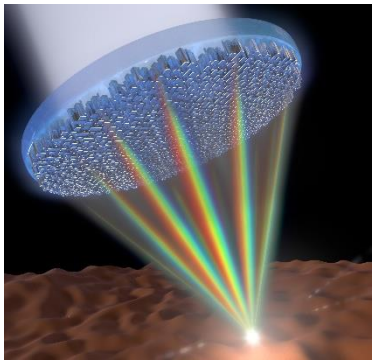
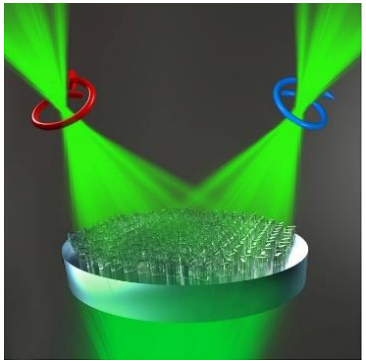
# OCT using Flat Lens

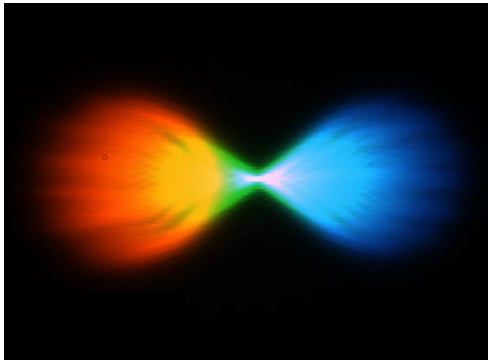
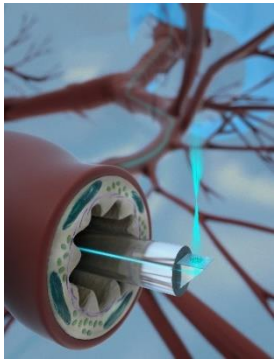
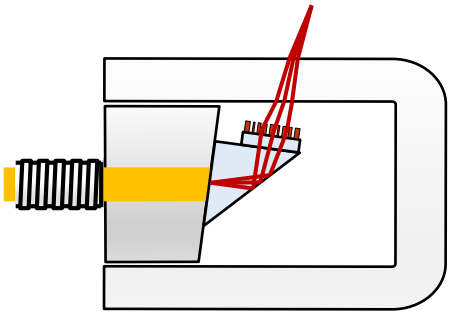
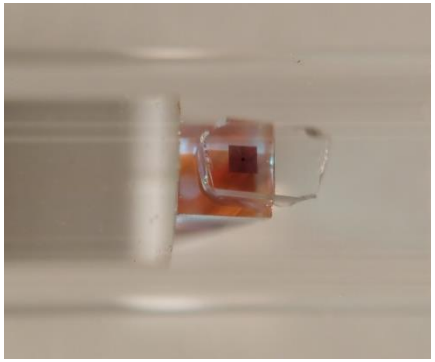
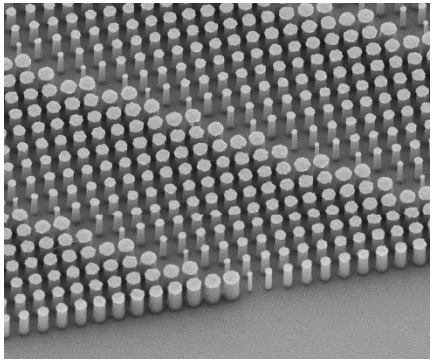



All scale bars are 500 μm

Nature Photonics, 12, 540 (2018).

# Summary

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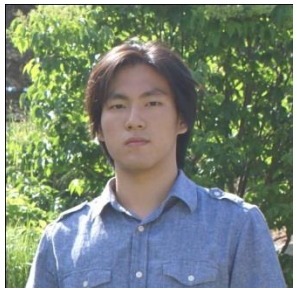
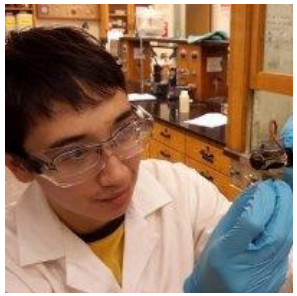

Jaewon Oh


Charles Carmes


David Rousso


Ishan Mishra

- **Funding, Collaboration and Fabrication Facility**

# Summary