Optics with Metasurfaces: From Spectroscopy to Medical Imaging

Reza Khorasaninejad
rzkhorasani@gmail.com
Motivation for Flat Optics

Lenses

Gratings and Filters

Wave-plates and Polarizers

Vertical Integration

www.thorlabs.com
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

Phase versus Diameter
Building Block: Polarization Sensitive

\[ n_{\text{extraordinary}} \]

\[ n_{\text{ordinary}} \]

\[ \text{Effective index} \]

\[ \text{Phase retardation (degree)} \]

\[ x(\mu\text{m}) \]

\[ y(\mu\text{m}) \]

\[ n_e \]

\[ n_o \]

\[ \text{Phase} \]
Building Block: Dispersion Engineering

![Diagram of a building block with dispersion engineering](image)

- **PC Efficiency (%)** vs **Frequency (THz)**
- **Phase (rad)** vs **Frequency (THz)**
- **Wavelength (nm)** vs **Phase (rad)**
- **Phase (rad)** vs **Wavelength (nm)**

**Parameter Values**
- \( l = 200 \text{ nm} \)
- \( l = 250 \text{ nm} \)

**Mode**
- FDTD
Summary
Fabrication Steps of TiO$_2$ Metasurfaces

1. Electron beam resist $t_{\text{resist}}$
2. Substrate
3. TiO$_2$ film
4. $t_{\text{film}} = w/2$
5. $h = t_{\text{resist}}$
Example of Fabricated Metasurfaces

Side view
Flat Lenses (Meta-lens)

- Ultra-Thin Lenses, High Numerical Aperture
- Diffraction-Limited Focusing
- Sub-Wavelength Imaging Resolution
- Dispersion Engineering
Design of Flat Lens

✓ Uniform amplitude
✓ Geometric Phase, $2\pi$ phase coverage

www.wikipedia.org

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

\[
\begin{align*}
\lambda &= 660 \text{ nm} & \lambda &= 532 \text{ nm} & \lambda &= 405 \text{ nm}
\end{align*}
\]

Flat Lens

Objective

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
\[ \varphi(r, \omega) = -\frac{\omega}{c}(\sqrt{r^2 + F^2} - F) \]

\[ F = k \times \omega^n \]

\[ \varphi(r, \omega) = \varphi(r, \omega_d) + \frac{\partial \varphi(r, \omega)}{\partial \omega} \bigg|_{\omega=\omega_d} (\omega - \omega_d) + \frac{\partial^2 \varphi(r, \omega)}{\partial \omega^2} \bigg|_{\omega=\omega_d} (\omega - \omega_d)^2 + \ldots \]
Dispersion Engineering

(a) $l_1$, $l_2$, $w_2$, $w_1$, $h$, $p$

(b) Image of dispersion engineering material

(c) Phase vs. Frequency (THz) for different wavelengths (nm):
- $\alpha = 0 \text{ deg}$
- $\alpha = 30 \text{ deg}$
- $\alpha = 60 \text{ deg}$

(d) PC Efficiency vs. Frequency (THz) for different wavelengths (nm):
- $l = 250 \text{ nm}$
- $l = 200 \text{ nm}$

(e) Wavelength vs. Phase (rad):
- Wavelength (nm) range: 450 to 650
- Phase (rad) range: -7 to 0
Phase Profile of Achromatic Flat Lens

![Graph showing phase profile](image)

**λ = 400 nm**

- **Phase** (rad)
- **Radial lens coordinate (μm)**

- **Realized Phase**
- **Required Phase**
Focusing and Imaging with Achromatic Flat Lens

(a) 470 nm  510 nm  550 nm  590 nm  630 nm  670 nm

(b) 100 μm

NA=0.02, f=5.5 mm, λ_d=530 nm
Tailoring Chromatic Dispersion

\[ f = k\omega^n \]

(a) Normalized focal length shift (%)

\begin{align*}
\text{Wavelength (nm)} & \quad -40 & \quad -30 & \quad -20 & \quad -10 & \quad 0 & \quad 10 & \quad 20 & \quad 30 & \quad 40 \\
450 & \quad 500 & \quad 550 & \quad 600 & \quad 650 & \quad 700 \\
\end{align*}

NA=0.2, f=63 \, \mu m, \lambda_d=530 \, \text{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

- **Reflection/Transmission**
  - Degree of Polarization (DOP)

- **Atomic/molecular transitions**
  - Fluorescence, Luminescence

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- Multifunctional Metasurface
- Resolving Chirality
Design of **Multispectral Chiral Lens (MCHL)**

- (a) 3D view of the design
- (b) Angle representations
- (c) Dimensions L, W, H
- (d) Materials: TiO$_2$, SiO$_2$
- (e) Projection of points $(x_{ob}, y_{ob}, z_{ob})$, $(x_{imL}, y_{imL}, z_{imL})$, $(x_{imR}, y_{imR}, z_{imR})$
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

- Off-axis focusing

Chromatic incidence
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

![Image of Meta-spectrometer]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nm</th>
<th>eV</th>
<th>Raman Shift cm⁻¹</th>
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<tbody>
<tr>
<td>Center Wavelength</td>
<td>500</td>
<td>2.48</td>
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<tr>
<td>Range Start</td>
<td>487.14</td>
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<tr>
<td>Range End</td>
<td>512.66</td>
<td>2.42</td>
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<tr>
<td>Bandpass</td>
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<td>Spectrum Resolution</td>
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<tr>
<td>Maximum Wavelength</td>
<td>1431.39</td>
<td>0.87</td>
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<tr>
<td>Nominal Dispersion</td>
<td>1 nm/mm</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Operating Grating Angle: 17.609 degrees

**SYSTEM SUMMARY**

- Newton 970 EMCCD 16µm - 1600 x 200
- Shamrock 750mm f/9.8 - 68mm grating
- Grating 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
OCT using Flat Lens

All scale bars are 500 µm
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Summary