Metasurface Flat Optics

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Planar technology is central to IC technology: Technology platform
- Same foundries will manufacture camera sensor and lenses using same technology (deep-UV stepper)
- Single phase mask (lithographic level) generates the metaoptical component
- Metasurfaces that give arbitrary control of the phase, amplitude and polarizations of light

Our goals:

CMOS compatible flat optics platform for high volume markets:
cameras (cell phone camera modules, laptops, automotive, biometrics), displays, wearable optics (augmented reality).

TiO2: high quality material platform for visible
Amorphous Si: same for near IR
Fused Silica (SiO2)

Example: lenses in cell phone camera modules will be replaced by metalenses fabricated by deep UV steppers (same foundry that makes the sensor chip): thinner, easier fabrication and alignment

Flat Optics for a wide range of optical components (lenses, holograms, polarizers, phase plates, etc.) machine vision, biomed imaging, scientific applications (OCT), drones, polarimetry laser lithography, OEM markets

Multifunctionality: single flat optical components replaces multiple standard components with attendant reduction of system complexity and footprint
Why Lenses are thick? Can we make a flat lens?

- All lenses suffer from distortions in the way they focus.
- Focal point is blurred by aberrations (spherical, astigmatism, coma, etc.).
- Can be corrected by using multiple lenses, which however makes the optics much thicker, bulky and heavier.
Lens becomes more demanding

- Conventional lens manufacturing: grinding, polishing and plastic molding

• Largan Precision company (major cell phone lens supplier) produces ~ 17 billions plastic lens modules
• These lenses are for various applications: cellphone/NB lenses, webcam lenses, car and camera lenses etc.

Ref: Optics and photonics, February 2019
Can we make a flat lens with no aberrations?

- All rays focused to the same point? i.e. diffraction limited.
- Two challenges: doing it first for “single” wavelength and then for a broad spectrum?
- By structuring with nanotechnology a planar surface so that all rays converge to the same focus

The surface is nanostructured: METASURFACE
Metasurfaces: complete wavefront control

- Huygens-Fresnel Principle

Benefits

- **Straight-Forward Fabrication**
  - One mask level, cost effective

- **Compact**
  - Light weight, capability to be vertically integrated

- **Unprecedented Control of Dispersion**

- **Overcome Limitations of Conventional Optics**
  - Aberrations, multifunctionality
Metasurface: Manipulating phase using nanostructures

- Control Amplitude, phase, polarization and wavenumber of light

\[ \vec{E} = A \cdot \exp^{i(k_z \cdot z + \varphi)} \hat{y} \]

- Example: Beam deflector
- Example: Lens
Fresnel Optics vs Metasurface Based Optics

<table>
<thead>
<tr>
<th>Fresnel Optics</th>
<th>Metasurface</th>
</tr>
</thead>
<tbody>
<tr>
<td>finite lateral phase control</td>
<td>sub wavelength phase control</td>
</tr>
<tr>
<td>polarization insensitive</td>
<td>polarization control</td>
</tr>
<tr>
<td><strong>multi wavelength operation hard</strong></td>
<td>controlled dispersion: achromatic</td>
</tr>
<tr>
<td>multiple steps of lithography: N phase level $\rightarrow \log_2 N$ steps</td>
<td>single lithographic step</td>
</tr>
<tr>
<td><strong>Limited functionality</strong></td>
<td><strong>multifunctional</strong></td>
</tr>
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A single digital pattern (one mask level) can create an arbitrary analog phase profile.
Unique properties of metalens

- Lithography-based Fabrication: nano-meter precision with high throughput
- Flat and Compact: compatible with wafer packing

Ref: Heptagon Inc. (Wafer level optics packaging)

- Tunable dispersion:
  - Refractive lens: dispersion is given by glass material

\[ F(\lambda) = \frac{R}{n(\lambda) - 1} \]

- Metalens: Tailorable through nanostructures

Ref: Heptagon Inc. (Wafer level optics packaging)
General design process

- Flow of convention metasurface design

1. Target phase profiles from analytical solution or raytracing

2. Build a nanostructure library by parameter sweep

3. Matching target phase with nanostructure phase for each spatial coordinate

- Most cases are related to geometric optics
- Hologram is an exception, which requires diffraction calculation to obtain target phase profile.

- Solving Maxwell's equations by a simulation software

- Choosing elements from the library based on a figure of merit
General principle

- Light rays propagate to the direction where there are in-phase.

- Phase \( \varphi = \frac{2\pi}{\lambda} \cdot n \cdot L \)

- Example: Lens

\[ \varphi(x = 0) + \frac{2\pi}{\lambda_d} f = \varphi(x) + \frac{2\pi}{\lambda_d} \sqrt{f^2 + x^2} \]

Set \( \varphi(0) = 0 \), because only relative phase matters

\[ \varphi(x) = -\frac{2\pi}{\lambda_d} \left( \sqrt{f^2 + x^2} - f \right) \]
More complicated cases

- **Immersion metalens**
  - Liquid
  - Substrate

\[ \phi(x) = ? \]


- **Doublet metalens**
  - \( \phi_1(x) = ? \)
  - \( \phi_2(x) = ? \)


- **Raytracing software** (Zemax: OpticsStudio, Synopsys: CodeV etc):
  - Binary 2 surface in OpticsStudio

Taylor expansion of \( \phi(x) \):

\[
\phi(x) = \sum_n a_n \left( \frac{x}{R} \right)^{2n}
\]

Only considers even terms, because lens phase profile is symmetric

The software tunes \( a_n \) to minimize figure of merit

Normalization constant
Available simulation packages

- Simulation packages (solving full Maxwell’s Equations)
  - CST: https://www.cst.com/
  - COMSOL: https://www.comsol.com/
  - Lumerical: https://www.lumerical.com/

- Our codes are developed based on Lumerical. However, the simulation principle is valid using other simulation packages.

- Other useful information:
  - Nano-hub: https://nanohub.org/courses/NPM
  - EM lab: On Youtube, search CEM lectures
Choose element based on merit functions

- **Target phase**

\[ \varphi(x) = -\frac{2\pi}{\lambda_d} \left( \sqrt{f^2 + x^2} - f \right) \]

- **Structure phase**

\[ FOM = \min\left( |\varphi_{\text{structures}} - \varphi_{\text{target}}(x_0)| \right) \]

- Repeat this for all coordinates to choose proper structure
Chromatic response of metalenses

- Polarization-insensitive chromatic metalens
- Polarization-sensitive achromatic metalens
Metalens Fabrication Process: ALD & Ebeam Lith.

- Current fabrication approach

1. Substrate with resist
2. Pattern Exposure
3. Initial ALD
4. Completed ALD
5. Top layer etch
6. Final metasurface

ALD process is compatible with deep UV lithography

The thicker the resist, the taller the structure.
TiO2 Metasurfaces by Atomic Layer Deposition:
Completely transparent in the visible;
Negligible roughness, Vertical walls

Diffraction Limited High NA Metalenses


\( \Phi = 2 \text{ mm}; f = 800 \mu \text{m} \)

\( \text{NA} = 0.8 \)

Focusing efficiency:
60% to 80% depending
For NA in 0.8 to 0.6 range
Experimental Setup for Point Spread Function Measurement
Chromatic dispersion control with Metasurfaces

Controlling chromatic dispersion is critical in
- Maintaining the same functionality over a bandwidth (important for imaging applications)
- Implementing different functionalities at different wavelengths (spectral multifunctionalities)

Chromatic dispersion (CD) is predetermined by material property and grating effect
CD can be tuned by engineering the phase shifters

Effect of chromatic aberration

Complexity of Achromatic Lens Design

- Conventional approaches for reducing chromatic aberration

- Singlet
- Doublet
- Triplet

- Limited choices of glass

- Conventional design approaches (doublets for example)
Under thin lens approximation, lack of clear physical insights

\[
\phi_1 + \phi_2 = \phi_{\text{total}}
\]

\[
\frac{\phi_1}{V_1} + \frac{\phi_2}{V_2} = 0
\]

- Lens power \( \phi = \frac{1}{f} \)  Abbe number \( V = \frac{n_{589nm} - 1}{n_{486nm} - n_{656nm}} \)

Achromatic metalens

• To realize achromatic focusing, one needs to manipulate wavepackets in both spatial and time domains.

\[
\phi(r, \omega) = \phi(r, \omega_d) + \frac{\partial \phi(r, \omega)}{\partial \omega} \bigg|_{\omega=\omega_d} (\omega - \omega_d) + \frac{1}{2} \frac{\partial^2 \phi(r, \omega)}{\partial \omega^2} \bigg|_{\omega=\omega_d} (\omega - \omega_d)^2 + \ldots
\]

gives lens function

Group delay (GD): time delay  Group delay dispersion (GDD): temporal width

Frequency-dependent phase profile:

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

gives lens function

Dispersion requirements for achromatic:

Group delay:

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

\[ F \rightarrow F(\omega) = k\omega^n \quad (k \text{ is a constant}) \]

Achromatic \( n = 0 \), Conventional diffractive \( n = 1 \), Anomalous diffractive \( n = 2 \), Refractive \( n = -1 \)
Requirement for GD and GDD

\[ \varphi(r, \omega) = -\frac{\omega}{c} \left( \sqrt{r^2 + F^2} - F \right), \quad F \rightarrow F(\omega) = k\omega^n \quad (k \text{ is a constant}) \]

Achromatic \( n = 0 \), Conventional diffractive \( n = 1 \), Anomalous diffractive \( n = 2 \), Refractive \( n = -1 \)

- Required phase at 530 nm
- Group delay (GD)
- Group delay dispersion (GDD)

- NA = 0.2, F = 64 µm at 530 nm
Polarization-insensitive lens consisting of anisotropic nanostructures

Nanostructures are either parallel or perpendicular to their neighbor to ensure polarization insensitivity.

REF: W-T Chen et al Nature Communications In press
Full lens simulation

- NA = 0.55, Dia = 6.5 μm
  - Layout: Achromatic and polarization-insensitive metalens
- FDTD simulation

Chromatic (Without dispersion Engineering)
Polarization-insensitive and Achromatic Metalens

- Metalens (NA = 0.2, Diameter = 26 µm)

- Capable of focusing any incident polarization
- Doubled efficiency compared to our previous results published in Nature Nano.
White light focusing
Phase profile of metacorrector

\[ \varphi(r, \omega) = \varphi(r, \omega_d) + \frac{\partial \varphi}{\partial \omega} (\omega - \omega_d) + \frac{\partial^2 \varphi}{\partial \omega^2} (\omega - \omega_d)^2 \]
Hybrid Metalens Design

- Ray-tracing simulation

Spherical lens (Thorlabs, LA1700 Plano-Convex-N-BK7, NA = 0.1)

Frequency-dependent metacorrector

- Spherical lens + metacorrector (Dia = 1.5 mm, NA = 0.075)
Inverse design of large-area multi-wavelength (RGB) metalenses

Design flow:

1. Determine objective function
2. Initial random design
3. Objective function evaluation
4. Re-design unit-cell parameters for the whole lens simultaneously
5. Final design: validation/fabrication

Objective function

\[ \max_{\lambda \in \lambda_s} \left( \min_{\bar{x}} \left( I_{\lambda}(\bar{x}_{\text{target}}, \bar{p}) \right) \right) \]

- Target position
- Design parameters

Fast approximate solver

Adjoint method

- Diameter: 1 cm
- NA: 0.3
- TiO₂ on fused silica
- Polarization insensitive

Measurements: Focal shift

- RGB-achromatic
- Maximum focal shift: 4.5 µm (0.03% of design focal length)
- Diffraction-limited focusing

*Collaboration with Raphael Pestourie, Steven Johnson, MIT

Device image

- Diameter: 1 cm
- NA: 0.3
- TiO₂ on fused silica
- Polarization insensitive

Measurements: Focal shift

- RGB-achromatic
- Maximum focal shift: 4.5 µm (0.03% of design focal length)
- Diffraction-limited focusing

*Collaboration with Raphael Pestourie, Steven Johnson, MIT
Virtual Reality platform

Meta-eyepiece X laser-illuminated micro-LCD

Eyepiece:
- Compact and lightweight
- High-resolution
- RGB-achromatic

Near-eye display:
- Pixel size: 8 µm
- High brightness
- Wide Color gamut
VR demos

Binary VR images resolving pixels

Greyscale VR image

Color-mixing results

VR movie: a running cat

- Frame refresh rate: 60Hz
Metalens Doublet to correct monochromatic aberrations (spherical, coma, astigmatism and field curvature)

- Doublet metalens: NA = 0.45, FOV = 50°
- Ray-tracing diagrams:
  - Singlet metalens
  - Doublet metalens

Ray-tracing diagrams:

- Singlet metalens
- Doublet metalens

Aperture metalens

Phase profile (2π)

Aperture meta-lens

Focal spot and imaging

- **Lens test set-up:**

- **Imaging set-up:**

Scale bar: 11 µm
Metalens for High Resolution Bronchoscopes

Hamid Pahlevani et al. Nature Photonics https://doi.org/10.1038/s41566-018-0224-2

- Collaboration with Mass General Hospital, Prof. Melissa Suter
Endoscopic imaging using metalens catheter

OCT images - Histological images

Ex vivo human lungs

In vivo sheep lung

epi: epithelium; bm: basement membrane; car: cartilage
ves: blood vessels; alv: alveolar; gp: glandular patterns
Fabrication of metalenses with semiconductor technology

- **Fabrication with deep-UV (DUV) projection lithography**
  - (Fused silica nanostructures etched into a fused silica wafer)

\[ D = 10 \text{ mm}, \ f = 50 \text{ mm}, \ \text{all-glass metalenses} \]

4 inch wafer

45 lens/wafer


**Experiment (633 nm)**

- Strehl ratio = 0.95
- 5 μm

**Theoretical**

- NA = 0.10

Focusing profile along optic axis

- **Metalens exhibits low spherical aberration**
Fabrication process (on 4-inch SiO₂ wafer)

- Cr coating
- DUV lithography
- Resist develop
- Cr dry etch (resist as etch mask)
- Resist strip
- SiO₂ dry etch (Cr as etch mask)
- Residual Cr dry etching

Projection lithography (same technique used in chip manufacturing)
Large diameter (10cm) metalens: Comparison with Similar Optical Power Refractive Lens

Metalens
(D=100 mm, f=150 mm @632.8 nm)

Refractive lens
(D=100 mm, f=150 mm @587.6 nm)

- **42x reduction in thickness, 16.5x reduction in weight**
- **Entire lens is monolithic fused silica.**
  - Low thermal expansion coefficient, high laser damage threshold.
- **Substrate’s backside** can be used for anti-reflective coating, color filter stack, polarization filter, etc.

Edmund Optics #67-18 7

https://pubs.acs.org/doi/abs/10.1021/acsnano.3c09462

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Optical Characterization of 100 mm Diameter Metalens

- Total metalens focusing efficiency: 40.4%
- Central area focusing efficiency: 63.1%

- Apparent reticle quality difference between inner/outer fields.
- Low-quality reticle did not resolve small-diameter nanopillars.
- Results in low diffraction efficiency at outer region.

Focusing Quality Measurement

- This 100 mm diameter metalens has 19 Billion glass nanopillars

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Meta-imaging the Heavens

Guide-scope with Guide camera

100 mm diameter metalens

Cooled CMOS monochromatic sensor

7 nm bandwidth Hα filter (656.28 nm)

Helical focuser

Equatorial mount (active tracking)
Astrophotography with 100 mm Metalens

➢ North America Nebula (NGC7000), Cambridge, MA

Image from Metalens

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Metalenz Inc.: spin-off (2016) from the Capasso group

https://www.metalenz.com

CEO Robert Devlin

Harvard University spin out since 2016

design, manufacture and sell meta-optics targeting the smartphone, consumer electronics and automotive markets

fabless with multiple foundry partners and rapid prototyping capability

launching with 3D sensing first

Boston-based, 20 employees

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Enabling the future of metaoptics in the semiconductor foundry

1000s of lens chips

Applications: Depth sensing
- Front facing dot pattern projector for face recognition in cell phones
- World-facing dot pattern projector for motion detection
- LIDAR

CEO: Robert Devlin, Ph.D. Harvard

https://www.metalenz.com/
## Metalens applications: Imaging

### Metrics

<table>
<thead>
<tr>
<th></th>
<th>4P</th>
<th>WLO</th>
<th>metalenz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>4P</td>
<td>2P</td>
<td>1M</td>
</tr>
<tr>
<td>Track Length (mm)</td>
<td>3.5</td>
<td>3.1</td>
<td>3.0</td>
</tr>
<tr>
<td>Module MTF 0F/0.7F (%) @nyq/2</td>
<td>36/26</td>
<td>15/10</td>
<td>38/32</td>
</tr>
<tr>
<td>RI (%)</td>
<td>40</td>
<td>20</td>
<td>70</td>
</tr>
<tr>
<td>Total intensity (a.u.)</td>
<td>1</td>
<td>0.75</td>
<td>2</td>
</tr>
<tr>
<td>Distortion (%)</td>
<td>2</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>Chief ray angle (deg)</td>
<td>30</td>
<td>30</td>
<td>0</td>
</tr>
</tbody>
</table>

Relative Illumination (RI) represents the combined effects of vignetting and roll-off % of illumination at any point on the sensor, normalized to the with maximum illumination.
Metalenz and STMicroelectronics deliver world's first optical metasurface technology for consumer electronics devices
June 09, 2022  STMicroelectronics N.V.

Forbes  Jun 8, 2022
World’s First Printable Optical Metasurface For Vision, 3D Sensing, LIDAR Now Shipping In Consumer Products
John Koetsier, Senior Contributor
Metalenz announced a partnership with UMC (major foundry) for high-volume manufacturing of optical lenses using commercial semiconductor processing platforms. UMC is amongst the largest semiconductor foundries in the world.

The partnership enables high-volume manufacturing of optical lenses for 3D imaging in applications ranging from smartphones and laptops to IoT (Internet of Things) and automotive sensing.

Extreme Ultraviolet Metalenses

M. Ossiander et al., Science 380, 59–63 (2023)
Extreme ultraviolet radiation

- Why focus XUV?
  - manipulate and observe electron motion in atoms and molecules
  - nonlinear attosecond dynamics
  - XUV semiconductor lithography

- Goal of this project: design and test a transmitting XUV-focusing metaoptic

- XUV Sources:
  - synchrotrons
  - free electron lasers
  - tin-droplets plasma
  - high harmonic generation

Source: DOI: 10.1126/science.1189401
Source: https://www.cecam.org/workshop-1552.html
High harmonic generation: spectrum

one attosecond pulse is generated every half-cycle of the driving laser
-> extreme ultraviolet harmonics are spaced by two fundamental photon energies
(Fourier transform)

IR-driving laser
Yb:KGW laser
λ = 1030 nm, 150 fs
(6 – 200) kHz, 6W

focusing mirror
argon filled target
EUV Material Properties

\[ n_{\text{material}} < n_{\text{vacuum}} \]

→ vacuum suddenly guiding

\[ k_{\text{material}} > 0 \]

→ thin device

→ thin / no substrate
But is it worth it?

Fresnel Zone Plate

Metasurface

propagation direction [um]
0 5 10 15 20
-3 -2 -1 0 1 2 3
transverse direction [um]

intensity (norm., [dB])
-30 -20 -10 0
-3 -2 -1 0 1 2 3
transverse direction [um]

intensity (norm., [dB])
-30 -20 -10 0
-2 -1 0 1 2
transverse direction [um]
EUV Metasurface Fabrication

back side spin coat MLA membrane area RIE-10, Bosch etch

BHF wet etched
Focussing of XUV radiation

- transmitting metaoptics
  - wavelength-scale structures made of Si
  - optimized for 50 nm radiation:

$E = 25 \text{ eV}$
$\lambda = 50 \text{ nm}$
$f = 1 \text{ cm}$

21st harmonic

Sample preparation:
Maryna Meretska
Soon Wei Daniel Lim

Numerics and concept:
Marcus Ossiander

Hana Hampel
Martin Schultze
Measurement

Intensity

beam waist \( d / \mu m \)

\[ d_{\text{fit}} = (1.24 \pm 0.20) \mu m \]
Multifunctional Meta-Optics

### Imaging Polarimetry

Photographic Scene

CMOS Sensor

Metasurface Grating

Imaging Scene

Polarimetric Image


### Angle-Tunable Birefringence

\[ |\text{in}\rangle \rightarrow |\text{out}(\theta)\rangle \]


### Jones Matrix Holography


### Multifunct. Wide-Angle Optics


### Singularities

Miniature spectrometers

- Recently freeform optics have emerged as a potential solution – these are off-axis, non-rotationally symmetric components.
- Examples include e.g. toroidal gratings, aspherical off-axis mirrors.
- Difficult to fabricate and generally bulky/expensive.

Diamond machining of off-axis mirrors
Rotationally symmetric, non-standard shapes
Other complex shapes and concave/toroidal gratings
Meta-spectrometers: Making good use of Chromatic Effect

- **Conventional grating-based spectrometers**
- **On-axis focusing metalens**
- **Off-axis focusing metalens**

- **Conventional grating-based spectrometers**
  - Achromatic reflective focusing lens
    - • angular dispersion

- **On-axis focusing metalens**
  - • longitudinal dispersion

- **Off-axis focusing metalens**
  - • angular dispersion + longitudinal dispersion

- **Off-axis metalens has better spectral resolution because of angular and longitudinal dispersions.**

- **Off-axis metalens suffers two major aberrations (field curvature and astigmatism), which limite its spectral resolution and range in a narrow bandwidth.**
Aberration-corrected metalens spectrometer

- Flat and perpendicular focal plane realized by dispersion-engineered metalens

- Coupled TiO₂ waveguide for fine tuning dispersion

- Measured focal spots (FWHM ~ 56 µm)

- Designed focal length $f_d = 4$ cm at 470 nm

- Metalens dispersion and spectral resolution
  - Dispersion
  - Spectral resolution

  (Reciprocal linear dispersion $\times$ Focal spot size)

  0.013 nm/µm $\times$ 56 µm

  ~ 0.73 nm spectral resolution from 470 to 660 nm in the visible
Light is subject to the diffraction limit.

There is a smallest angle or volume it can be localized in.

There is no diffraction limit for dark.

Singularities can be arbitrarily localized.
Consider complex scalar field $E(\mathbf{r}) = Re[E(\mathbf{r})] + i \cdot Im[E(\mathbf{r})] = 0$.

Intersection of surfaces $Re[E(\mathbf{r})] = 0$ and $Im[E(\mathbf{r})] = 0$ gives singularity.

- Two surfaces typically intersect on a line.

1D first-order singularities are robust against small field perturbations.

1D first-order singularity existence is preserved under small deformations or displacements of the zero-surfaces (topologically-protected).

Our Recipe for sheet singularities: maximize phase gradient orthogonal to desired sheet!
Point Singularities

(a) Zero-isosurfaces

(b) Phase [\(\pi\) rad]

(c) Intensity [dB]

(d) Phase gradient mag.
**Inverse design of point singularities**

Cylindrically symmetric phase profile yields cylindrically symmetric field profile.

- **Design strategy:**
  - Step 1: Produce point singularities at each position.
  - Step 2: Equalize optical environment across positions.

Experimental realization

- Phase-only metasurface using TiO$_2$ nanopillars on SiO$_2$.
- Protocol [1]:
  1. Electron beam lithography to produce nano-holes.
  2. Backfill of holes with TiO$_2$ using atomic layer deposition.
  3. Etch back of excess TiO$_2$ with reactive ion etching.
  4. Deposition of gold aperture mask to eliminate stray light.

Experimental results

Experimental setup:

- Slight axial displacement due to $\lambda = 760.9$ nm used instead of target $\lambda = 760$ nm.
Topologically Protected Phase and Polarization Singularity

Topological protection

Perturbation

Simulation

Experiment
Sheet phase singularities

- Sheet singularity with heart-shaped cross-section designed using phase gradient maximization and fabricated.
  - For 532 nm wavelength.
  - Metasurface platform: TiO$_2$ nanopillars on SiO$_2$
- Fidelity and contrast attained is superior to that obtained using the Gerchberg-Saxton (GS) algorithm.

Soon Wei Daniel Lim, Joon-Suh Park, Maryna L. Meretska, Ahmed H. Dorrah, and F. Capasso., Nature Communications, 12, 4190 (2021)
3D singularity sheet structure flythrough

Experimental setup:

- Close correspondence between simulated and experimental intensity and phase profiles as a function of axial position (z).
- This sheet singularity is unstable with propagation, like fractional topological charge vortices [1-2] and high-order vortices.
  - But some highly symmetric sheet singularities are stable: e.g., 1D diffraction fringes, Bessel beam nodes.

Soon Wei Daniel Lim, Joon-Suh Park, Maryna L. Meretska, Ahmed H. Dorrah, and F. Capasso., Nature Communications, 12, 4190 (2021)
Structuring dark around obstacles
Metasurfaces provide arbitrary control of the wavefront (phase, amplitude and polarization)

Metasurfaces enable flat optics: compact, thinner, easier fabrication and alignment

Multifunctionality: single flat optical components can replace multiple standard components

Flat Optics for a wide range of optical components (lenses, holograms, polarizers, phase plates, etc.) and applications: machine vision, biomed imaging, drones, polarimetry, polarization sensitive cameras

Same foundries will manufacture camera sensor and lenses using same technology (deep-UV stepper) CMOS compatible flat optics platform for high volume markets: Examples: lenses in cell phone camera modules will be replaced by metalenses fabricated by DUV lithography (same foundry that makes the sensor chip)

Displays, wearable optics (augmented reality).

Metasurfaces can generate arbitrary vector beams (structured light) well beyond the capabilities of SLM

Importance of inverse design, co-design of hardware & software, impact of AI on optics
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