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Design and Optimization of Dielectric Metasurface Optics

Alan Zhan
Department of Physics
University of Washington, Seattle
June 12th, 2019

Optics

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Applications for optical hardware

Applications for optical hardware

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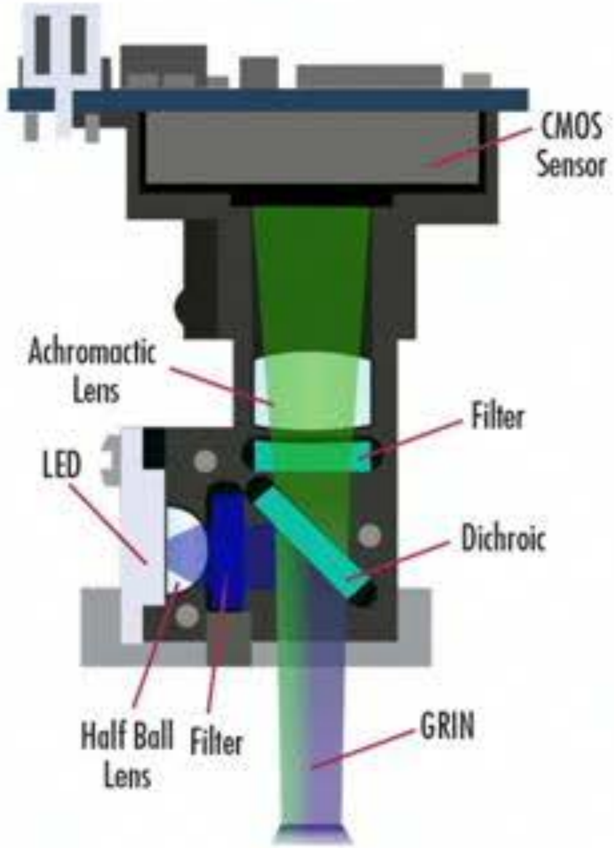
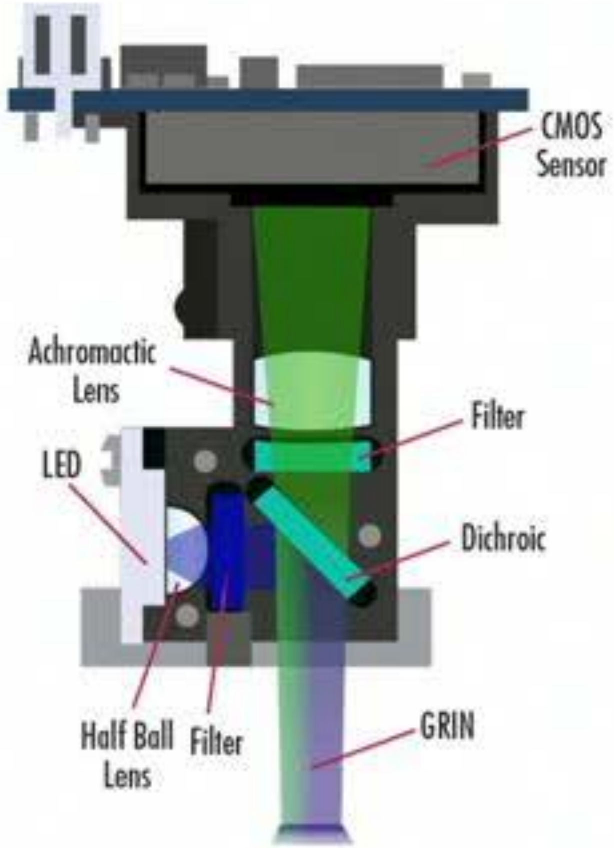
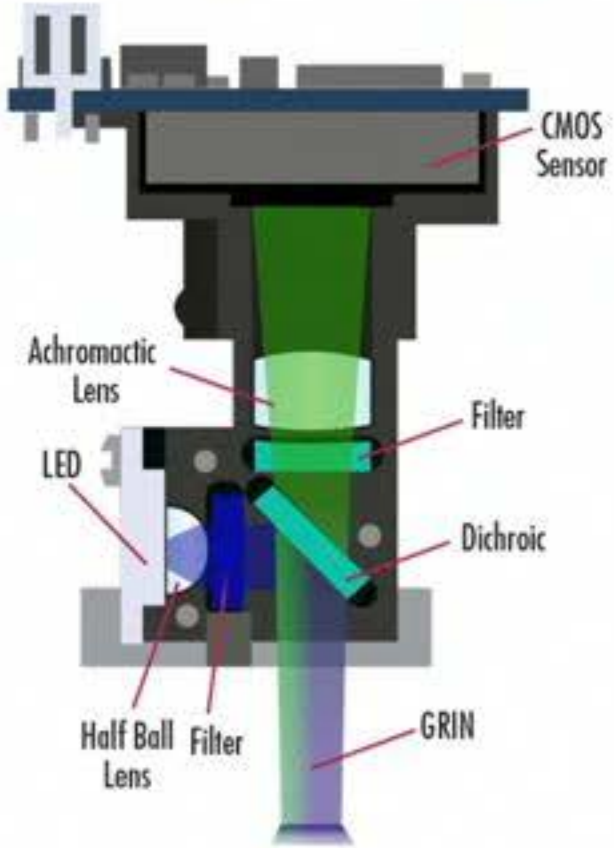


Applications for optical hardware



Applications for optical hardware



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Diffractive optics

Diffractive optics

Amplitude

Phase

Diffractive optics

Amplitude

Phase

Diffractive optics

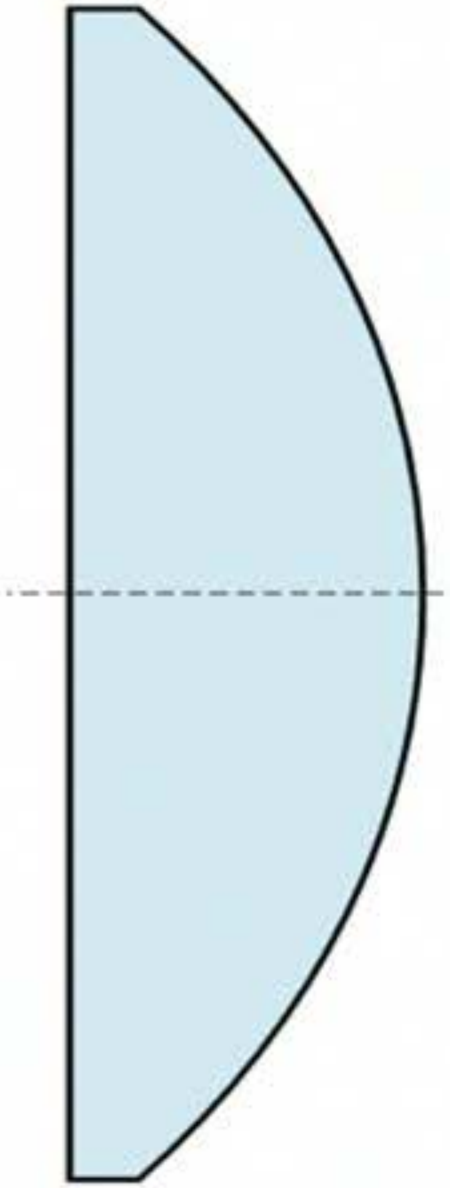
Amplitude

Phase

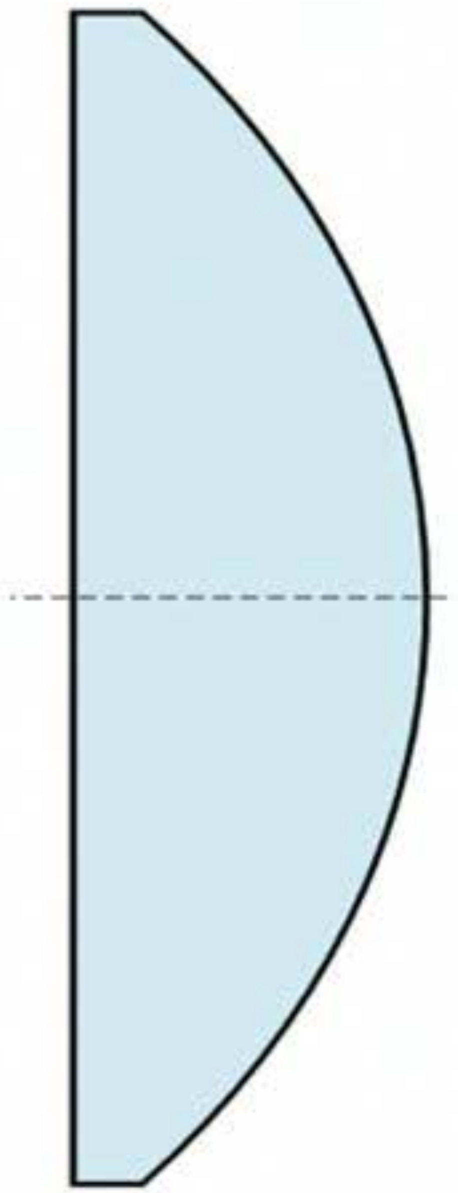
Walsby et al. Opt. Lett. **32**, 9 (2007)

From refractive to diffractive optics

From refractive to diffractive optics

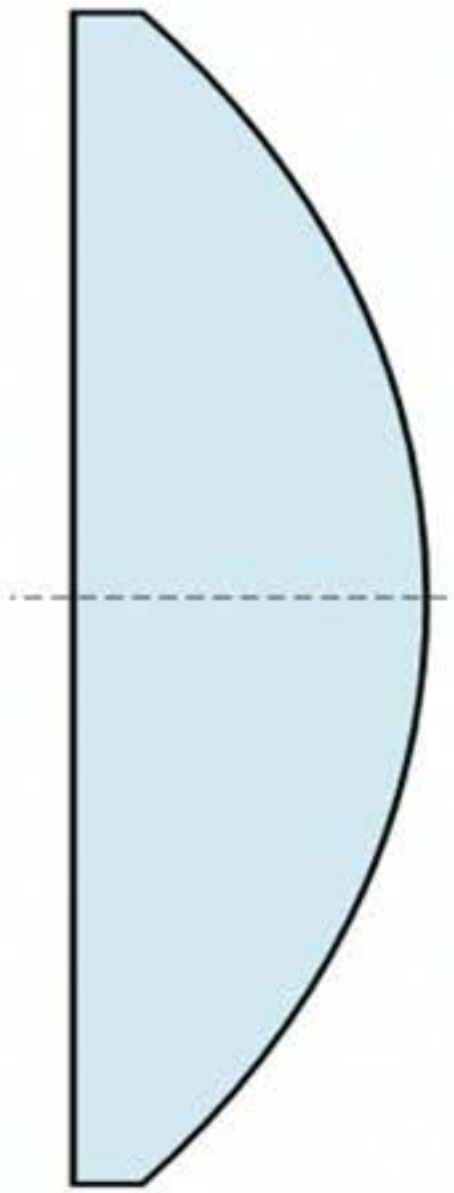


From refractive to diffractive optics



$$\varphi(x) = \frac{2\pi n}{\lambda} t(x)$$

Diffractive optics



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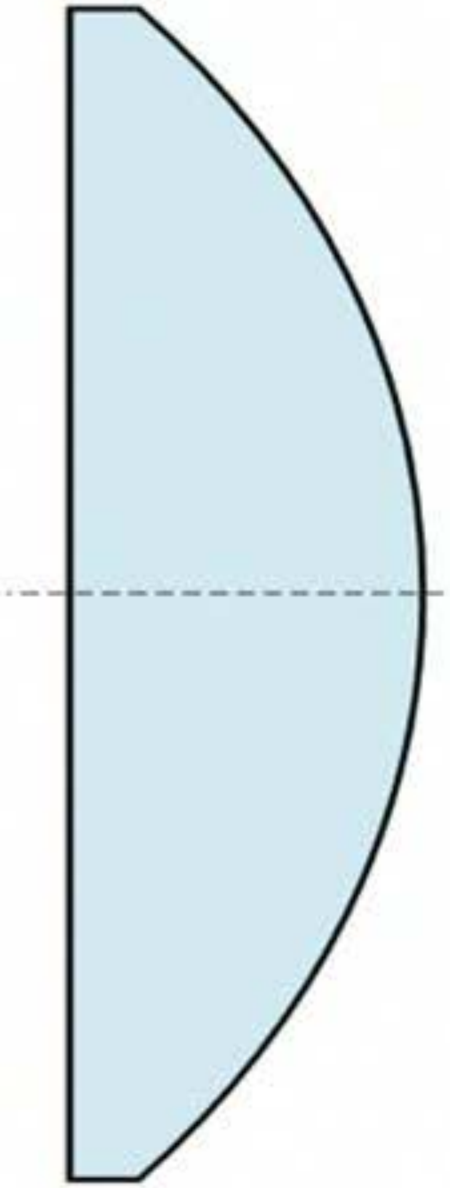

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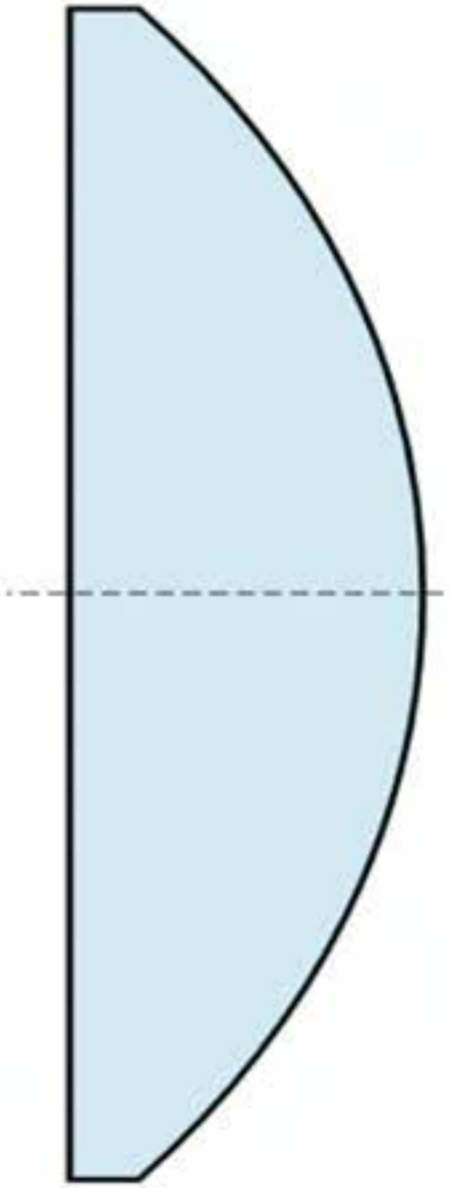

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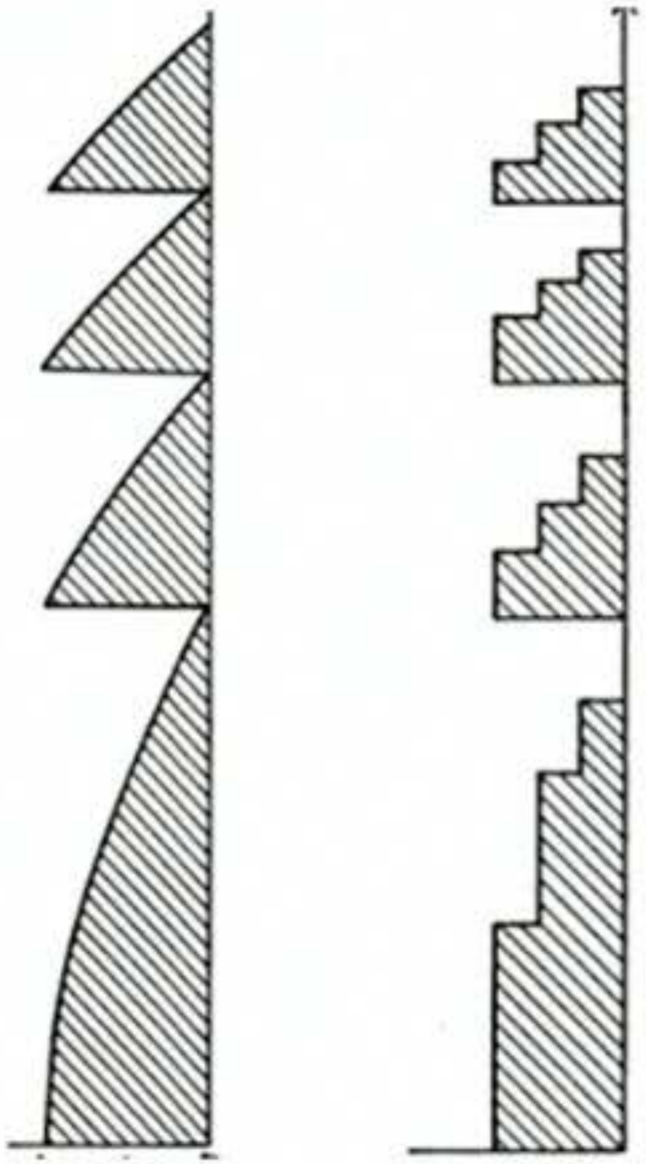

Diffractive grating optics

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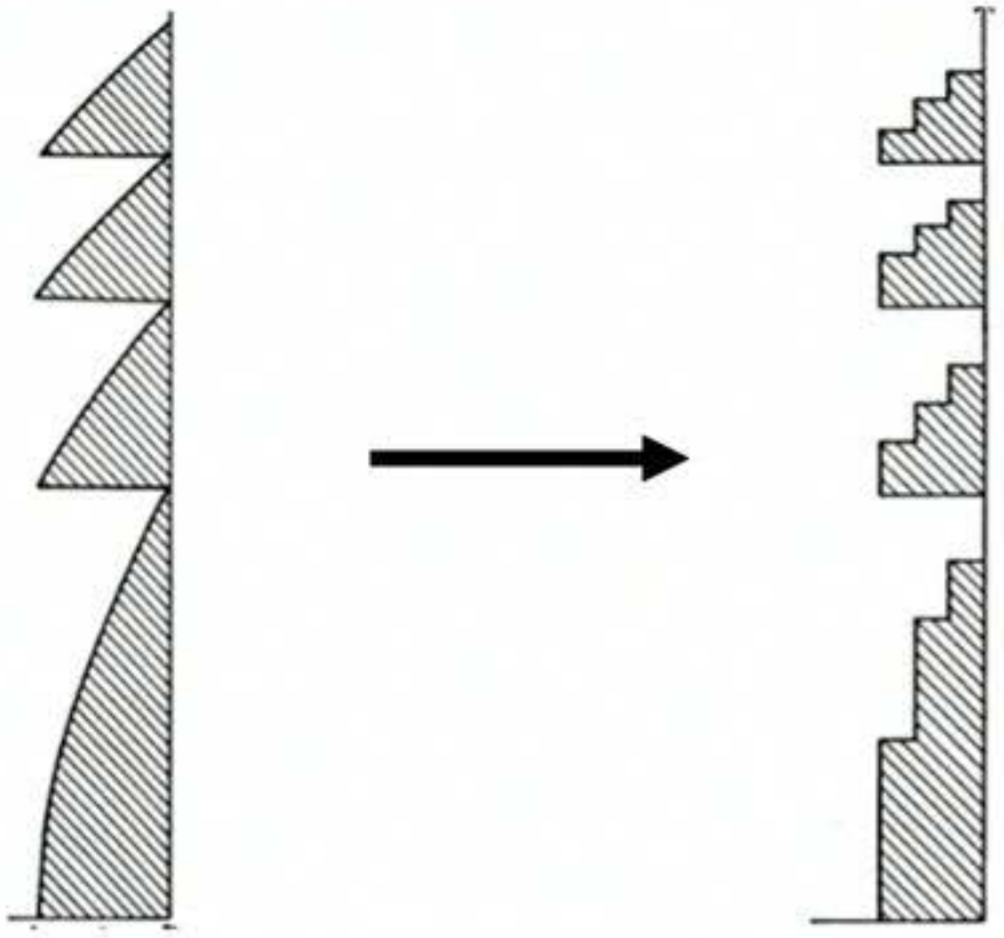
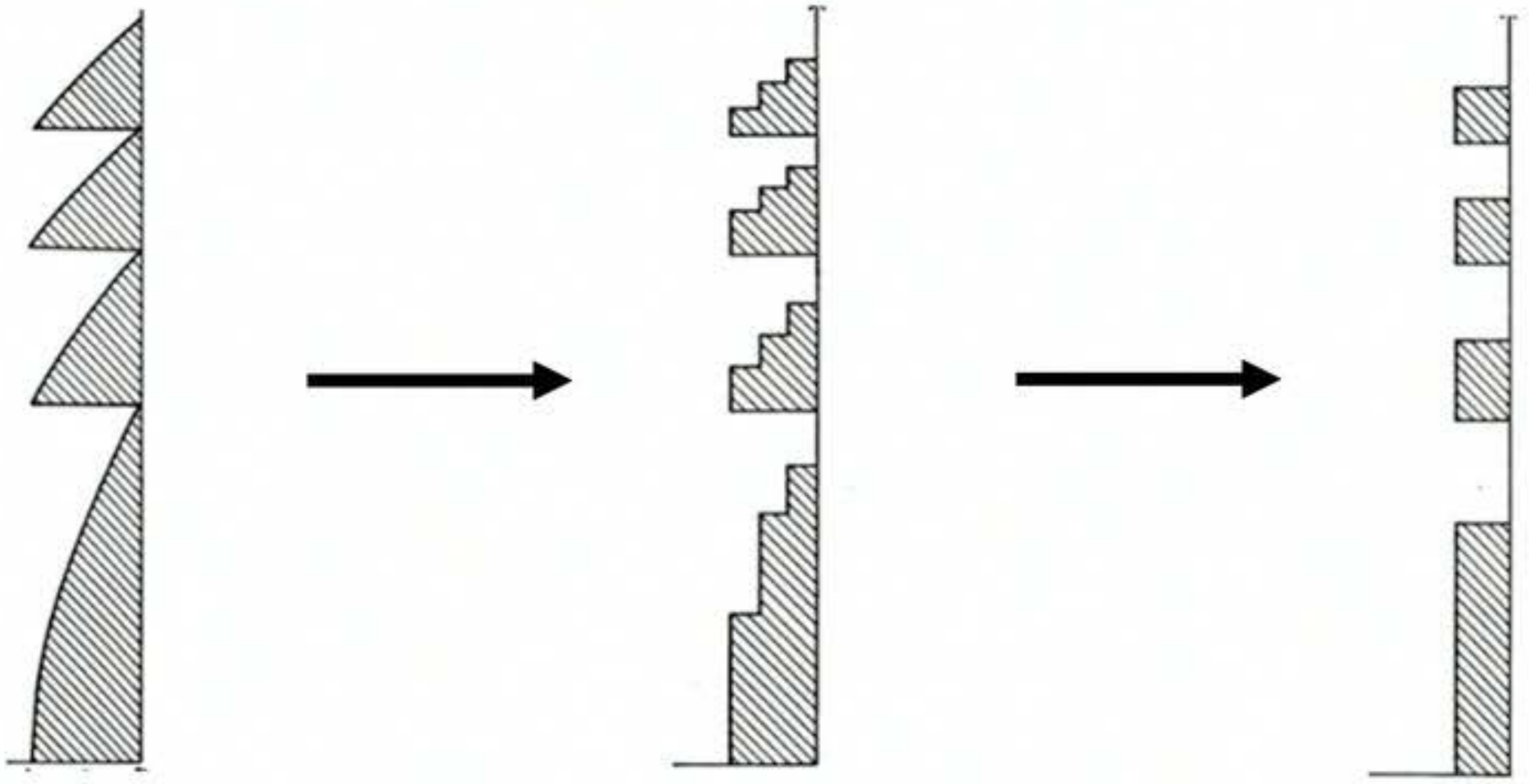
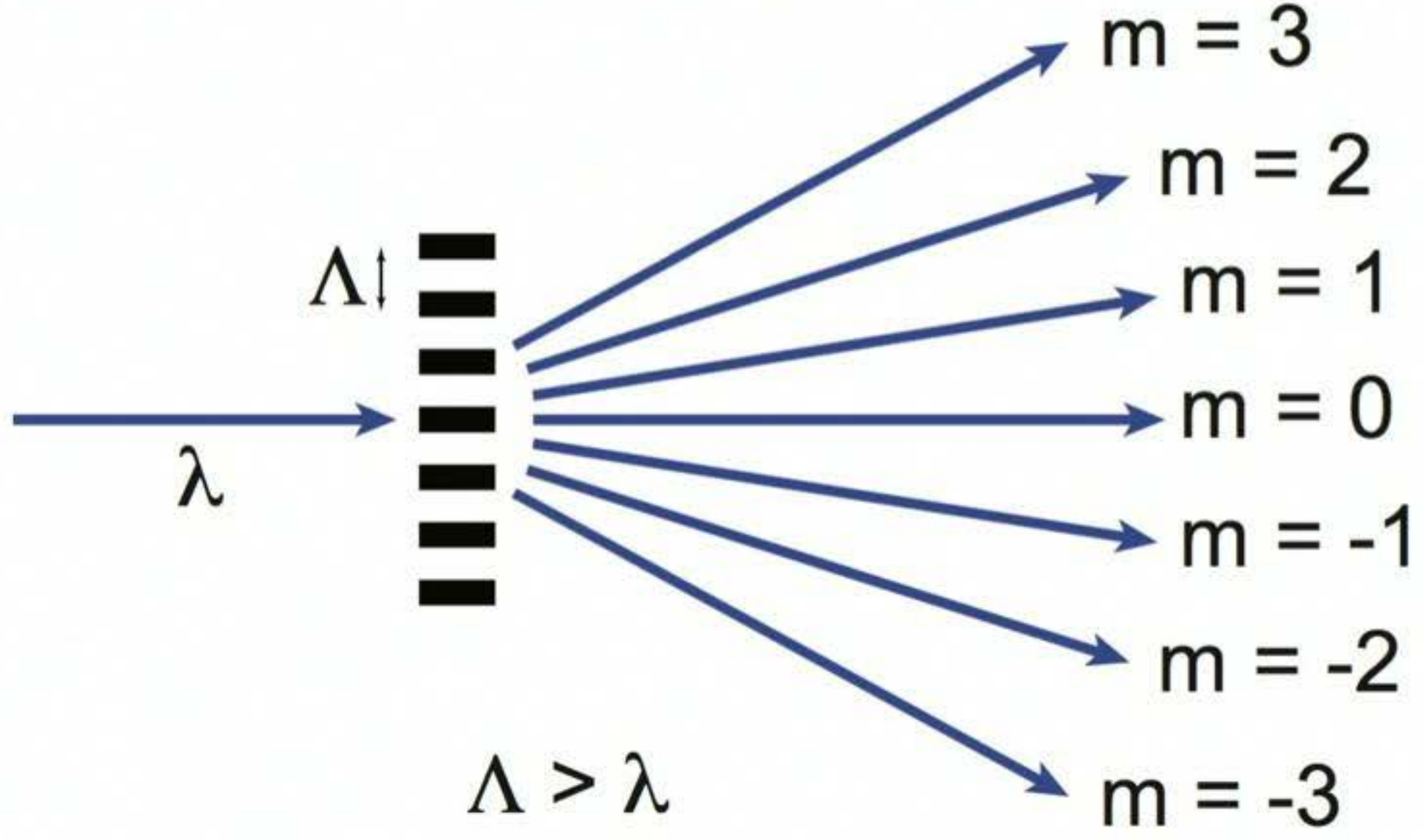


Diffractive grating optics

$$\varphi(x) = \frac{2\pi n}{\lambda} t(x) \qquad \varphi(x) \sim \frac{2\pi n_{eff}(x)}{\lambda} t$$



Grating diffraction



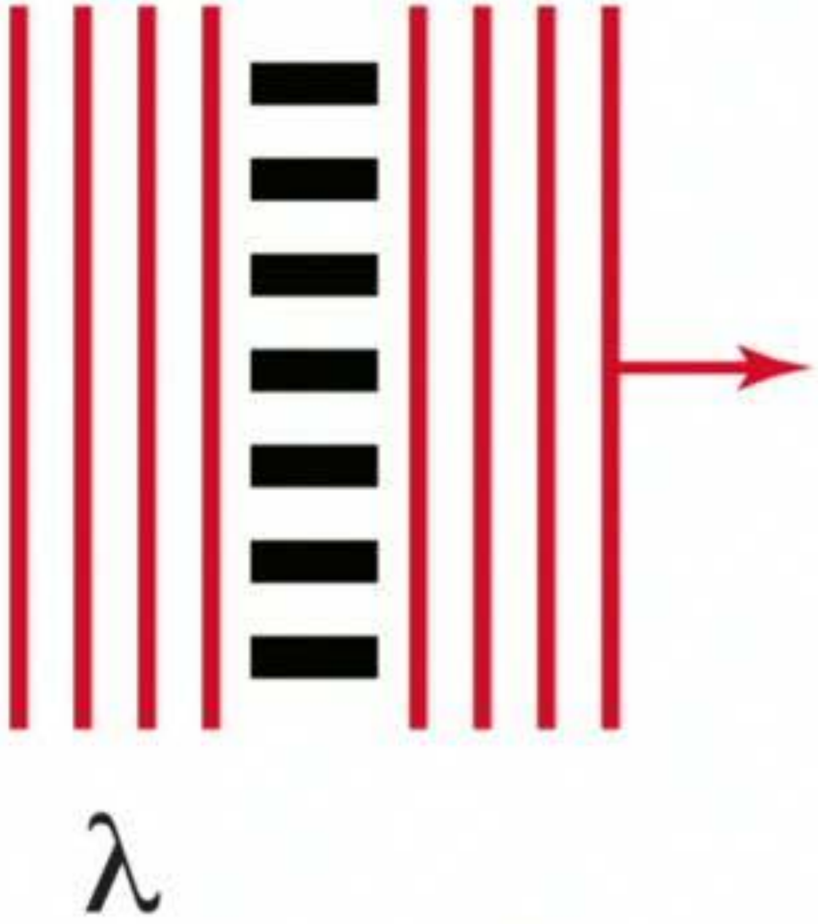
Metasurface optics

$\Lambda < \lambda$

Modulating phase

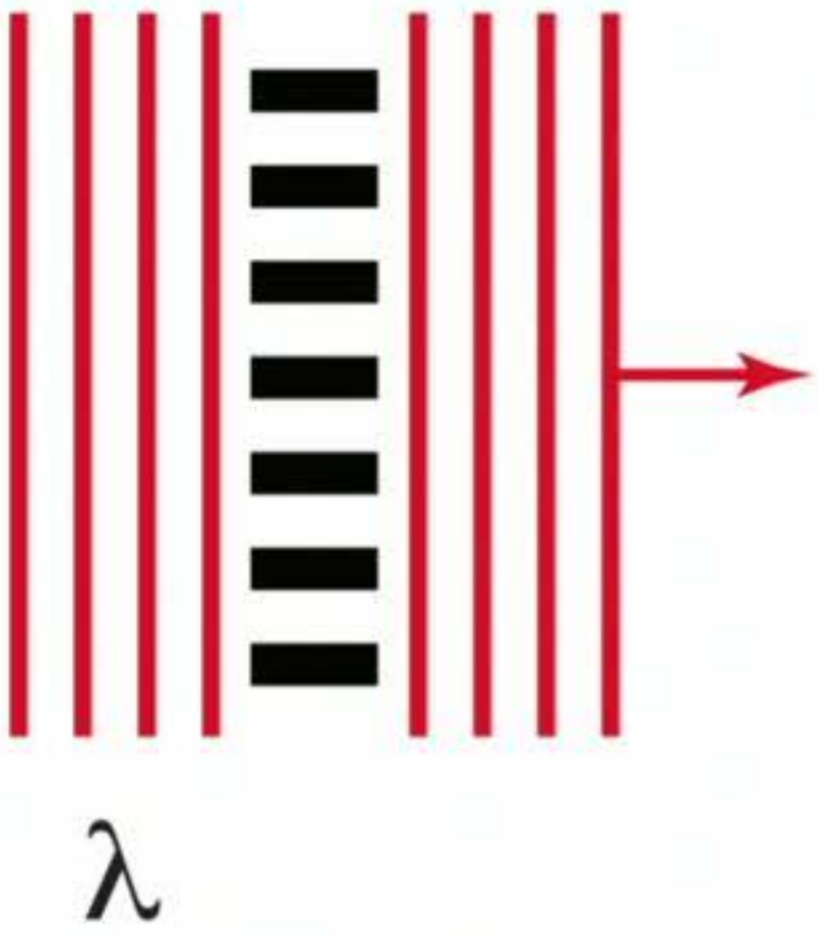
Modulating phase

Uniform phase shift

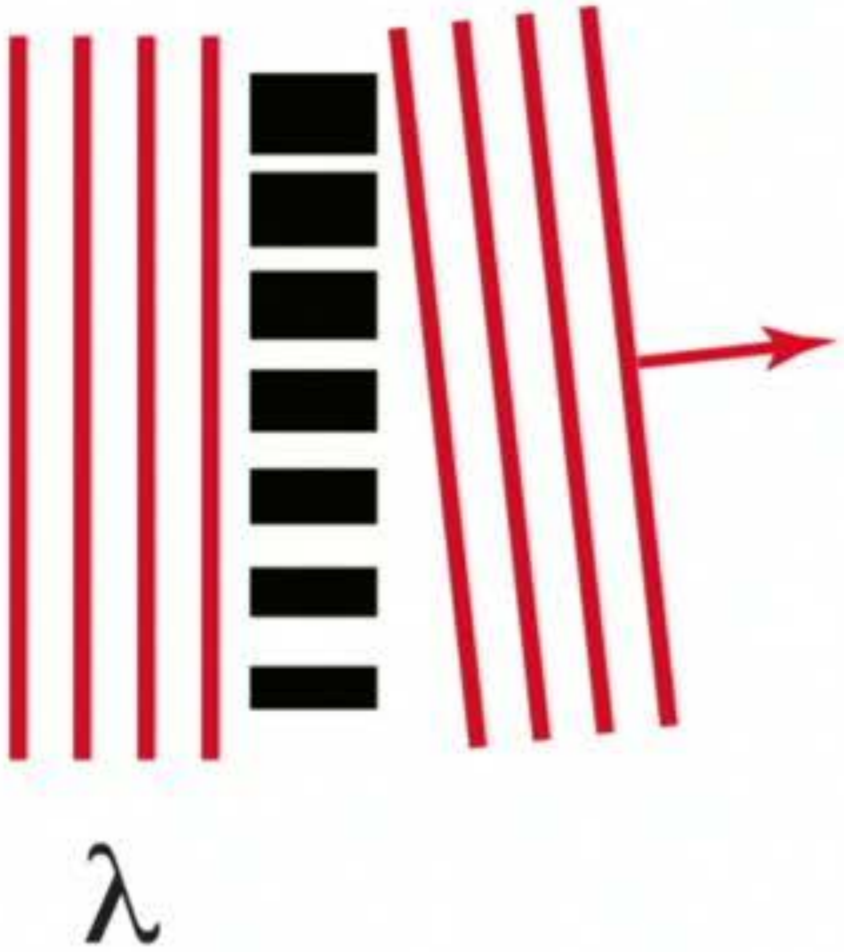


Modulating phase

Uniform phase shift



Spatially varying phase shift



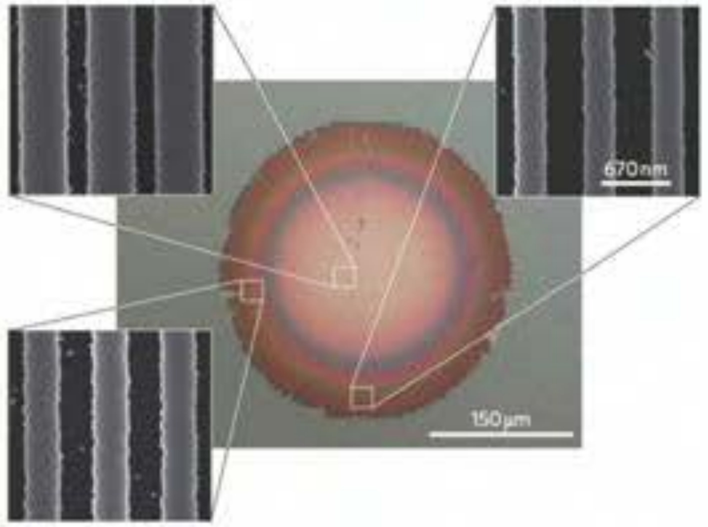
Dielectric metasurface optics

Dielectric metasurface optics

Lalanne et al. Opt. Lett. **23**, 14 (1998)

Dielectric metasurface optics

Lalanne et al. Opt. Lett. **23**, 14 (1998)



Fattal et al. Nat. Photon. **4**, 466 (2010)

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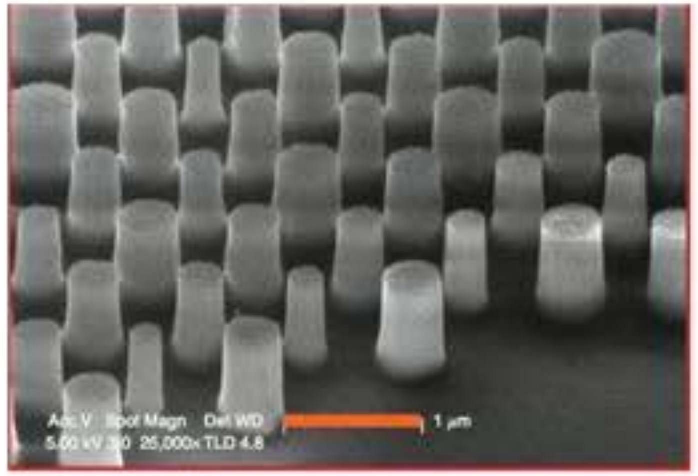
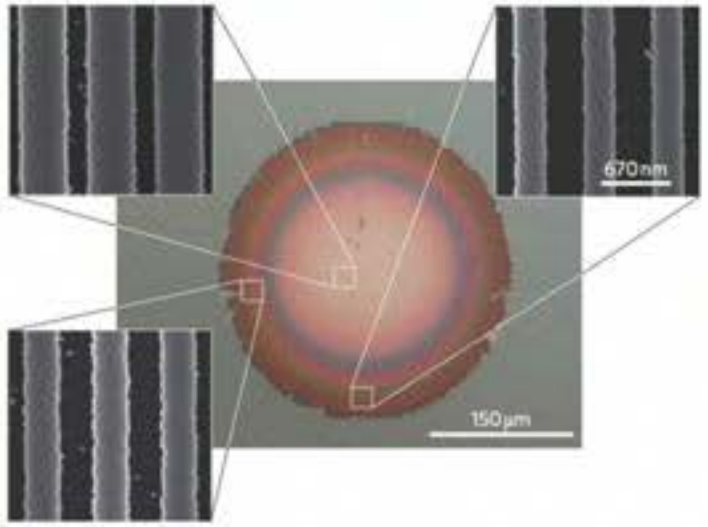


Arbabi et al. Nat. Comm. **6**, 7069 (2015)



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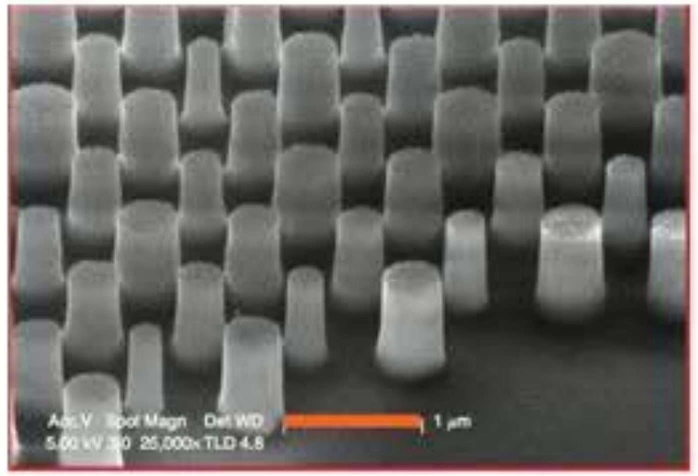

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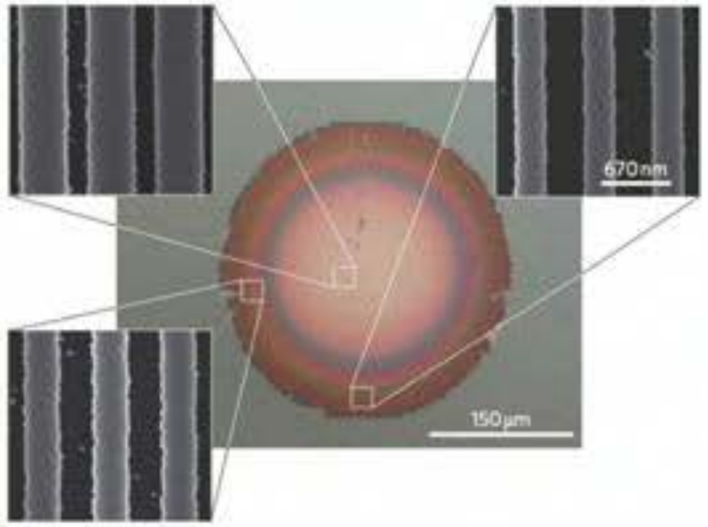

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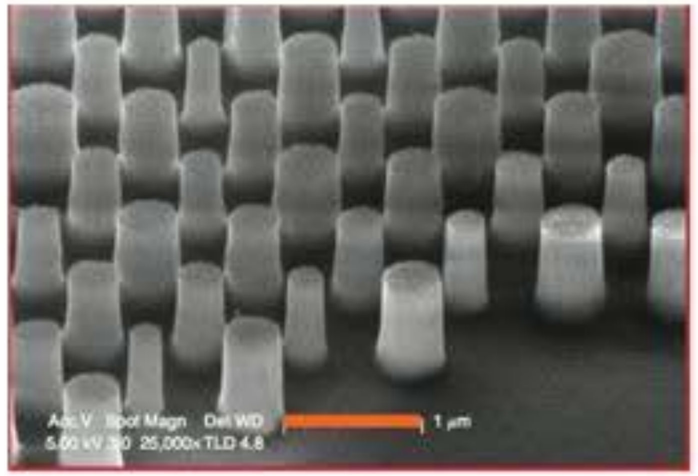

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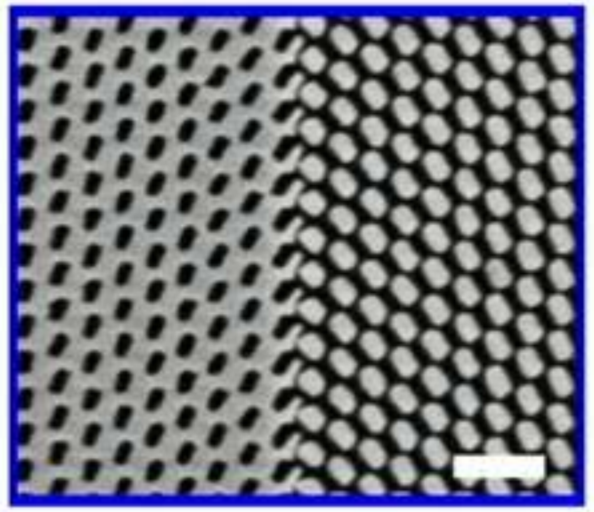
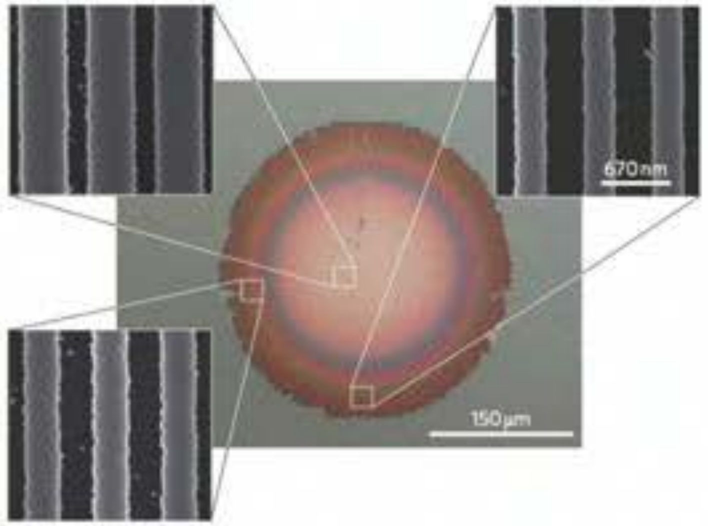


Wang et al. Nat. Nano. **13**, 227 (2018)



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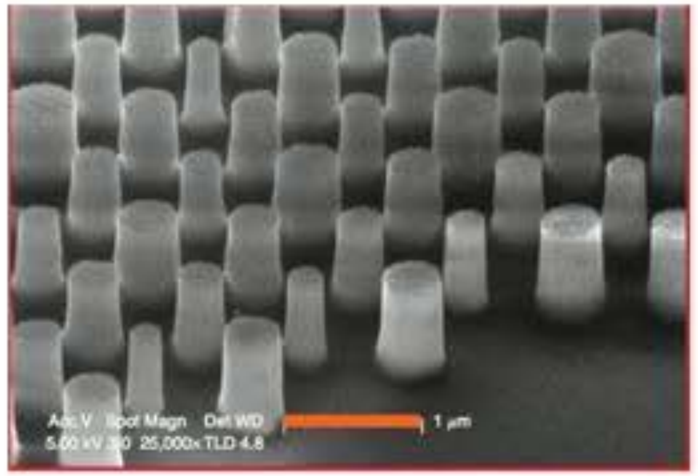

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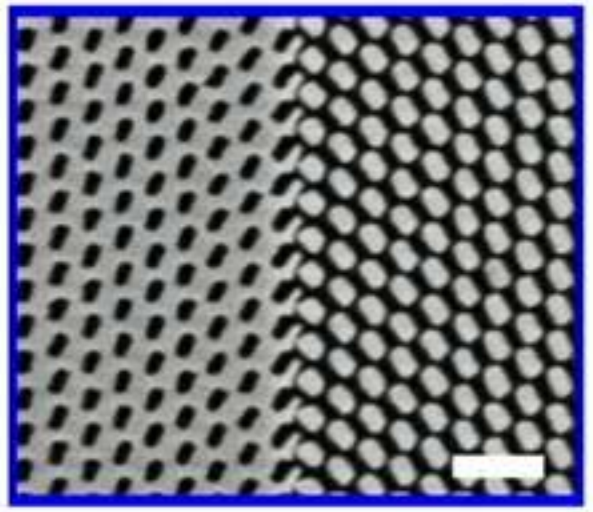

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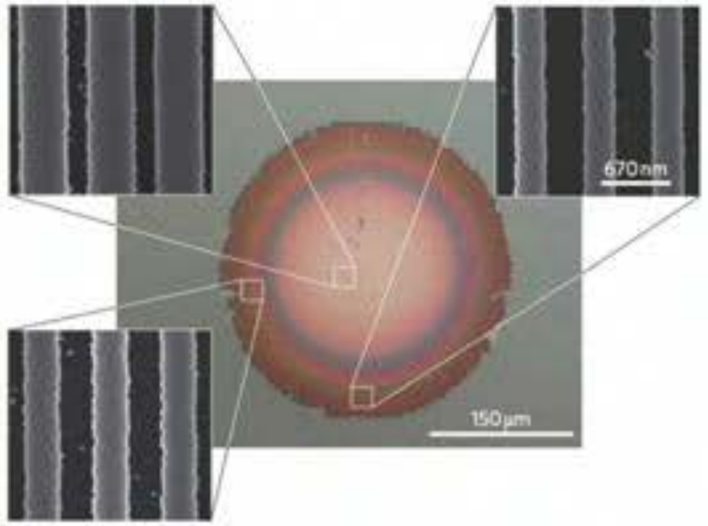

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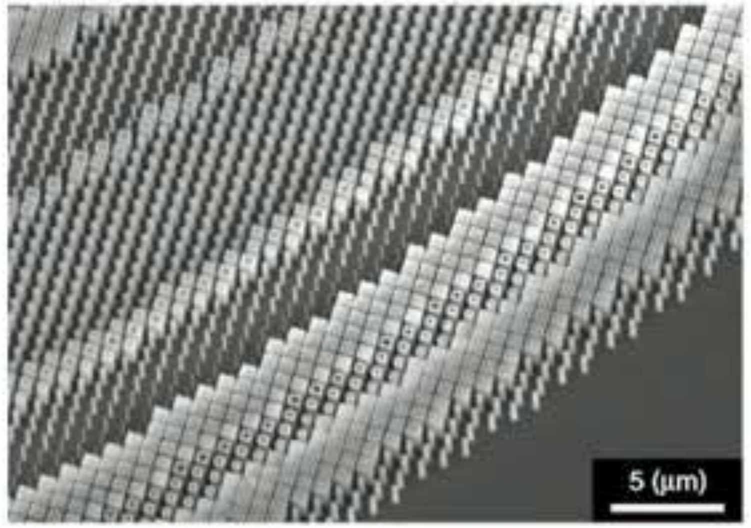

Shrestha et al. Light: Sci. and Appl. **7**, 95 (2018)

The design problem

How do I best implement a given optical function on a metasurface?

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How do I <u>best</u> implement a given optical function on a metasurface?

Comes down to:

How do I best take advantage of the large numbers of degrees of freedom?

The design problem

How do I <u>best</u> implement a given optical function on a metasurface?

Comes down to:

How do I best take advantage of the large numbers of degrees of freedom?

A relatively small $100 \times 100\ \mu m^2$ metasurface with periodicity $500\ nm$ has at least 4×10^4 degrees of freedom

Solving the design problem

Solving the design problem

Forward design

- Intuition based

Solving the design problem

Forward design

Intuition based

Scatterers → Functionality

Solving the design problem

Forward design

Intuition based

Scatterers ⟶ Functionality

Inverse design

Computation based

Solving the design problem

Forward design

Intuition based

Scatterers → Functionality

Inverse design

Computation based

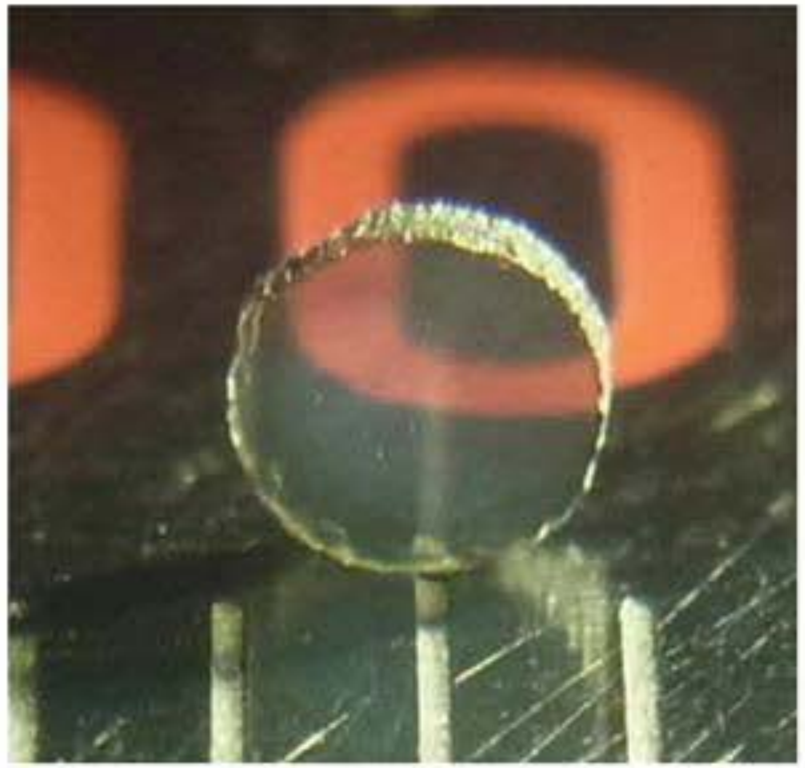
Functionality → Scatterers

Agenda

1. Single element metasurface optics
2. Towards metasurface optical systems
3. Inverse design and optimization of metasurfaces
4. Future work and outlook

Silicon nitride

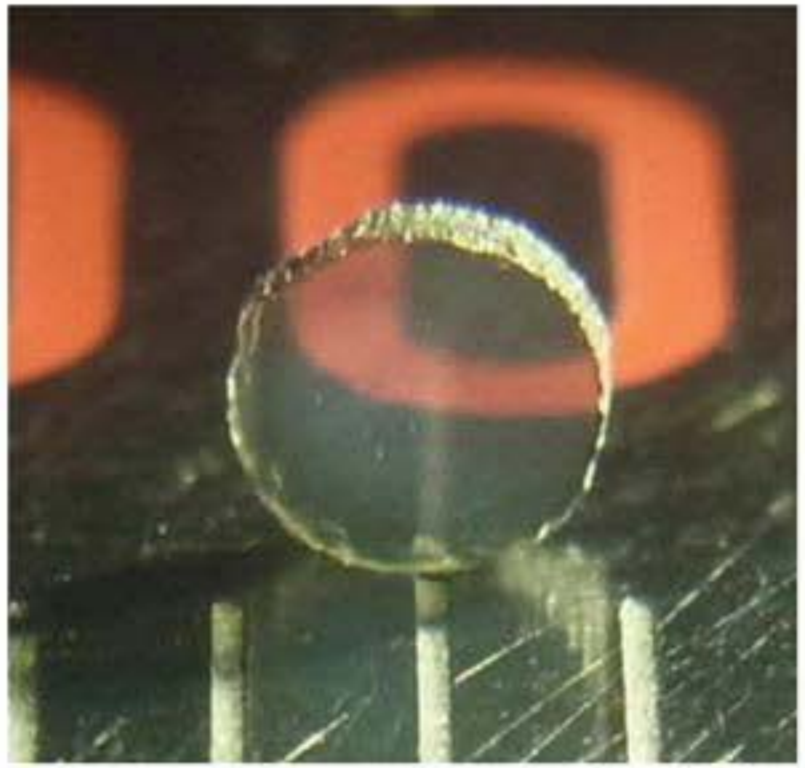
Silicon nitride



Nishiyama et al. Sci. Reports. **7**, 44755 (2017)

Silicon nitride

Refractive index ~ 2



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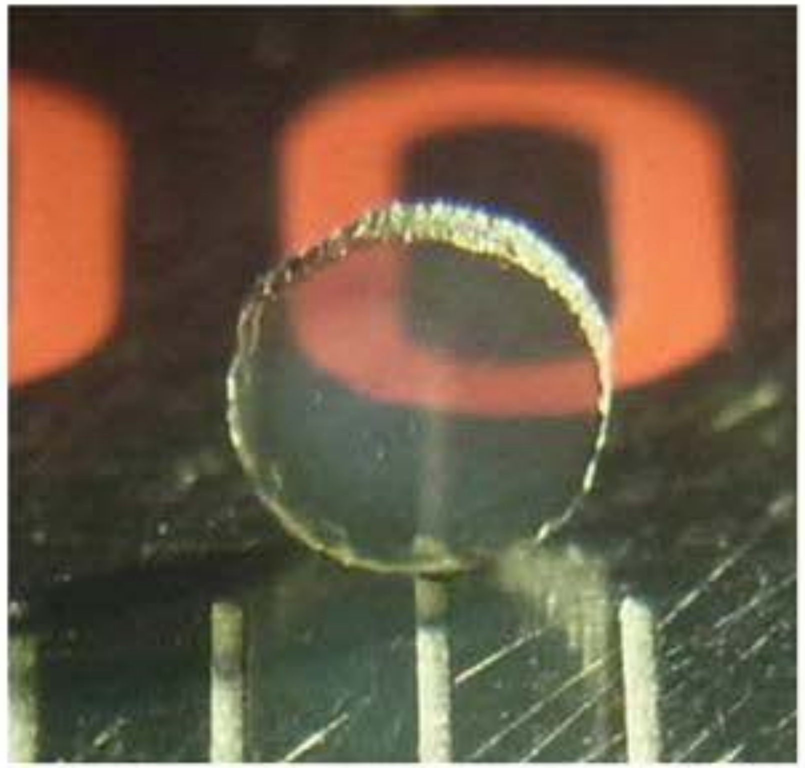
Band gap ~ 4-5 eV



Nishiyama et al. Sci. Reports. **7**, 44755 (2017)

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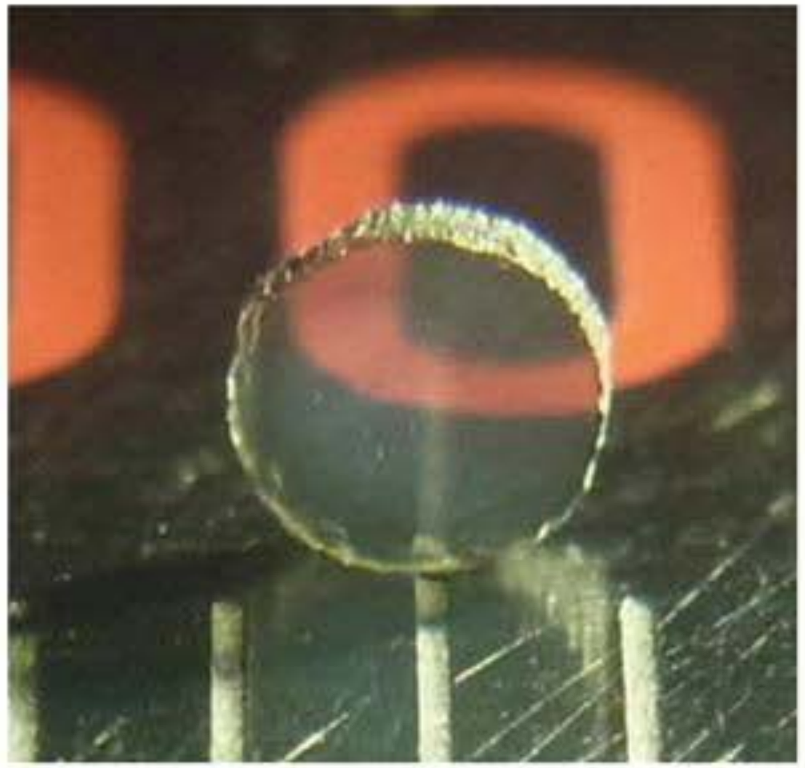
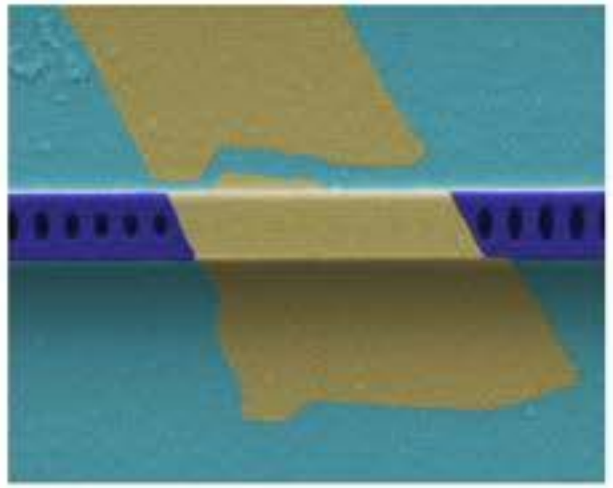


Nishiyama et al. Sci. Reports. **7**, 44755 (2017)

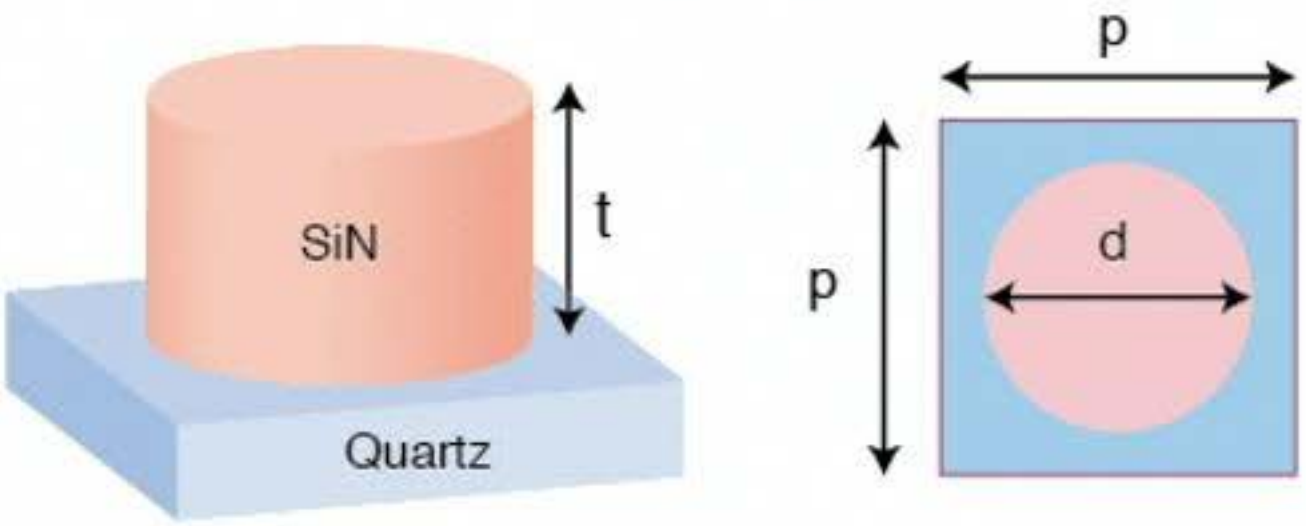


Fryett et al. ACS Photonics (2018)

Parameter search

Parameter search

Rigorous Coupled Wave Analysis (RCWA)



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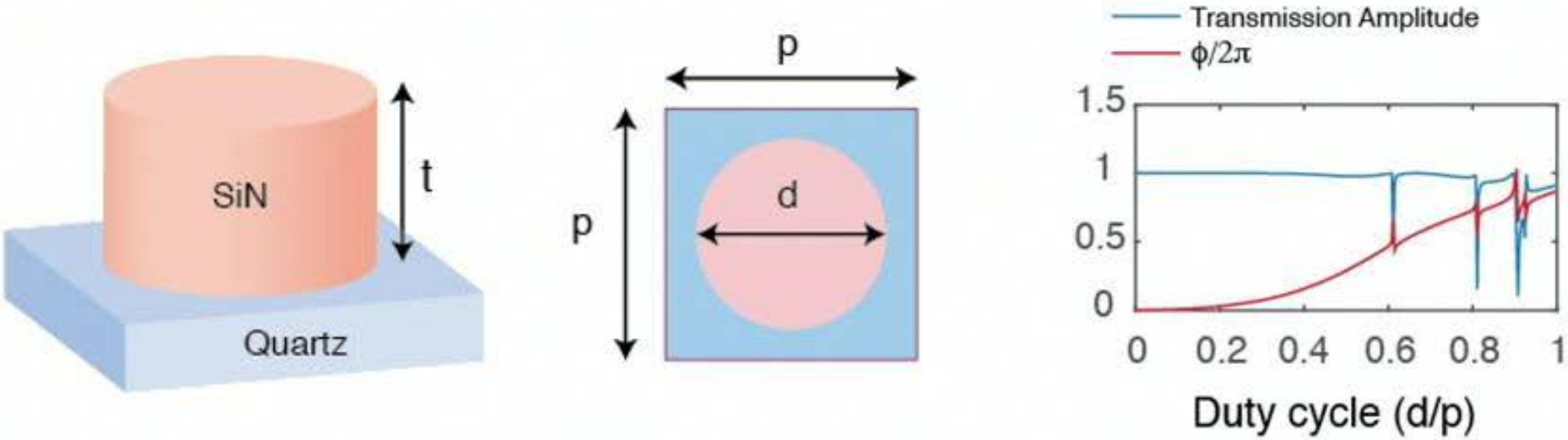

Implementing the phase profile

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$$\varphi(r,\theta) = \frac{2\pi}{\lambda}\left(\sqrt{r^2+f^2}-f\right)+l\theta$$

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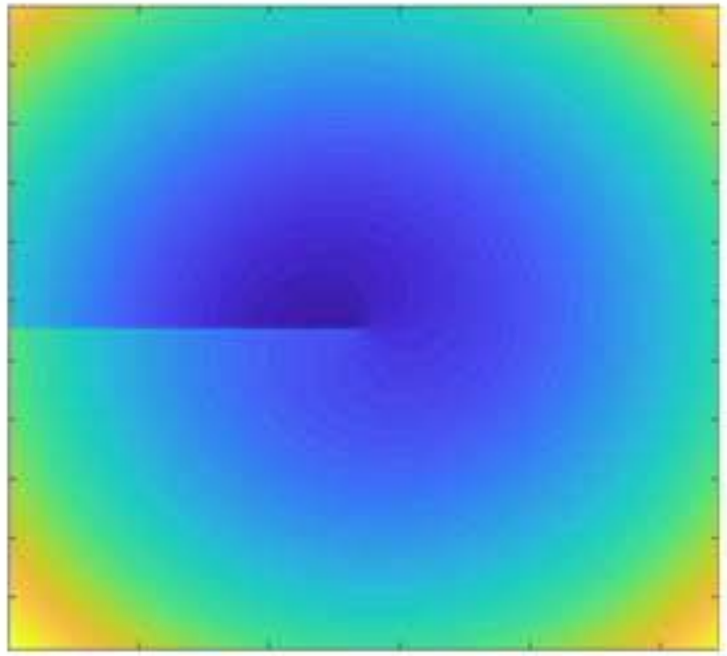
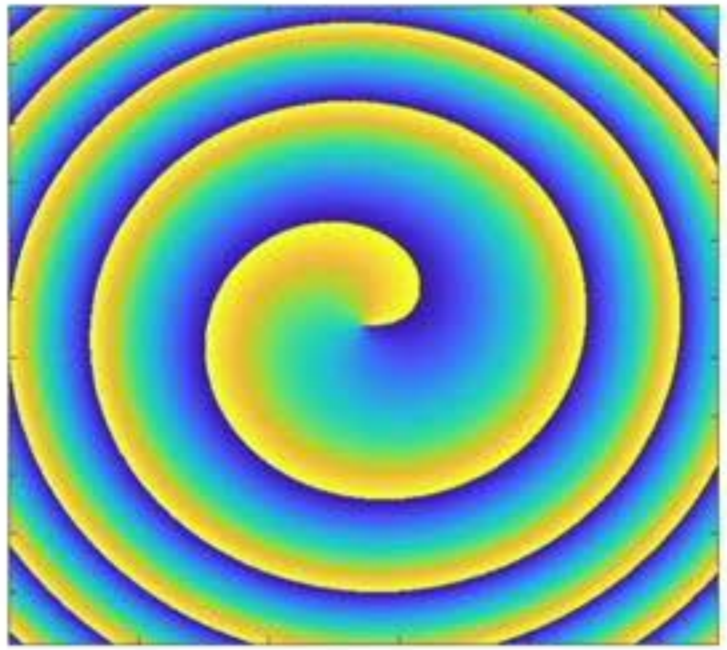


Implementing the phase profile

$$\varphi(r,\theta) = mod\left(\frac{2\pi}{\lambda}\left(\sqrt{r^2+f^2}-f\right)+l\theta, 2\pi\right)$$



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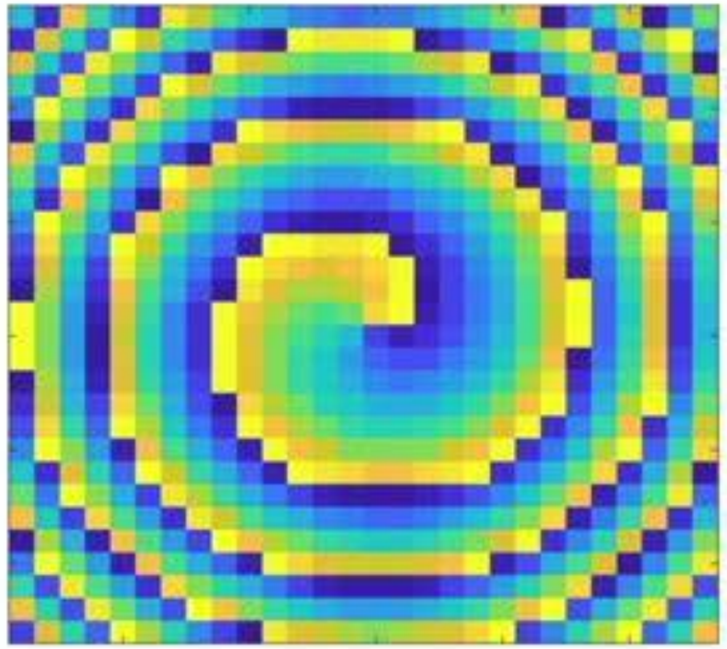

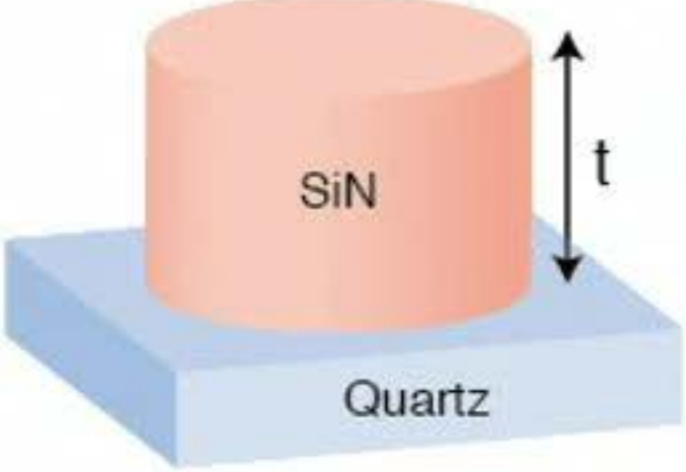

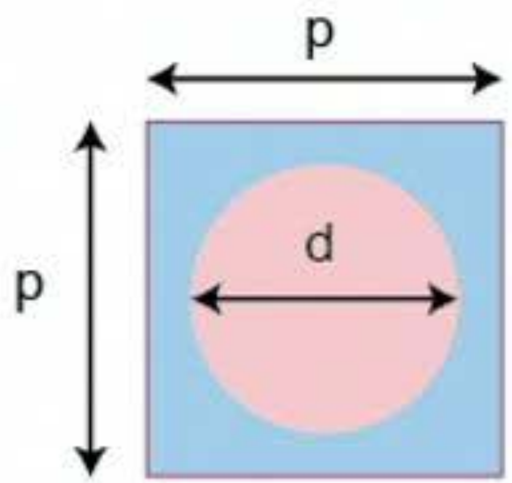

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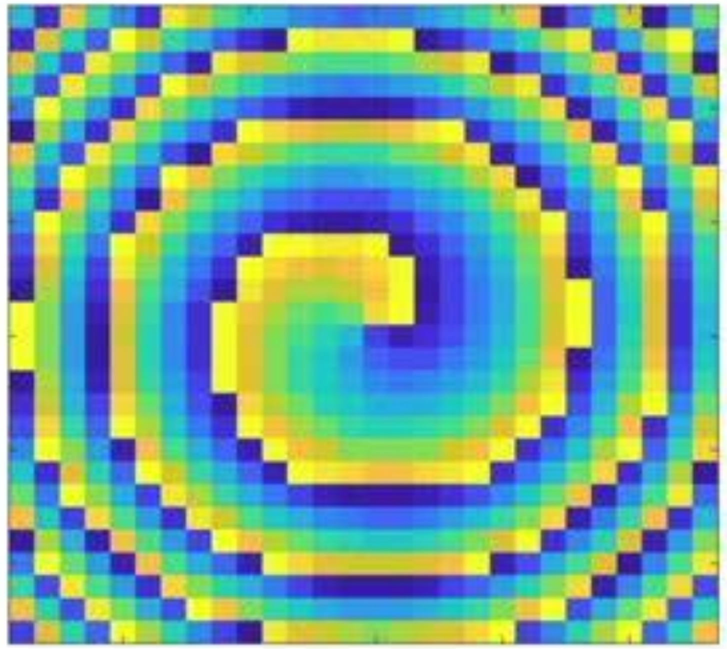
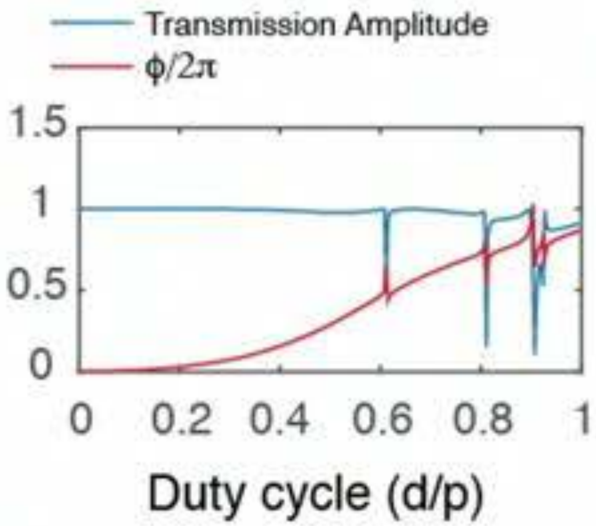
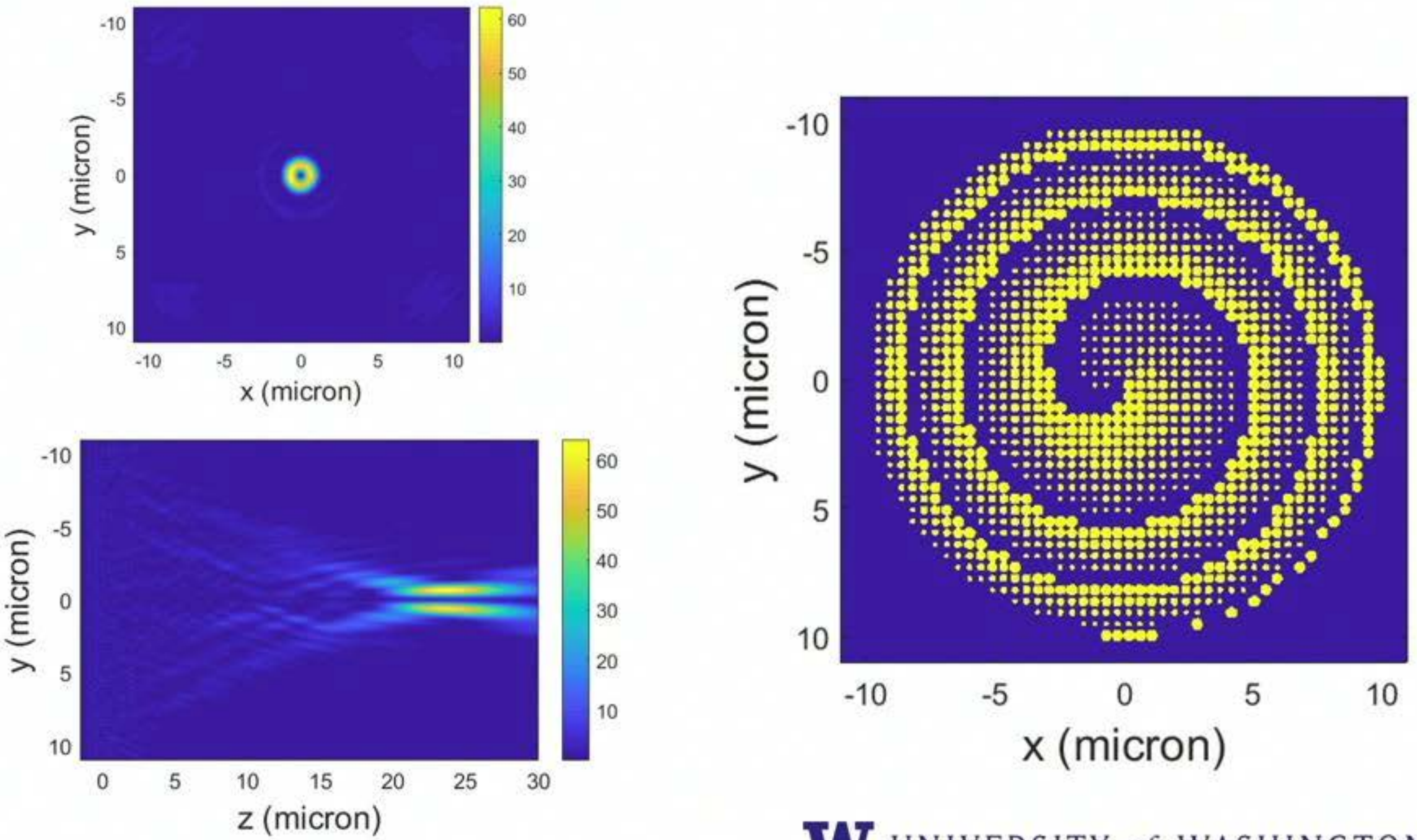
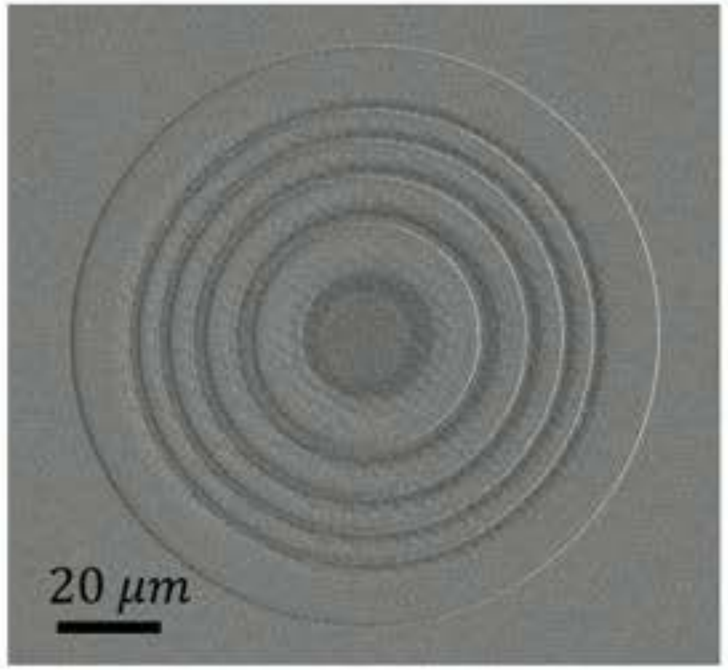




Finite difference time domain simulation



Fabricated structure



A. Zhan et al, ACS Photonics. **3**, 2 (2016)

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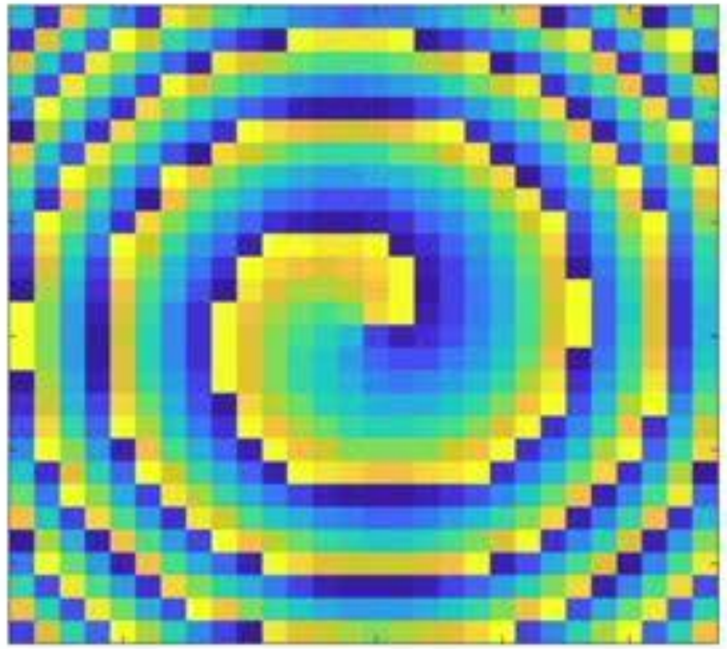

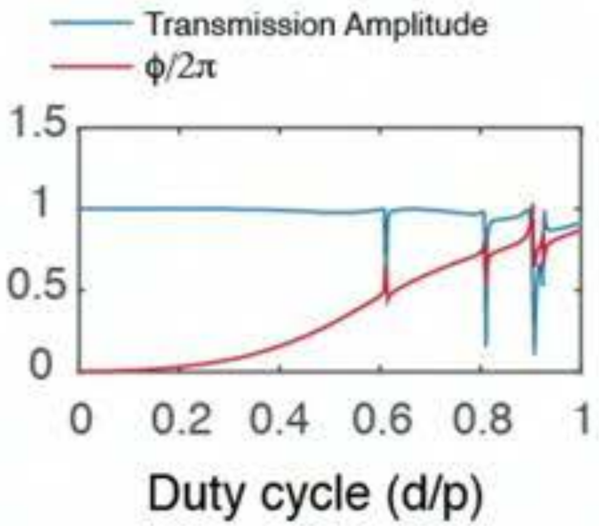

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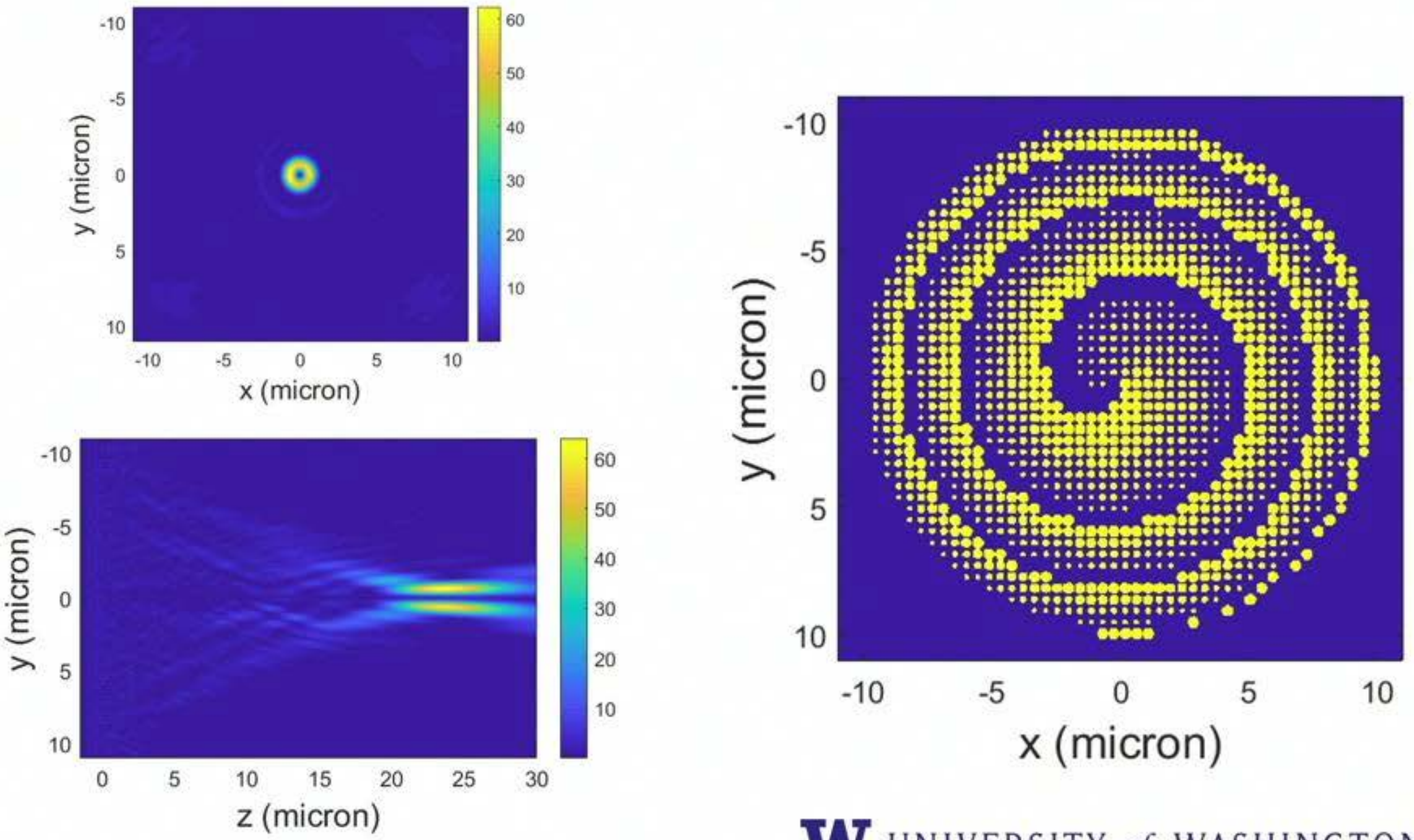

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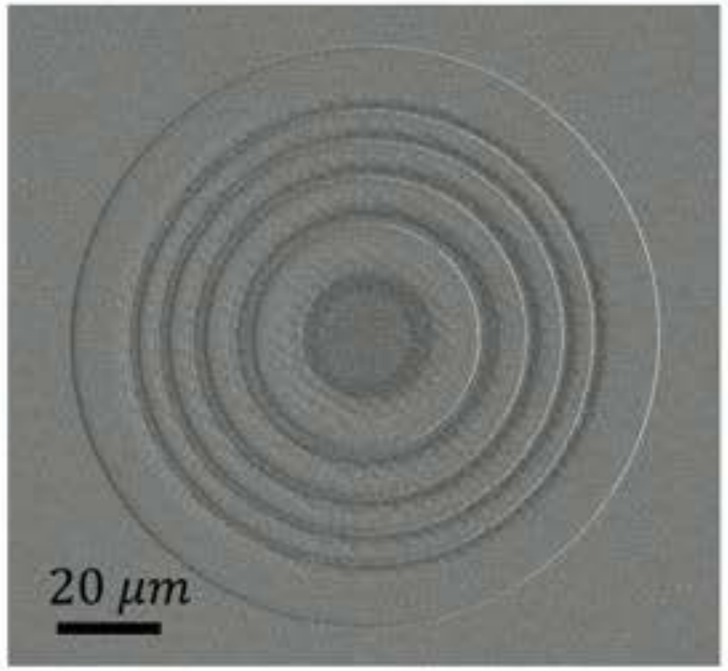

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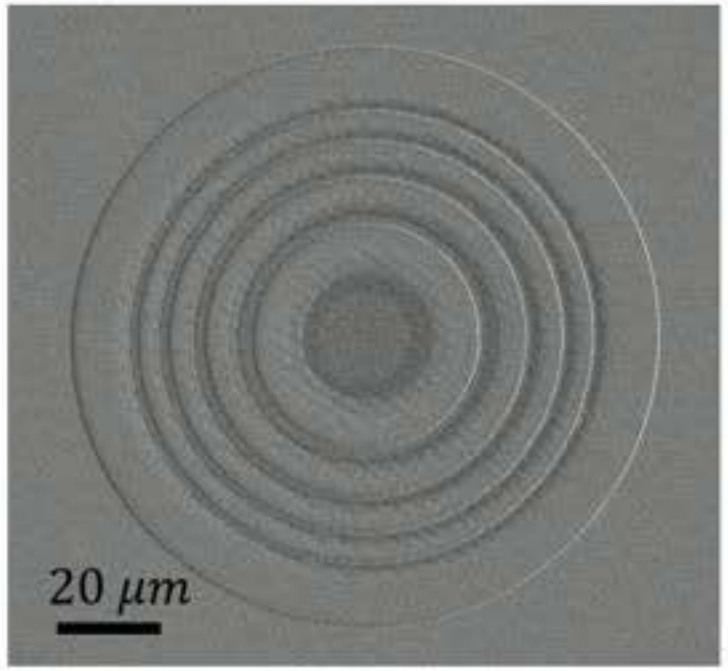

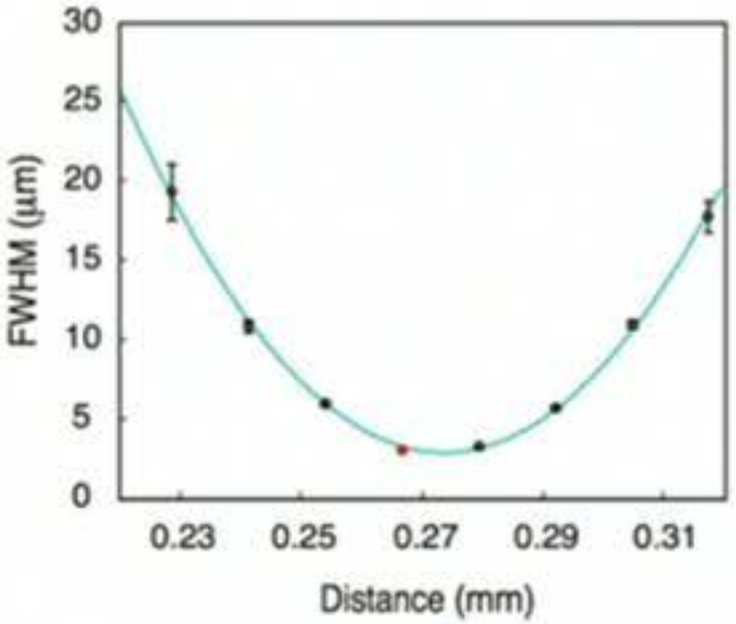

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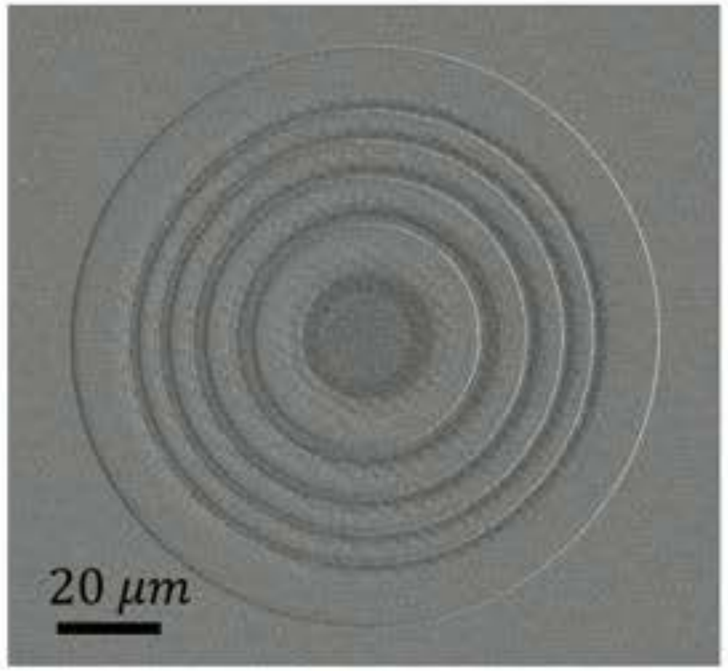

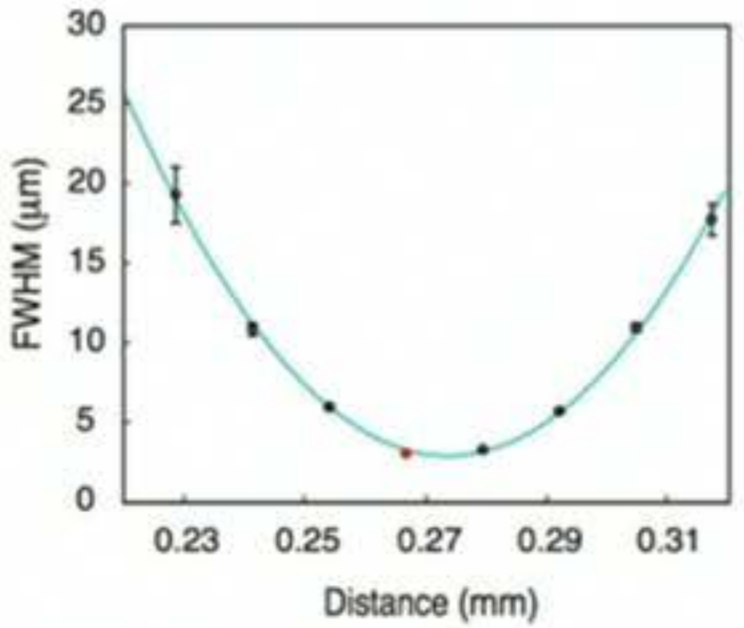

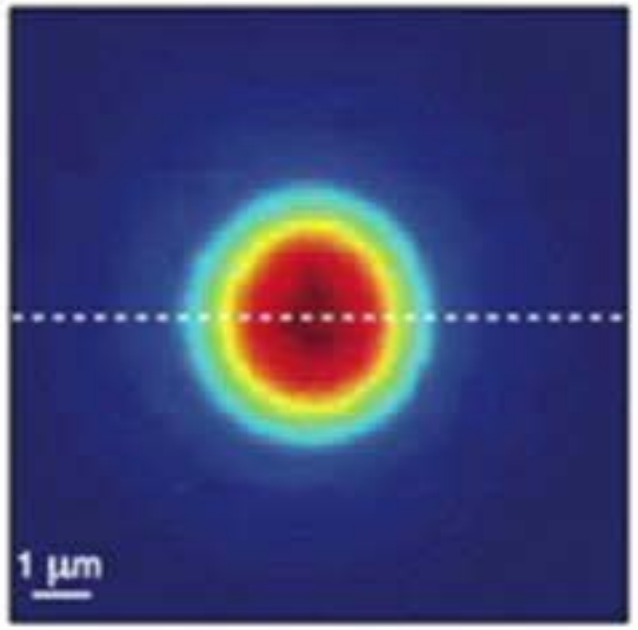

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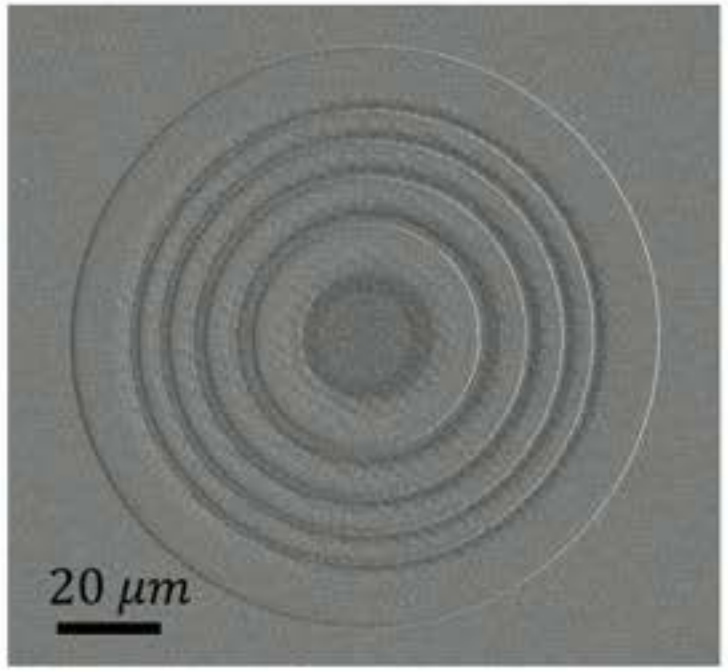

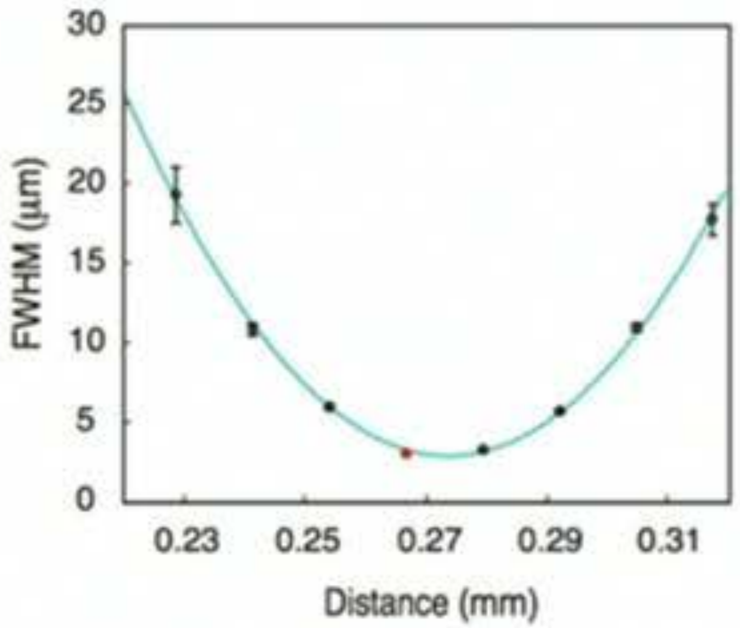

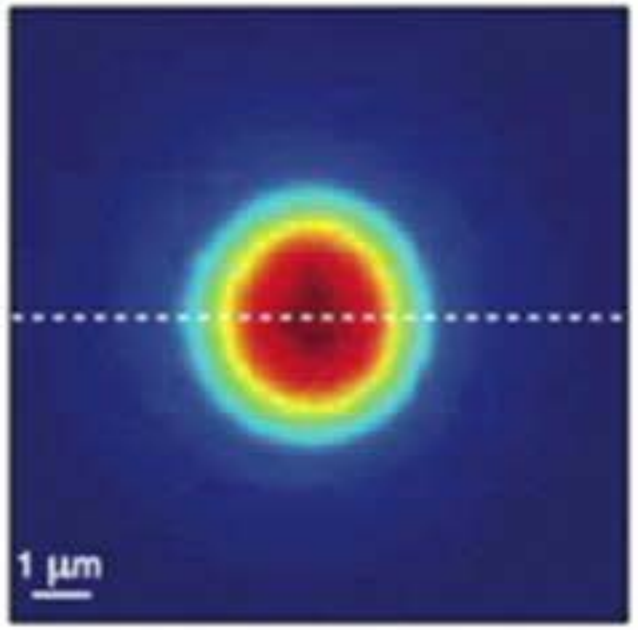

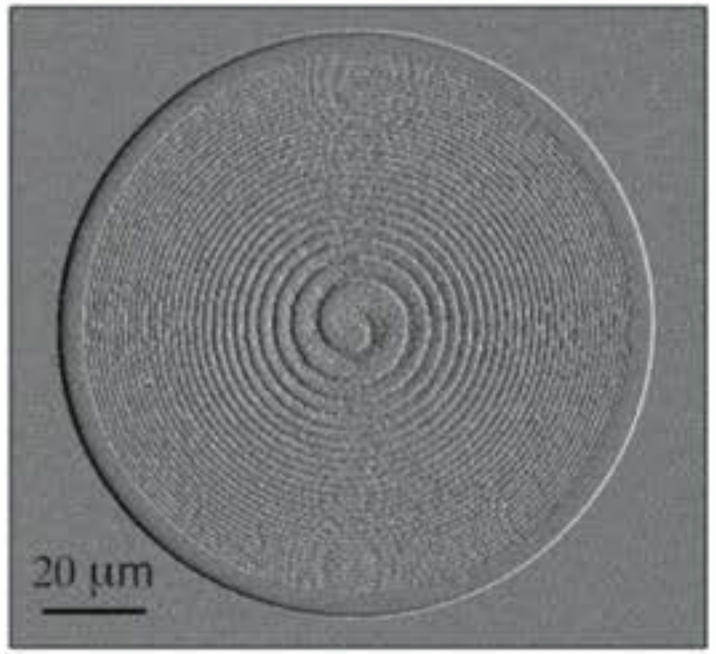

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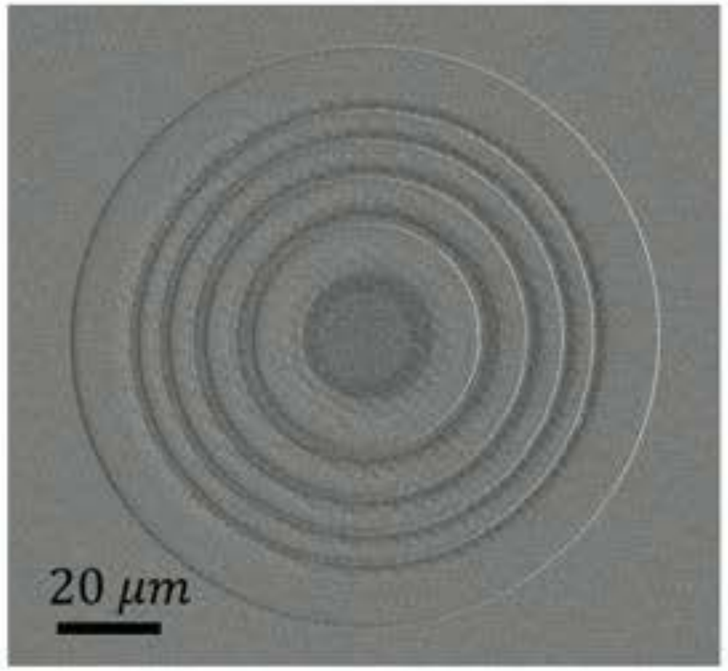
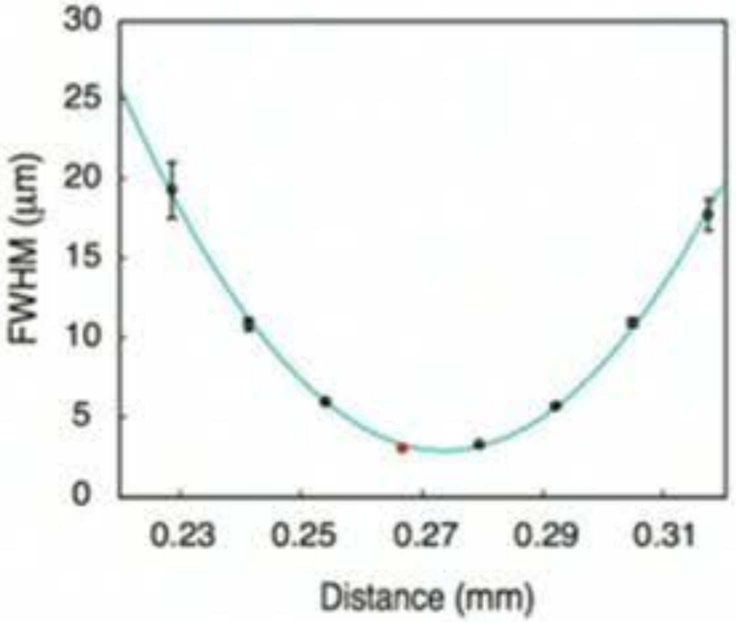
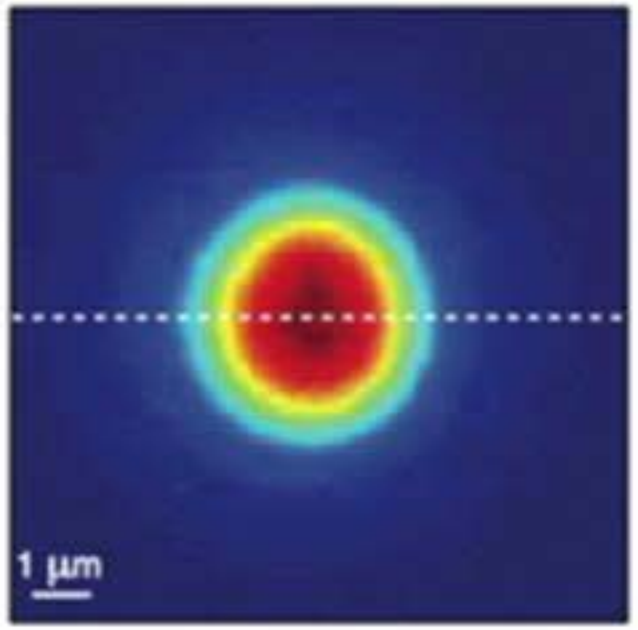
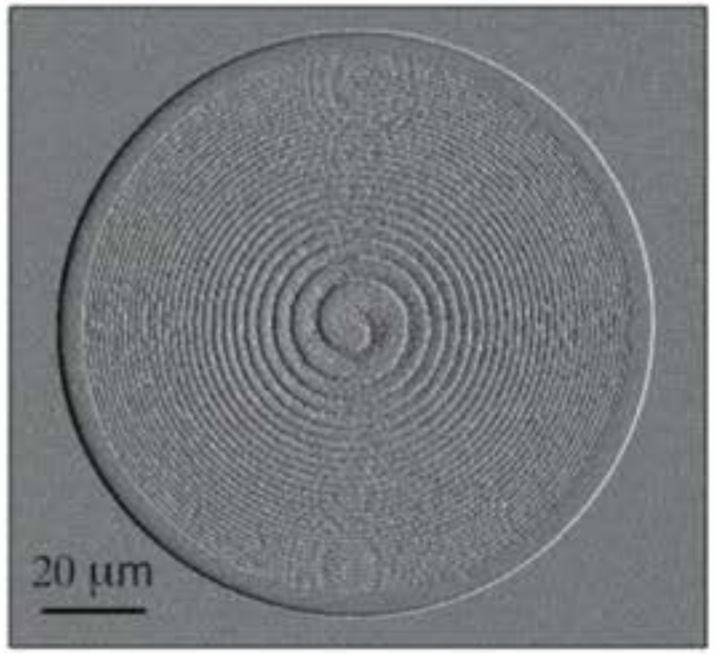
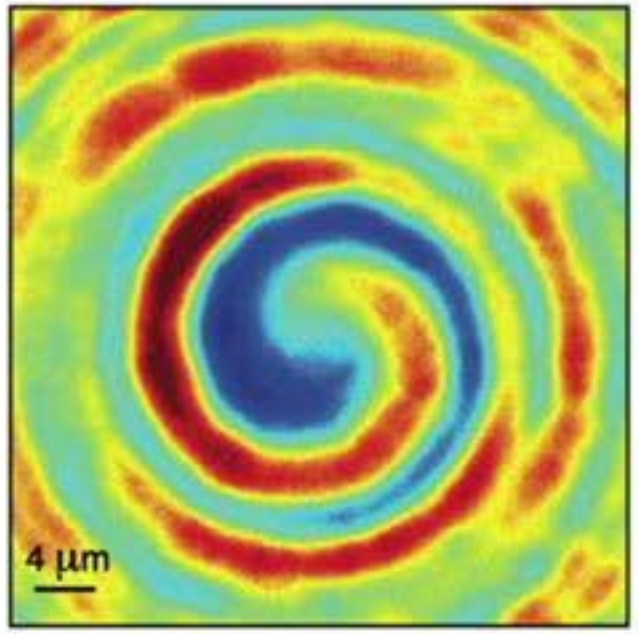




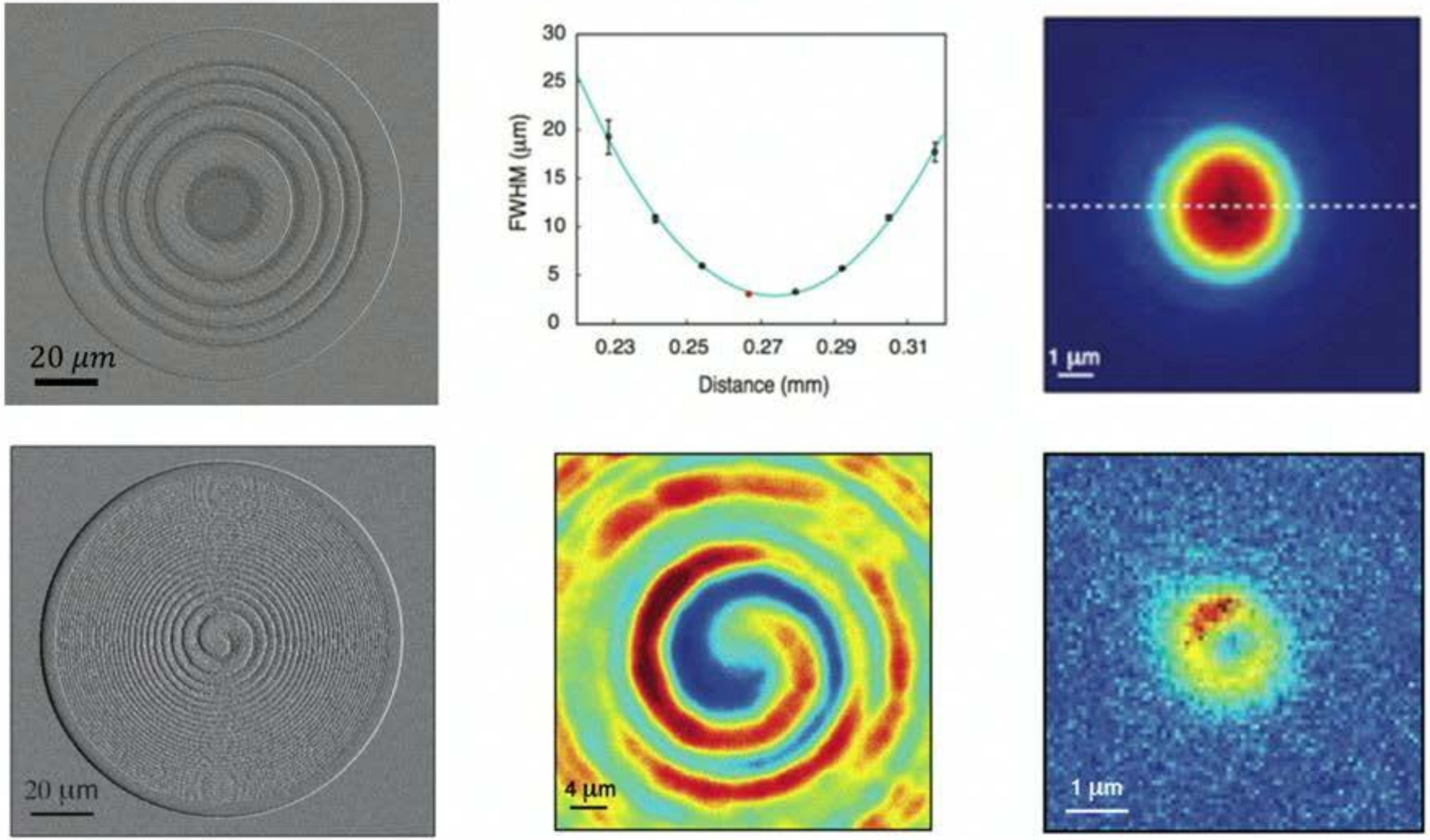






A. Zhan et al, ACS Photonics. **3**, 2 (2016)

Fabricated structure



A. Zhan et al, ACS Photonics. **3**, 2 (2016)

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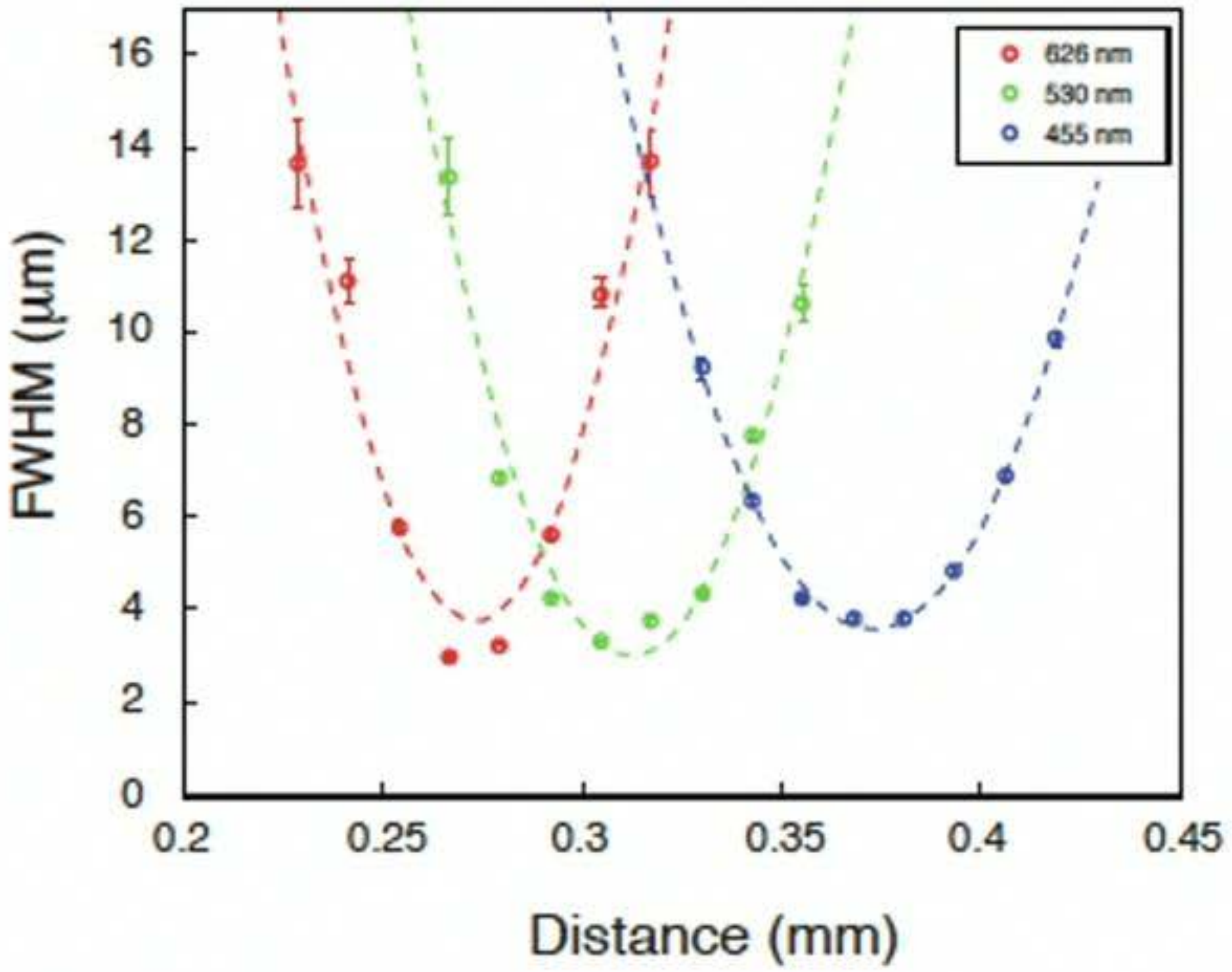
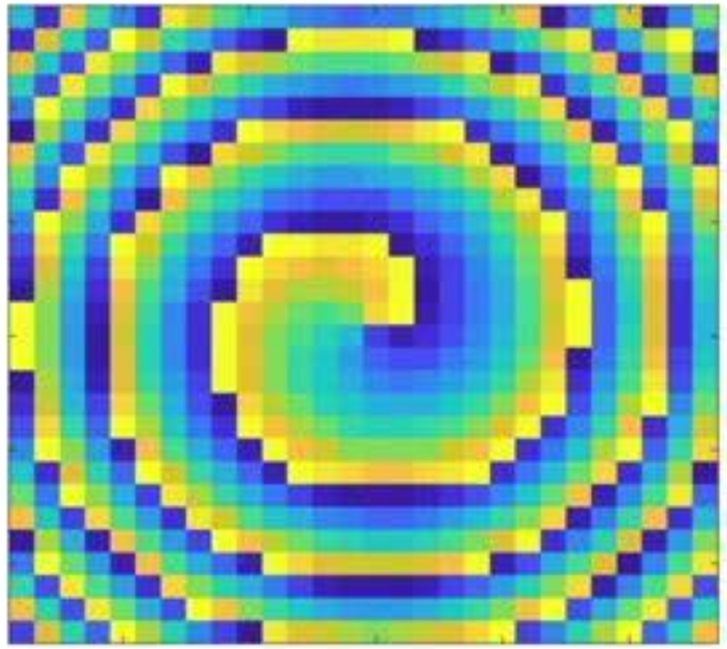
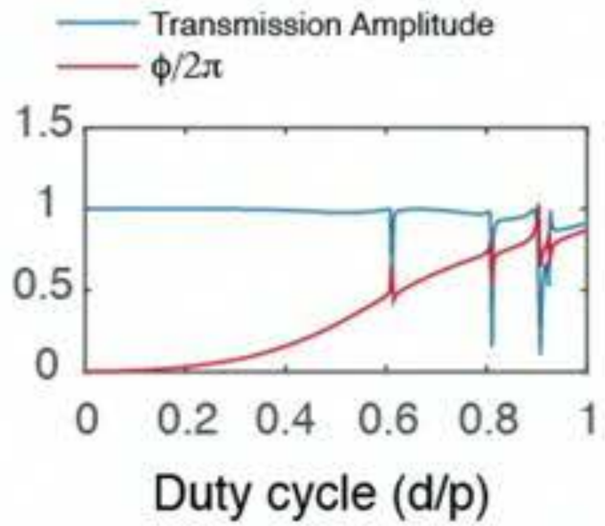
Chromatic aberration



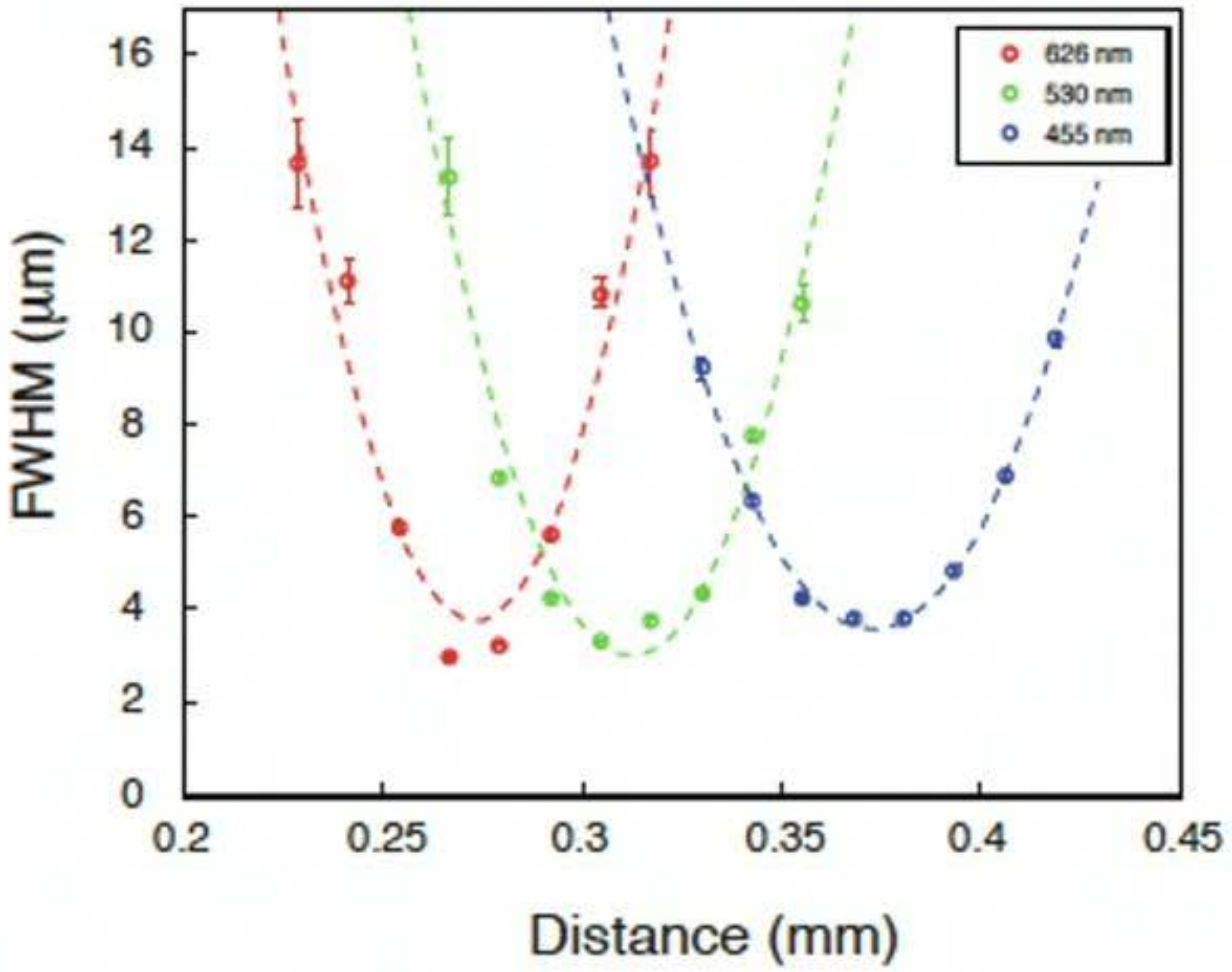
Implementing the phase profile

$$\varphi(r,\theta) = mod\left(\frac{2\pi}{\lambda}\left(\sqrt{r^2+f^2}-f\right)+l\theta, 2\pi\right)$$





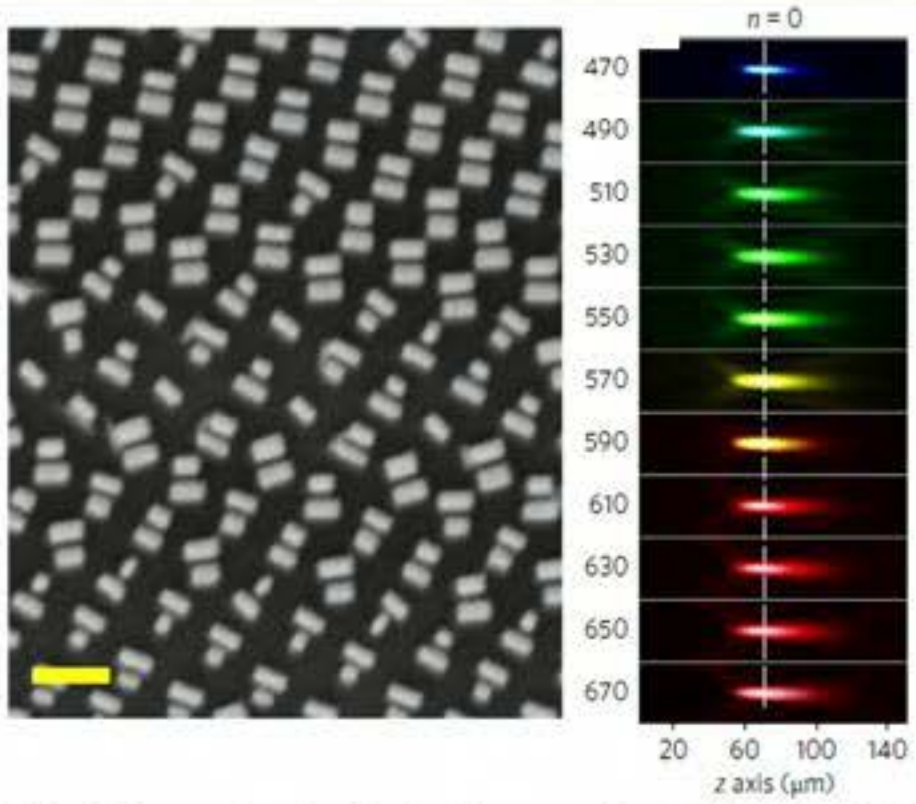
Chromatic aberration



Chromatic aberration in photography

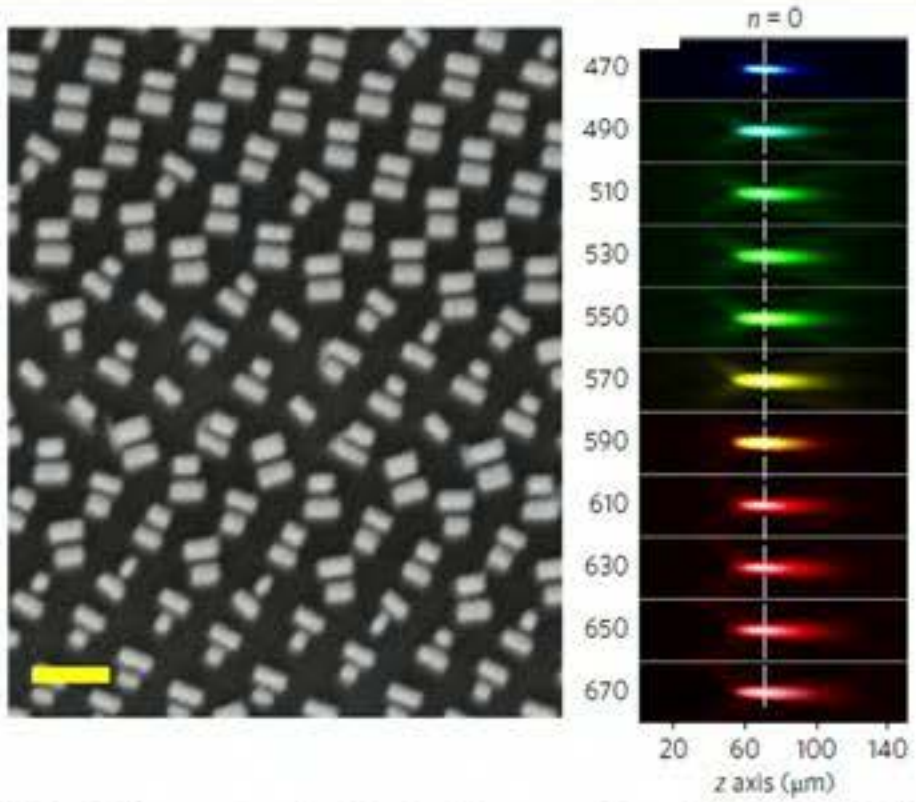
Correcting chromatic aberrations

Correcting chromatic aberrations

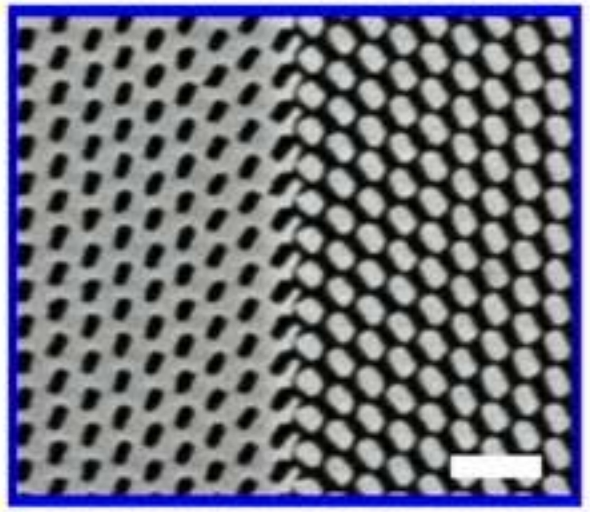


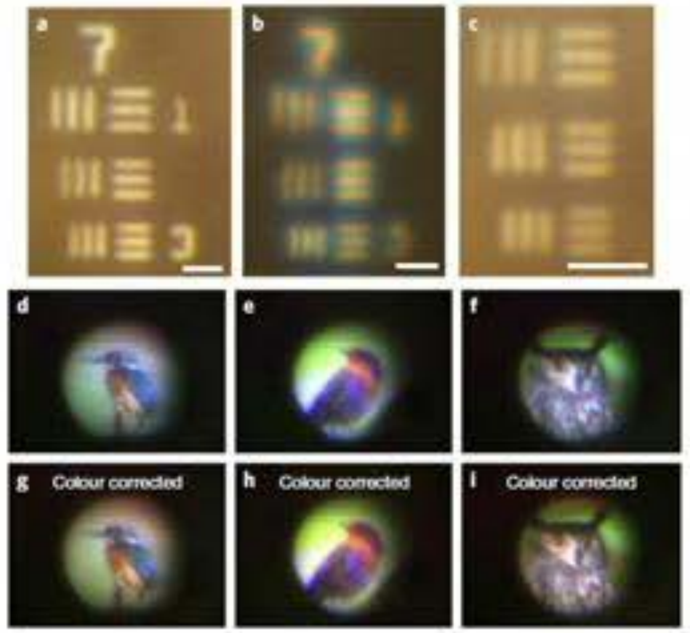
W. Chen et al, Nat. Nano. **13**, 220 (2018)

Correcting chromatic aberrations

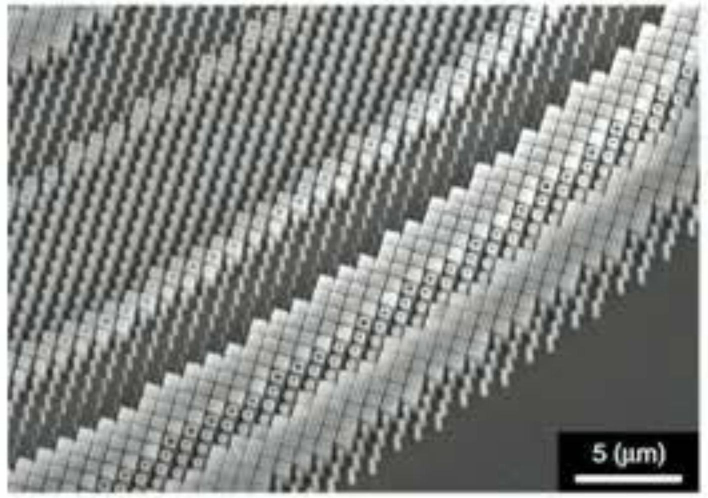


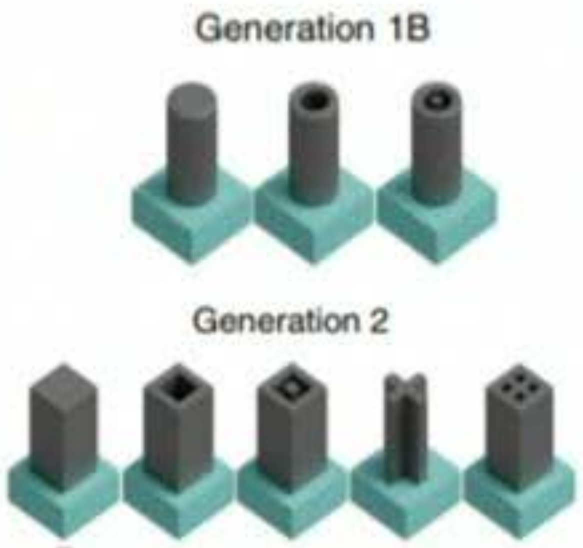
W. Chen et al, Nat. Nano. **13**, 220 (2018)





S. Wang et al, Nat. Nano. **13**, 227 (2018)





Shrestha et al. Light: Sci. and Appl.
7, 95 (2018)

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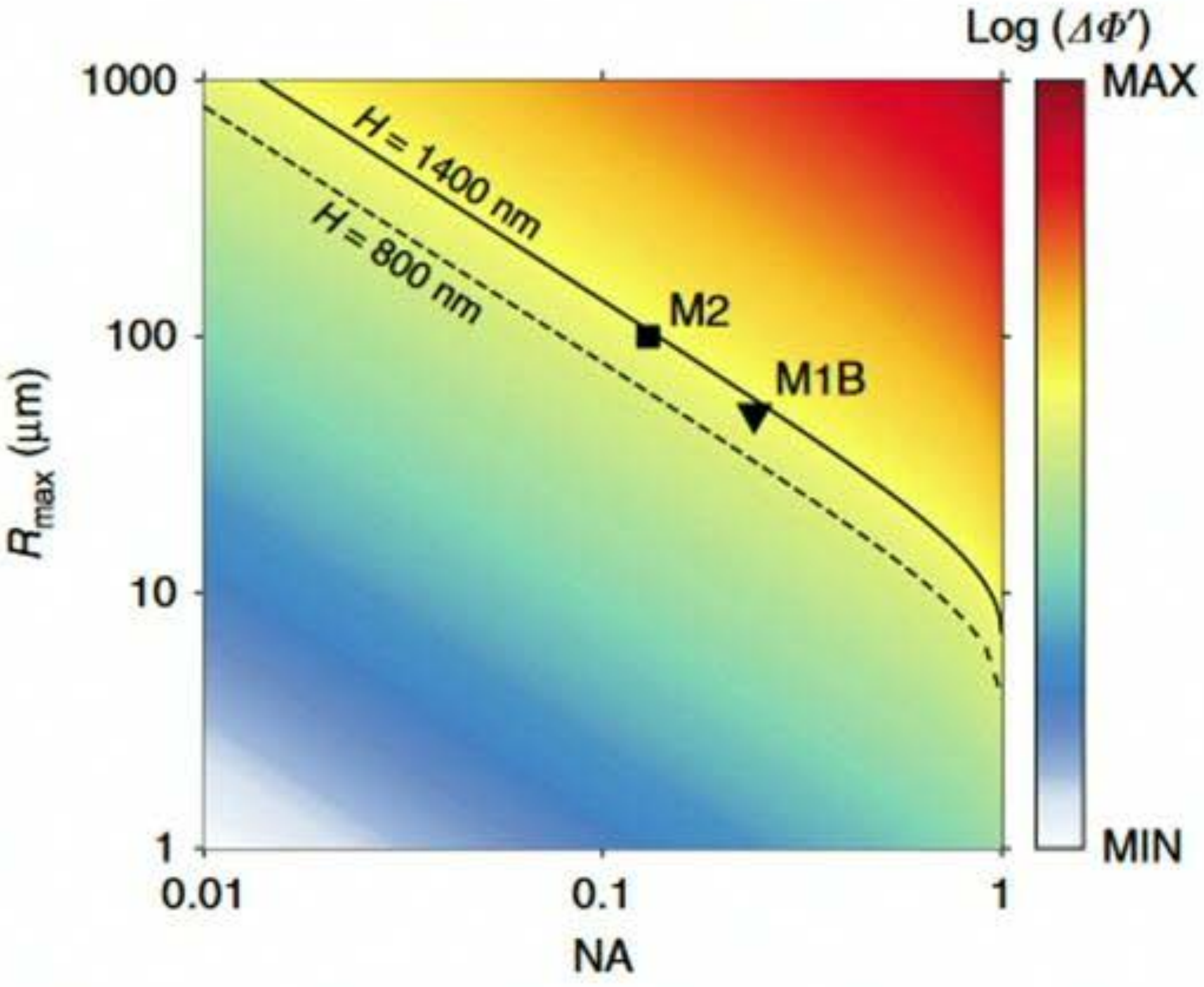
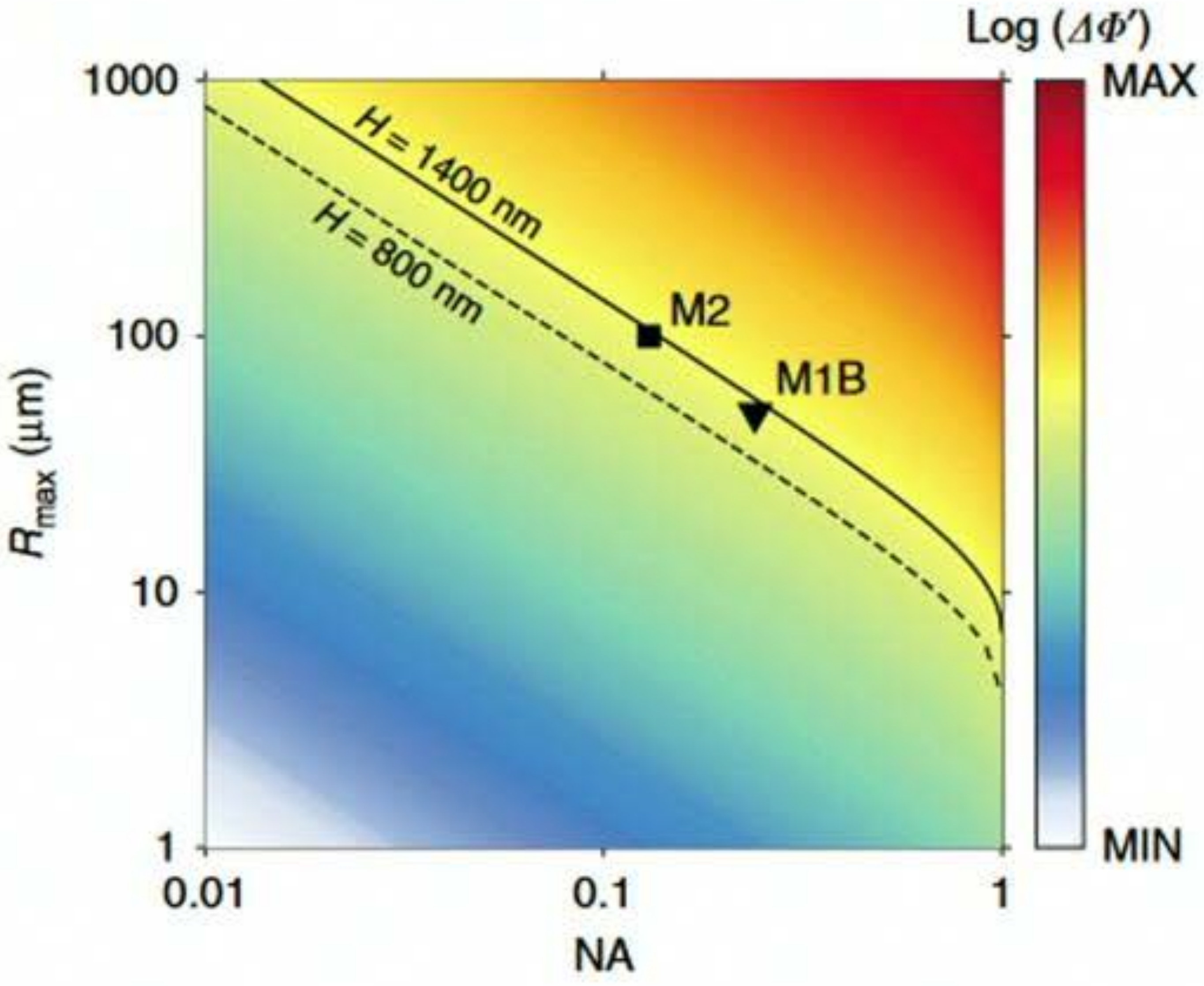
Limits of dispersion engineering

Limits of dispersion engineering



Shrestha et al. Light: Sci. and Appl.
7, 95 (2018)

Limits of dispersion engineering



Shrestha et al. Light: Sci. and Appl. **7**, 95 (2018)

$$R_{max} = \frac{\Delta\Phi'}{\Delta\omega\left(\frac{1}{NA} - \sqrt{\frac{1}{NA^2} - 1}\right)}$$

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Computational imaging approach

Computational imaging approach

$$\varphi = \frac{2\pi}{\lambda}\left(\sqrt{x^2 + y^2 + f^2} - f\right) + \frac{\alpha}{L^3}\left(x^3 + y^3\right)$$

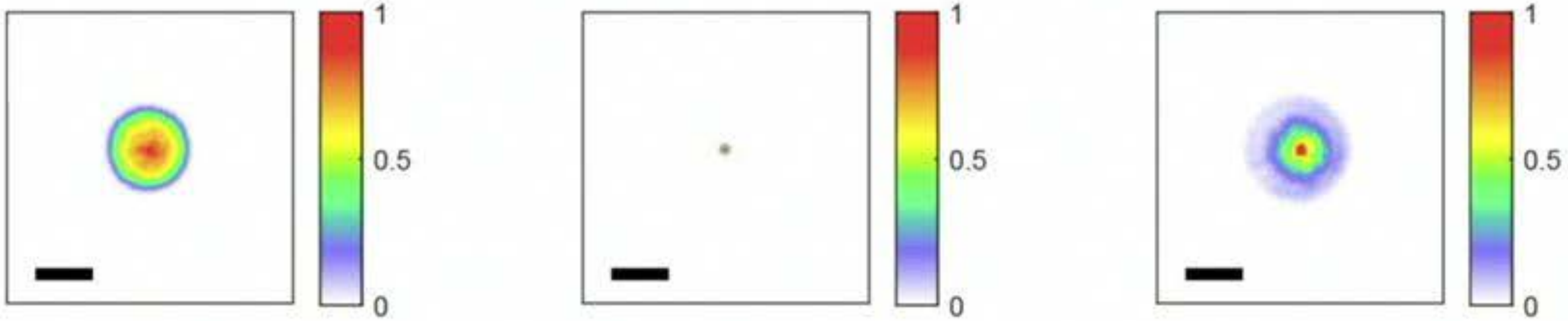
S. Colburn et al. Science Advances **4**, eaar2114 (2018)

Computational imaging approach

$$\varphi = \frac{2\pi}{\lambda}\left(\sqrt{x^2 + y^2 + f^2} - f\right) + \frac{\alpha}{L^3}\left(x^3 + y^3\right)$$

Blue Green Red

$\alpha = 0$



S. Colburn et al. Science Advances **4**, eaar2114 (2018)

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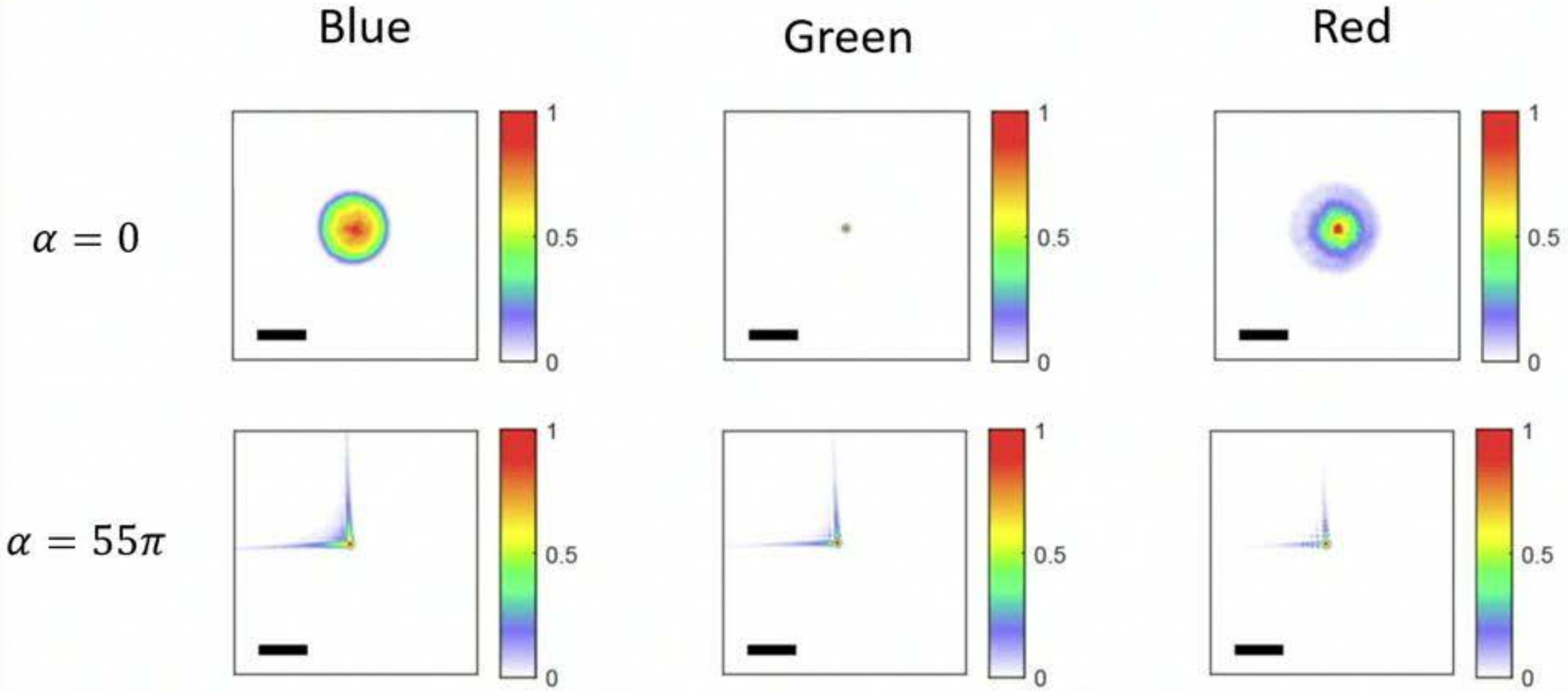

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S. Colburn et al. Science Advances **4**, eaar2114 (2018)

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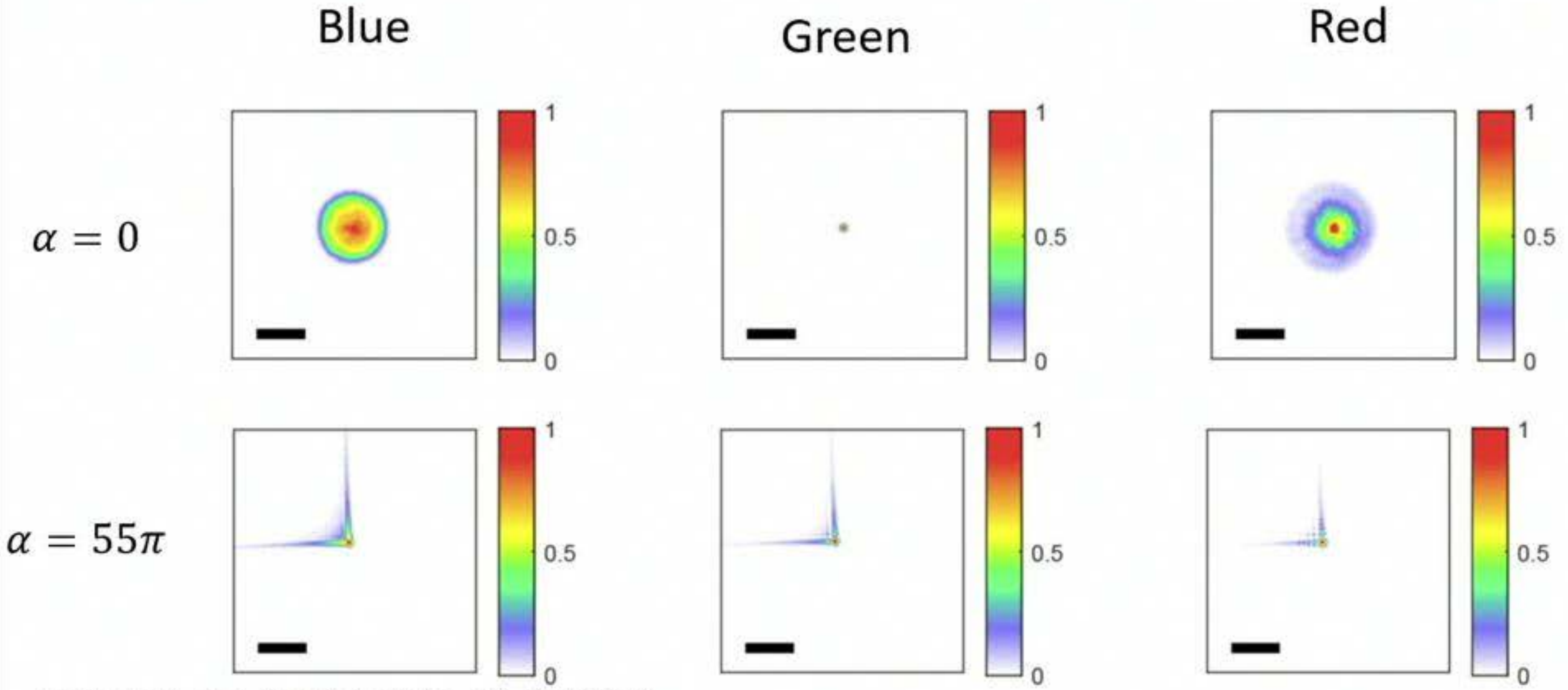


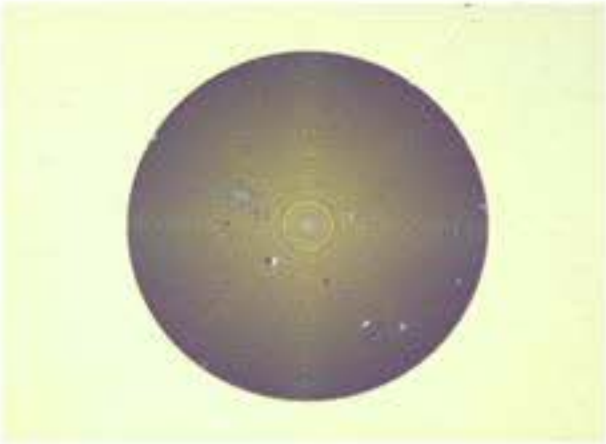
E. Dowski et al. Applied Optics, **34**, 11 (1995)
H. Wach et al. Applied Optics, **37**, 23 (1998)
S. Colburn et al. Science Advances **4**, eaar2114 (2018)

Computational imaging approach

S. Colburn et al. Science Advances **4**, eaar2114 (2018)

Computational imaging approach

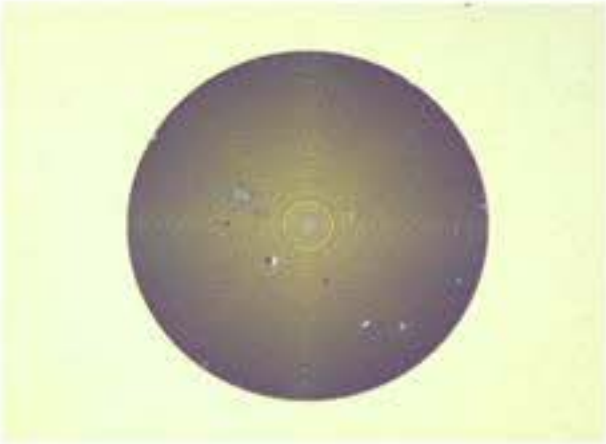
Singlet



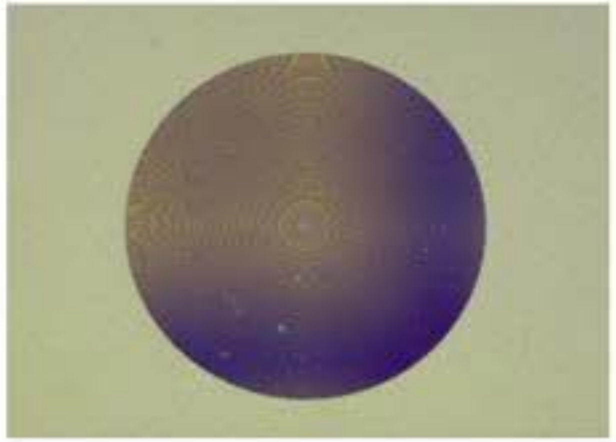
S. Colburn et al. Science Advances **4**, eaar2114 (2018)

Computational imaging approach

Singlet

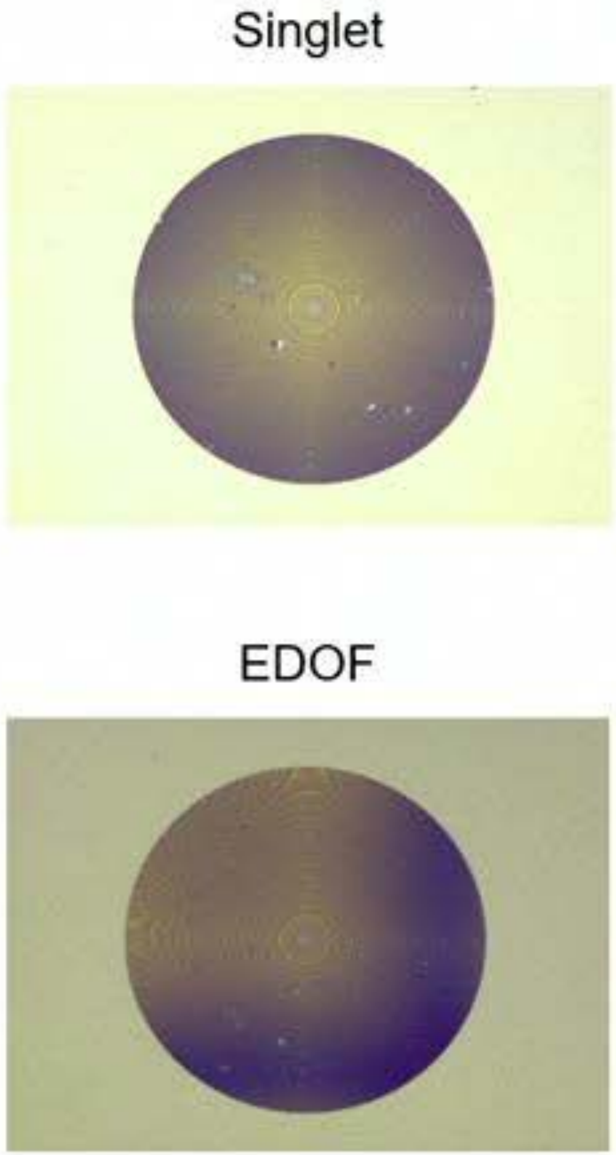


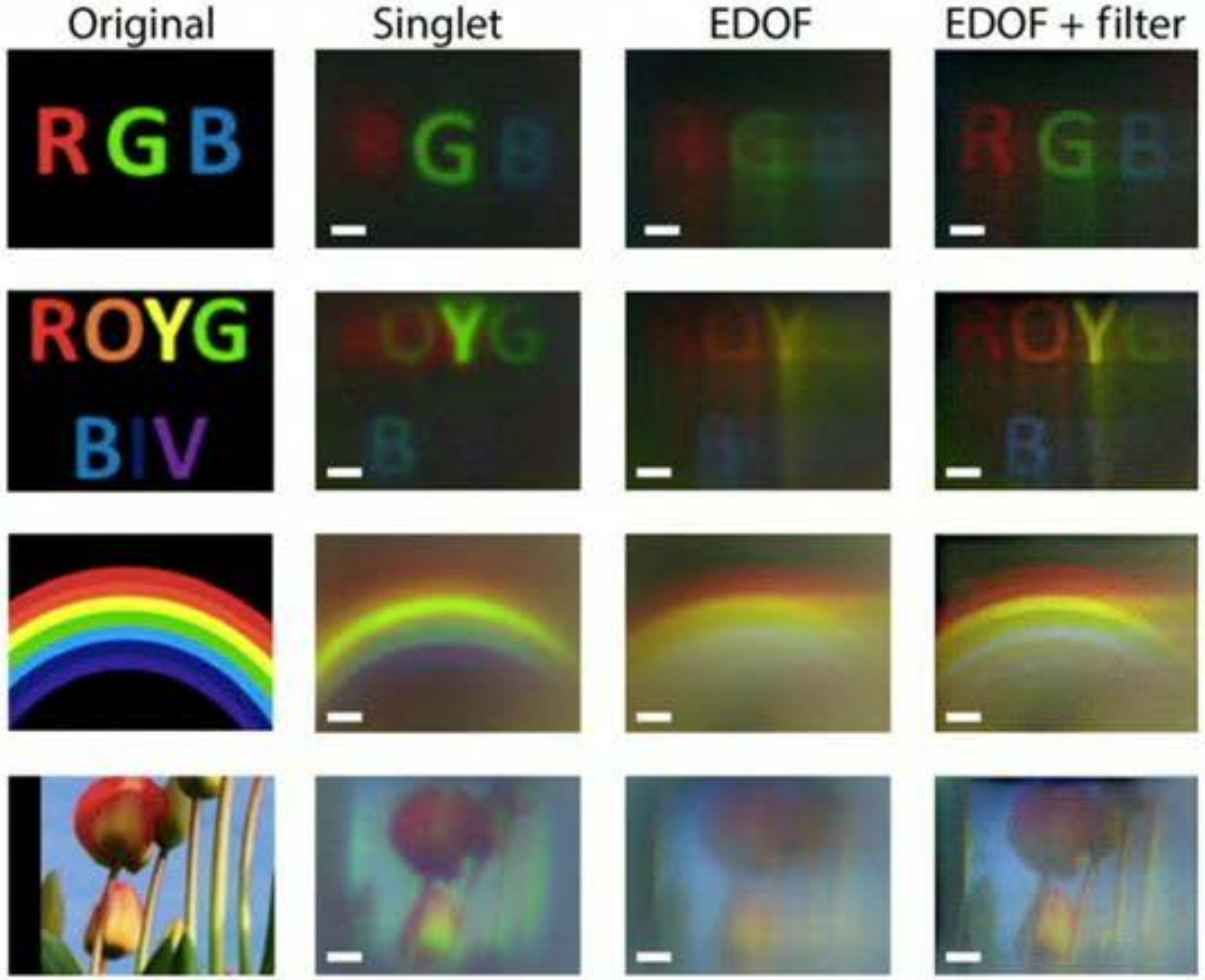
EDOF



S. Colburn et al. Science Advances **4**, eaar2114 (2018)

Computational imaging approach





S. Colburn et al. Science Advances **4**, eaar2114 (2018)

Other works

Holography

L. Huang et al. Nanophotonics **7**, 6 1169-1190 (2018)

Polarization optics

A. Arbabi et al. Nat. Nano. **10**, 937-943 (2015)

N. Rubin et al. Optics Express. **26**, 17 (2018)

Nonlinear optics

A. Krasnok et al. Materials Today. **21**, 1 (2018)

Review articles

S. Kamali et al. Nanophotonics **7**, 6 (2018)

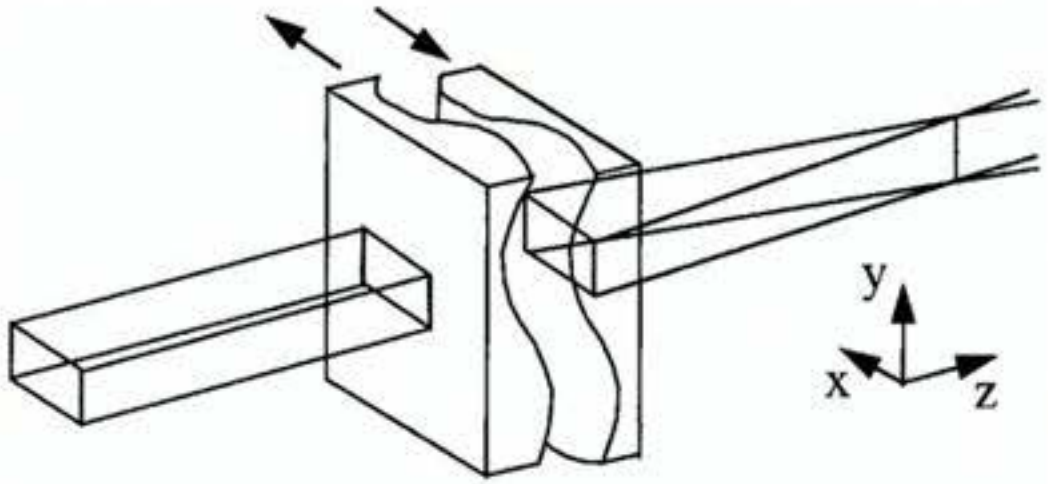
D. Neshev et al. Light, Sci. and Appl. **7**, 58 (2018)

Agenda

1. Single element metasurface optics
2. Towards metasurface optical systems
3. Inverse design and optimization of metasurfaces
4. Future work and outlook

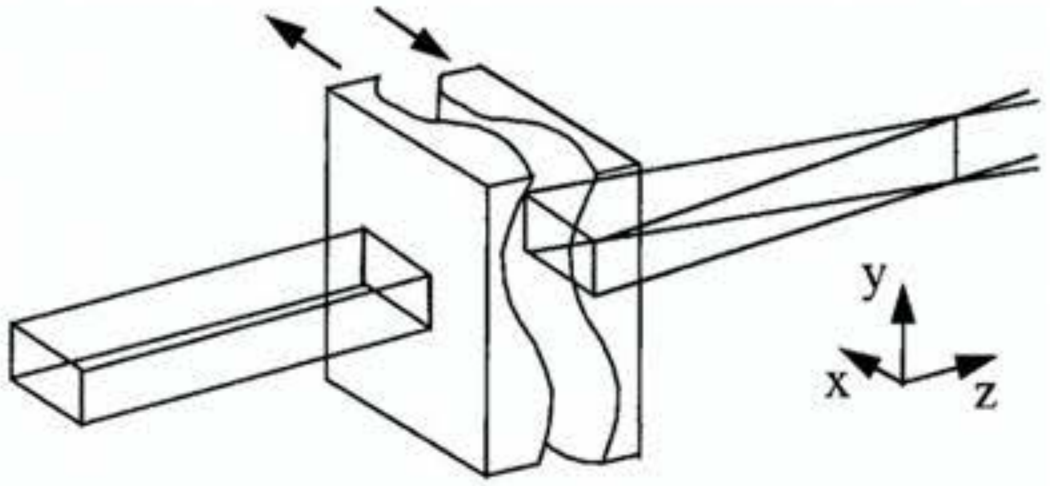
Alvarez lens

31



Alvarez lens

31



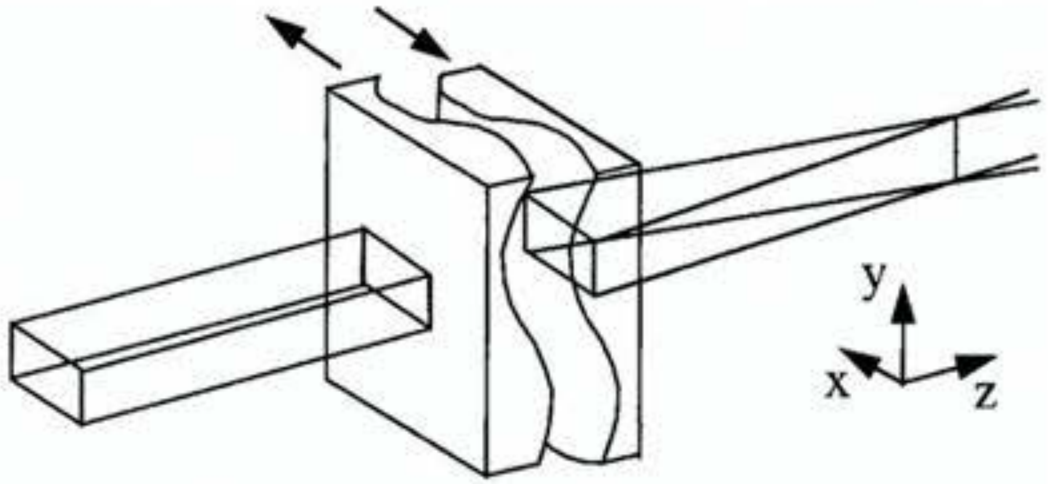
Barton et al. Opt. Lett. **25**, 1 (2000)

$$\varphi_{Alv}(x,y) = A\left(\frac{1}{3}x^3 + xy^2\right)$$

$$\varphi_{Inv}(x,y) = -A\left(\frac{1}{3}x^3 + xy^2\right)$$

$$f(d) = \frac{1}{4Ad}$$

Alvarez lens



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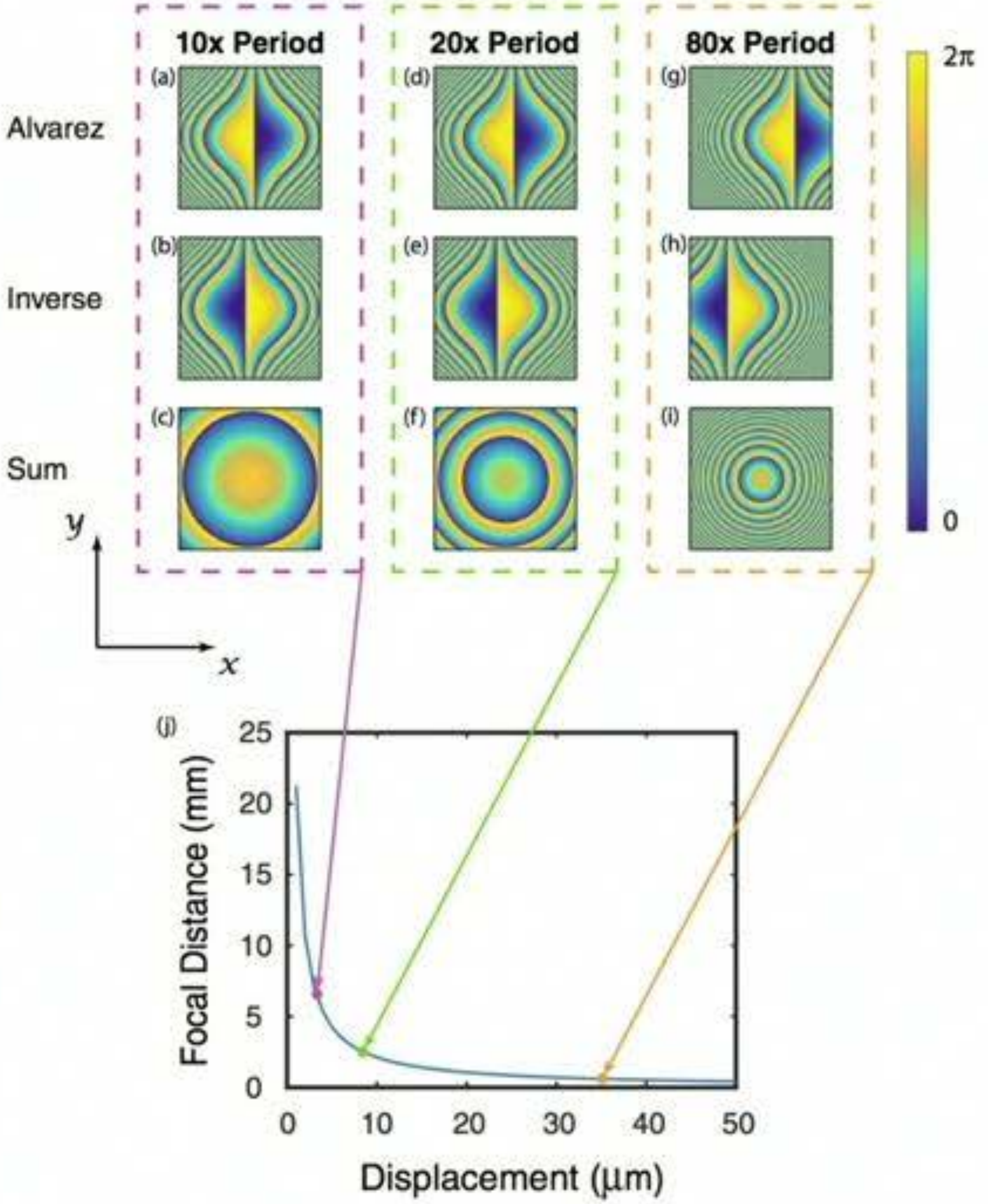
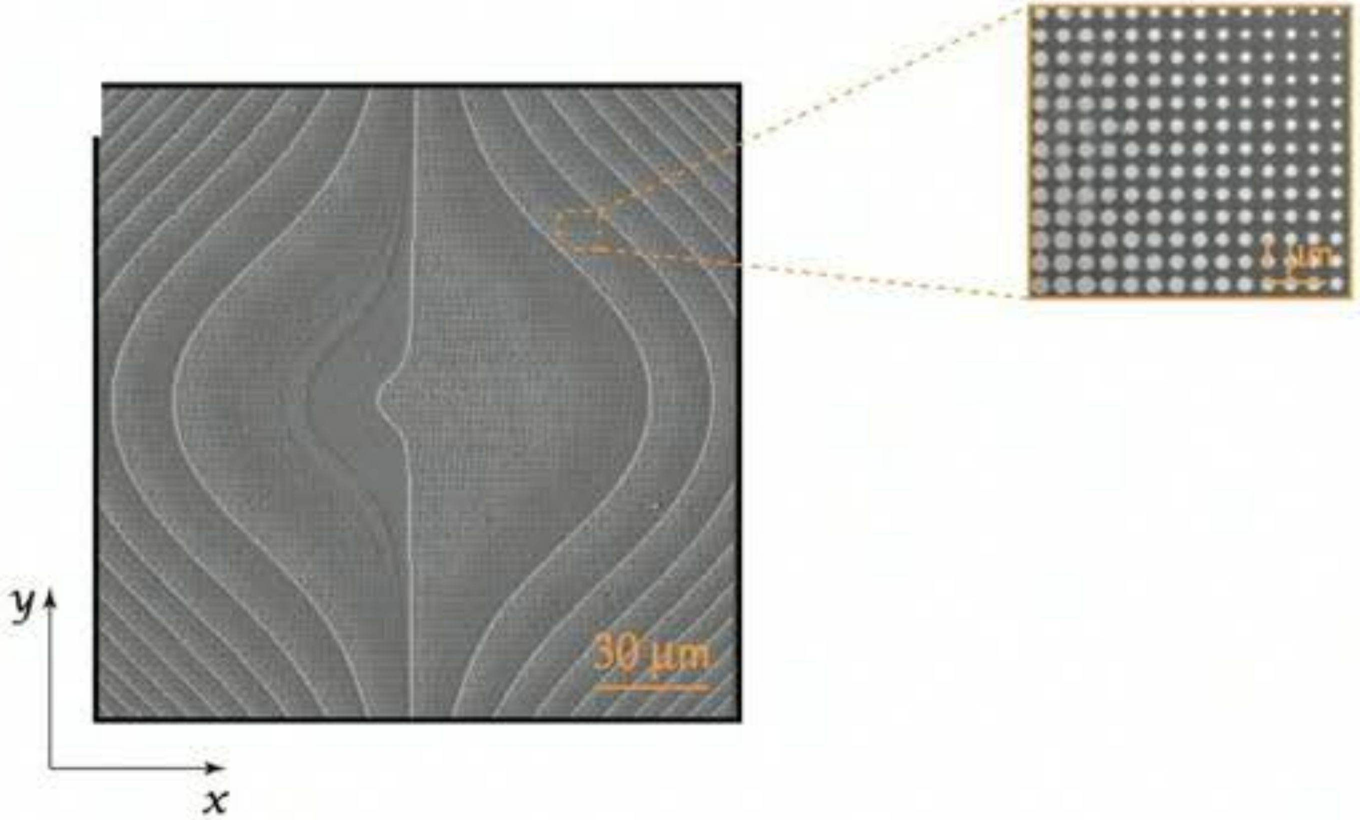
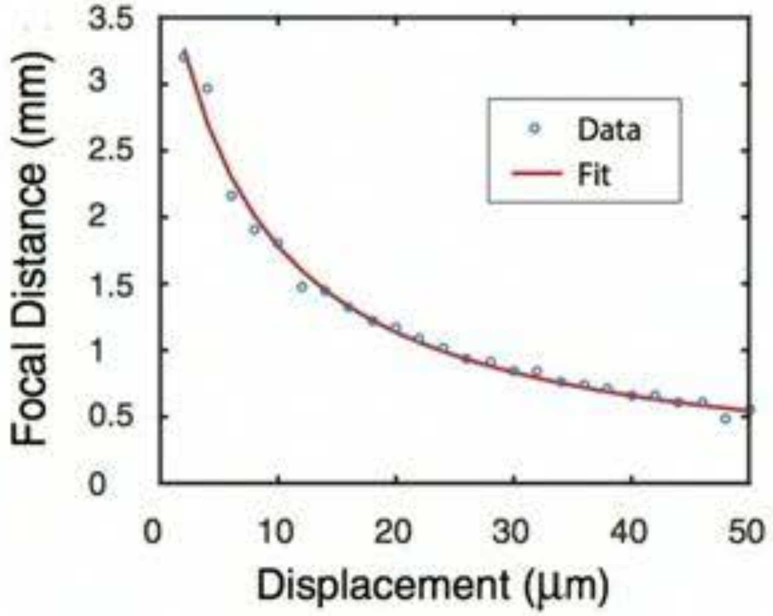
A. Zhan et al, Scientific Reports. **7**, 1 (2017).



Alvarez lens

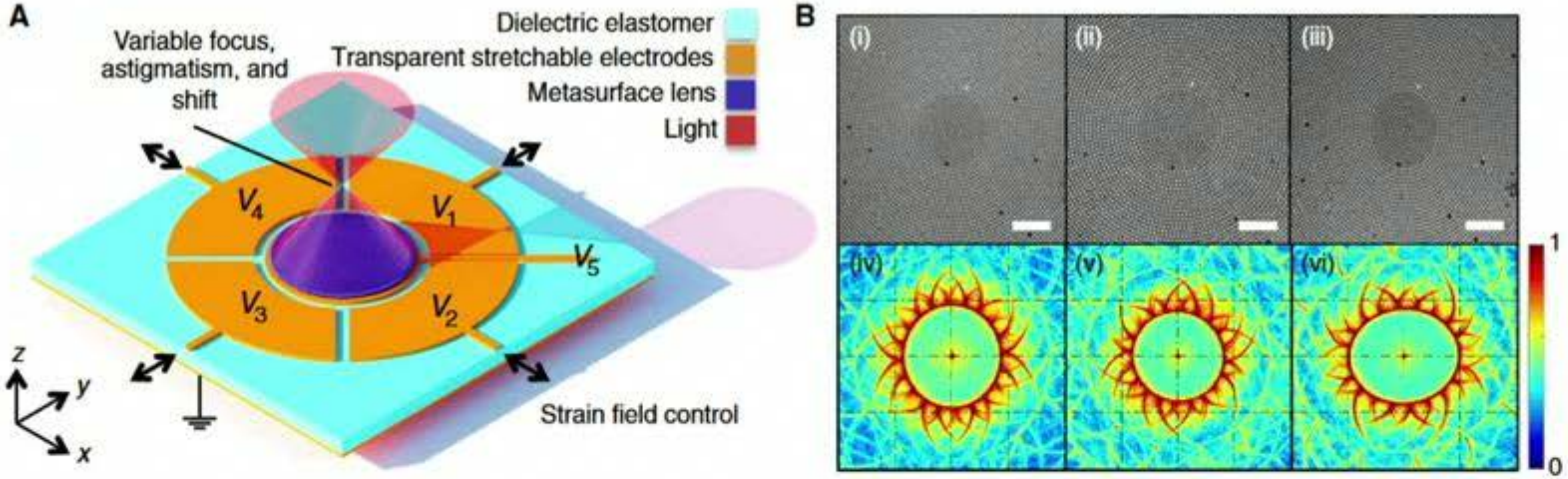




A. Zhan et al, Scientific Reports. **7**, 1 (2017).

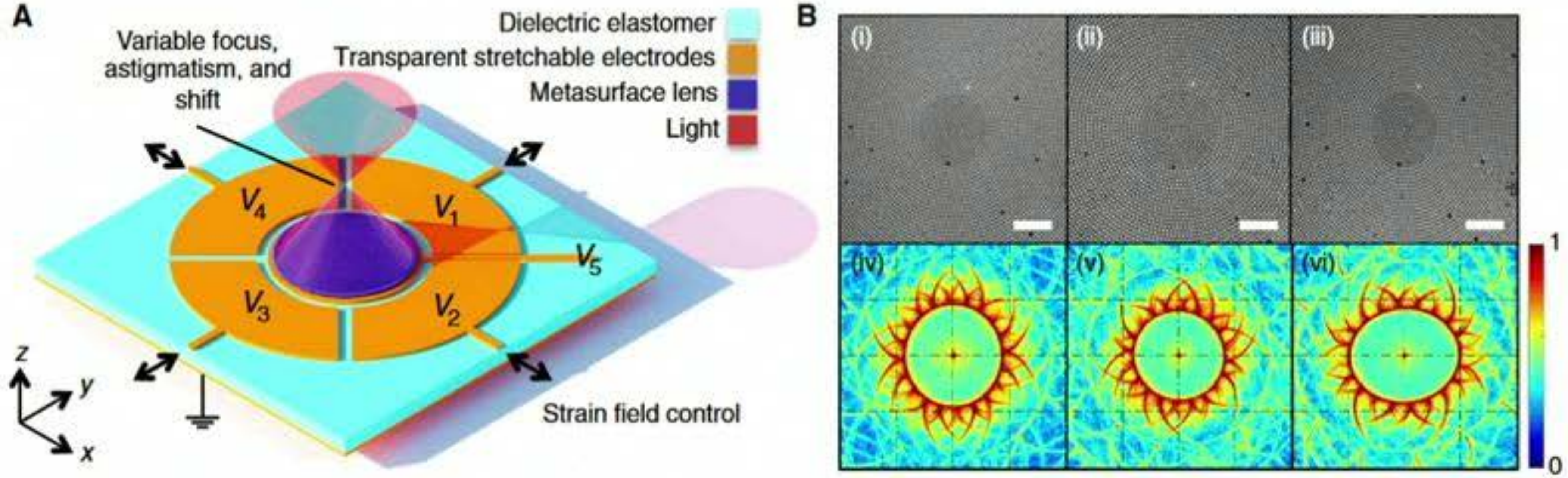
Other tunable systems

Other tunable systems

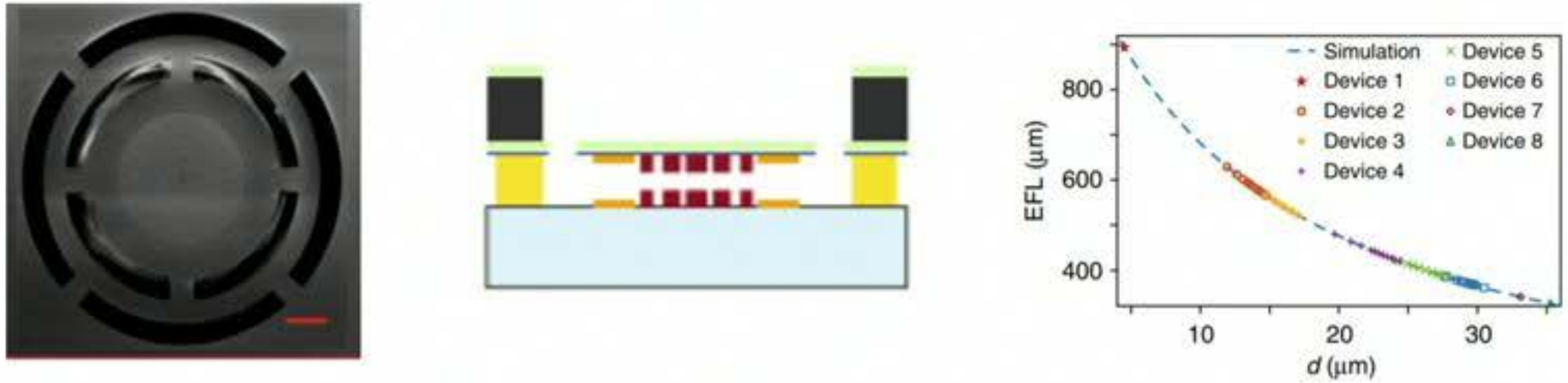


A. She et al, Science Advances. **4**, 2 eaap9957 (2018)

Other tunable systems



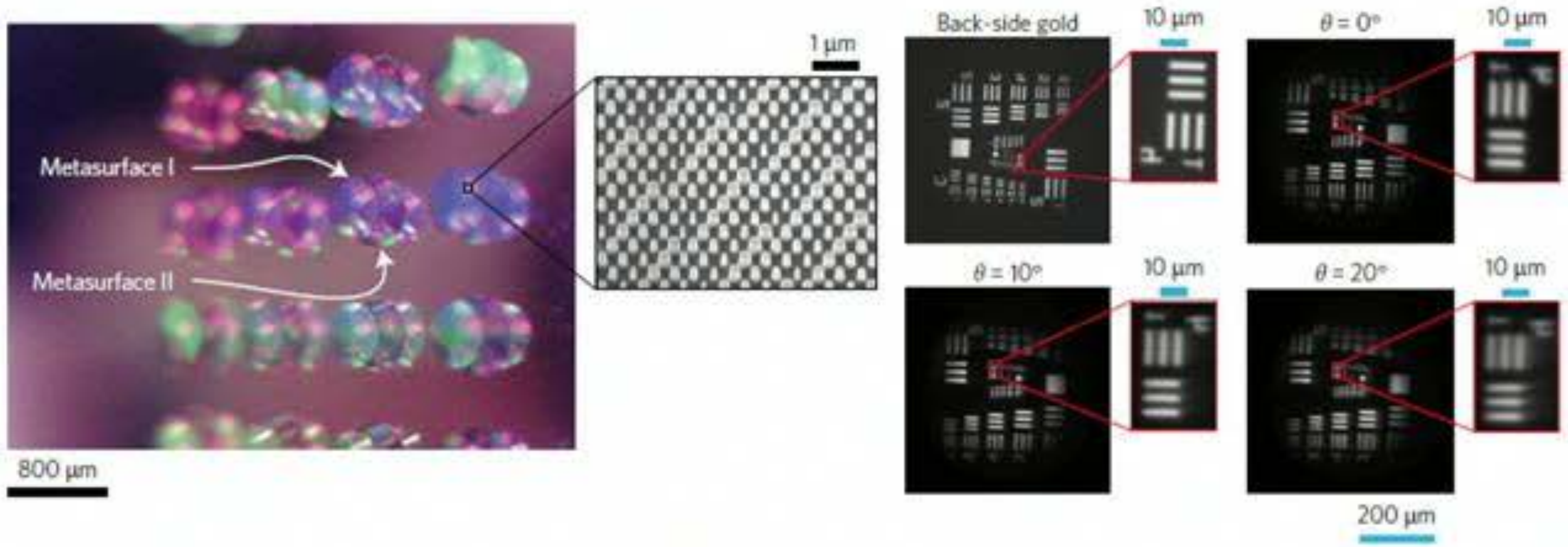
A. She et al, Science Advances. **4**, 2 eaap9957 (2018)



A. Arbabi et al, Nature Communications. **9**, 812 (2018)

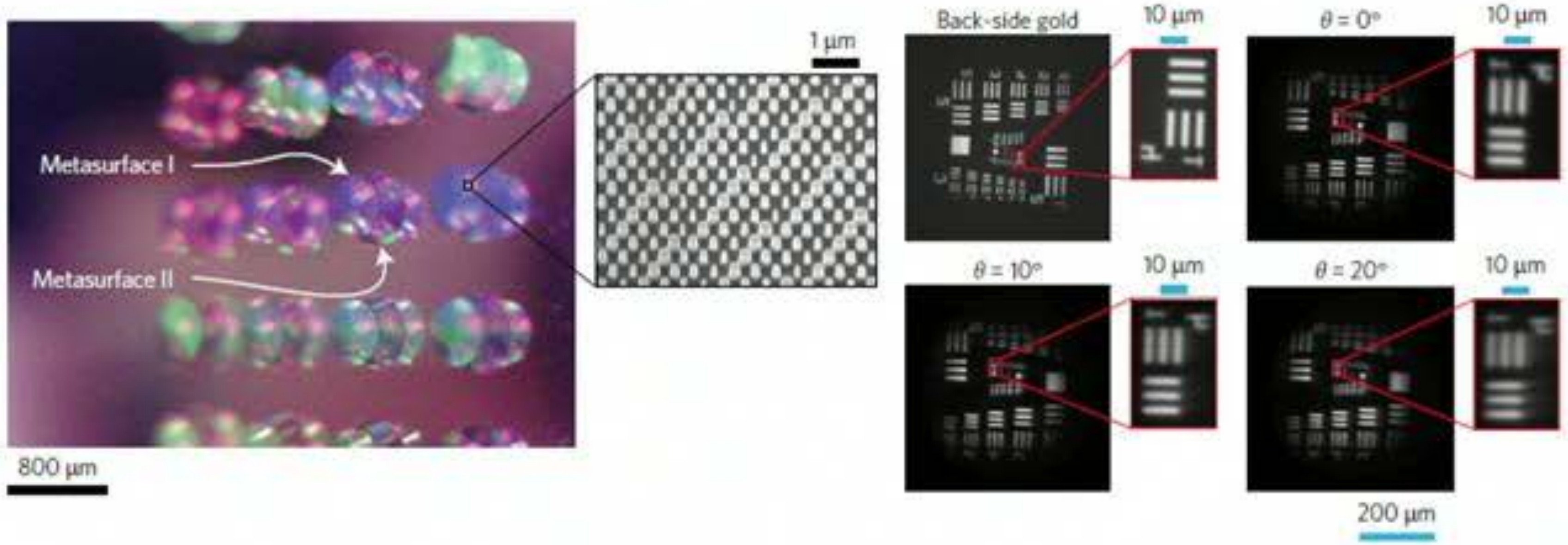
Systems for angular incidence

Systems for angular incidence

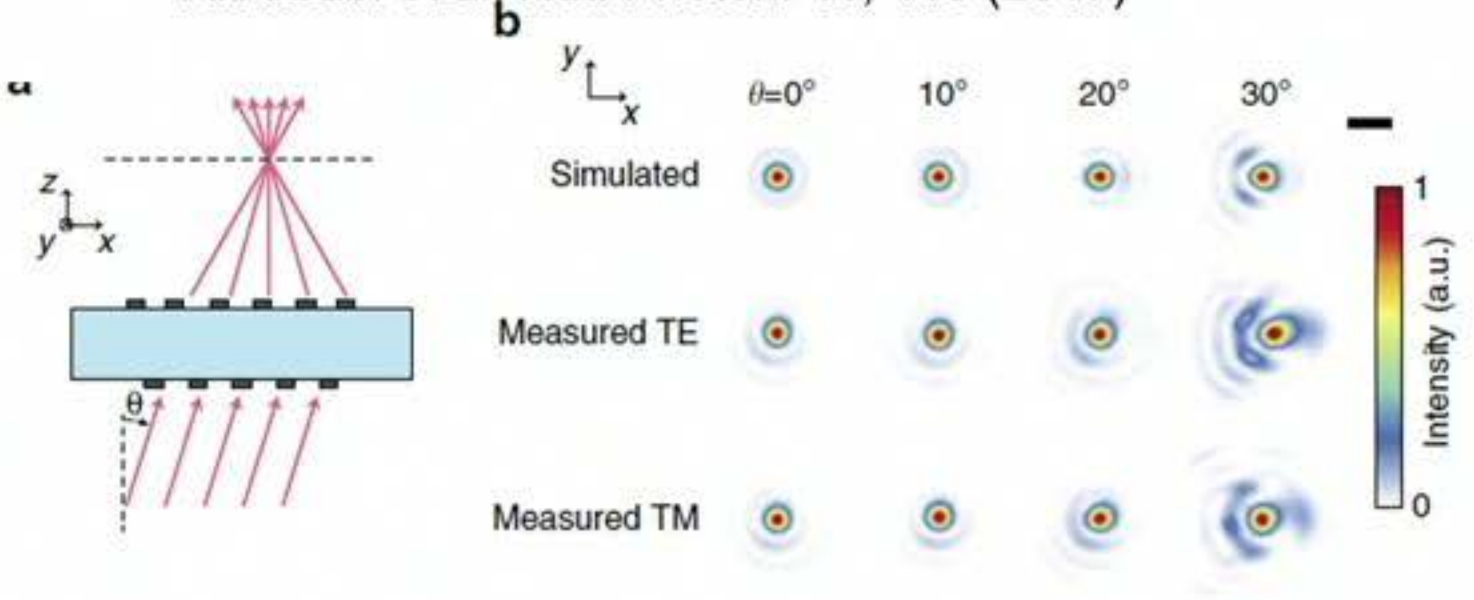


A. Arbabi et al, Nat. Photon. **11**, 415 (2017)

Systems for angular incidence

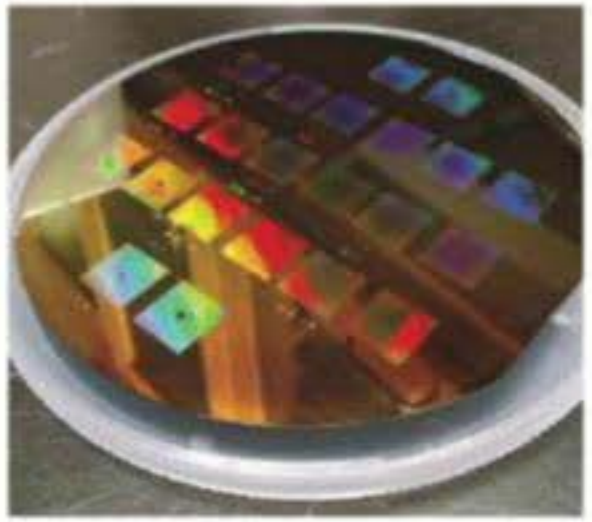


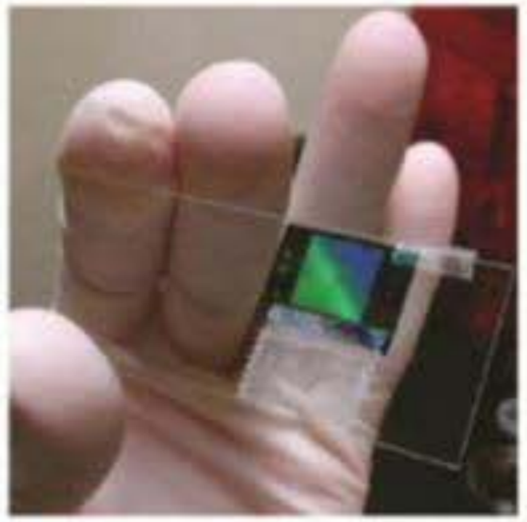
A. Arbabi et al, Nat. Photon. **11**, 415 (2017)

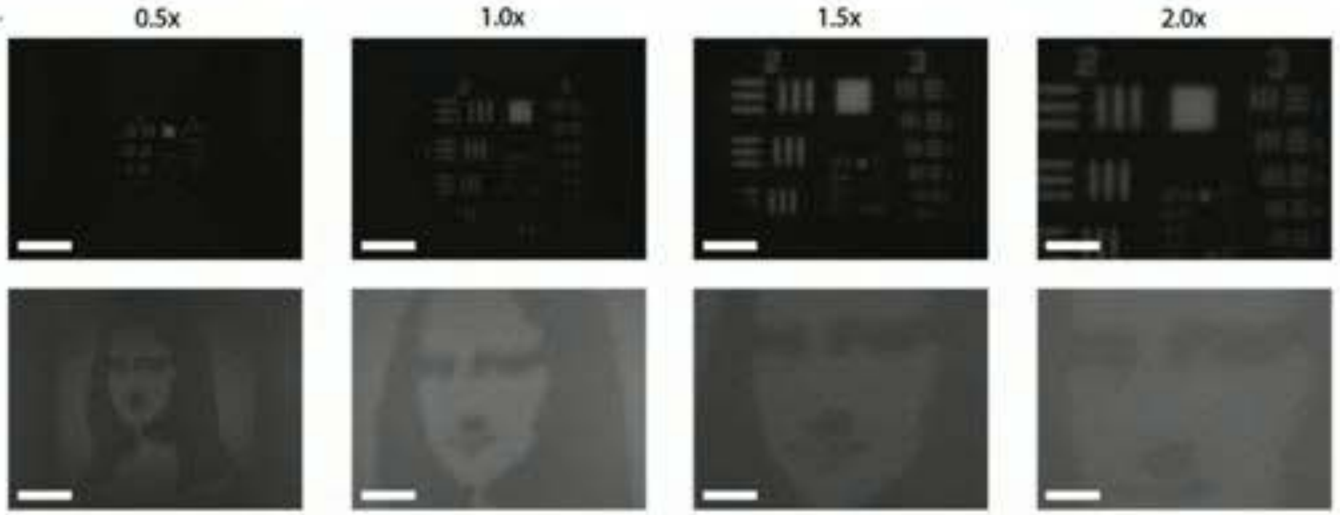


A. Arbabi et al, Nat. Comm. **7**, 13862 (2017)

Large area design

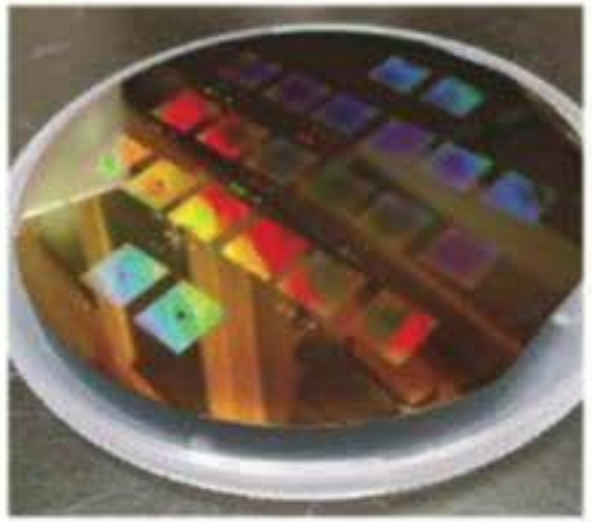


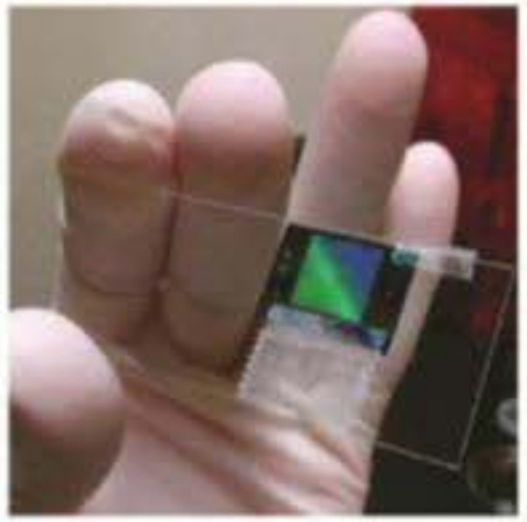


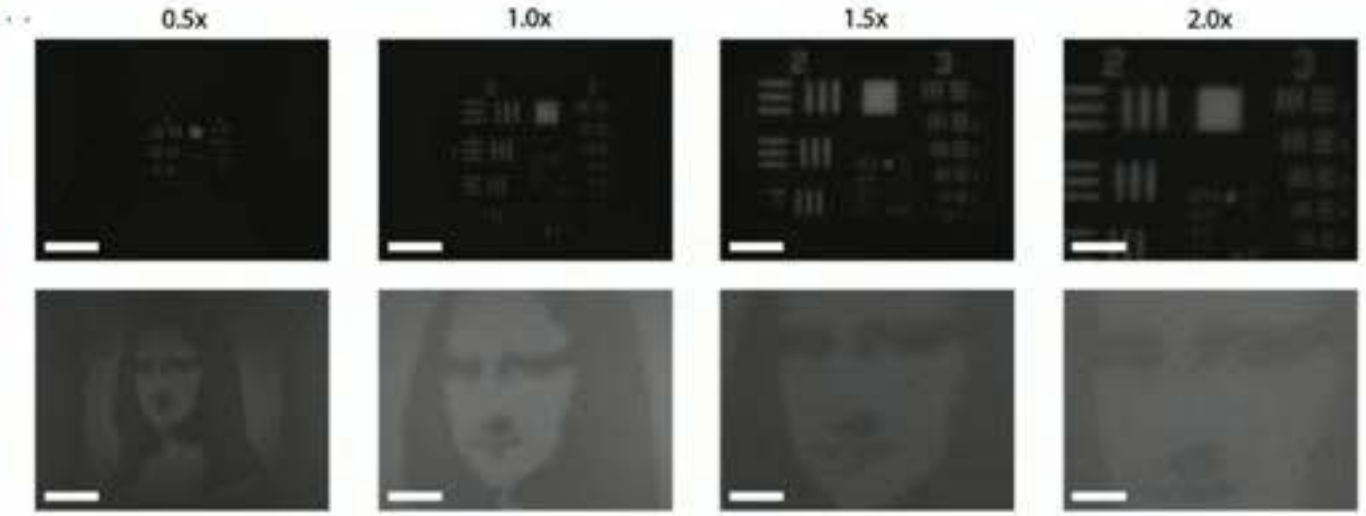


S. Colburn et al. Optica **5**, 7 (2018)

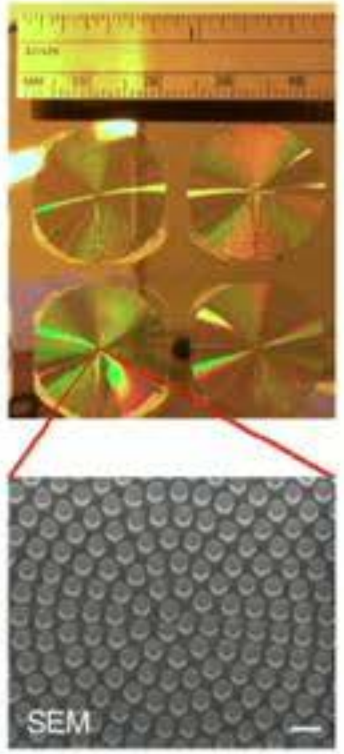
Large area design

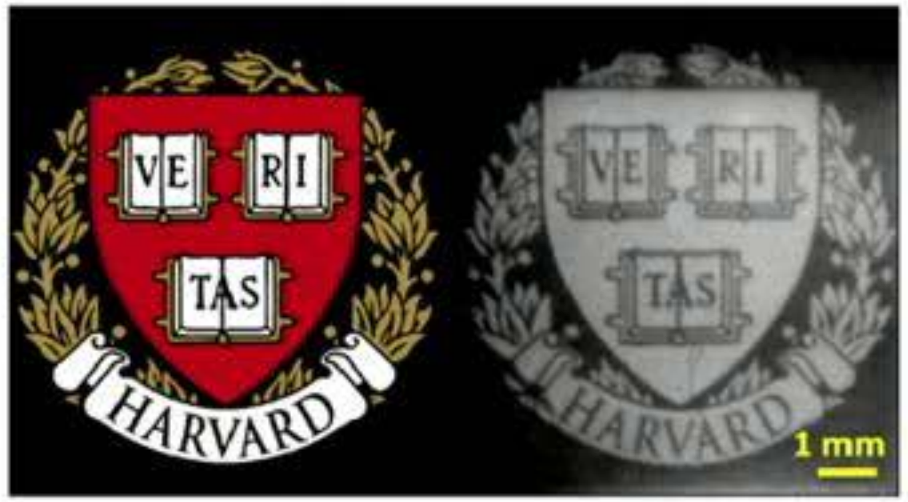


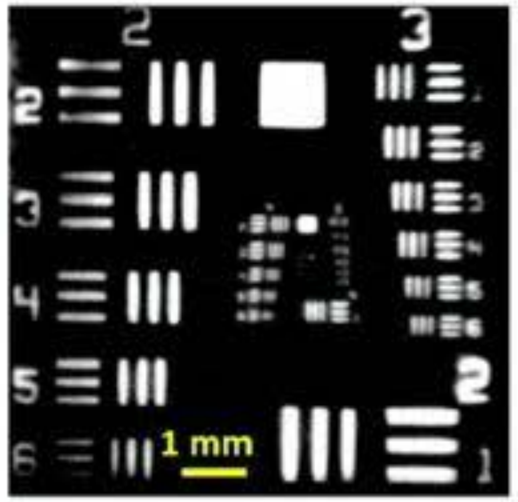




S. Colburn et al. Optica **5**, 7 (2018)







A. She et al. Optics Express **26**, 2 (2018)

Agenda

1. Single element metasurface optics
2. Towards metasurface optical systems
3. **Inverse design and optimization of metasurfaces**
4. Future work and outlook

The design problem

Forward design

Intuition based

The design problem

Forward design

Intuition based

Scatterers → Functionality

Inverse design

Computation based

Functionality → Scatterers

The design problem

Inverse design

Computation based

Functionality ⟶ Scatterers

Implementation

Formulated as a non-linear optimization problem:

Implementation

Formulated as a non-linear optimization problem:

Given some figure of merit $f(x(p))$ find some set of parameters p that minimizes $f(x(p))$ while $x(p)$ is constrained to solve the equation $A(p)x(p) = y(p)$

Implementation

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Given some figure of merit $f(x(p))$ find some set of parameters p that minimizes $f(x(p))$ while $x(p)$ is constrained to solve the equation $A(p)x(p) = y(p)$

In general, a gradient based solution is used

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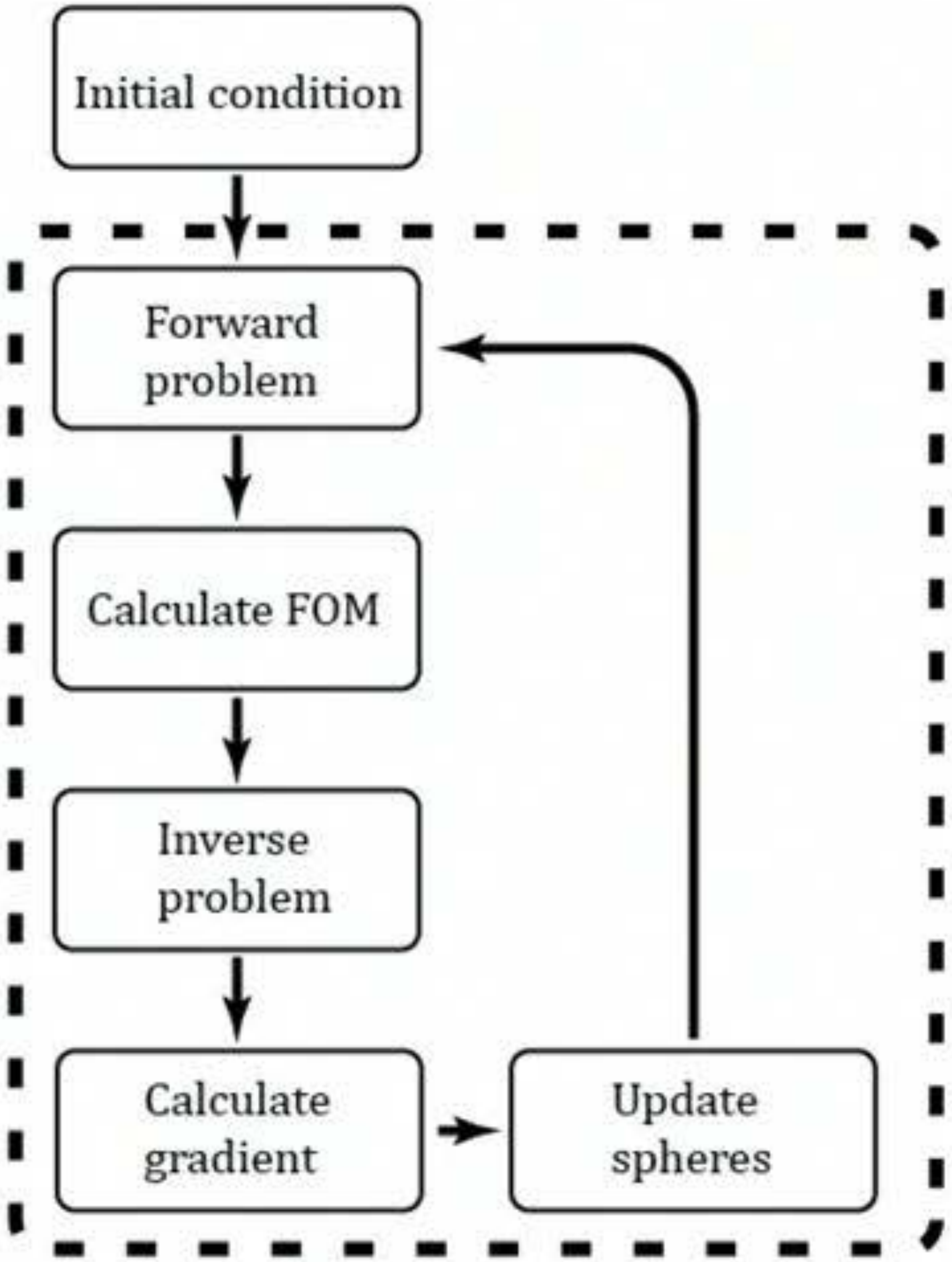
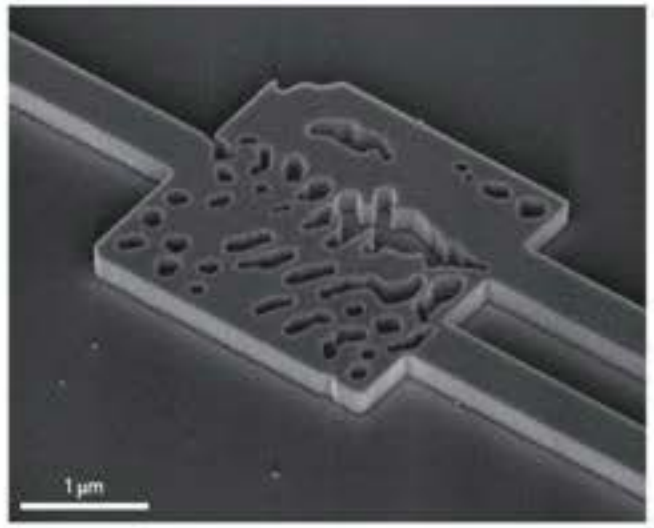
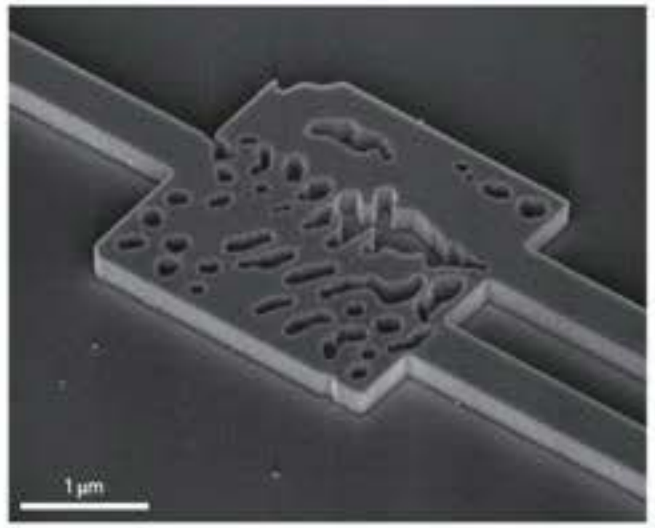


Inverse design based on Maxwell's equations



Piggot et al. Nat. Photon. **9**, 6 (2015)

Inverse design based on Maxwell's equations



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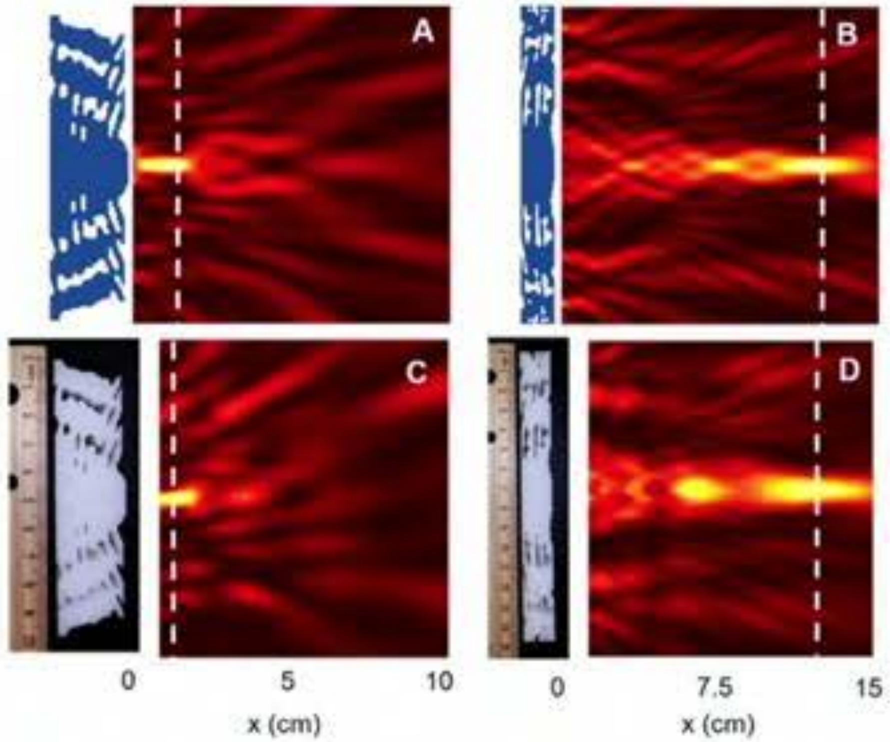

Callewaert et al. Appl. Phys. Lett. **112**, 91102 (2018)

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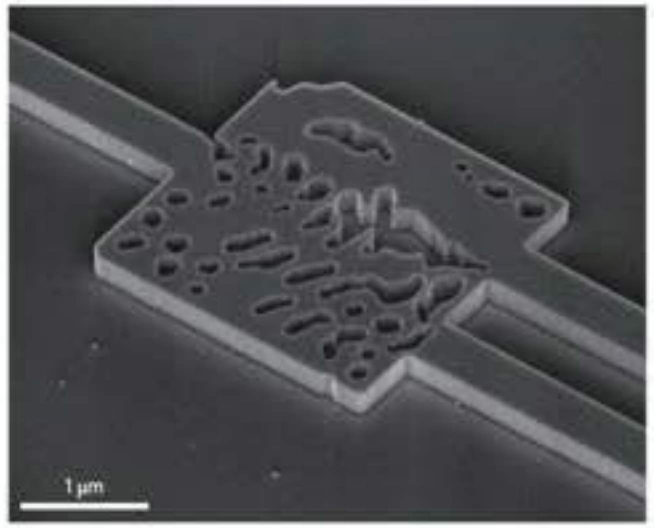
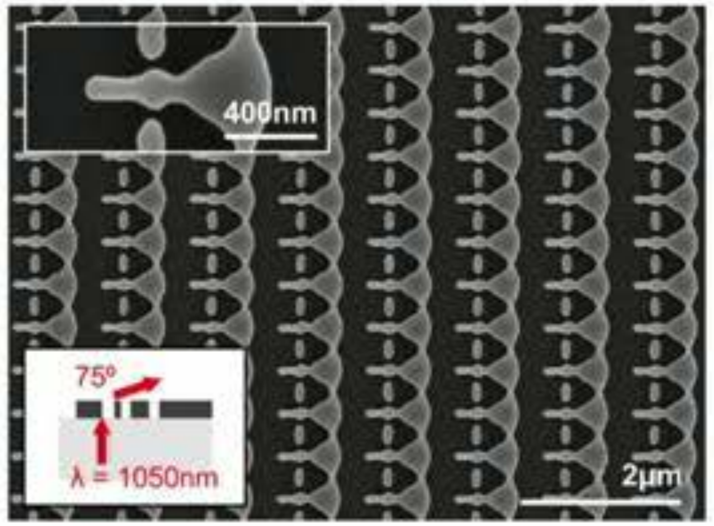
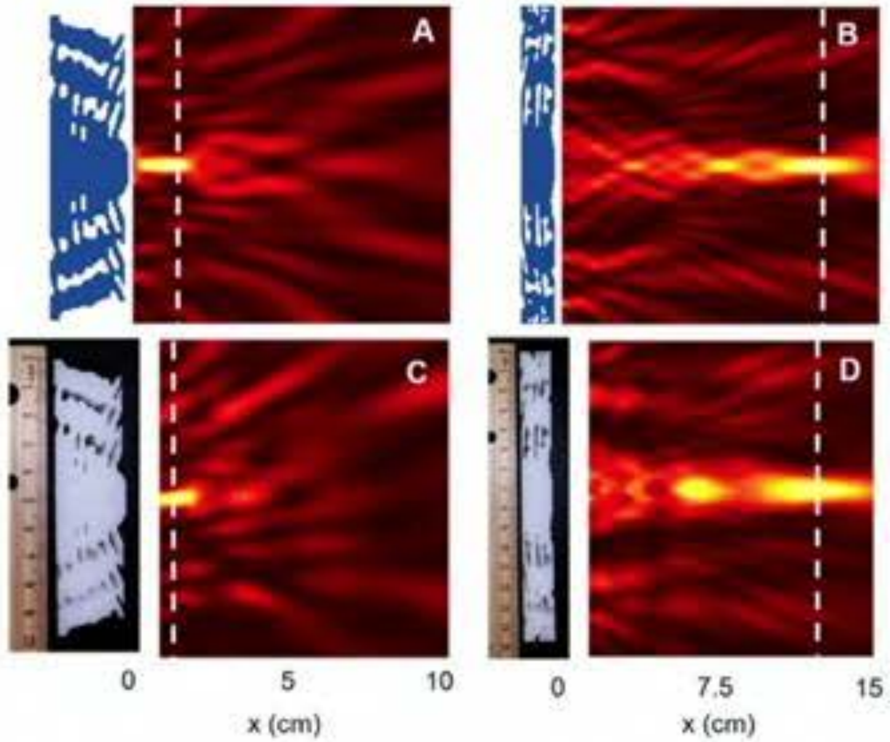
Inverse design based on Maxwell's equations

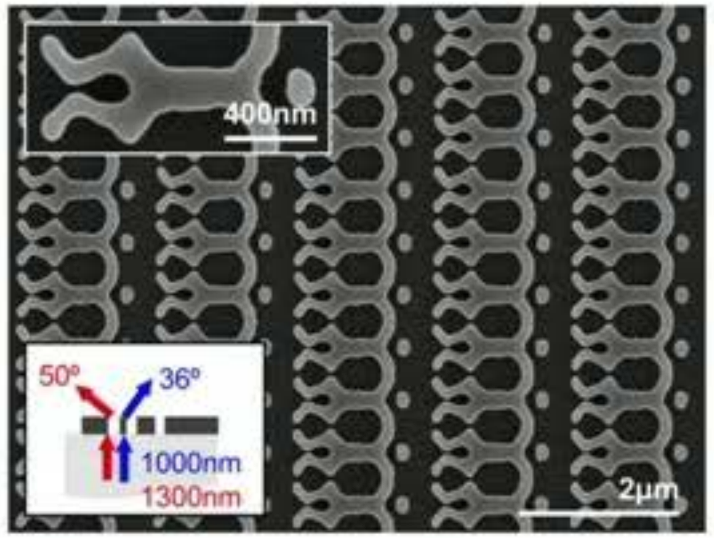


Piggot et al. Nat. Photon. **9**, 6 (2015)





Callewaert et al. Appl. Phys. Lett. **112**, 91102 (2018)



Sell et al. Nano Lett. **17**, 6 (2017)

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Finite difference methods

Time Domain

$$\nabla \cdot (\epsilon \mathbf{E}) = \rho_f$$

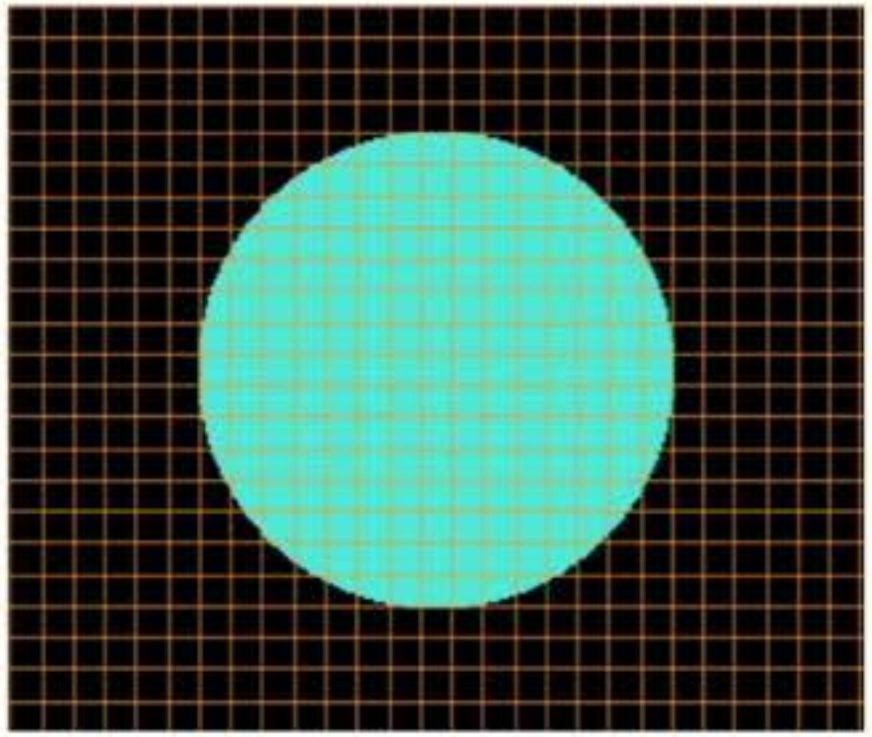
$$\nabla \cdot \mathbf{H} = 0$$

$$\nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial (\epsilon \mathbf{E})}{\partial t}$$

Frequency Domain

$$\nabla \times \nabla \times \mathbf{E} - \omega^2 \mu_0 \epsilon \mathbf{E} = -i\omega\mu_0 \mathbf{J}_f$$



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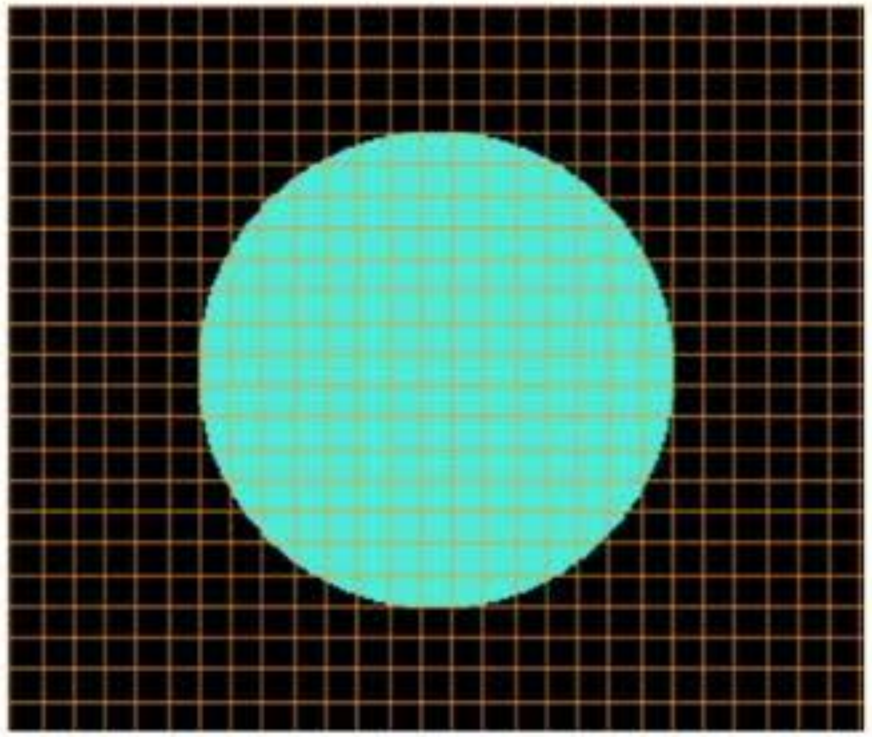
$$\nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial (\epsilon \mathbf{E})}{\partial t}$$



Frequency Domain

$$\nabla \times \nabla \times \mathbf{E} - \omega^2 \mu_0 \epsilon \mathbf{E} = -i\omega\mu_0 \mathbf{J}_f$$

Problem: Memory scales with the volume of the system!

Towards large scale optimization

Two main challenges:

Towards large scale optimization

Two main challenges:

1. **Fast and memory efficient simulation method**

Towards large scale optimization

Two main challenges:

1. **Fast and memory efficient simulation method**
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The idea:

Achieve both with an analytical scattering theory, namely the generalized multi-sphere Mie method (GMMT)

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Solving GMMT

celes

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$$M(\boldsymbol{R})b(\boldsymbol{R}) = T(\boldsymbol{R})a$$

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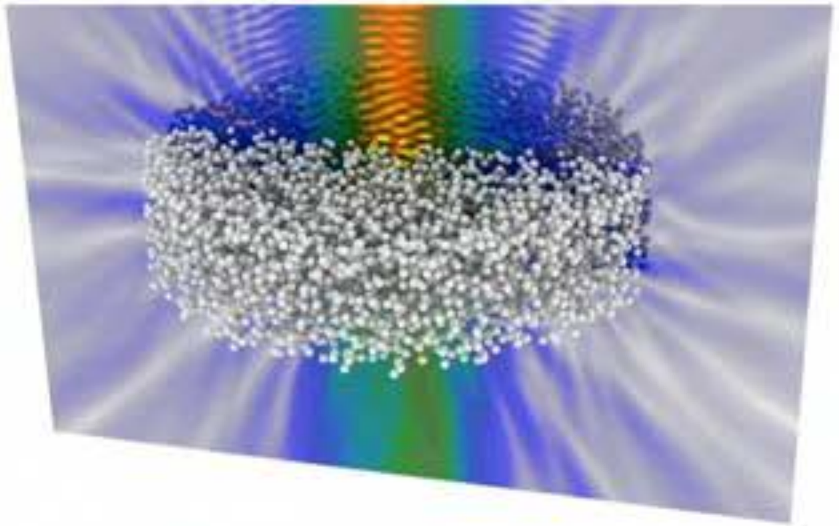
celes

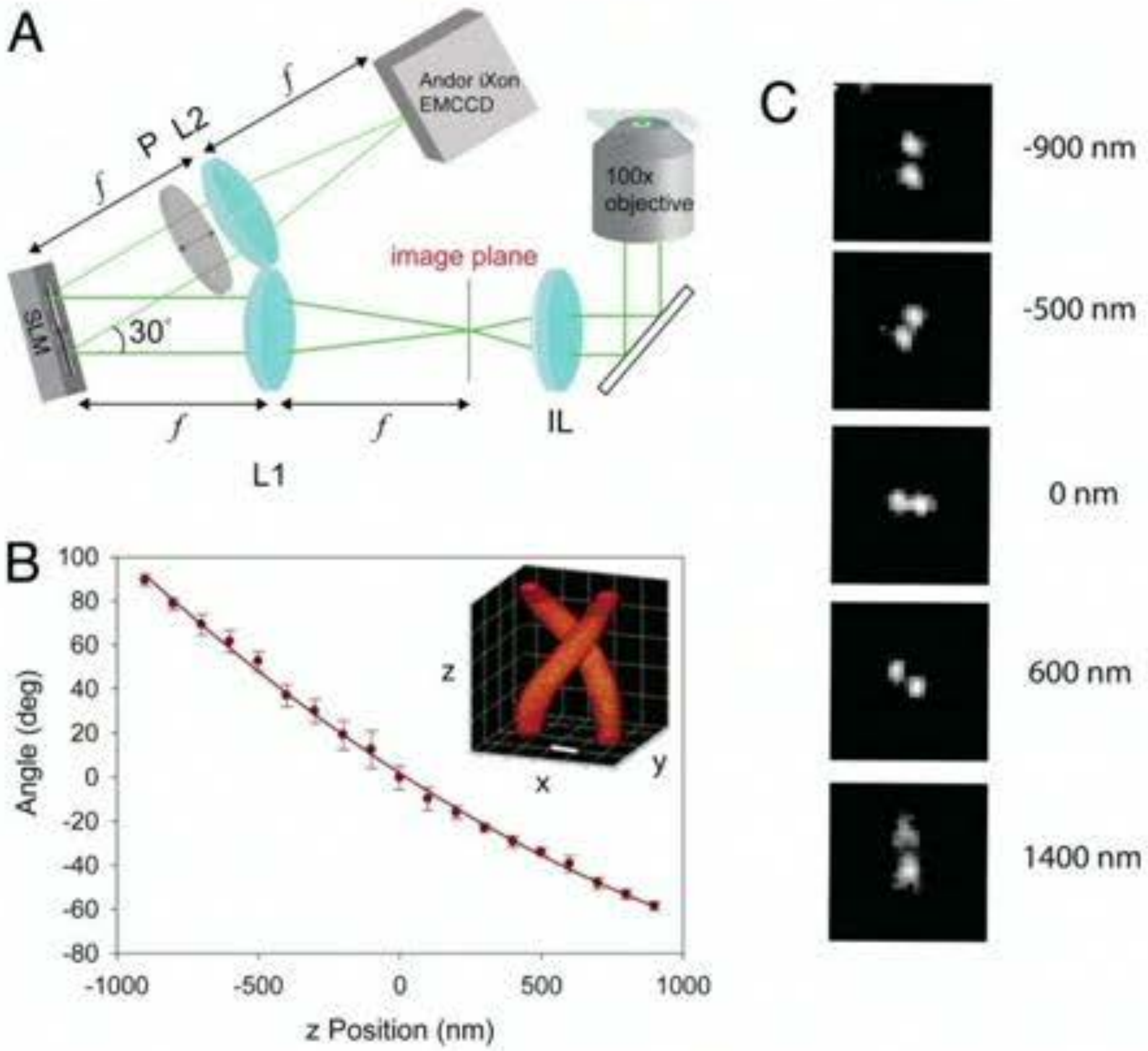


$$M(\boldsymbol{R})b(\boldsymbol{R}) = T(\boldsymbol{R})a$$

Egel et al. J of Quant. Spec and Rad. Trans. **199** (2017)

https://github.com/disordered-photonics/celes

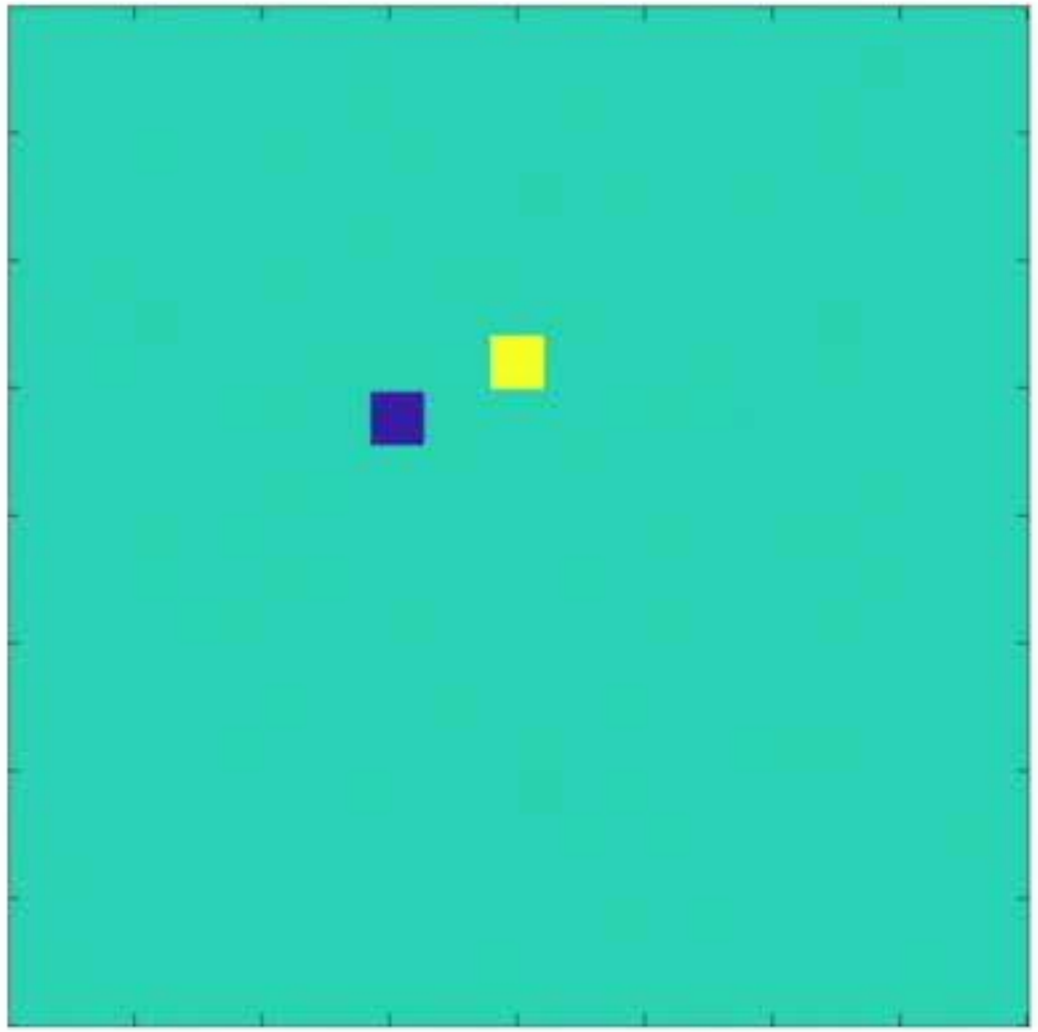
Depth-variant PSF



S. R. P. Pavani et al, PNAS **106**, 9 (2009).

Figure of merit

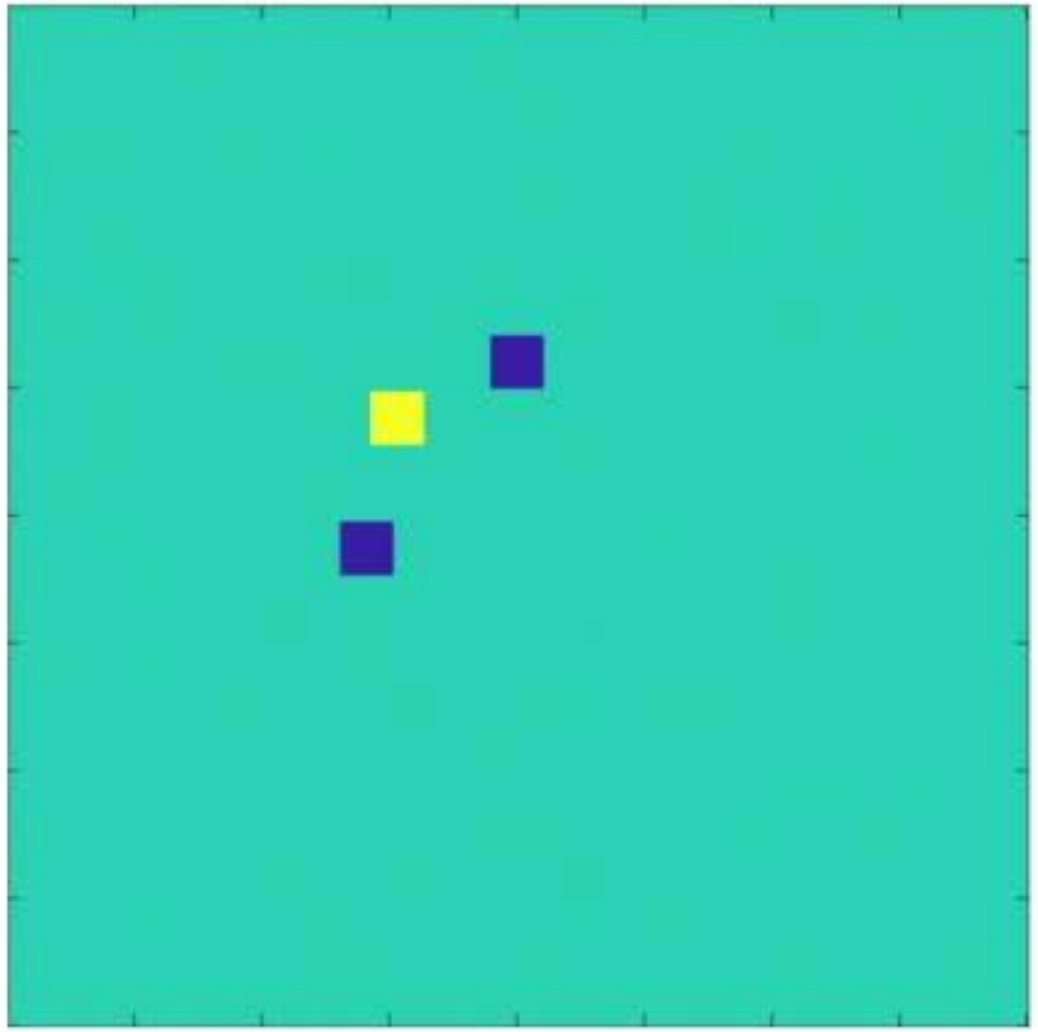
100 µm



Zhan et al. Under review

Figure of merit

128 µm



Zhan et al. Under review

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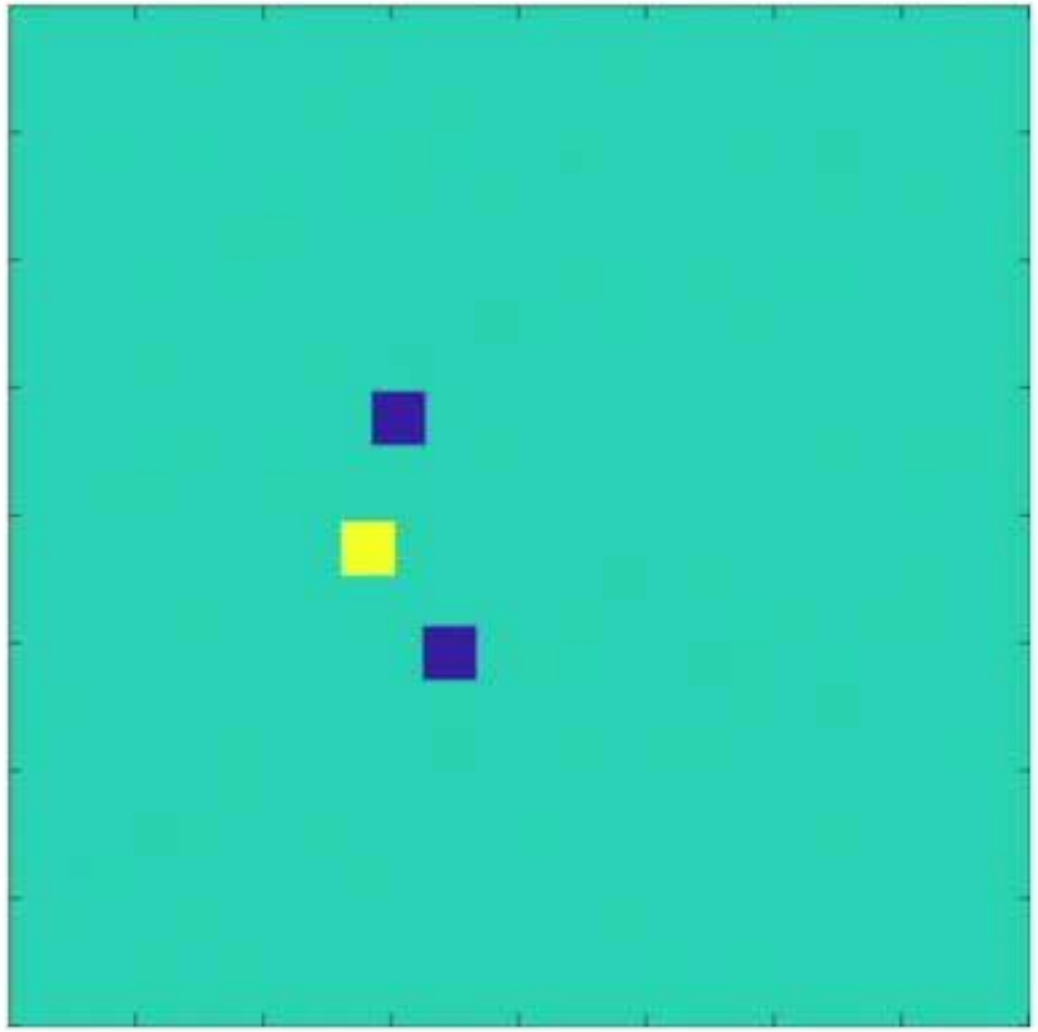
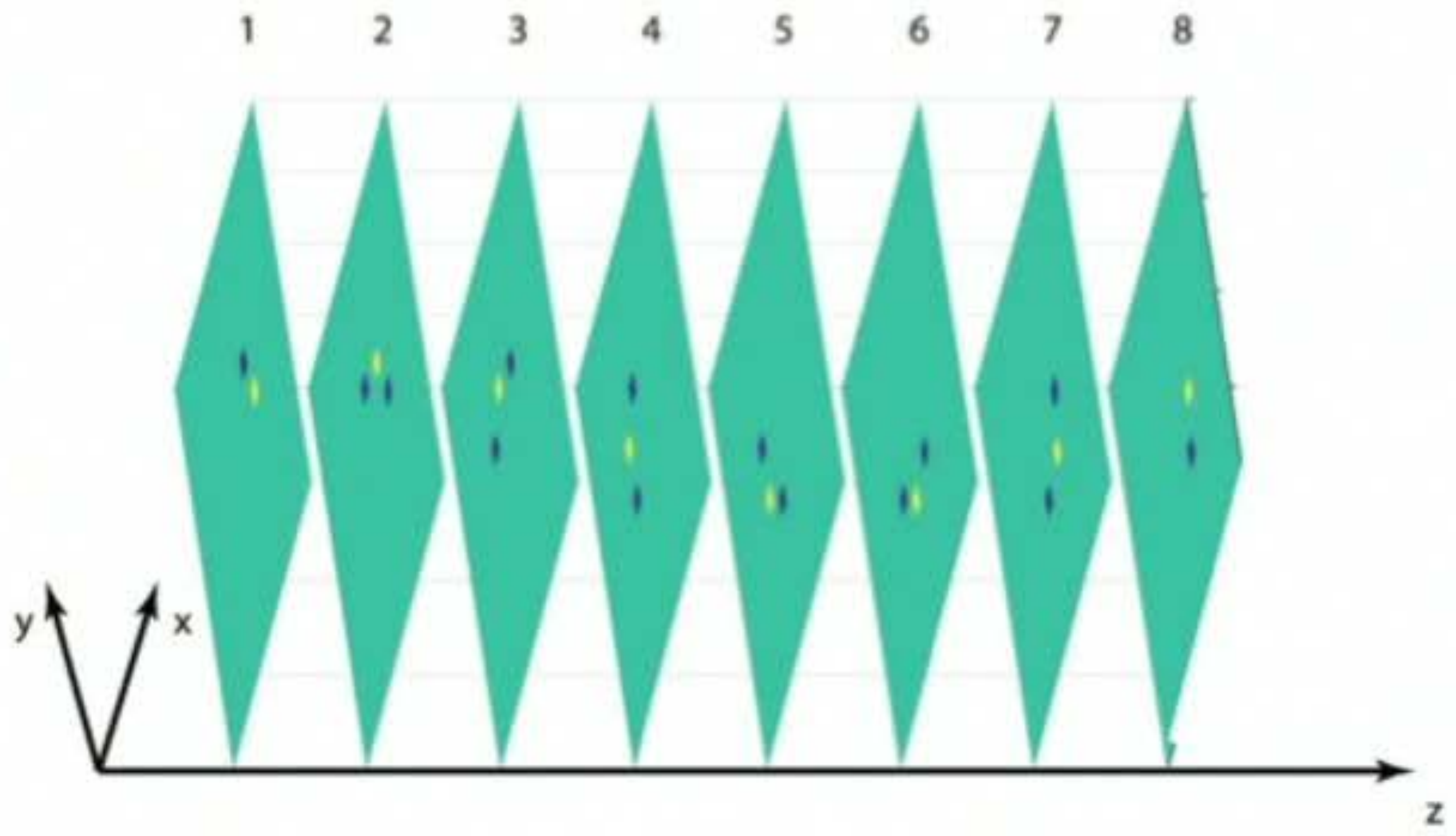
Figure of merit

157 µm



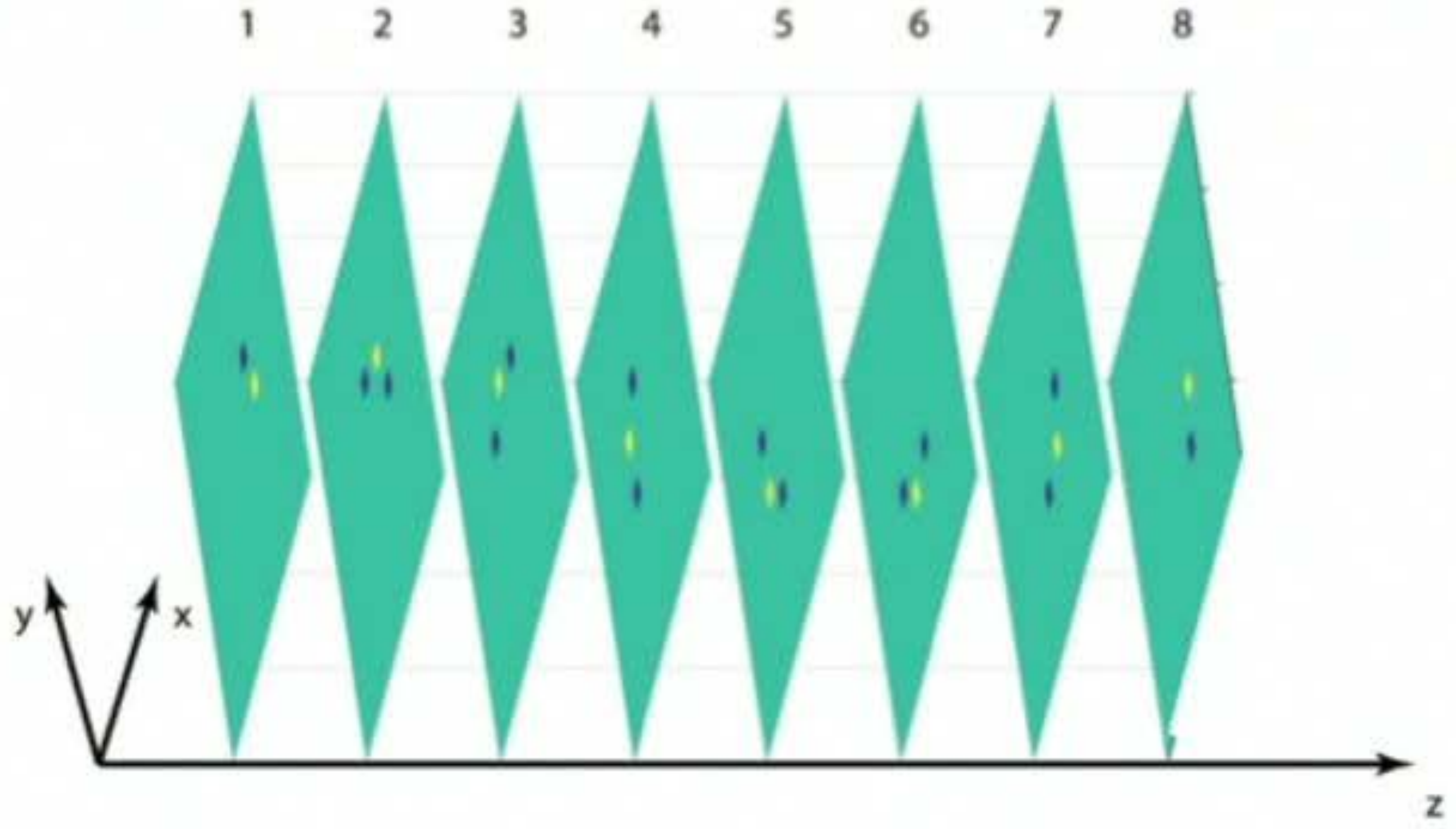
Zhan et al. Under review

Figure of merit definition



Zhan et al. Under review

Figure of merit definition



$$FOM_i = \sum_{j=1}^{8} (I_{yellow}(\mathbf{r}_j) - I_i(\mathbf{r}_j))^2 + \sum_{k=1}^{14} (I_{blue}(\mathbf{r}_k) - I_i(\mathbf{r}_k))^2$$

Zhan et al. Under review

Radius output

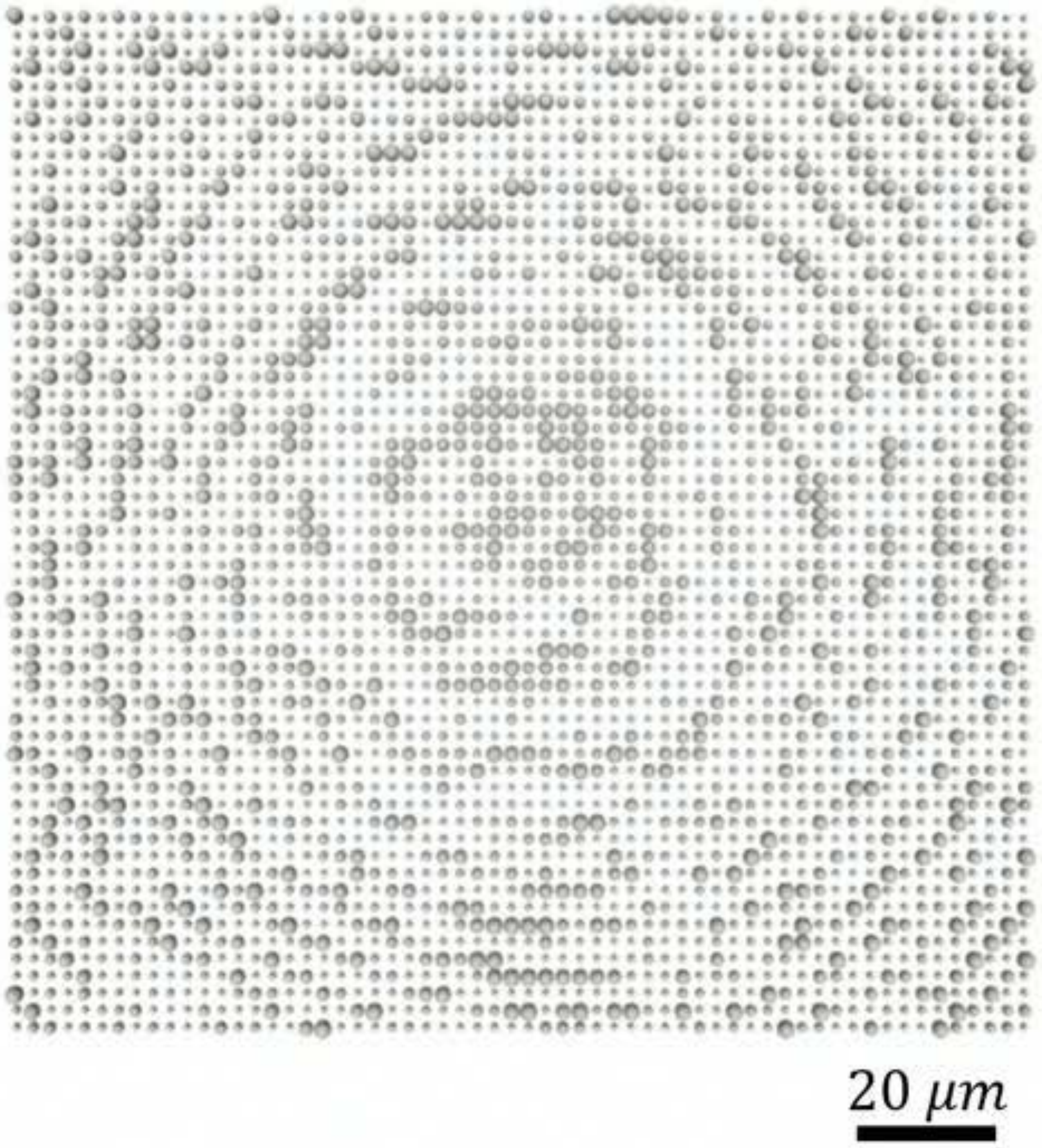


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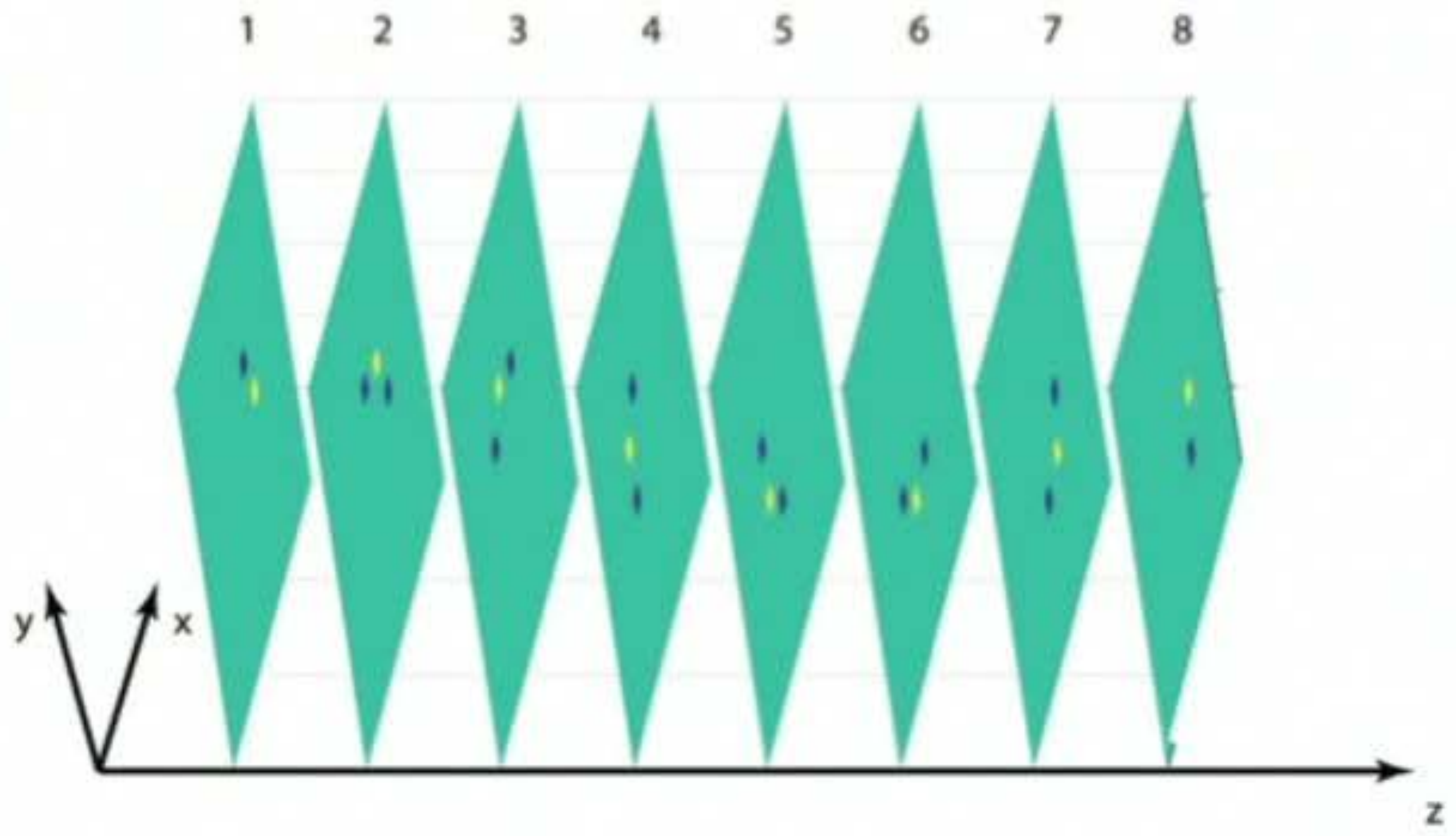
Figure of merit definition



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Zhan et al. Under review

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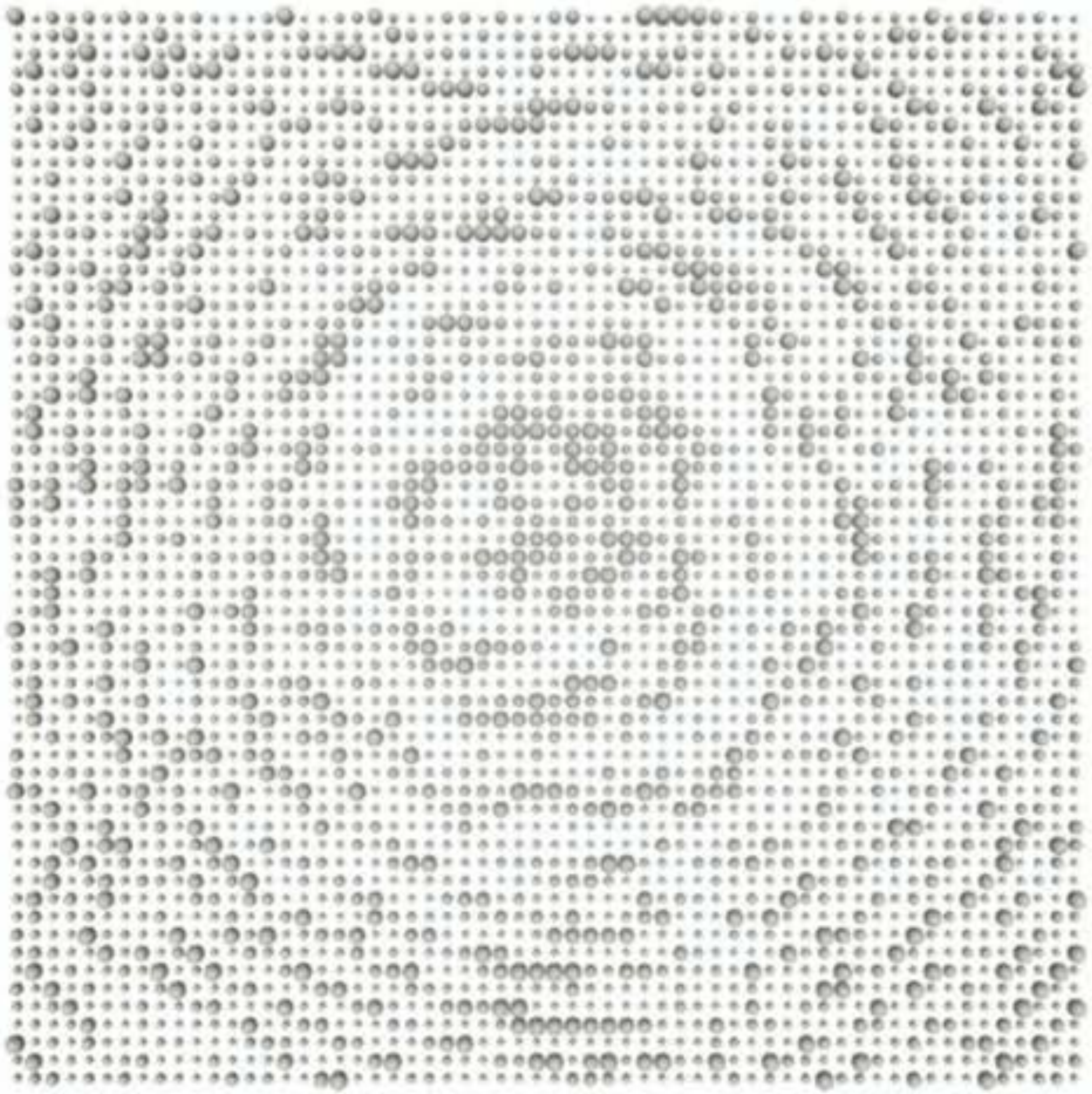

20 μm

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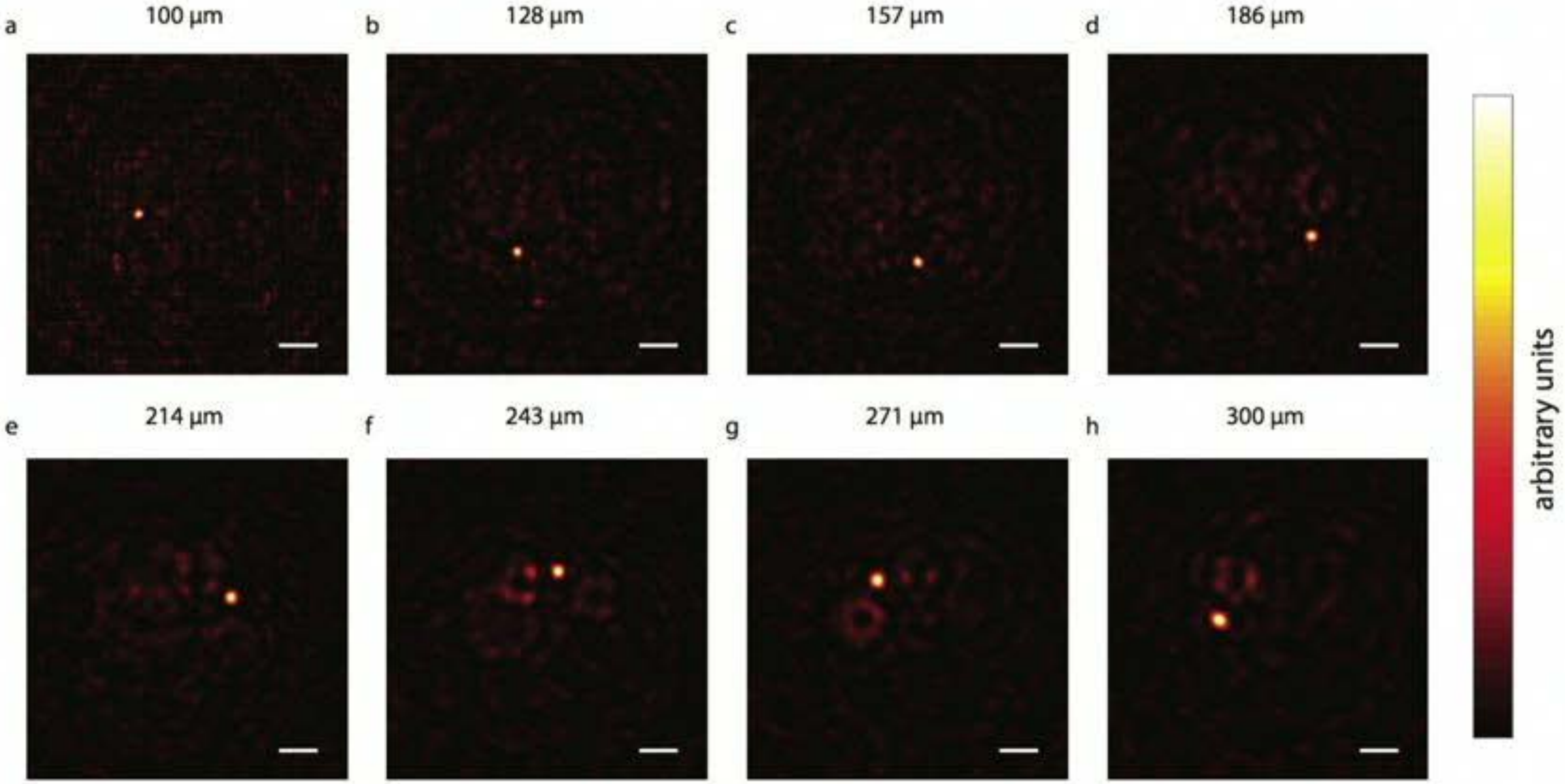
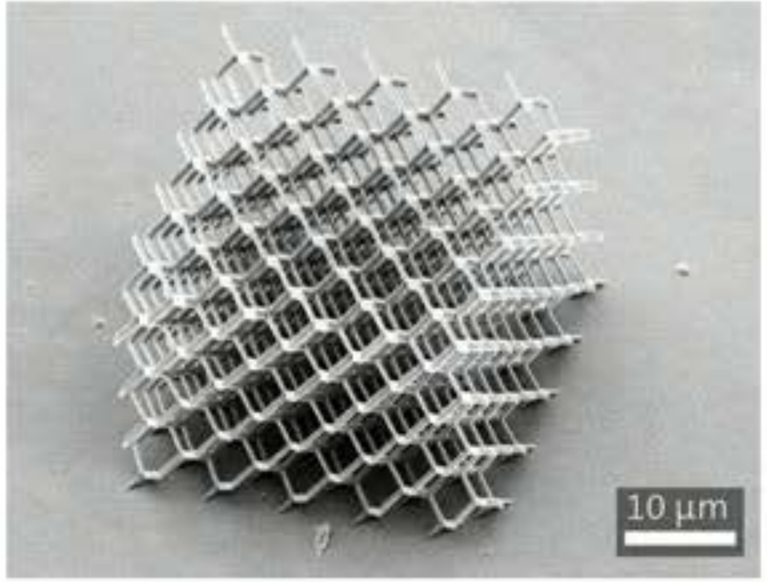
Simulation

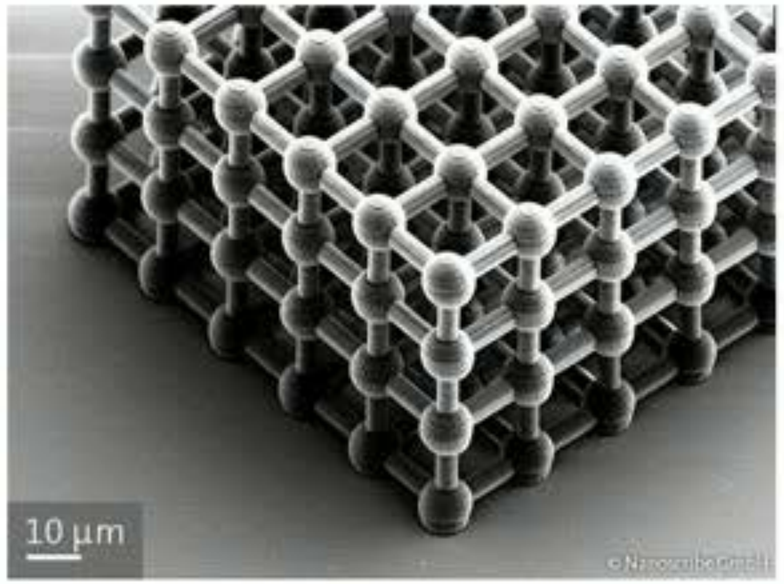


Scale bar 10 µm

Zhan et al. Under review

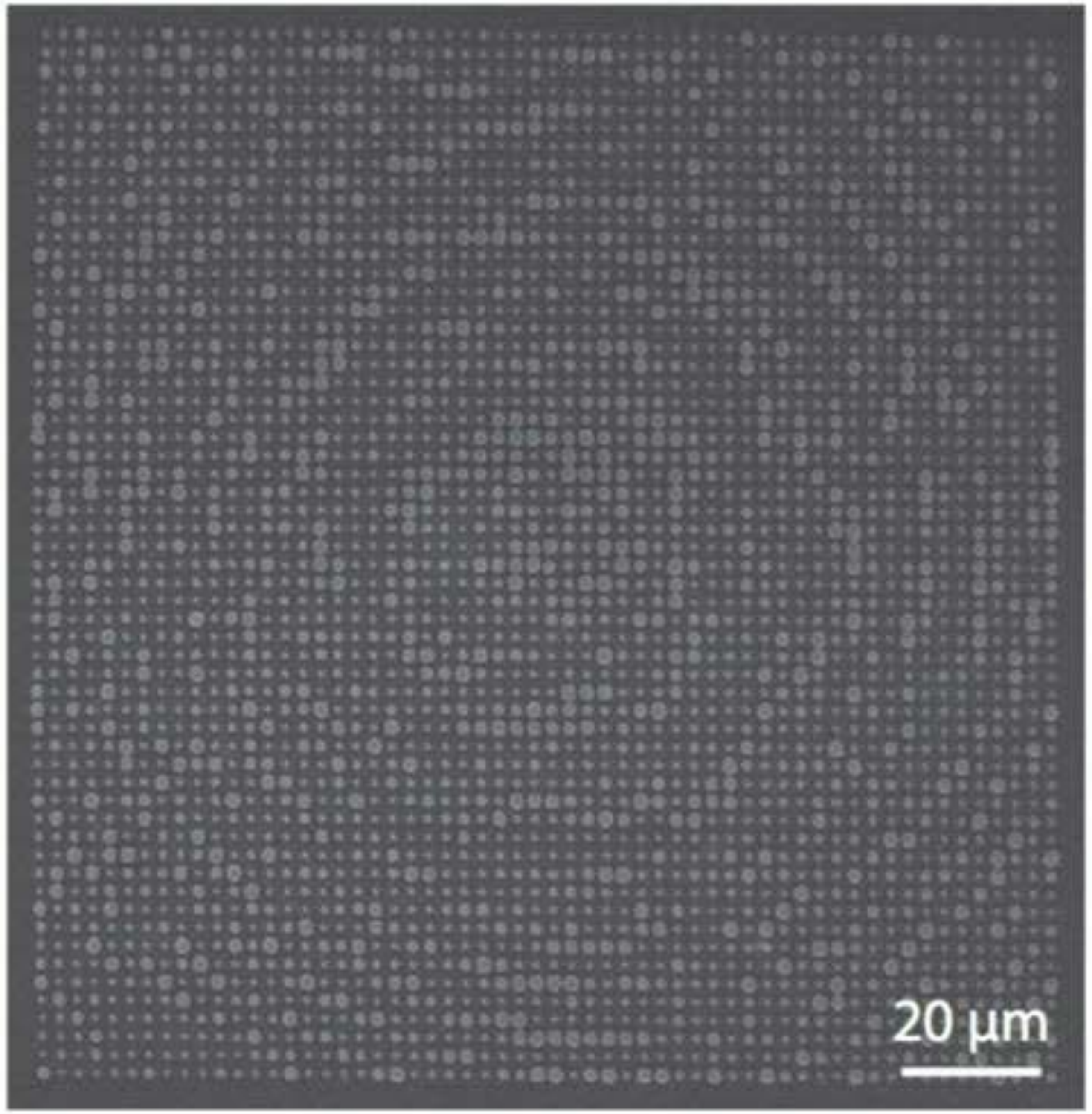
Nanoscribe GT

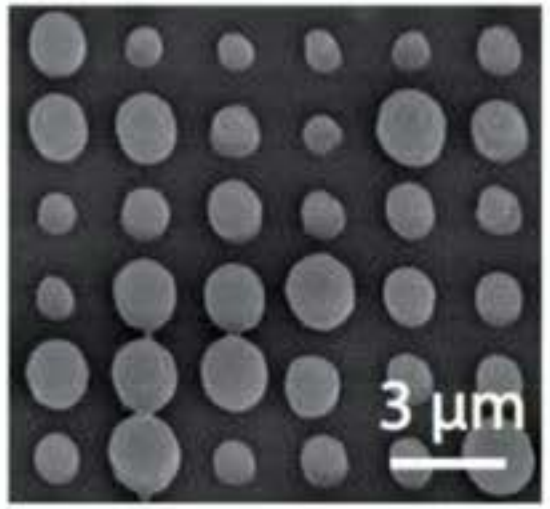


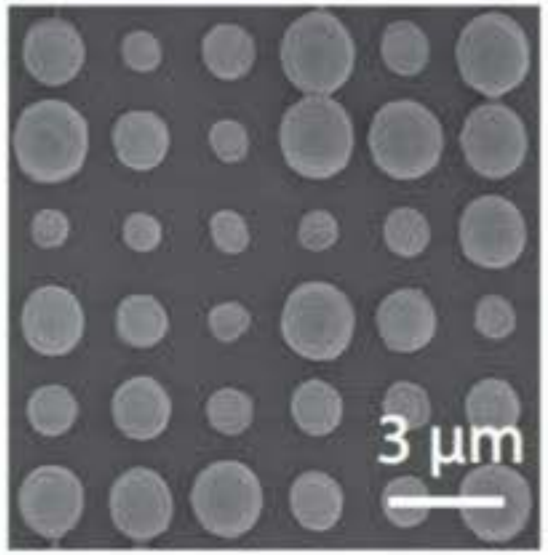


Images from Nanoscribe GmbH

Fabrication







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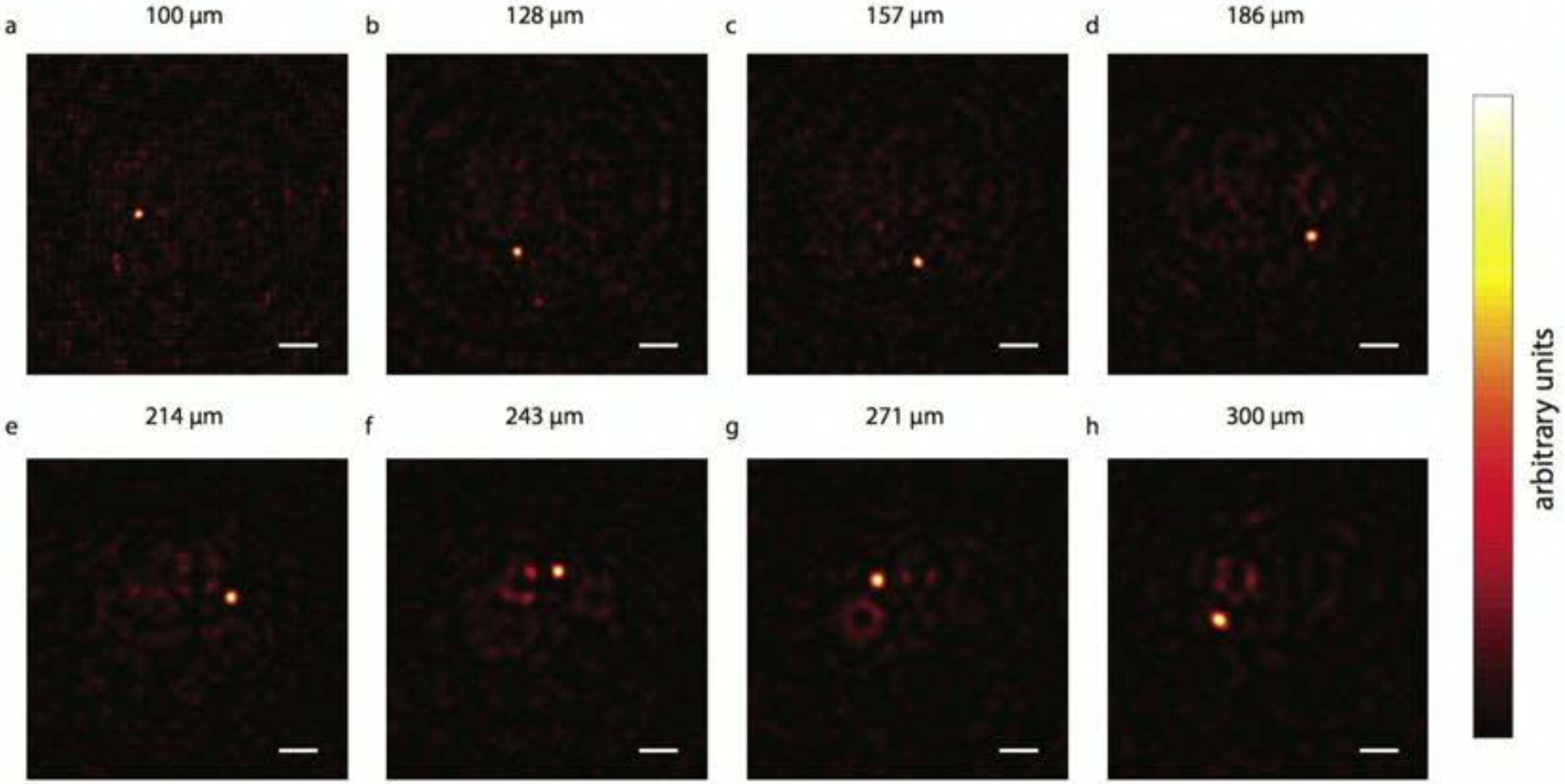
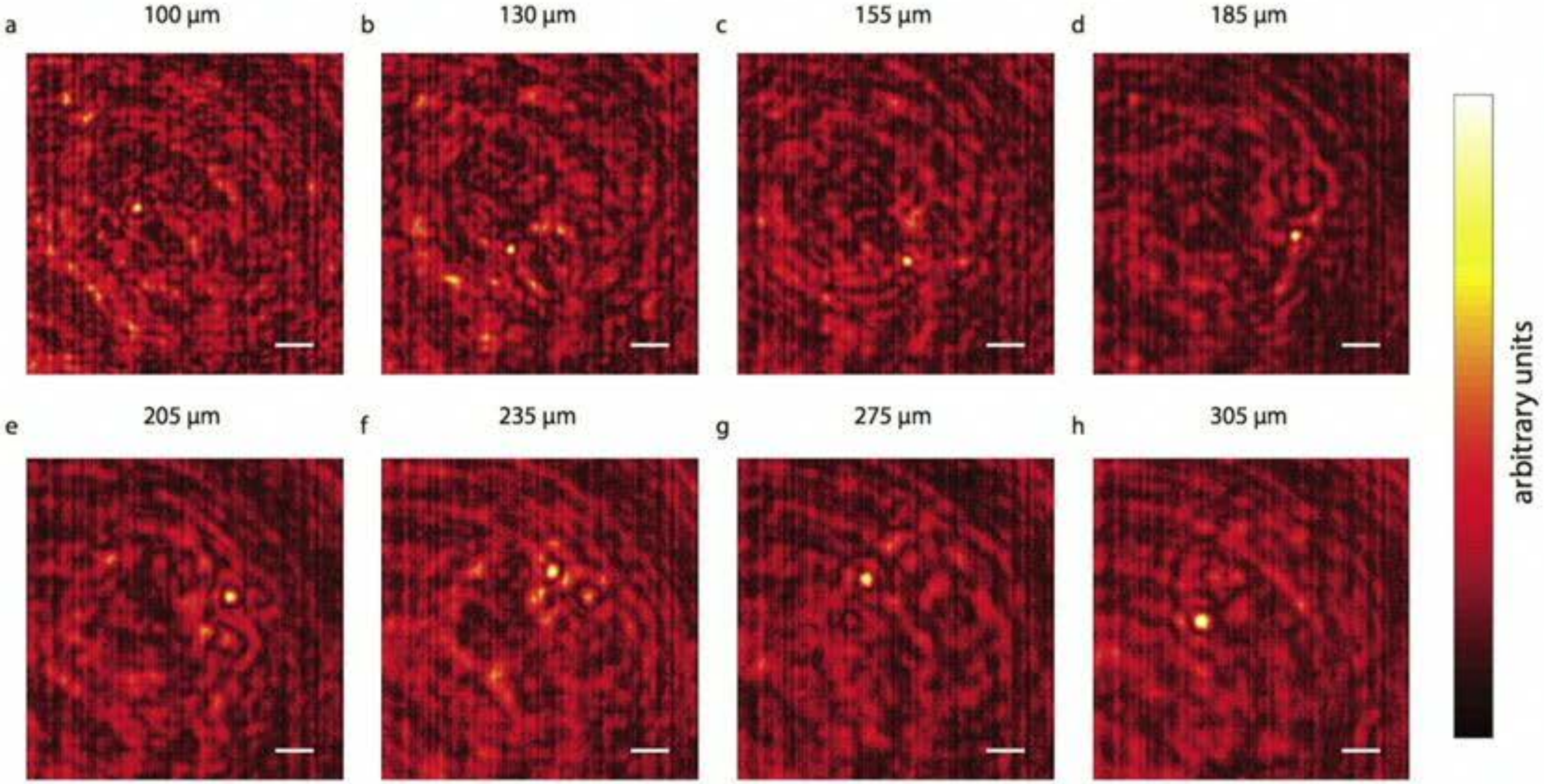
Simulation



Scale bar 10 µm

Zhan et al. Under review

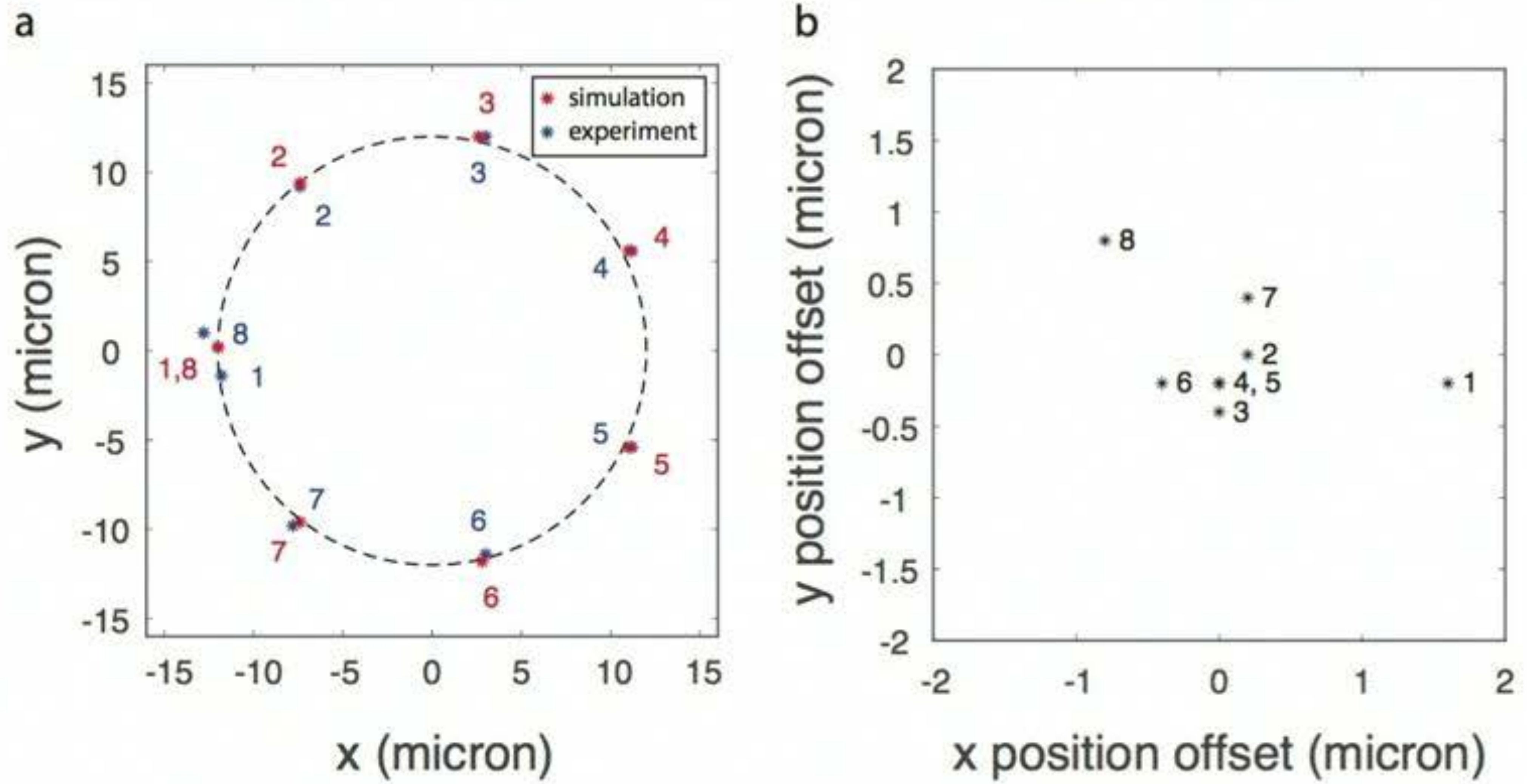
Experiment



Scale bar 10 µm

Zhan et al. Under review

Comparison



Zhan et al. Under review

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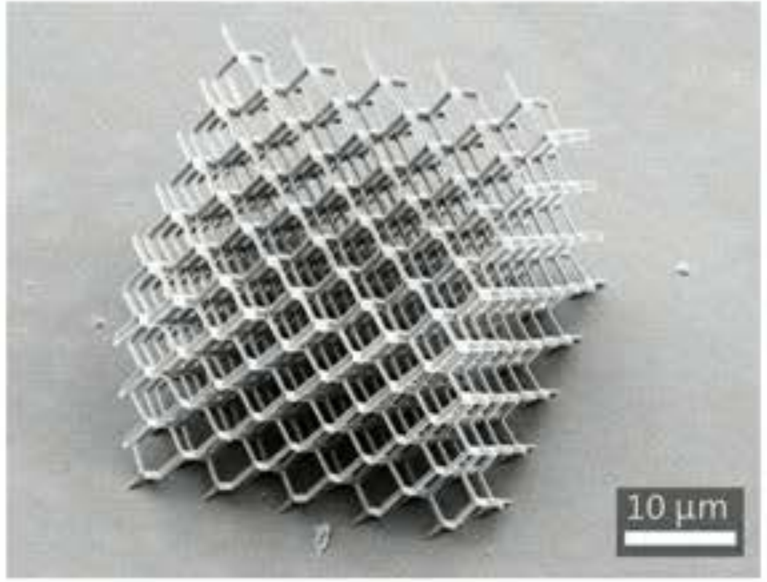
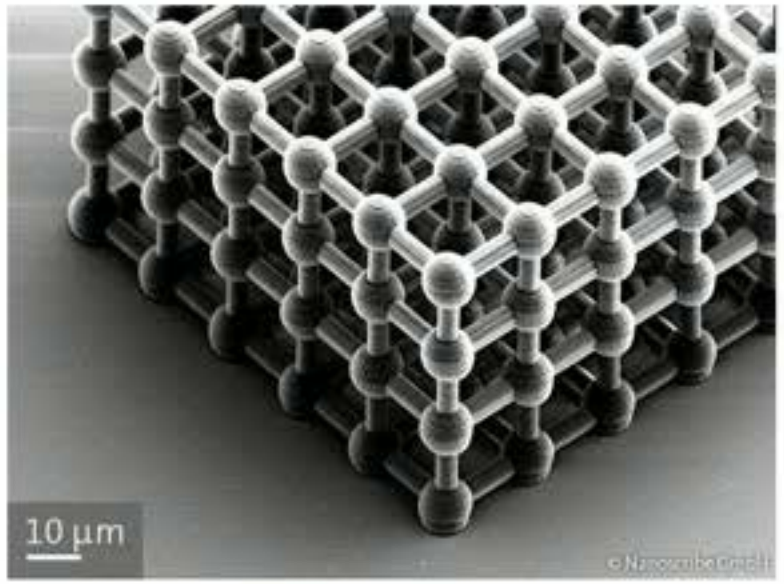
Agenda

1. Single element metasurface optics
2. Towards metasurface optical systems
3. Inverse design and optimization of metasurfaces
4. **Future work and outlook**

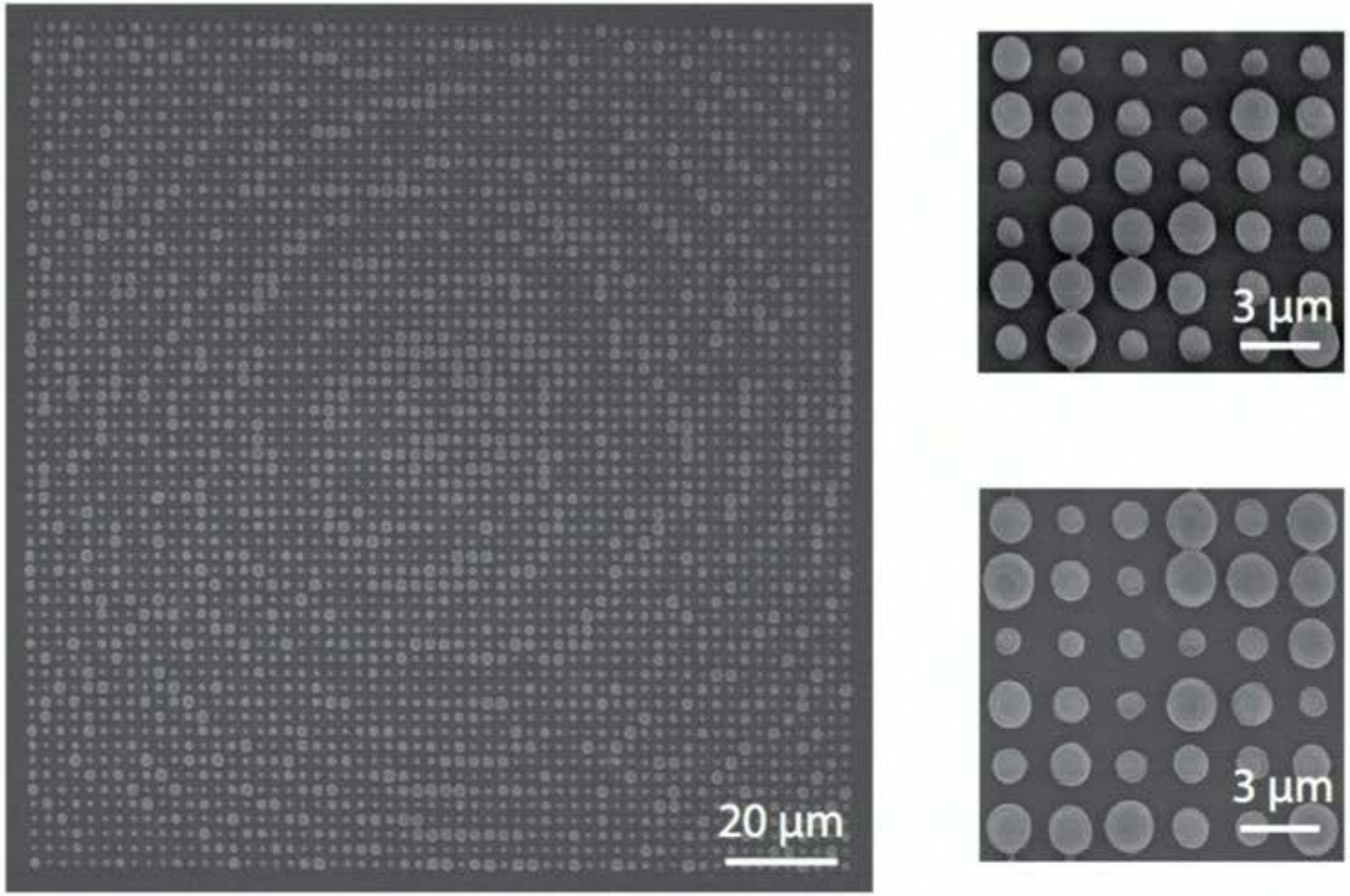
Nanoscribe GT





Images from Nanoscribe GmbH

Fabrication



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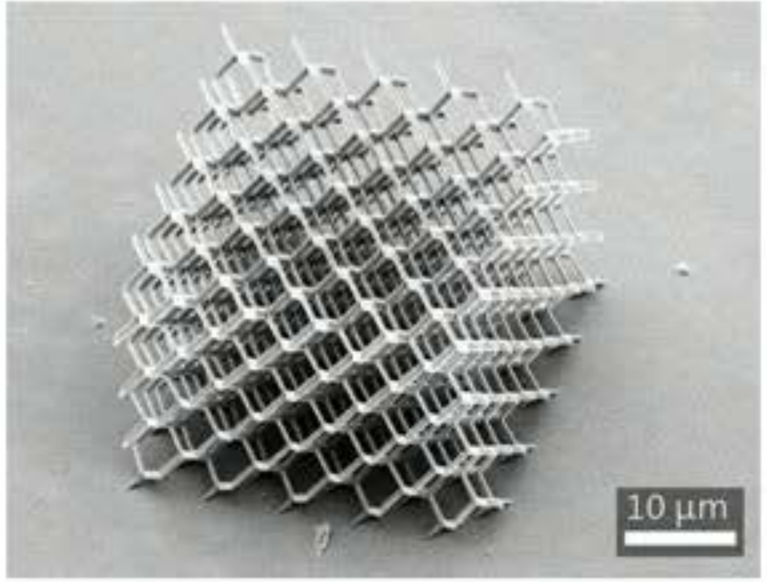
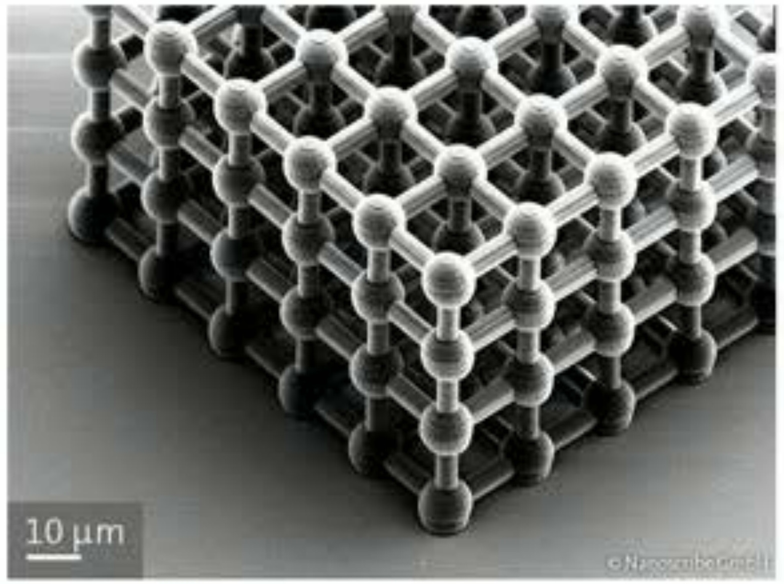
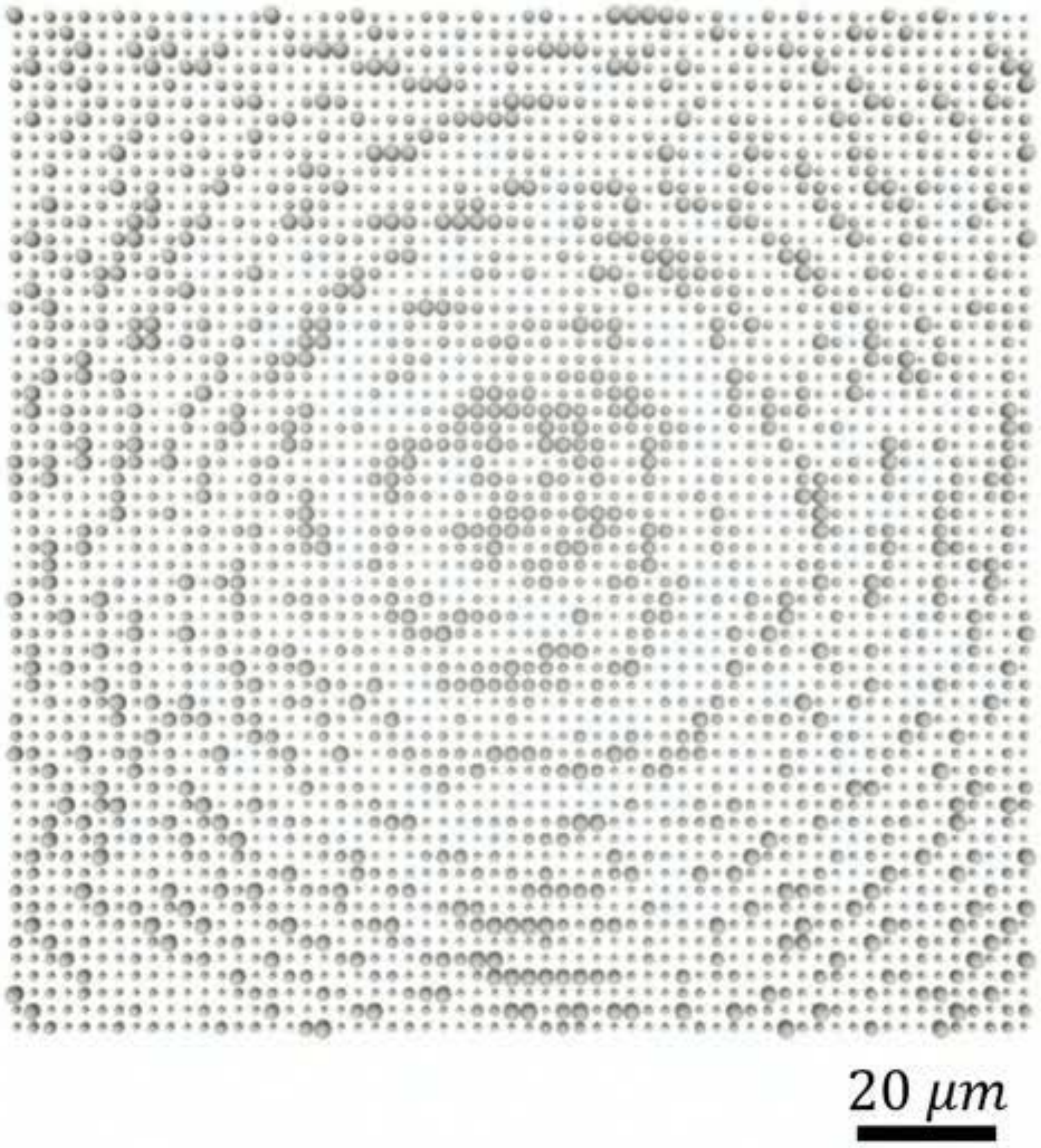




Images from Nanoscribe GmbH

Radius output



Agenda

1. Single element metasurface optics
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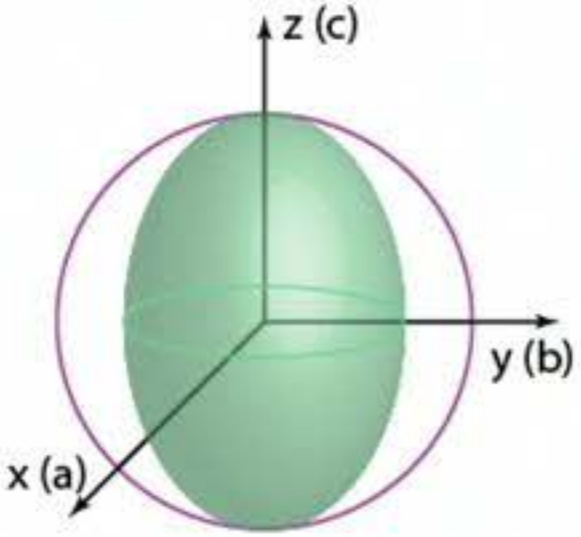
Extension to arbitrary scatterers

There is a straightforward extension to arbitrary shapes using the T-matrix method

Extension to arbitrary scatterers



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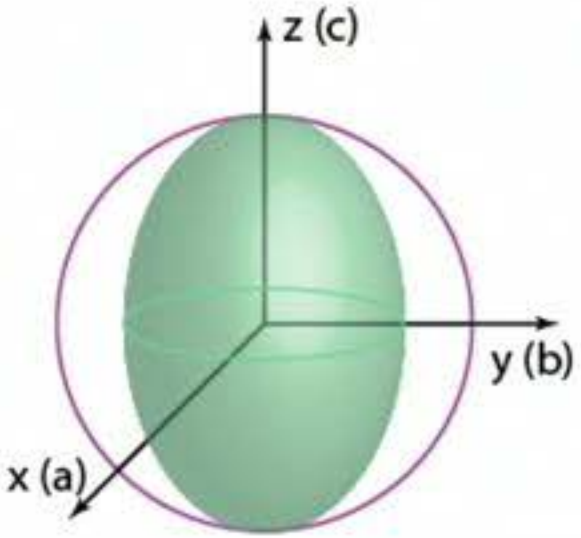
Extension to arbitrary scatterers



There is a straightforward extension to arbitrary shapes using the T-matrix method

Preliminary result shows we can increase efficiency of a 0.83 NA lens from 20% to 26% using ellipsoidal scatterers

Designer optics

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Currently, the model for optical elements is to buy off a shelf.

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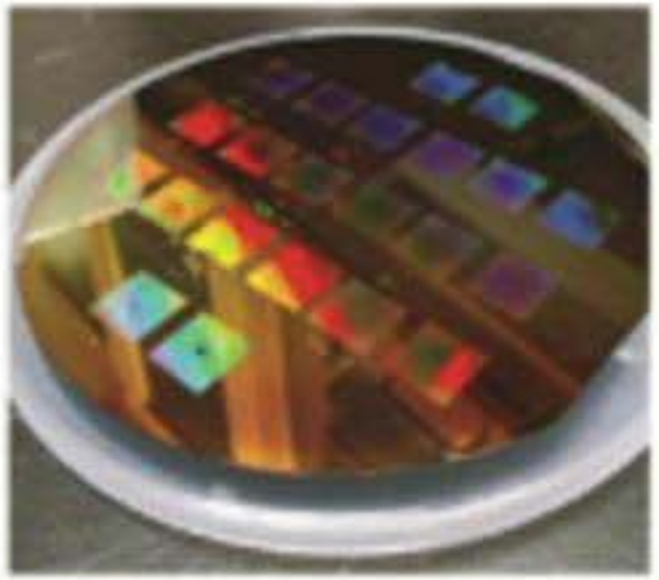
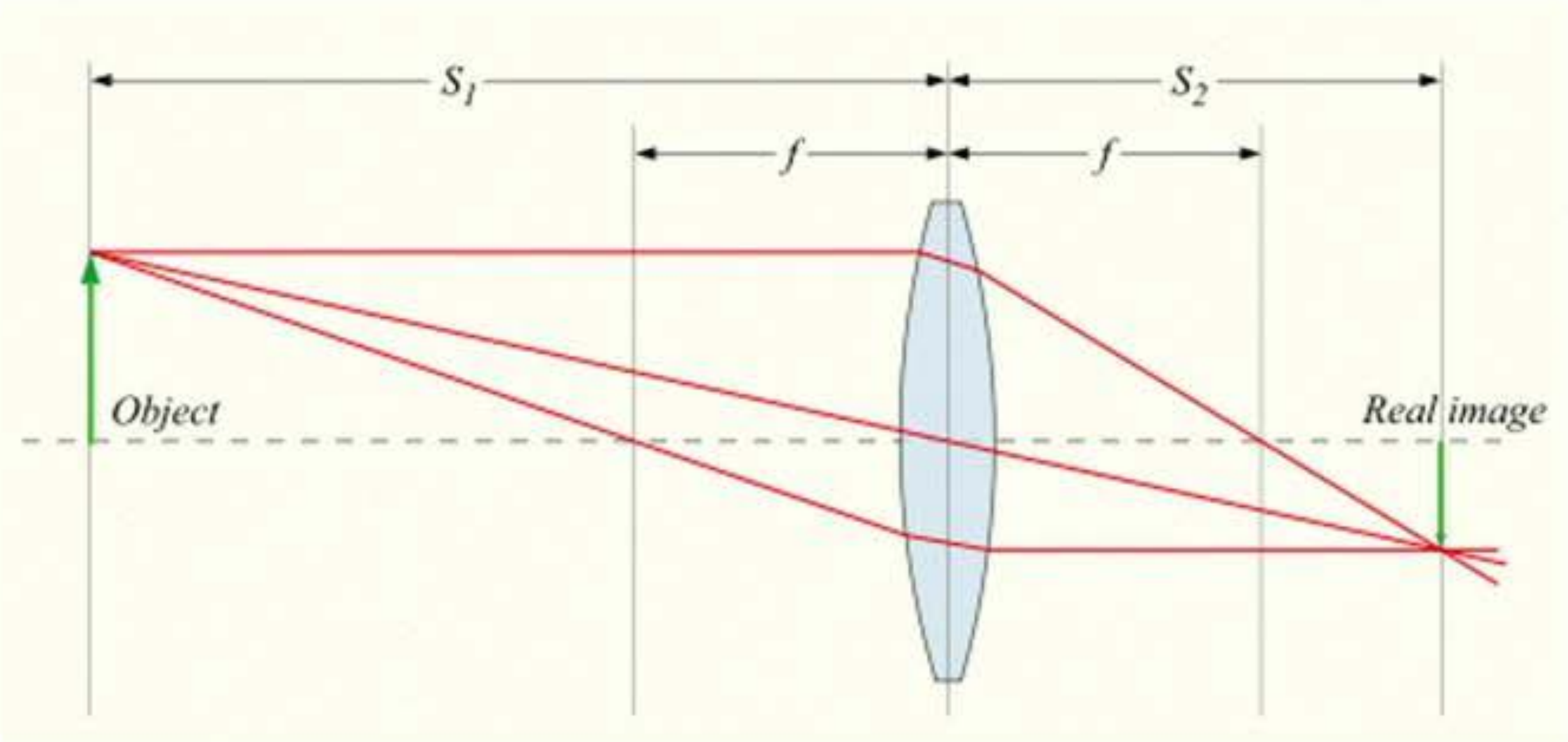


A new model where custom optical elements are tailored and designed for specific applications

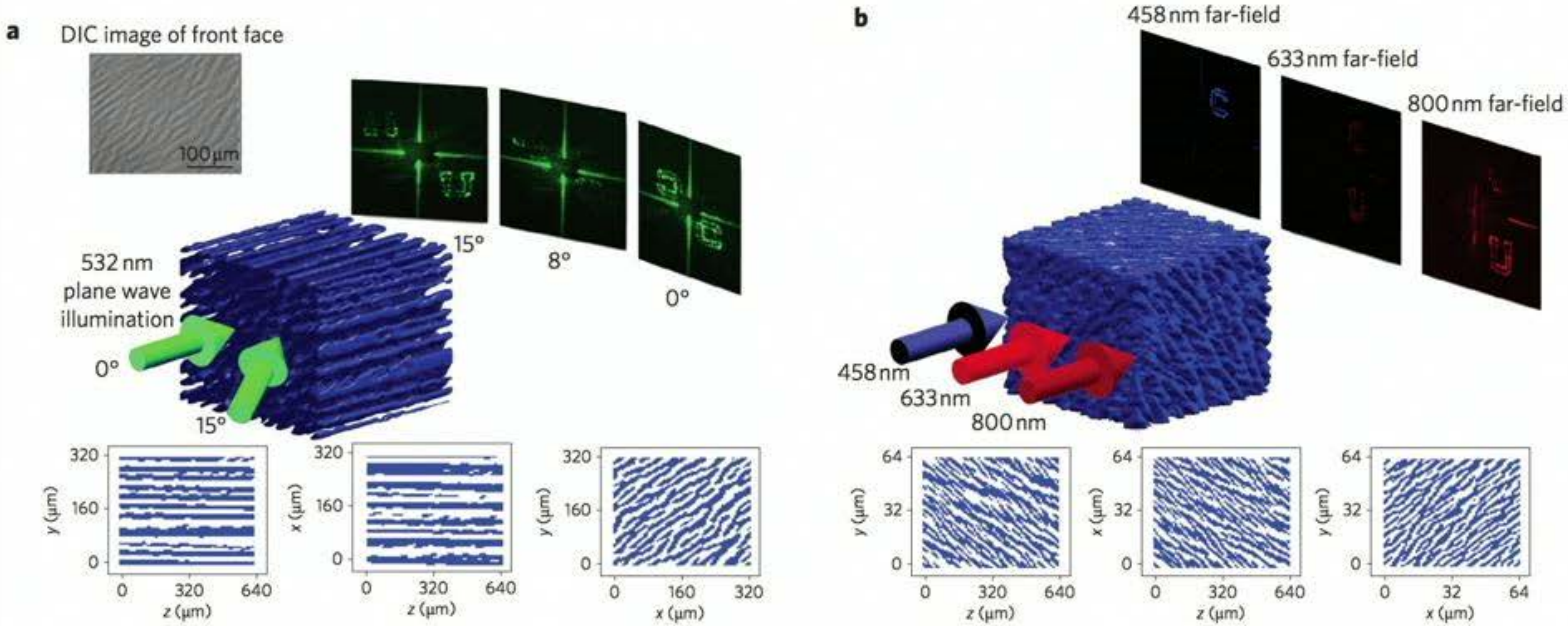
Towards volume optics

When we think about optical elements, generally we think about a 2D input plane incident on a 2D object forming a 2D output plane…



Toward volume optics

... But why restrict ourselves to that?



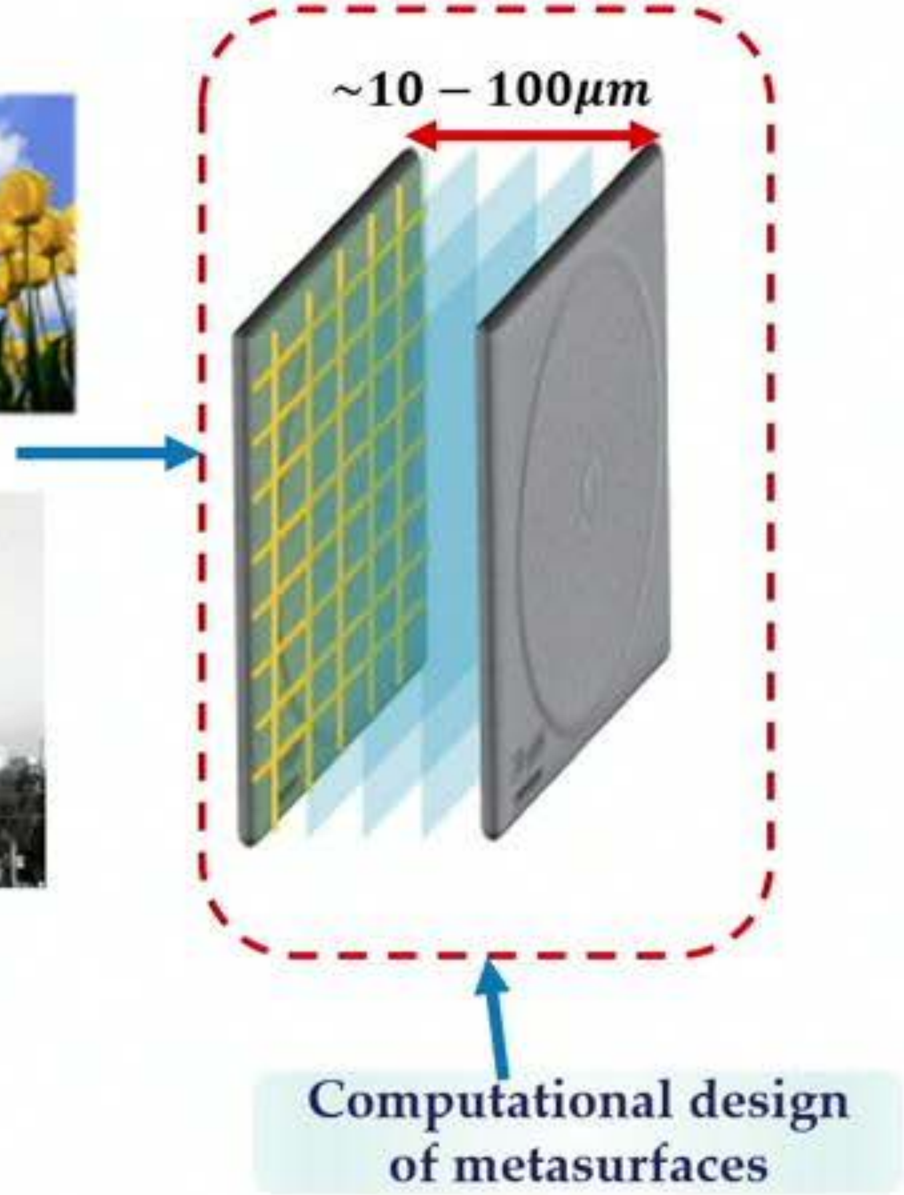
Gerke et al. Nat. Photon. **4**, 3 (2010)

Optics and computational algorithm co-optimization

Optics and computational algorithm co-optimization

Make decision
(Building: y/n)
Object identification

Optics and computational algorithm co-optimization



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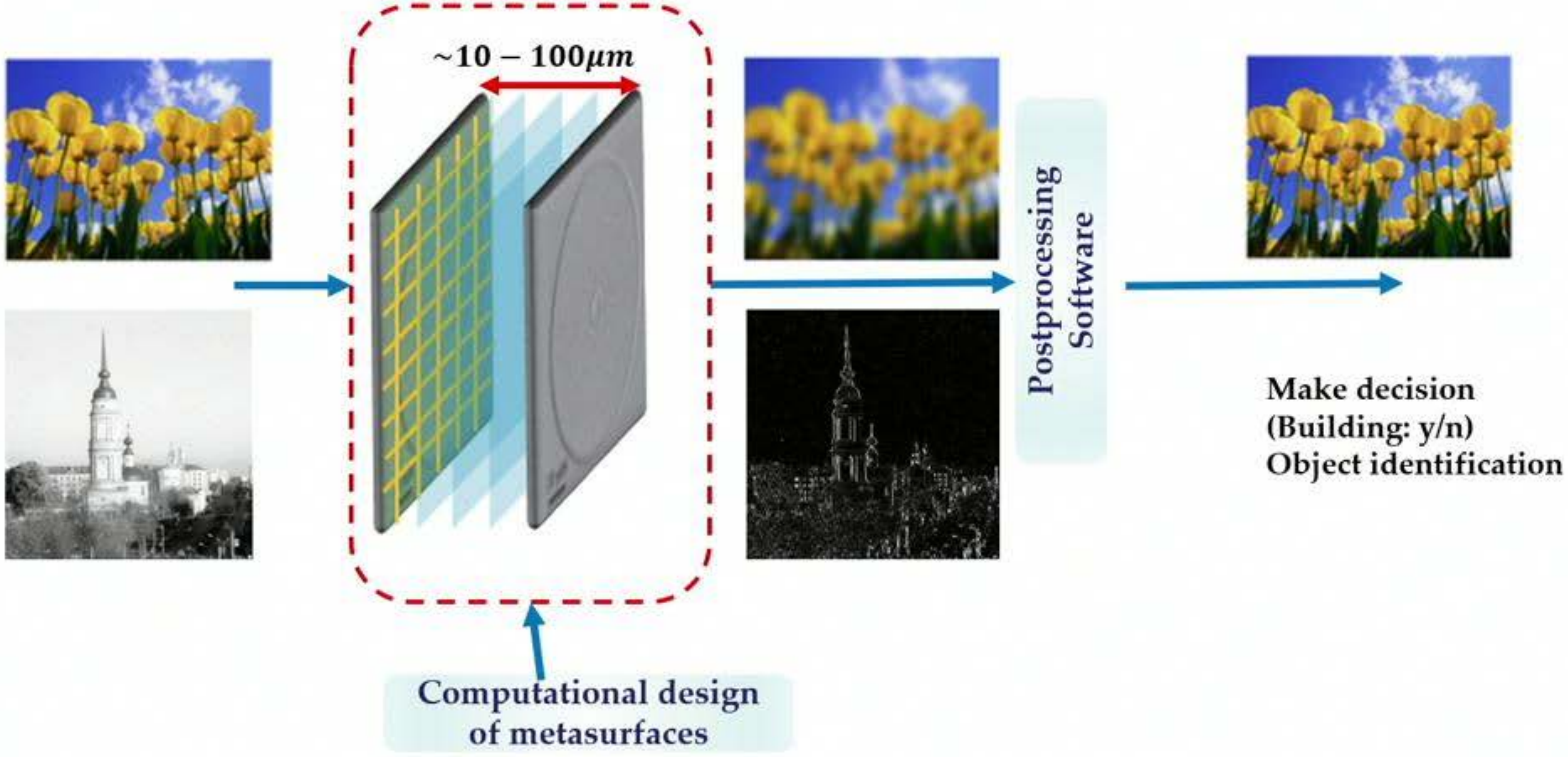
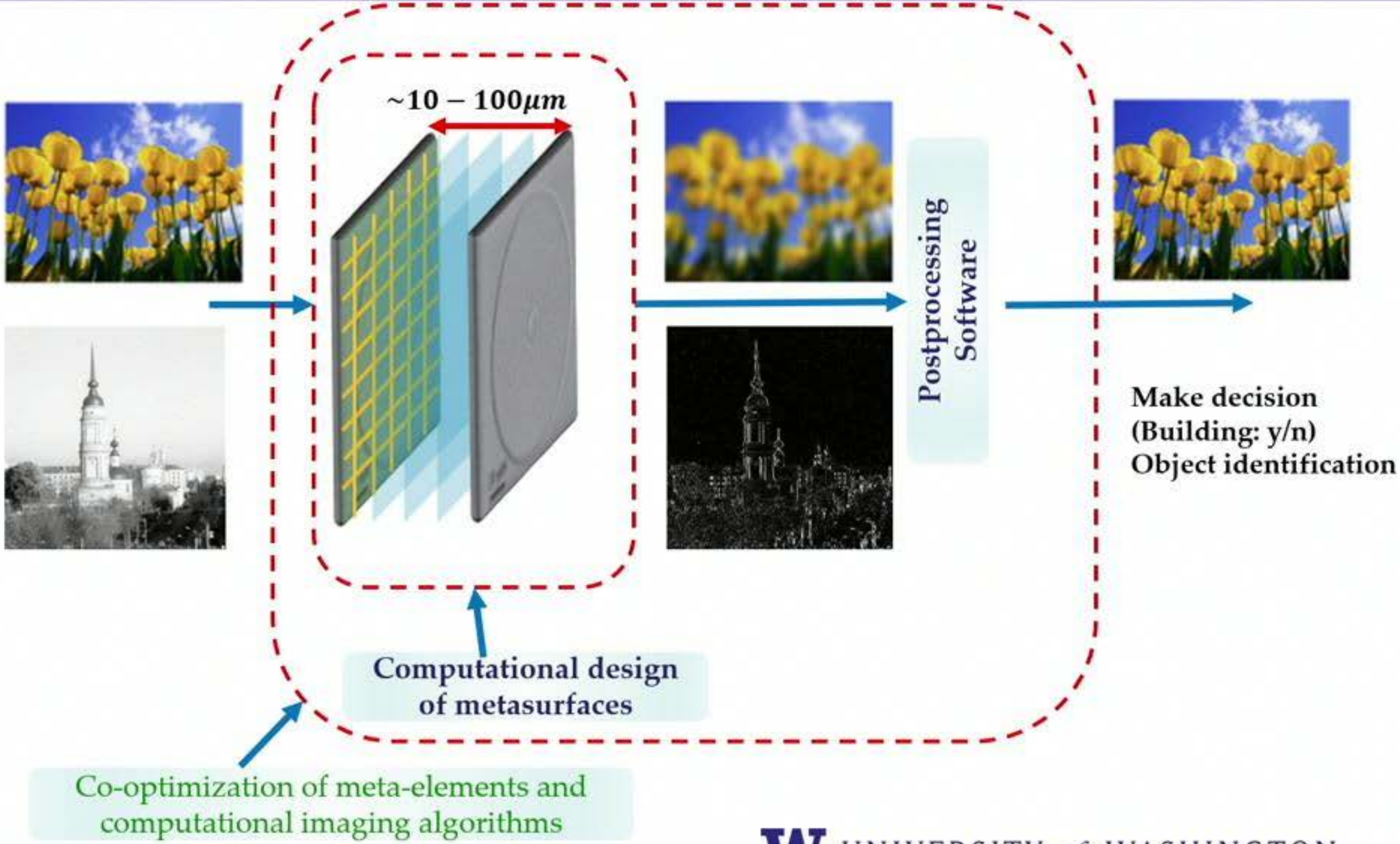


Optics and computational algorithm co-optimization



Recap

1. **Single element metasurfaces**
    1. Design process
    2. Chromatic aberration
2. **Towards metasurface optical systems**
    1. Tunable devices, aberration correction
    2. Large area fabrication
3. **Inverse design and optimization of metasurfaces**
    1. Sphere based diffractive optics
    2. Local phase method

Acknowledgements

NOISE:Nano Optoelectronic Integrated System Engineering






Collaborators at the Air Force Research Lab:
Joshua Hendrickson
Ricky Gibson
Evan Smith

Developers of CELES:
Amos Egel
Lorezno Pattelli

Funding sources:
NSF
UW Reality Lab
Google
Samsung
Facebook
Amazon

National Nanotechnology Coordinated Infrastructure

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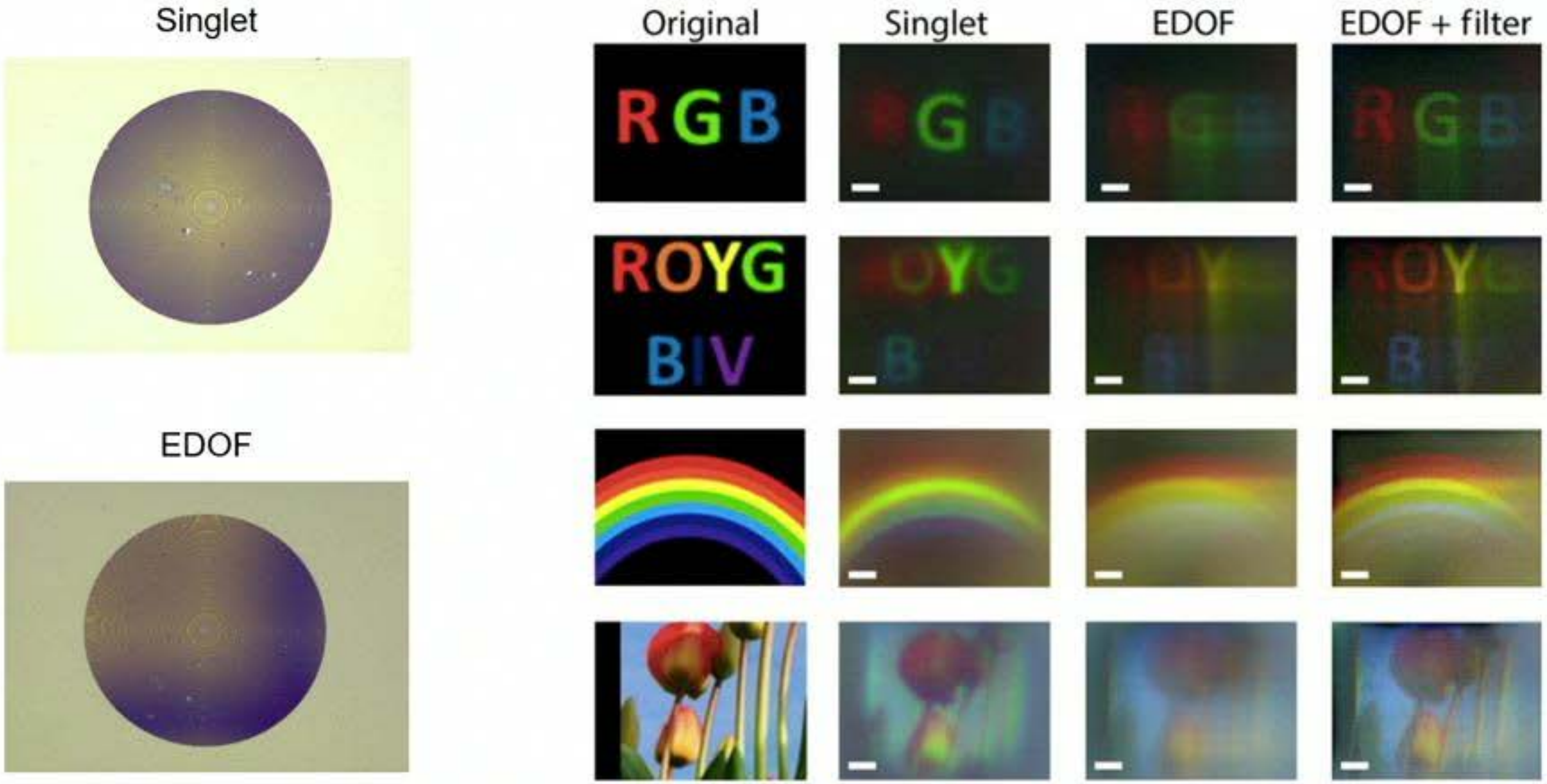
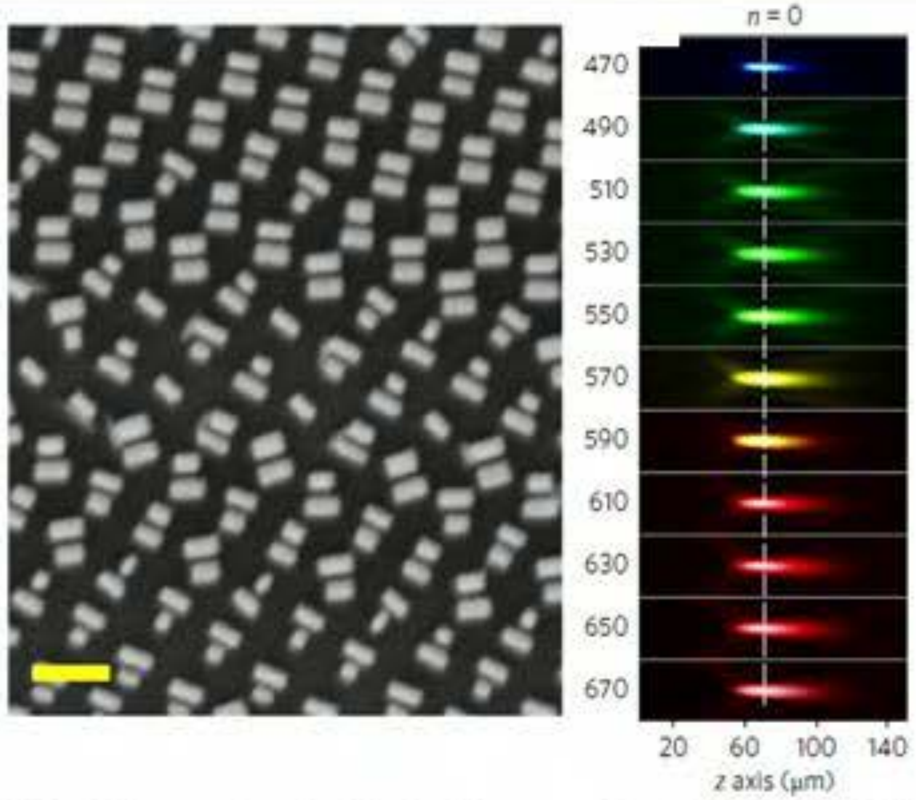
Computational imaging approach

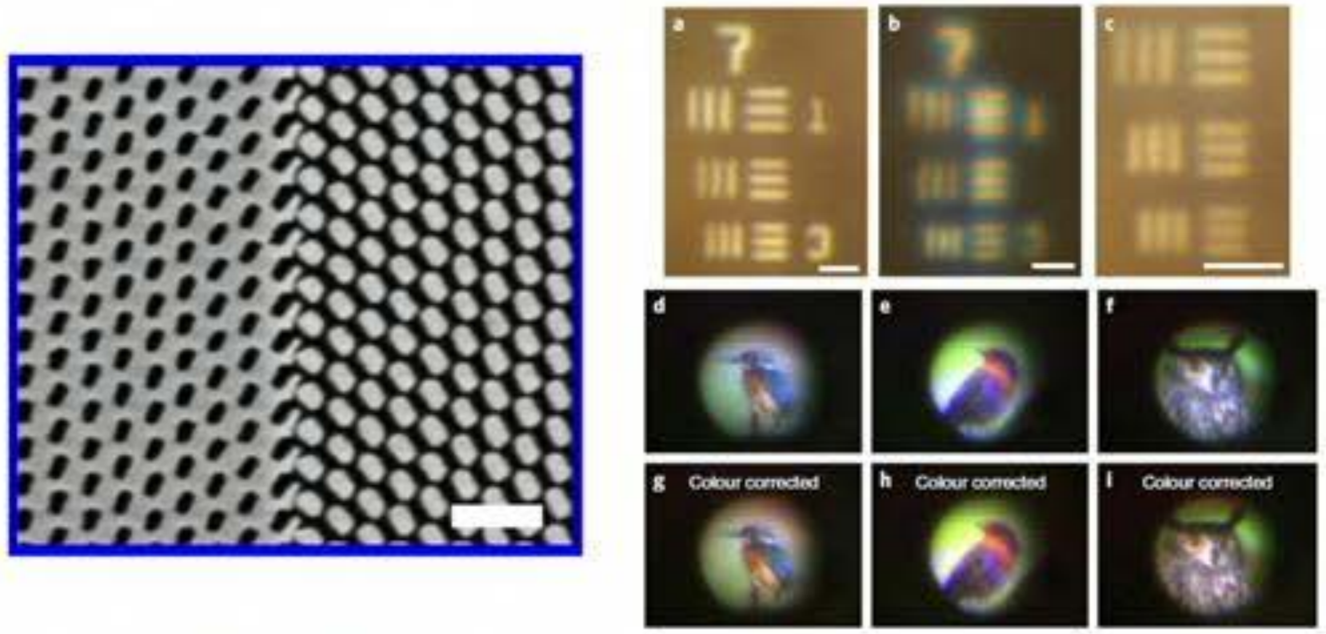


S. Colburn et al. Science Advances **4**, eaar2114 (2018)

Correcting chromatic aberrations



W. Chen et al, Nat. Nano. **13**, 220 (2018)



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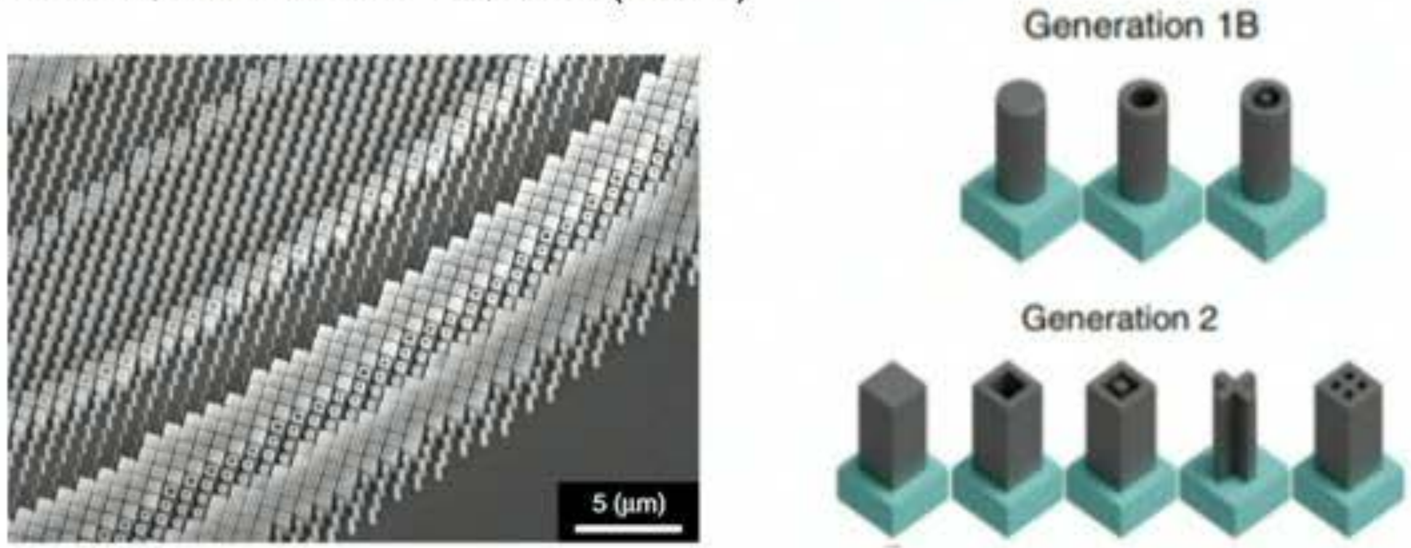
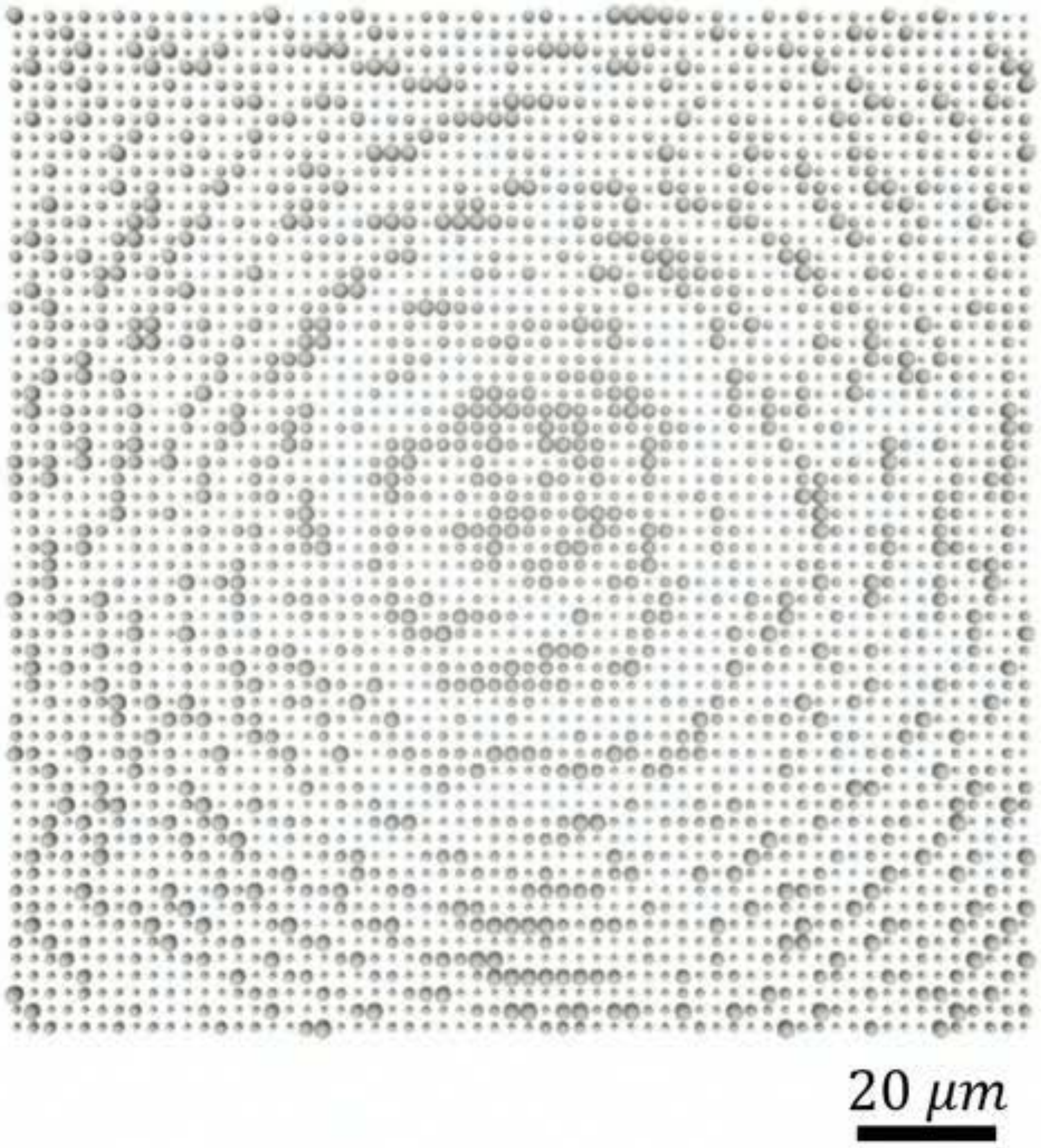


Shrestha et al. Light: Sci. and Appl. **7**, 95 (2018)

Radius output



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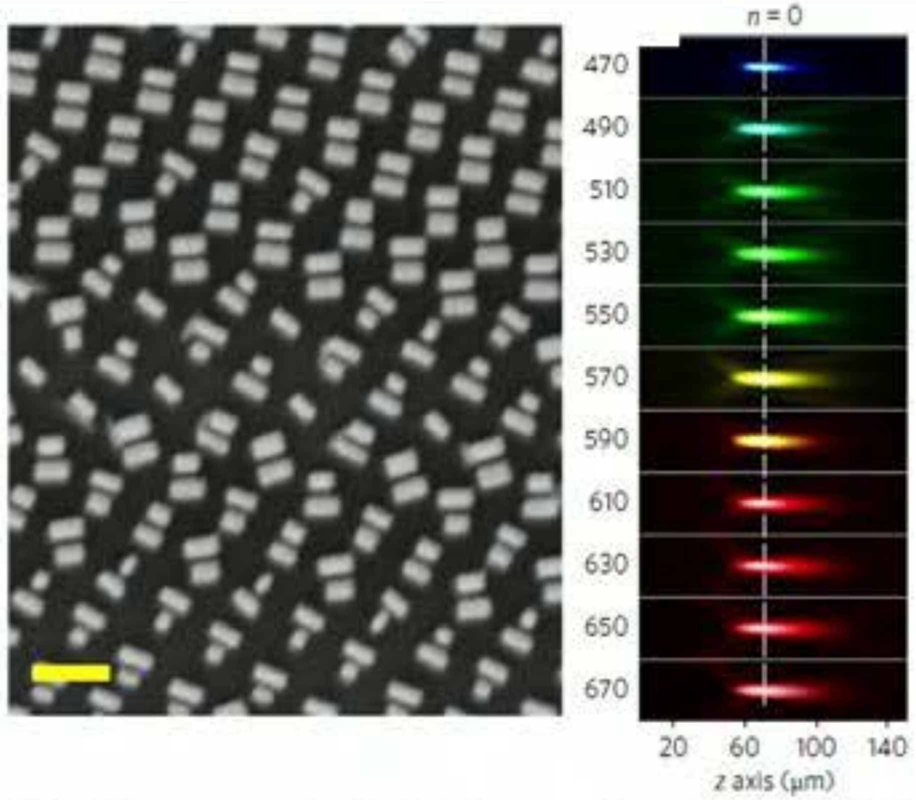
Correcting chromatic aberrations



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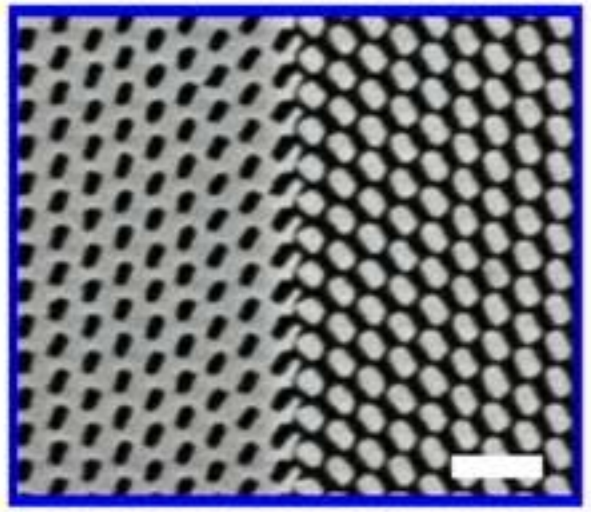
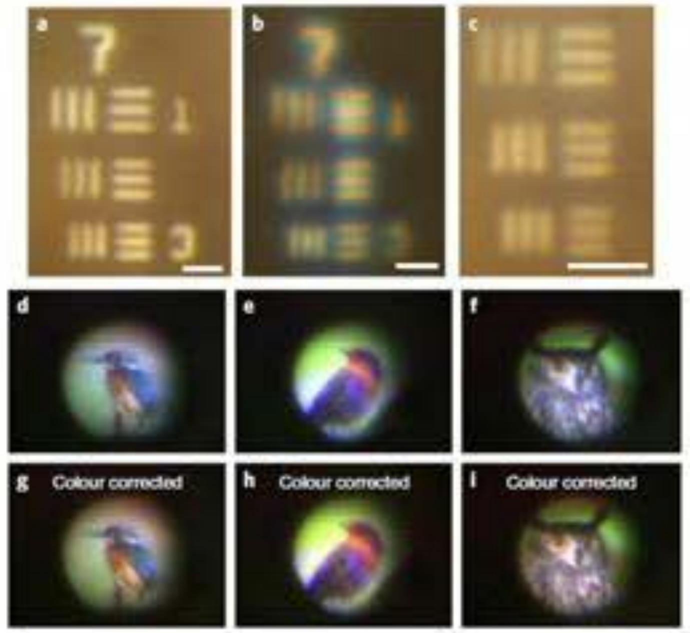
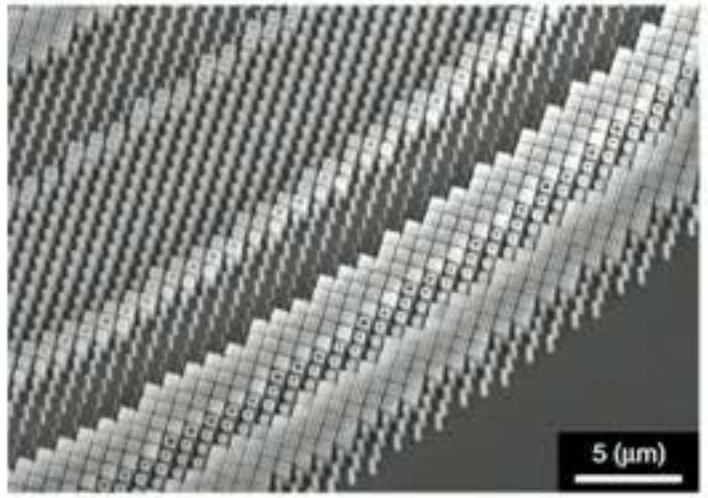
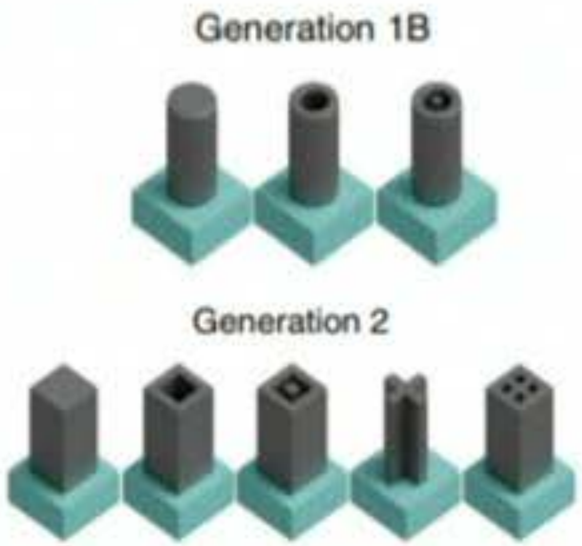




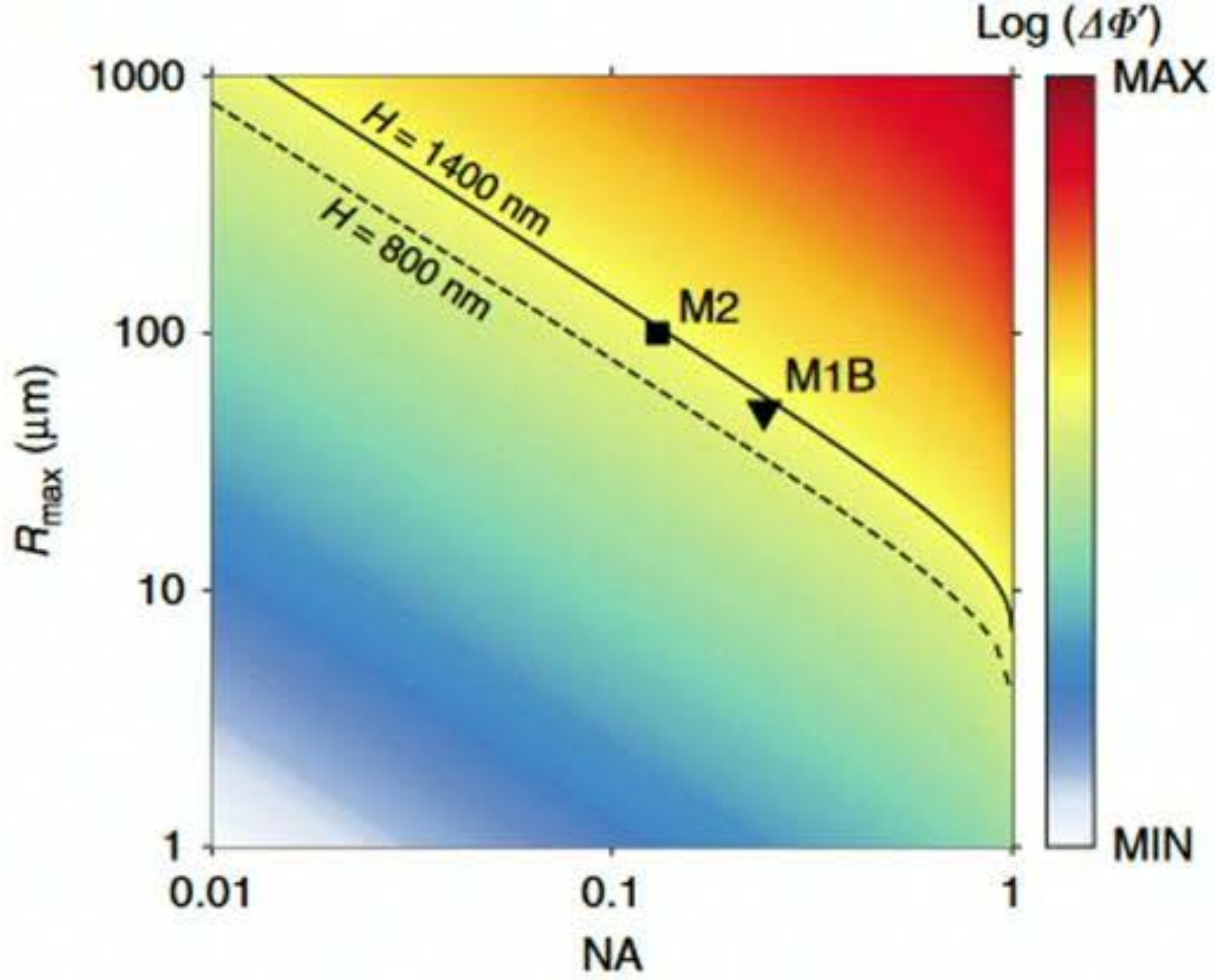
S. Wang et al, Nat. Nano. **13**, 227 (2018)





Shrestha et al. Light: Sci. and Appl. **7**, 95 (2018)

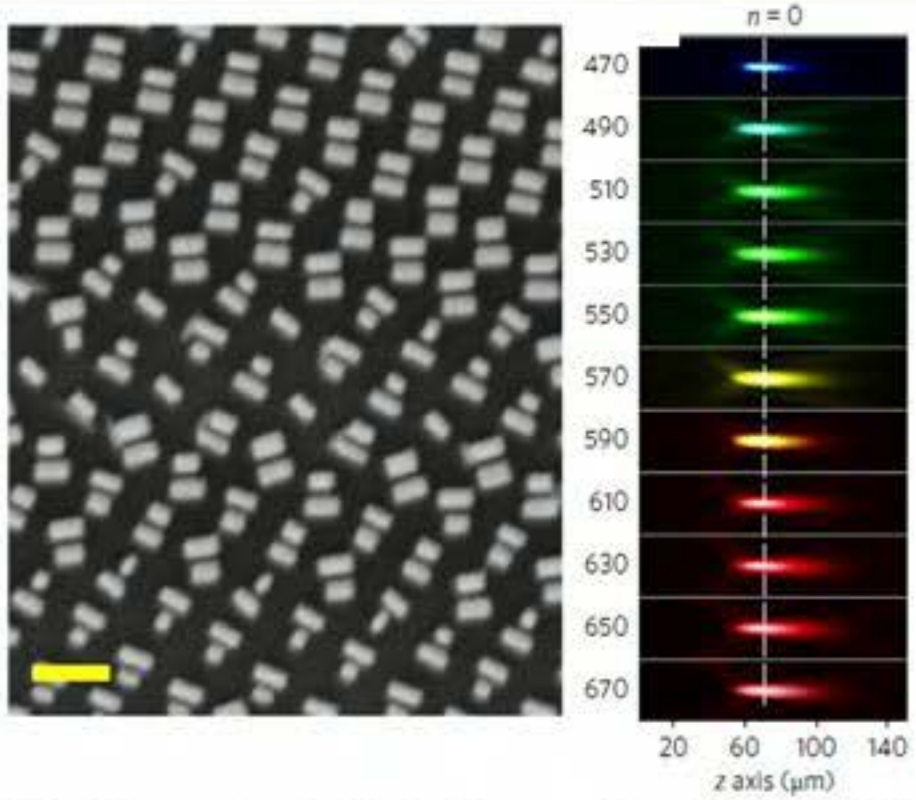
Limits of dispersion engineering



$$R_{max} = \frac{\Delta\Phi'}{\Delta\omega\left(\frac{1}{NA} - \sqrt{\frac{1}{NA^2} - 1}\right)}$$

Shrestha et al. Light: Sci. and Appl.
7, 95 (2018)

Correcting chromatic aberrations



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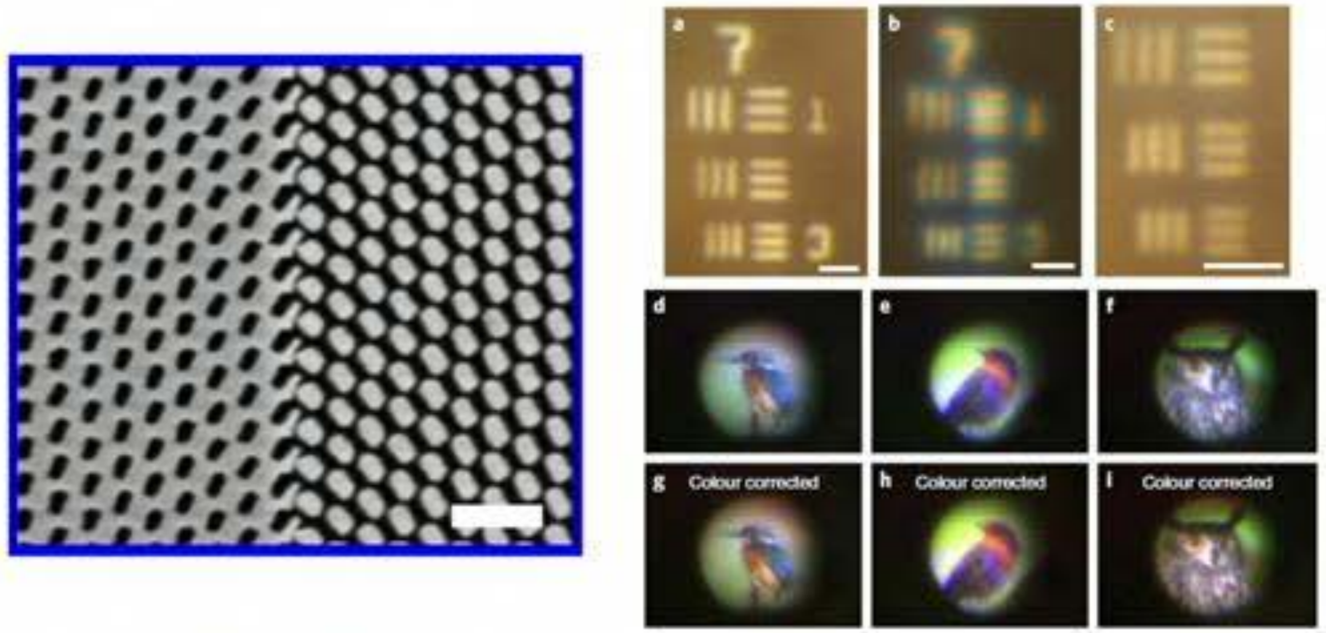

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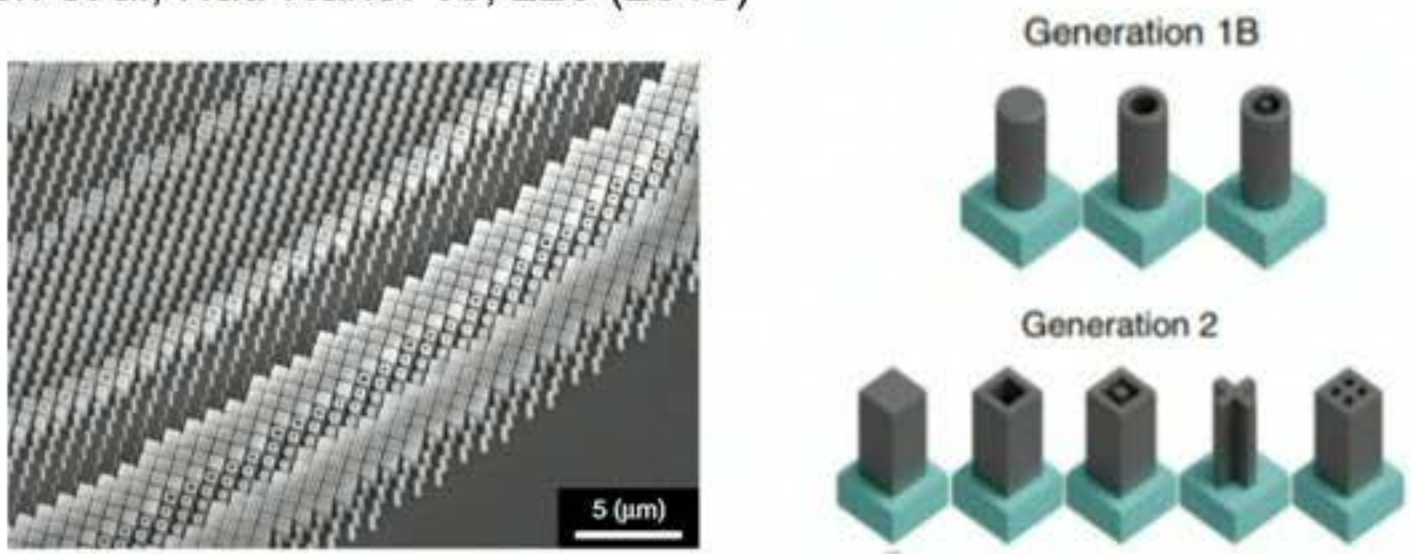

Shrestha et al. Light: Sci. and Appl. **7**, 95 (2018)