Broadband, High-Efficiency, Large-Aperture Metalenses in the Visible

David Woolf, Joe Goodwin, Joel Hensley (PSI)

Jonathan Fan, Anton Ovcharenko, Mingkun Chen, Peter Phan (Stanford)

06.29.2021

OSA Optical Design and Fabrication Congress

27 June 2021 – 01 July 2021

OSA Virtual Event

Flat Optics and Metasurfaces III (FTu2C)

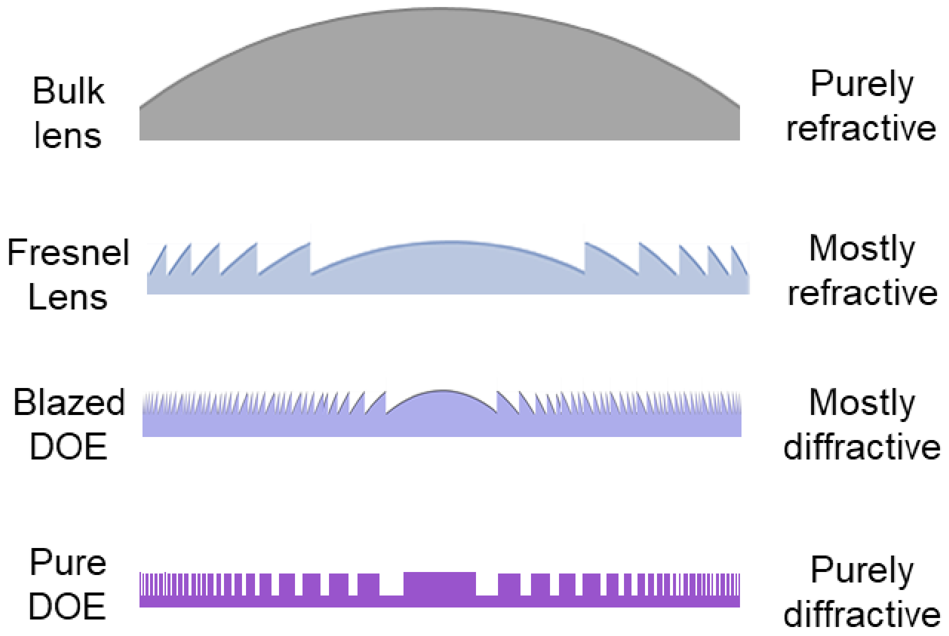
Acknowledgement of Support and Disclaimer

This material is based upon work supported by the Defense Advanced Research Projects Agency (DARPA) under Contract No. 140D0420C0065. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Defense Advanced Research Projects Agency (DARPA); or its Contracting Agent, the U.S. Department of the Interior, Interior Business Center, Acquisition Services Directorate, Division III.

This material is based upon work supported by the DARPA STTR Program Office under Contract No. W31P4Q-21-C-0031. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the DARPA STTR Program Office.

What is a metalens?

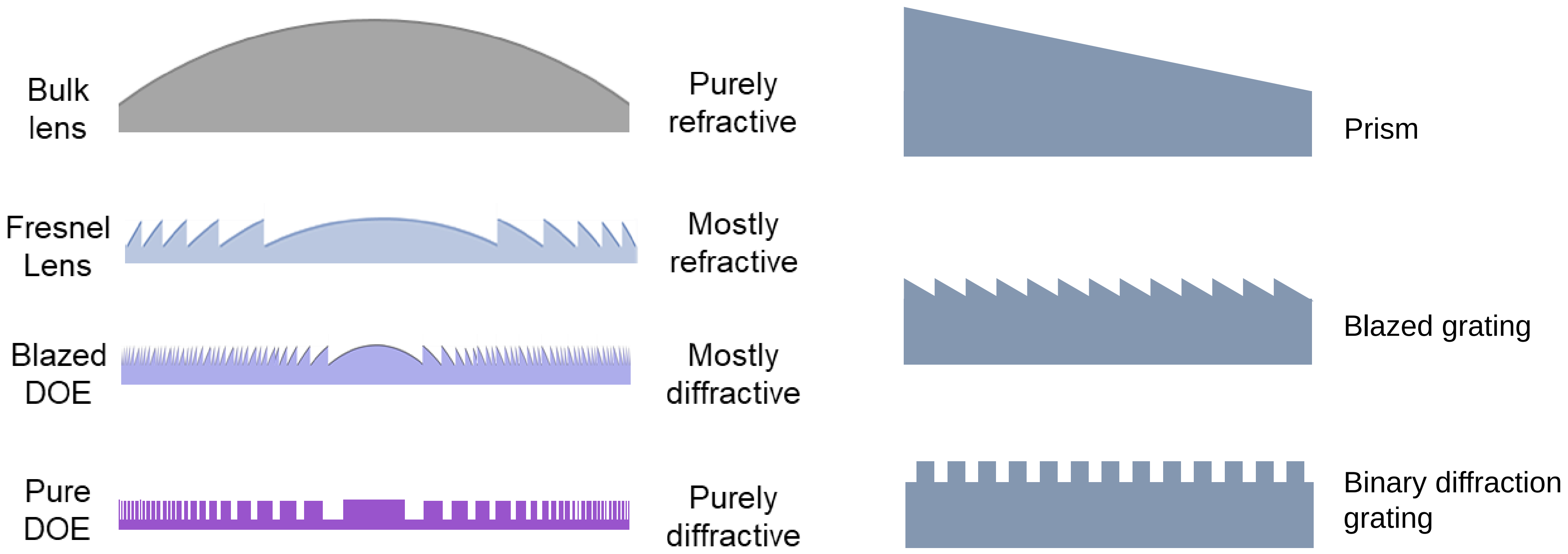
- **A focusing optic that uses sub-wavelength-scale resonators to modify the phase delay that light experiences when travelling through it.**



- **Exists on the end of a continuum, with bulk lenses on the other side, of focusing optics that use refraction or diffraction to generate focusing.**

What is a metalens?

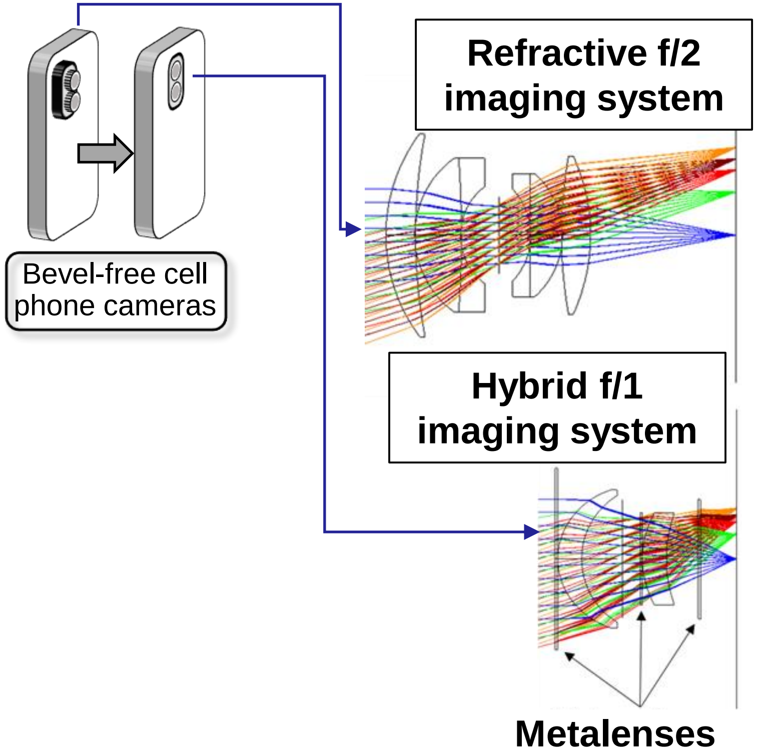
- **A focusing optic that uses sub-wavelength-scale resonators to modify the phase delay that light experiences when travelling through it.**



- **Exists on the end of a continuum, with bulk lenses on the other side, of focusing optics that use refraction or diffraction to generate focusing.**
  - Prisms and diffraction gratings exist on a similar continuum

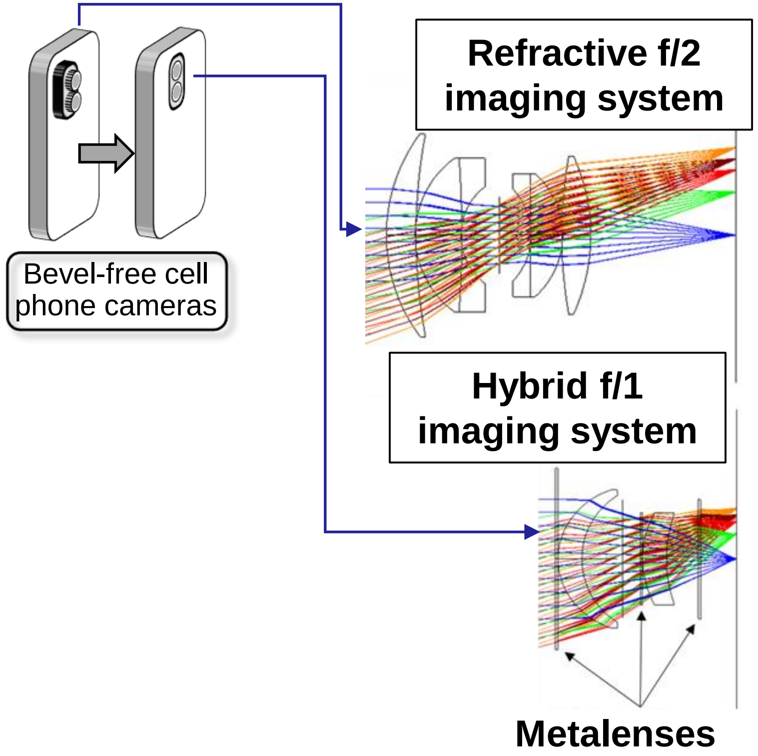
Why broadband metalenses?

- **Broadband metalens applications**
  - **Imaging**
  - AR/VR
  - Sensing
  - …



Why broadband metalenses?

- **Broadband metalens applications**
  - **Imaging**
  - AR/VR
  - Sensing
  - …



Broadband and Efficient Diffraction

Céline Ribot, Mane-Si Laure Lee, Stéphane Collin, Shailendra Bansropun, Patrick Plouhinec, Didier Thenot, Simone Cassette, Brigitte Loiseaux, Philippe Lalanne

A broadband achromatic metalens for focusing and imaging in the visible

Wei Ting Chen[1], Alexander Y. Zhu[1], Vyshakh Sanjeev[1,3], Mohammadreza Khorasaninejad[1], Zhujun Shi[2], Eric Lee[1,3] and Federico Capasso[1,*]

High-NA achromatic metalenses by inverse design

HAEJUN CHUNG[1,2] AND OWEN D. MILLER[1,3]

A broadband achromatic metalens array for integral imaging in the visible

Zhi-Bin Fan[1,2], Hao-Yang Qiu[1,2], Han-Le Zhang[3], Xiao-Ning Pang[1,2], Li-Dan Zhou[1], Lin Liu[1], Hui Ren[3], Qiong-Hua Wang[3] and Jian-Wen Dong[1,2]

Octave bandwidth photonic fishnet-achromatic-metalens

Abdoulaye Ndao[1,2,5], Liyi Hsu[1,2,5], Jeongho Ha[1,2], Jun-Hee Park[1,2], Connie Chang-Hasnain[1] & Boubacar Kanté[1,2,3,4]

Controlling the sign of chromatic dispersion in diffractive optics with dielectric metasurfaces

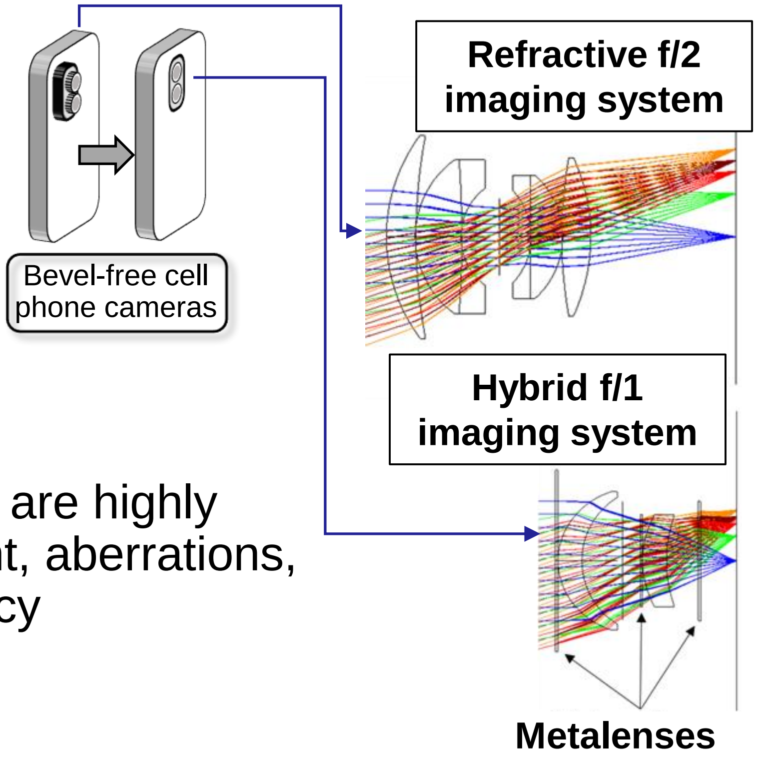
EHSAN ARBABI,[1] AMIR ARBABI,[1,2] SEYEDEH MAHSA KAMALI,[1] YU HORIE,[1] AND ANDREI FARAON[1,*]

Broadband achromatic dielectric metalenses

Sajan Shrestha[1], Adam C. Overvig[1], Ming Lu[2], Aaron Stein[2] and Nanfang Yu[1]

Why broadband metalenses?

- **Broadband metalens applications**
  - **Imaging**
  - AR/VR
  - Sensing
  - …



- **Primary Challenge**
  - Imaging applications are highly sensitive to stray light, aberrations, transmission efficiency

- **Approaches**
  - Tall meta-elements
  - Interleaved metalenses
  - Doublets
  - Polarization sensitive metasurfaces

    ➢ **Most of these approaches are trying for achromatism**

Broadband and Efficient Diffraction

Céline Ribot, Mane-Si Laure Lee, Stéphane Collin, Shailendra Bansropun, Patrick Plouhinec, Didier Thenot, Simone Cassette, Brigitte Loiseaux, Philippe Lalanne

A broadband achromatic metalens for focusing and imaging in the visible

Wei Ting Chen[1], Alexander Y. Zhu[1], Vyshakh Sanjeev[1,3], Mohammadreza Khorasaninejad[1], Zhujun Shi[2], Eric Lee[1,3] and Federico Capasso[1,*]

High-NA achromatic metalenses by inverse design

Haejun Chung[1,2] and Owen D. Miller[1,3]

A broadband achromatic metalens array for integral imaging in the visible

Zhi-Bin Fan[1,2], Hao-Yang Qiu[1,2], Han-Le Zhang[3], Xiao-Ning Pang[1,2], Li-Dan Zhou[1], Lin Liu[1], Hui Ren[3], Qiong-Hua Wang[3] and Jian-Wen Dong[1,2]

Octave bandwidth photonic fishnet-achromatic-metalens

Abdoulaye Ndao[1,2,5], Liyi Hsu[1,2,5], Jeongho Ha[1,2], Jun-Hee Park[1,2], Connie Chang-Hasnain[1] & Boubacar Kanté[1,2,3,4]

Controlling the sign of chromatic dispersion in diffractive optics with dielectric metasurfaces

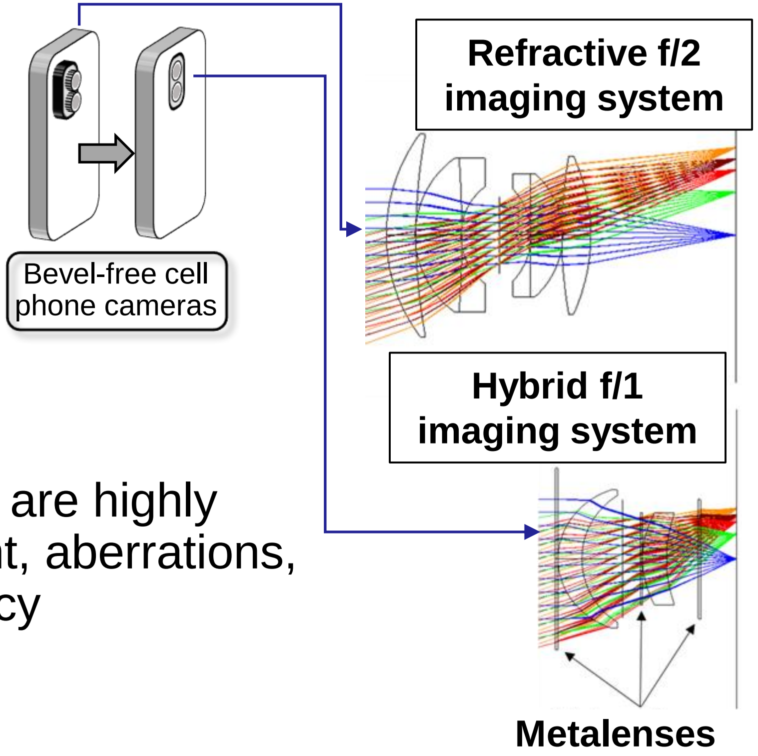
Ehsan Arbabi,[1] Amir Arbabi,[1,2] Seyedeh Mahsa Kamali,[1] Yu Horie,[1] and Andrei Faraon[1,*]

Broadband achromatic dielectric metalenses

Sajan Shrestha[1], Adam C. Overvig[1], Ming Lu[2], Aaron Stein[2] and Nanfang Yu[1]

Why broadband metalenses?

- **Broadband metalens applications**
  - **Imaging**
  - AR/VR
  - Sensing
  - …



- **Primary Challenge**
  - Imaging applications are highly sensitive to stray light, aberrations, transmission efficiency

- **Approaches**
  - Tall meta-elements
  - Interleaved metalenses
  - Doublets
  - Polarization sensitive metasurfaces
    - ➢**Most of these approaches are trying for achromatism**

Broadband and Efficient Diffraction

Céline Ribot, Mane-Si Laure Lee, Stéphane Collin, Shailendra Bansropun, Patrick Plouhinec, Didier Thenot, Simone Cassette, Brigitte Loiseaux, Philippe Lalanne

A broadband achromatic metalens for focusing and imaging in the visible

Wei Ting Chen[1], Alexander Y. Zhu[1], Vyshakh Sanjeev[1,3], Mohammadreza Khorasaninejad[1], Zhujun Shi[2], Eric Lee[1,3] and Federico Capasso[1,*]

High-NA achromatic metalenses by inverse design

Haejun Chung[1,2] and Owen D. Miller[1,3]

A broadband achromatic metalens array for integral imaging in the visible

Zhi-Bin Fan[1,2], Hao-Yang Qiu[1,2], Han-Le Zhang[3], Xiao-Ning Pang[1,2], Li-Dan Zhou[1], Lin Liu[1], Hui Ren[3], Qiong-Hua Wang[3] and Jian-Wen Dong[1,2]

Octave bandwidth photonic fishnet-achromatic-metalens

Abdoulaye Ndao[1,2,5], Liyi Hsu[1,2,5], Jeongho Ha[1,2], Jun-Hee Park[1,2], Connie Chang-Hasnain[1] & Boubacar Kanté[1,2,3,4]

Controlling the sign of chromatic dispersion in diffractive optics with dielectric metasurfaces

Ehsan Arbabi,[1] Amir Arbabi,[1,2] Seyedeh Mahsa Kamali,[1] Yu Horie,[1] and Andrei Faraon[1,*]

Broadband achromatic dielectric metalenses

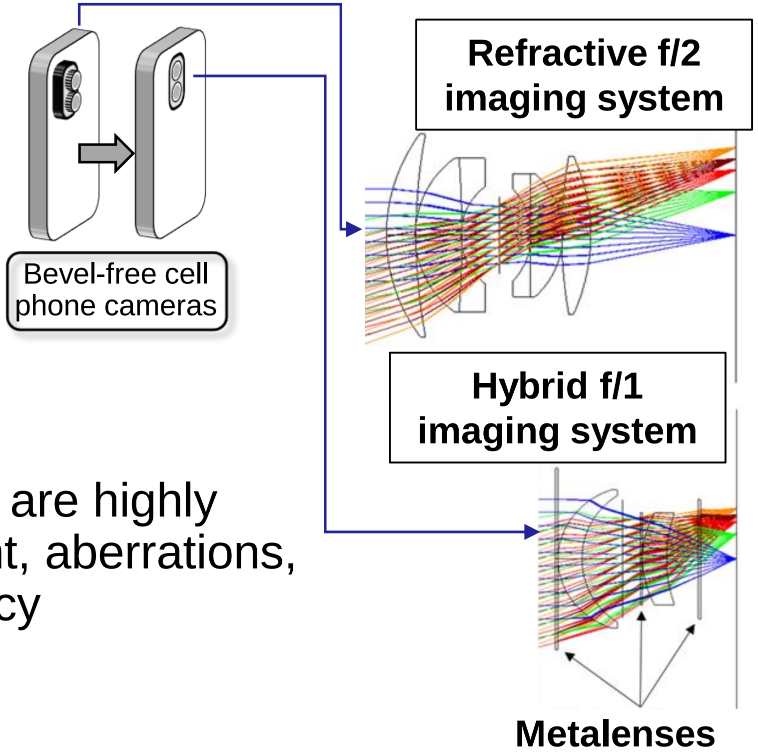
Sajan Shrestha[1], Adam C. Overvig[1], Ming Lu[2], Aaron Stein[2] and Nanfang Yu[1]

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

Physical Sciences Inc.

Why broadband metalenses?

- **Broadband metalens applications**
  - **Imaging**
  - AR/VR
  - Sensing
  - …



- **Primary Challenge**
  - Imaging applications are highly sensitive to stray light, aberrations, transmission efficiency

- **Approaches**
  - Tall meta-elements
  - Interleaved metalenses
  - Doublets
  - Polarization sensitive metasurfaces
    - ➢**Most of these approaches are trying for achromatism**

Broadband and Efficient Diffraction

Céline Ribot, Mane-Si Laure Lee, Stéphane Collin, Shailendra Bansropun, Patrick Plouhinec, Didier Thenot, Simone Cassette, Brigitte Loiseaux, Philippe Lalanne

A broadband achromatic metalens for focusing and imaging in the visible

Wei Ting Chen[1], Alexander Y. Zhu[1], Vyshakh Sanjeev[1,3], Mohammadreza Khorasaninejad[1], Zhujun Shi[2], Eric Lee[1,3] and Federico Capasso[1,*]

High-NA achromatic metalenses by inverse design

Haejun Chung[1,2] and Owen D. Miller[1,3]

A broadband achromatic metalens array for integral imaging in the visible

Zhi-Bin Fan[1,2], Hao-Yang Qiu[1,2], Han-Le Zhang[3], Xiao-Ning Pang[1,2], Li-Dan Zhou[1], Lin Liu[1], Hui Ren[3], Qiong-Hua Wang[3] and Jian-Wen Dong[1,2]

Octave bandwidth photonic fishnet-achromatic-metalens

Abdoulaye Ndao[1,2,5], Liyi Hsu[1,2,5], Jeongho Ha[1,2], Jun-Hee Park[1,2], Connie Chang-Hasnain[1] & Boubacar Kanté[1,2,3,4]

Controlling the sign of chromatic dispersion in diffractive optics with dielectric metasurfaces

Ehsan Arbabi,[1] Amir Arbabi,[1,2] Seyedeh Mahsa Kamali,[1] Yu Horie,[1] and Andrei Faraon[1,*]

Broadband achromatic dielectric metalenses

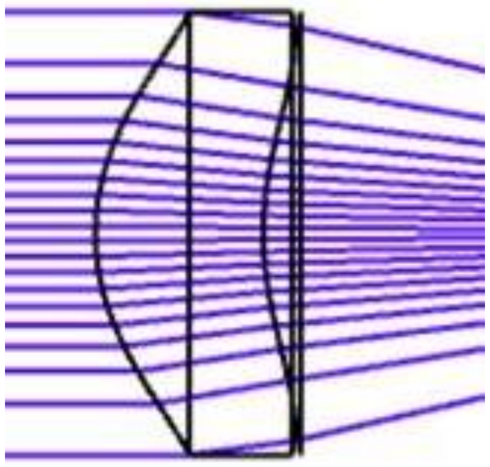
Sajan Shrestha[1], Adam C. Overvig[1], Ming Lu[2], Aaron Stein[2] and Nanfang Yu[1]

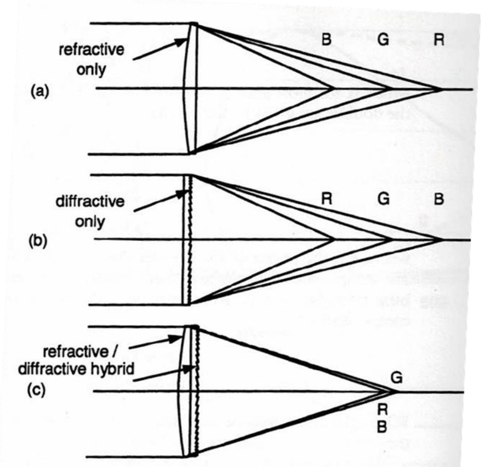
$$R_{max} \leq \frac{\Delta\Phi' c}{\Delta\omega\left(\frac{1}{NA} - \sqrt{\frac{1}{NA^2} - 1}\right)}$$

No high efficiency, achromatic focusing across full visible band for apertures > 150 um

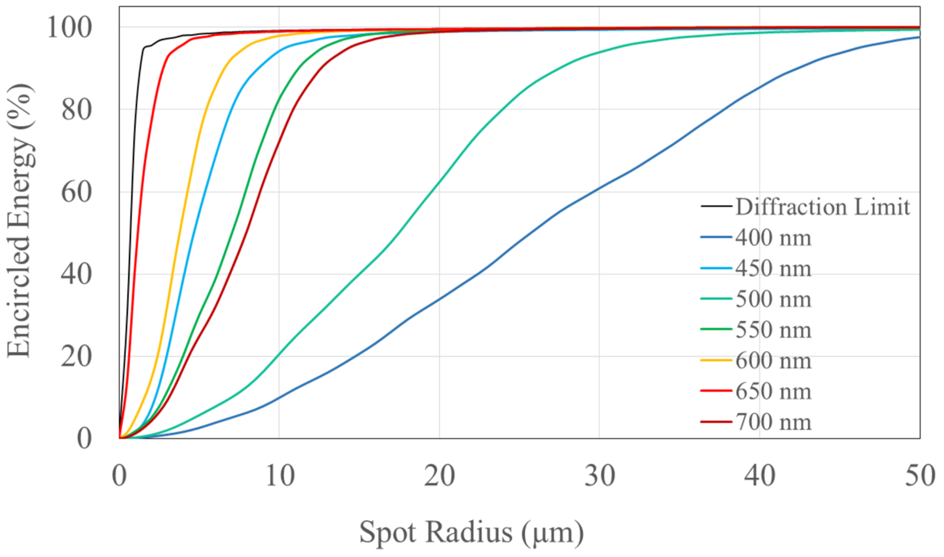
Hybrid lenses

- **A metalens can be broadband, large aperture, and high efficiency if it is *not* achromatic (and still useful!)**
- **Example: Cemented doublet**
  - Meniscus asphere + metalens

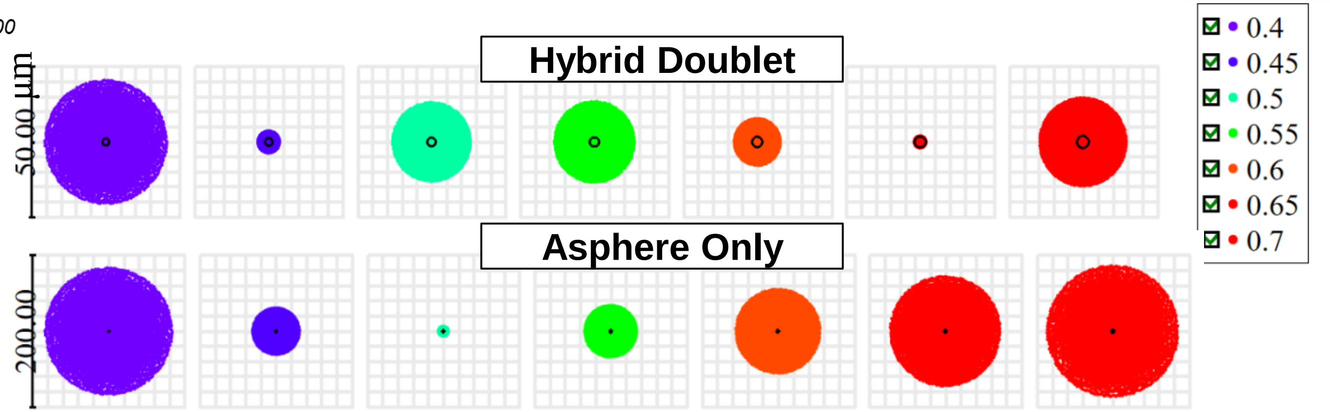




Source: Fischer and Tadic-Galeb, *Optical System Design*, 2000



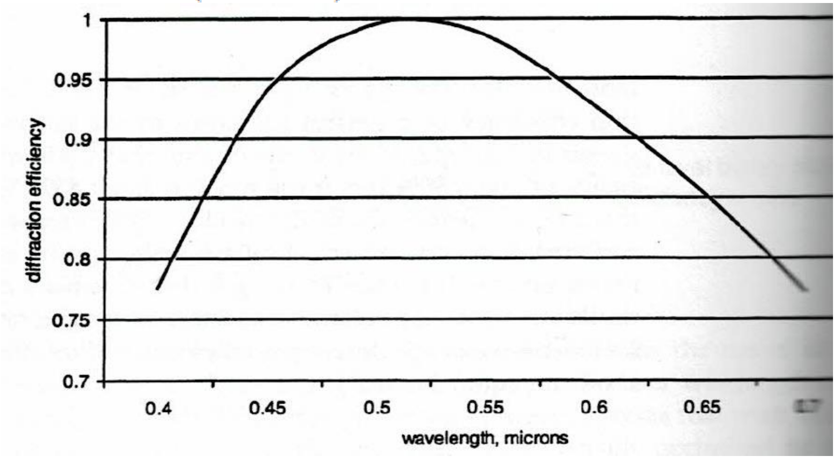
  - ~ diffraction limited performance at
    - 450 nm and 650 nm
  - 80% encircled energy within 10 um for
    - 425-500 nm
    - 575-700 nm



Broadband focusing performance is good, but what about efficiency?

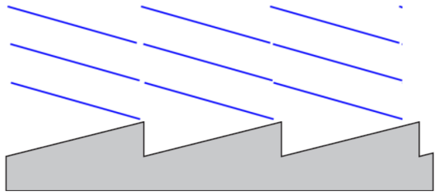
Efficiency of Metalenses/Diffractive Optical Elements

- **Diffractive optics are inefficient away from their design wavelengths**
  - $\eta(\lambda) = \text{sinc}^2\left(\frac{\Phi(\lambda)}{2\pi} - 1\right)$ with $\Phi(\lambda) = \frac{2\pi\lambda_0}{\lambda}\frac{n(\lambda)-1}{n(\lambda_0)-1}.$

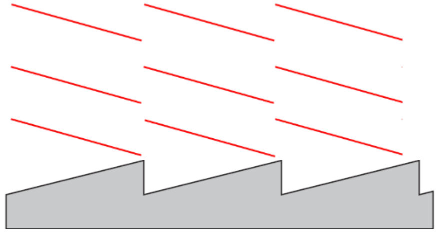


Source: Fischer and Tadic-Galeb, *Optical System Design, 2000*

- **And only reach peak efficiency when blazed**

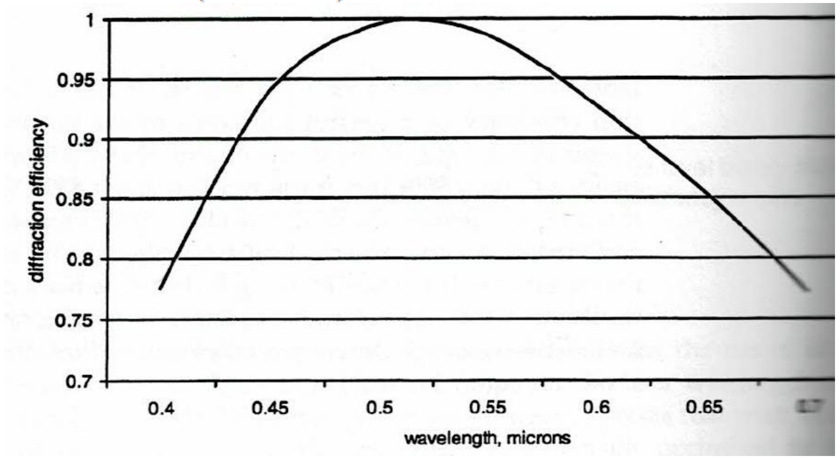


- **Since the blaze is only optimized at one wavelength, light at other wavelengths goes into other diffraction orders**



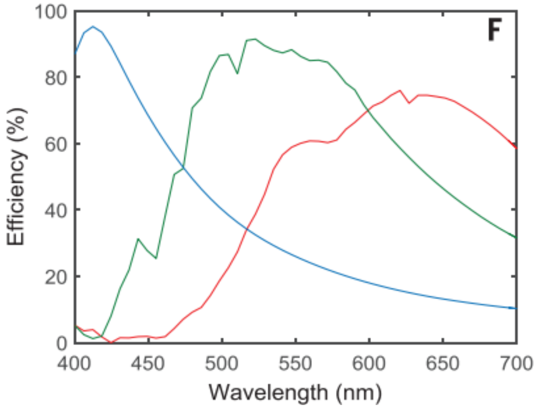
Efficiency of Metalenses/Diffractive Optical Elements

- **Diffractive optics are inefficient away from their design wavelengths**
  - $\eta(\lambda) = \text{sinc}^2\left(\frac{\Phi(\lambda)}{2\pi} - 1\right)$ with $\Phi(\lambda) = \frac{2\pi\lambda_0}{\lambda}\frac{n(\lambda)-1}{n(\lambda_0)-1}$.



Source: Fischer and Tadic-Galeb, *Optical System Design, 2000*

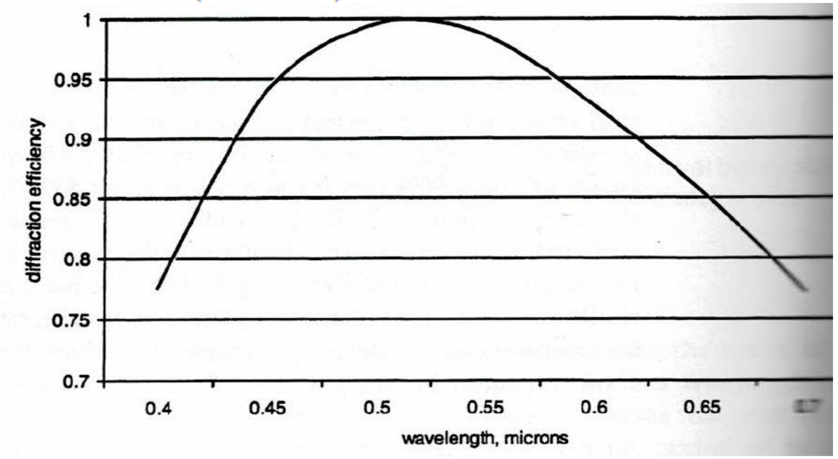
- **This kind of efficiency vs wavelength trend was seen frequently in early metalens papers**



Source: Khorasaninejad, et. al, *Science,* 2016 (Capasso group)

Efficiency of Metalenses/Diffractive Optical Elements

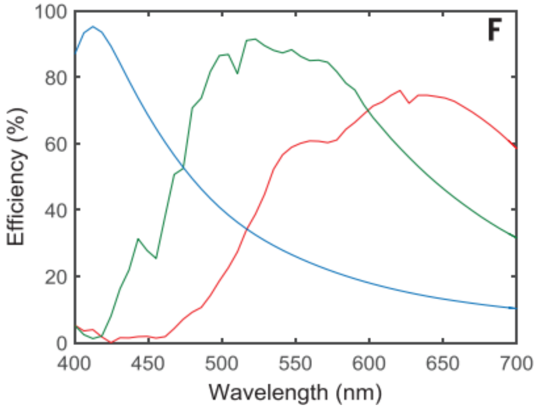
- **Diffractive optics are inefficient away from their design wavelengths**
  - $\eta(\lambda) = \mathrm{sinc}^2\left(\frac{\Phi(\lambda)}{2\pi} - 1\right)$ with $\Phi(\lambda) = \frac{2\pi\lambda_0}{\lambda}\frac{n(\lambda)-1}{n(\lambda_0)-1}$.



Source: Fischer and Tadic-Galeb, *Optical System Design, 2000*

➢ **There's really no difference between this and a metalens (or a grin lens, for that matter), in terms of the basic physics.**
  - They are all blazed diffractive optics

- **This kind of efficiency vs wavelength trend was seen frequently in early metalens papers**



Source: Khorasaninejad, et. al, *Science*, 2016 (Capasso group)

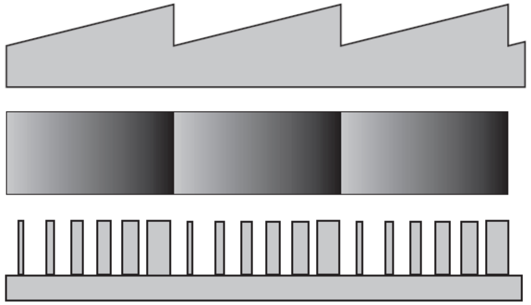


FIG. 7 Similarity between surface relief profiles (top), gradient-index materials (middle), and sub-wavelength structures (bottom) all realising a blazing phase if the effective refractive index and thickness of the DOE are chosen properly as given in Figure 8 for a GRIN-DOE.

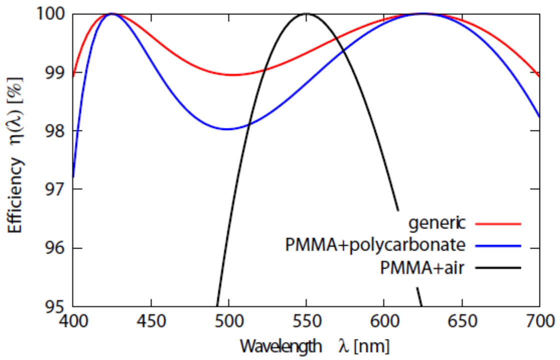
Source: Kleemann, *Design concepts for broadband high–efficiency DOEs*, J. European Opt. Society, 2008

How to improve diffractive optic efficiency

- **Bilayer diffractive optic**

FIG. 5 Three optically equivalent embodiments of a multilayer EA-DOE.

  – Two materials with different dispersive properties can be combined to produce high-efficiency diffraction across a broadband



Source: Kleemann, *Design concepts for broadband high–efficiency DOEs*, J. European Opt. Society, 2008

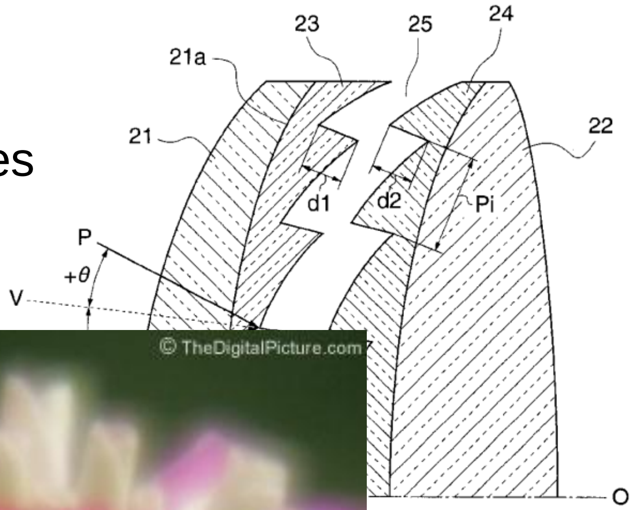
  – Use differences in dispersion to effectively make the blaze work at two wavelengths simultaneously

- **Blazes are usually tall, limiting field of view and f/# due to losses from shadowing and stray light**

$$h_1 = \frac{\lambda_1 n_{22} - \lambda_2 n_{21}}{n_{11} n_{22} - n_{12} n_{21}}$$

$$h_2 = \frac{\lambda_1 n_{12} - \lambda_2 n_{11}}{n_{11} n_{22} - n_{12} n_{21}}$$

- **Nevertheless these have been commercialized**
  – Canon has at least two telephoto lenses featuring bilayer diffractive optics



Source: Canon patent 6,473,232

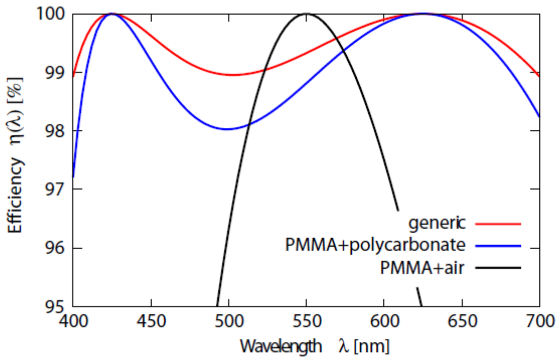
Physical Sciences Inc.

How to improve diffractive optic efficiency

- **Bilayer diffractive optic**

FIG. 5 Three optically equivalent embodiments of a multilayer EA-DOE.

  – Two materials with different dispersive properties can be combined to produce high-efficiency diffraction across a broadband



Source: Kleemann, *Design concepts for broadband high–efficiency DOEs*, J. European Opt. Society, 2008

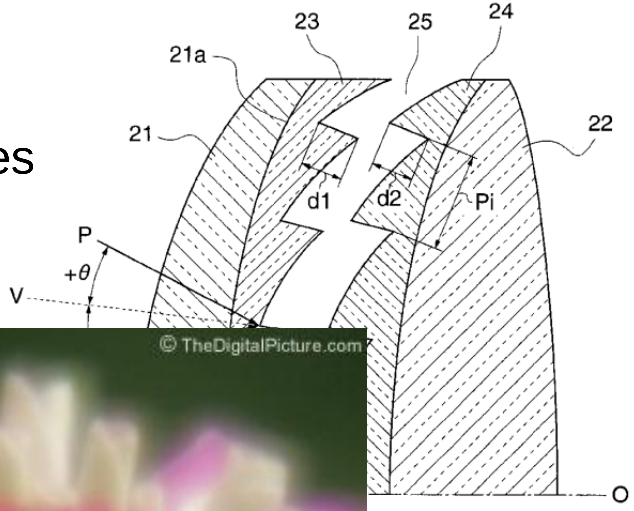
  – Use differences in dispersion to effectively make the blaze work at two wavelengths simultaneously

- **Blazes are usually tall, limiting field of view and f/# due to losses from shadowing and stray light**

$$h_1 = \frac{\lambda_1 n_{22} - \lambda_2 n_{21}}{n_{11} n_{22} - n_{12} n_{21}}$$

$$h_2 = \frac{\lambda_1 n_{12} - \lambda_2 n_{11}}{n_{11} n_{22} - n_{12} n_{21}}$$

- **Nevertheless these have been commercialized**
  – Canon has at least two telephoto lenses featuring bilayer diffractive optics

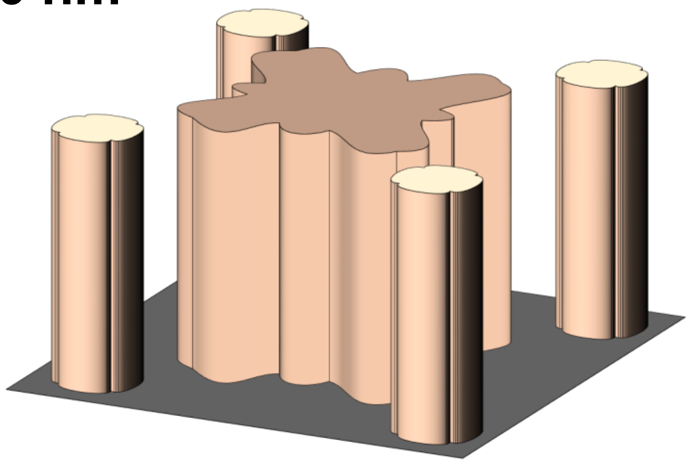


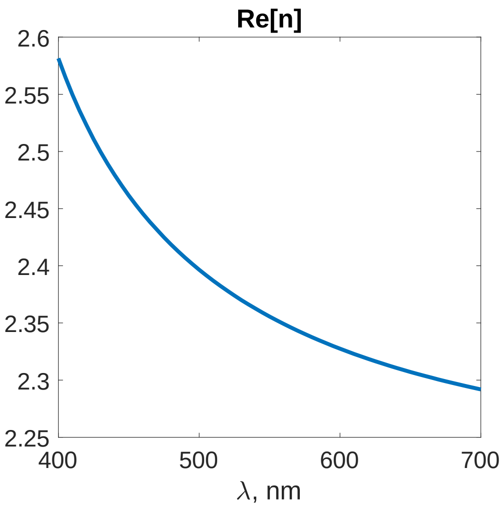
Source: Canon patent 6,473,232

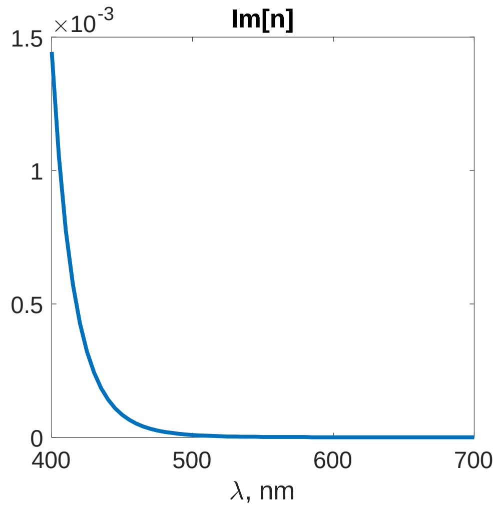
This kind of dispersion engineering can be performed in a single layer metalens

Building the library for a broadband, efficient metalens

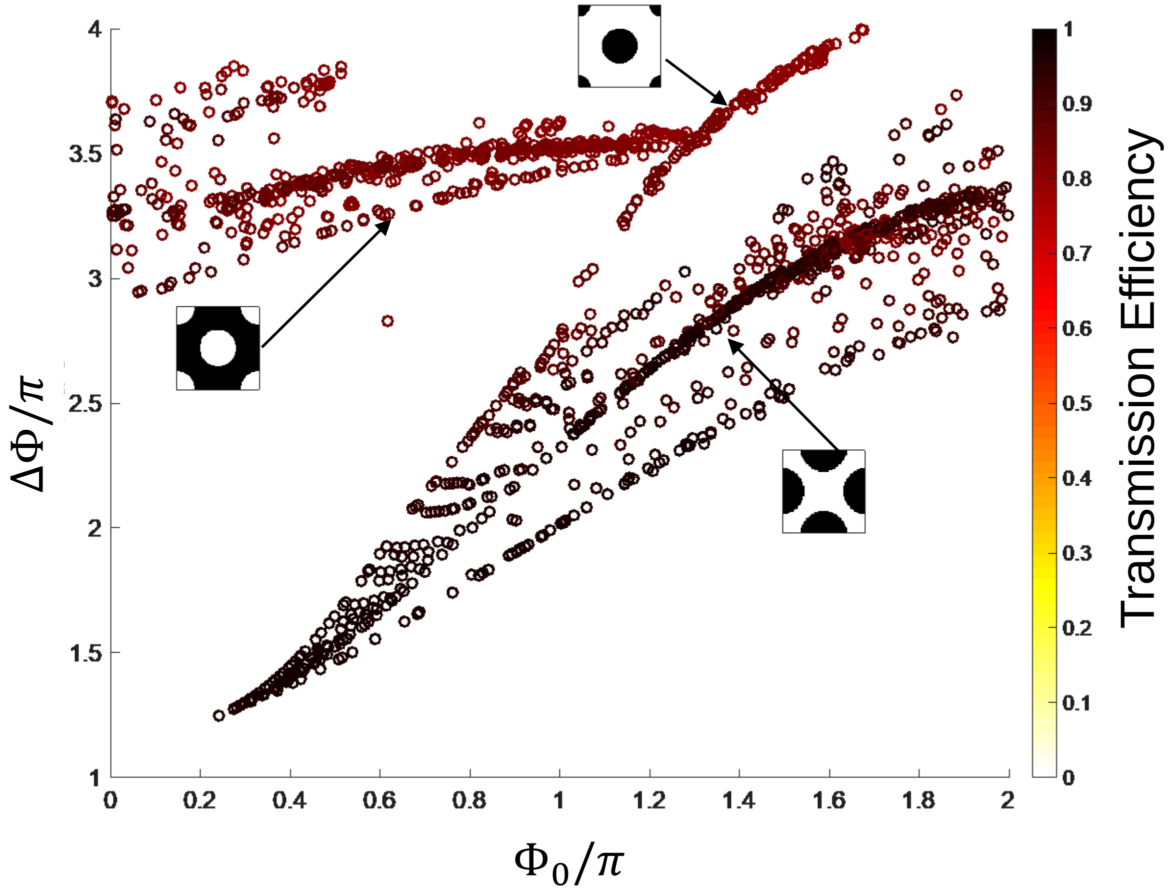
- **2392 entries with mean(T) > 0.8**
- **Bandwidth: 400 – 700 nm**
- **C4 symmetry**
- **TiO_2 on SiO_2**





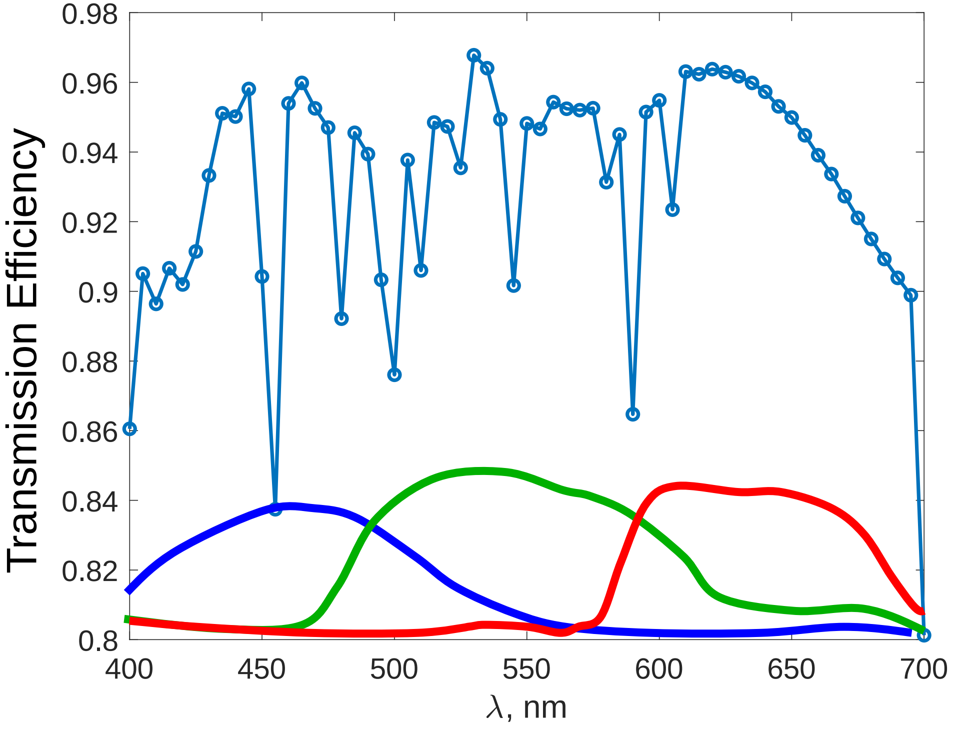


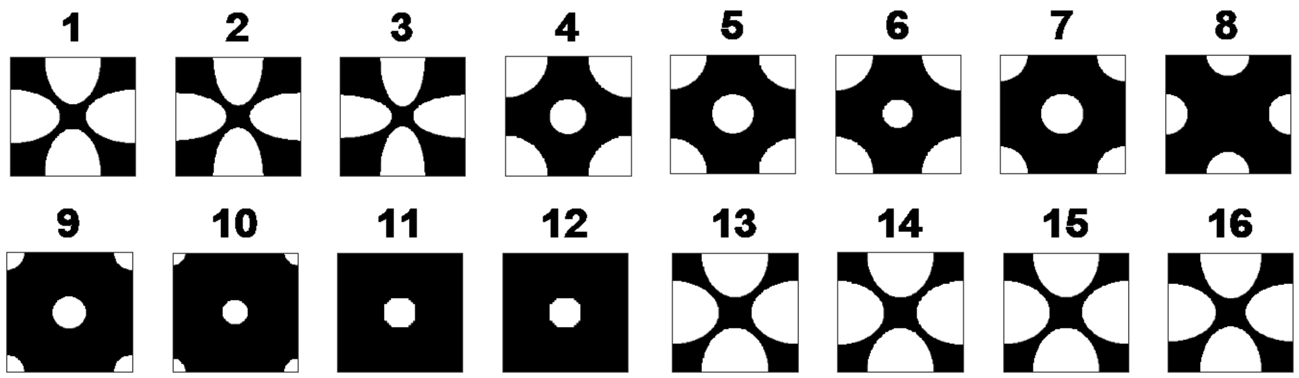
- **500 element sub-library showing Φ_0, $\Delta\Phi$ and average transmission > 0.8**



High efficiency Broadband Diffractive Optic

- **16 elements that are comprised only of circular holes or ovals**
  - Offer the best trade-off between theoretical performance and manufacturability



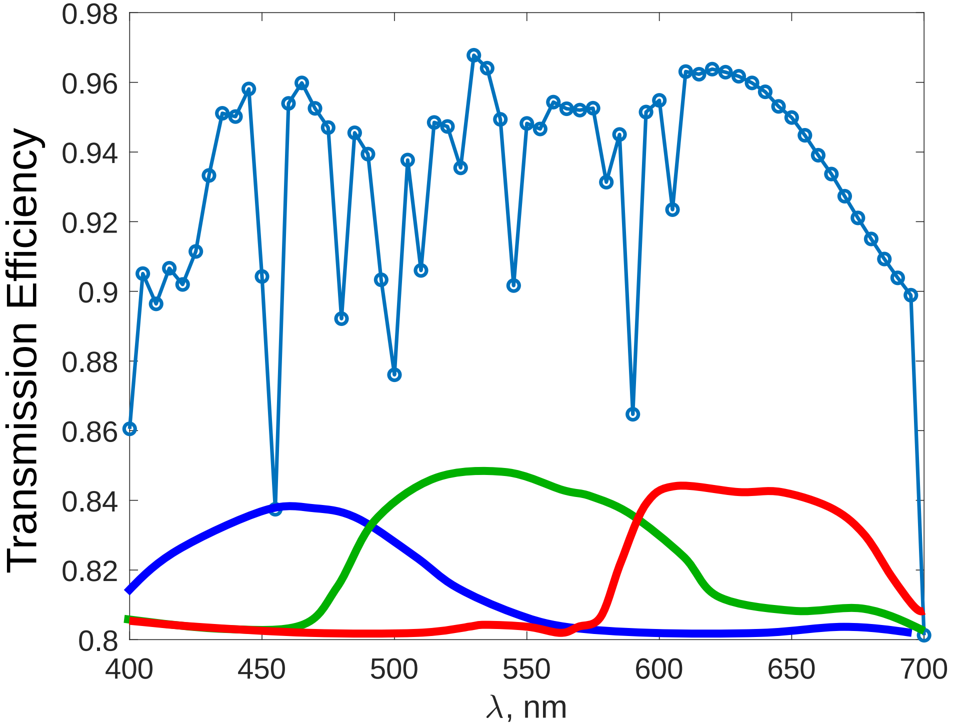


  - Perform well in each visible color band
  - Scalable to almost any f/# and aperture

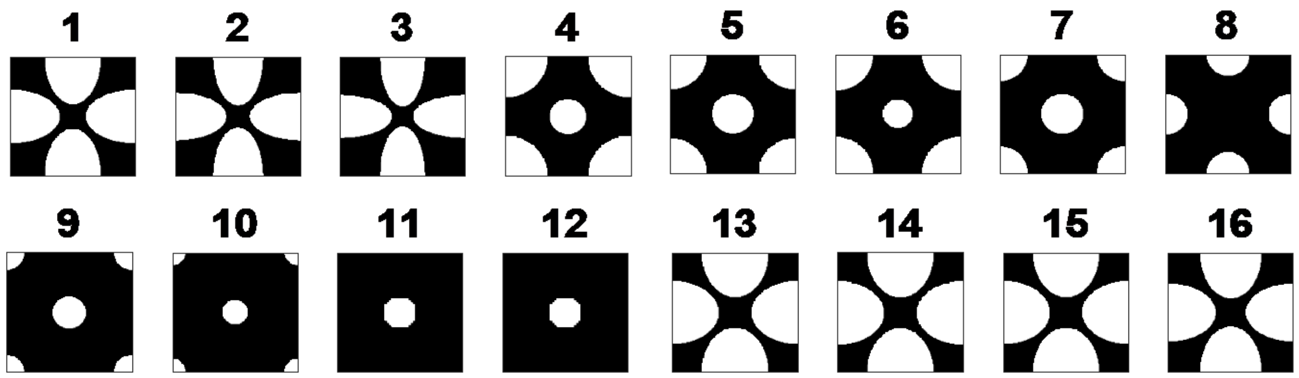
Physical Sciences Inc.

High efficiency Broadband Diffractive Optic

- **16 elements that are comprised only of circular holes or ovals**
  - Offer the best trade-off between theoretical performance and manufacturability

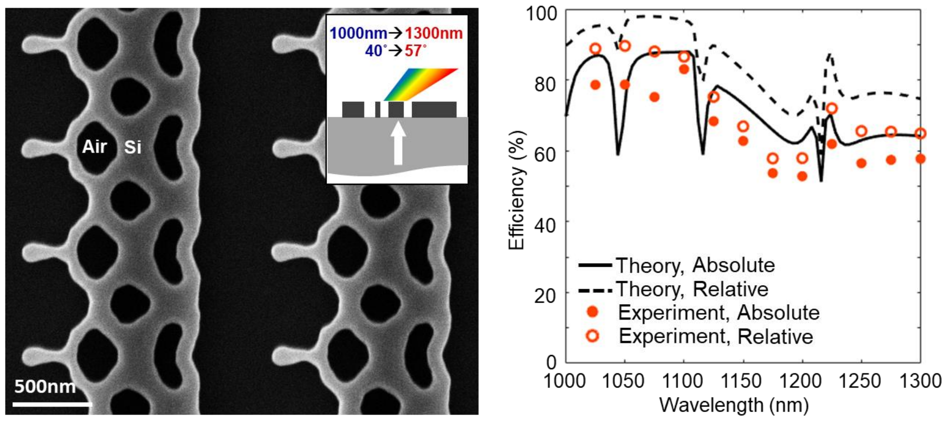


  - Perform well in each visible color band
  - Scalable to almost any f/# and aperture



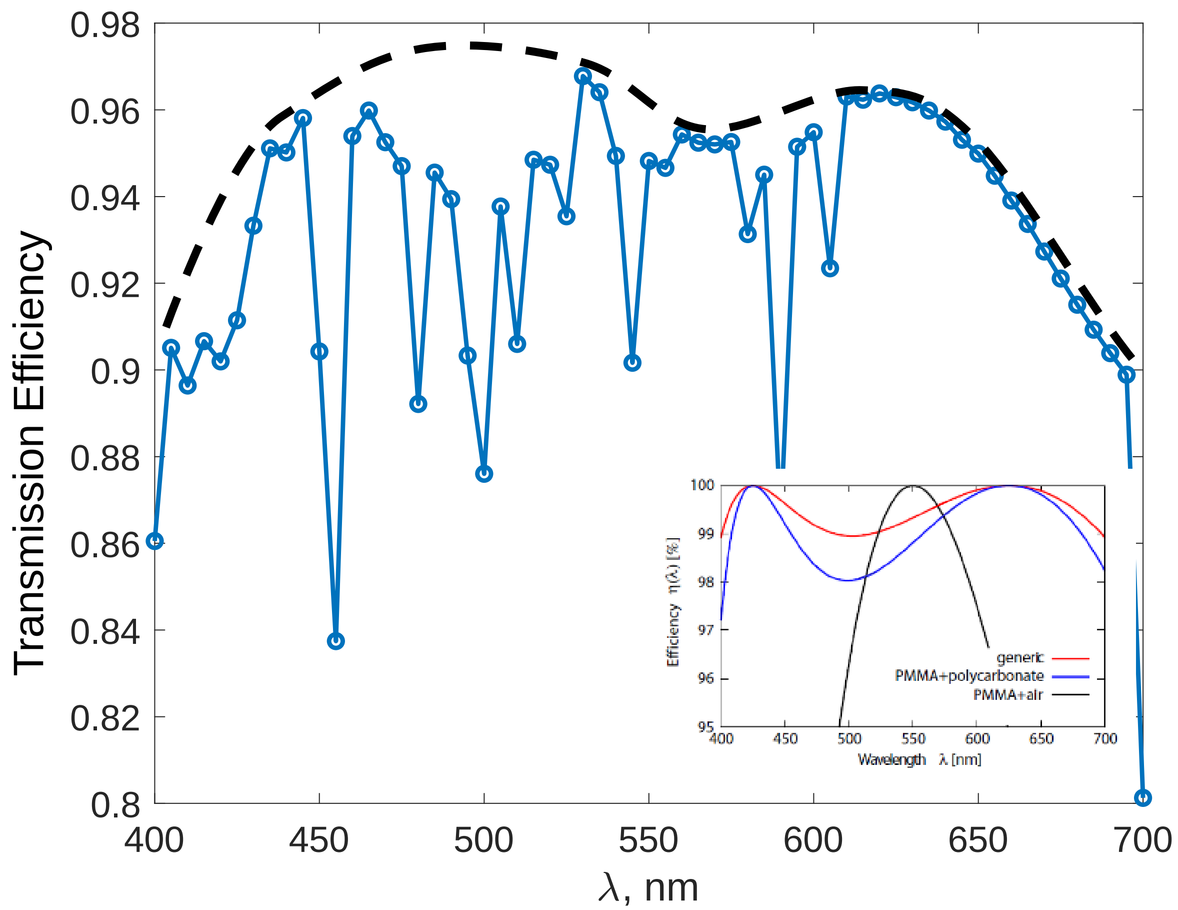
The same physics that led to high efficiency metagratings from the Fan Group

Broadband diffraction



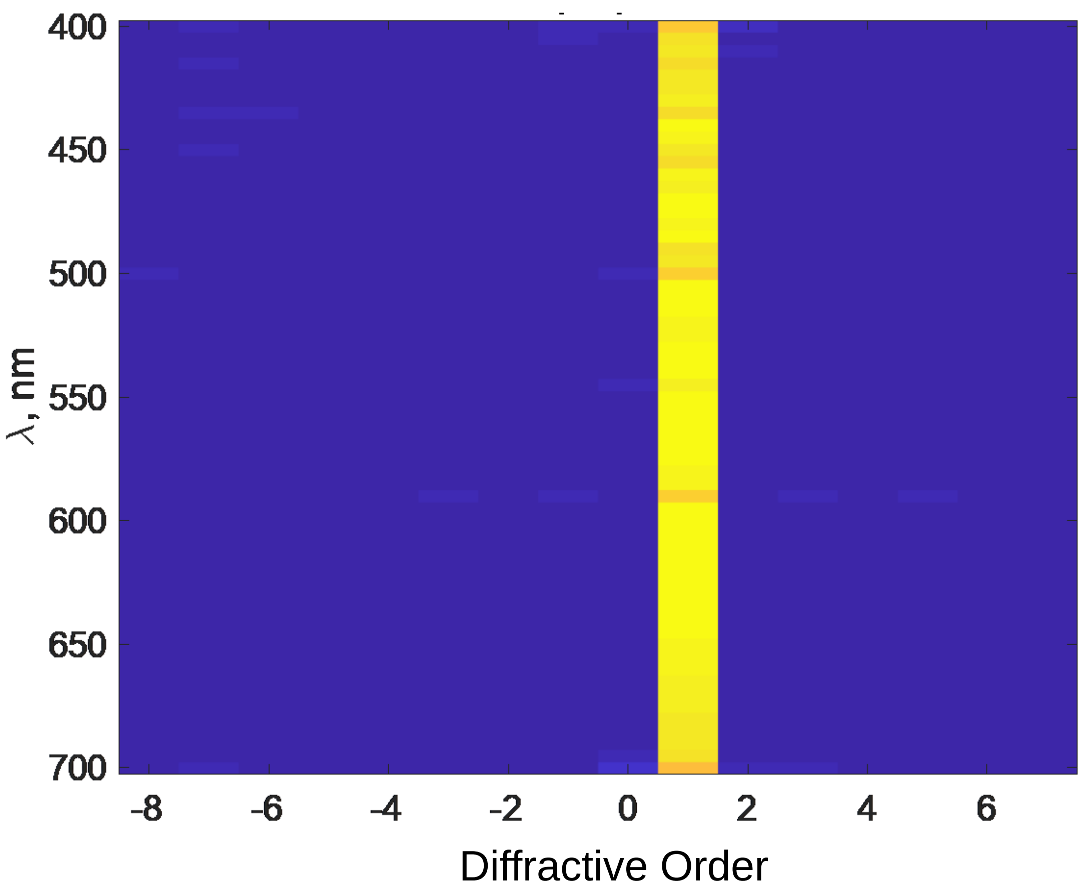
ACS Photonics, 5, 2402-2407 (2018)

High efficiency, broadband metalens



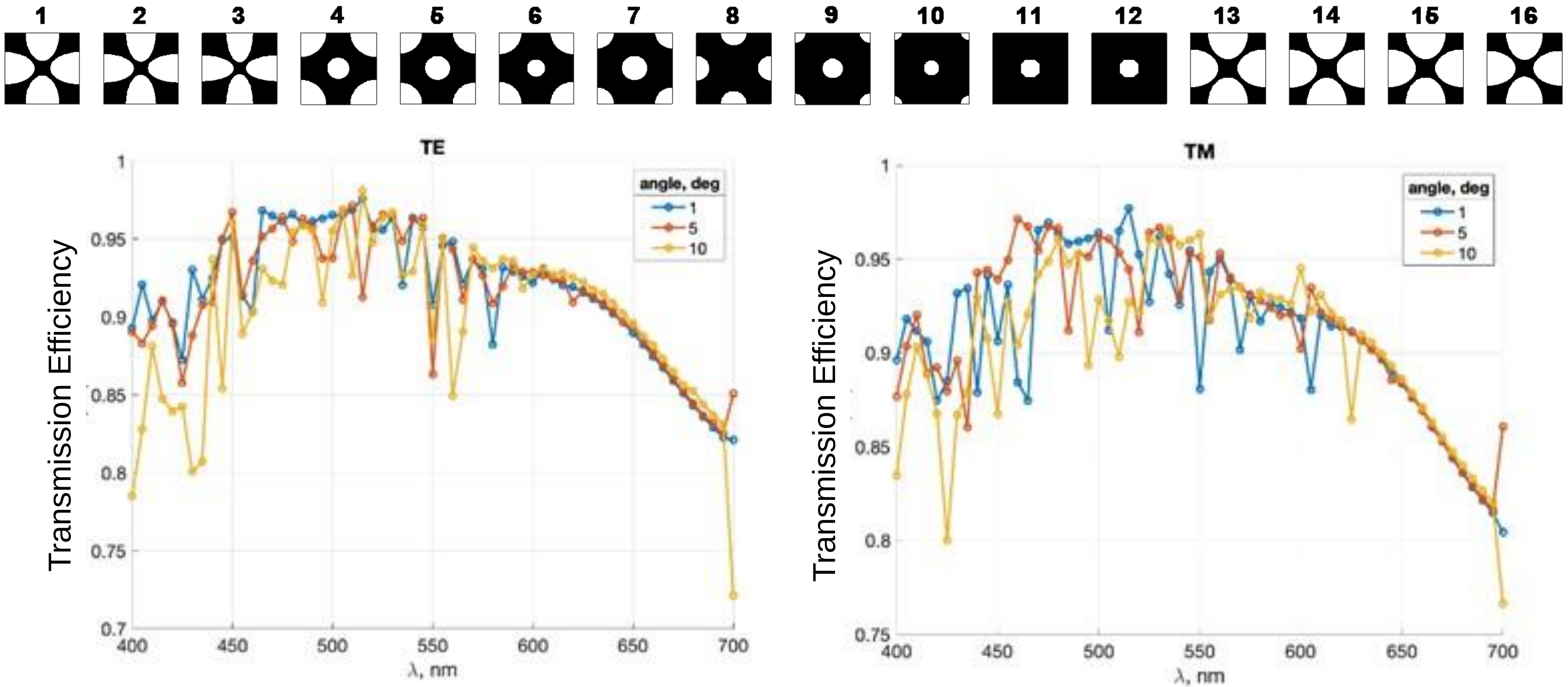
- Performance matches with theory for "double blazed" diffractive optics – two peaks in transmission efficiency at 475 and 625 nm

- **Majority of diffracted light is going into +1 order, with no other orders having significant population.**



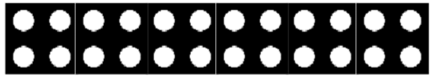
Efficiency as a function of angle of incidence

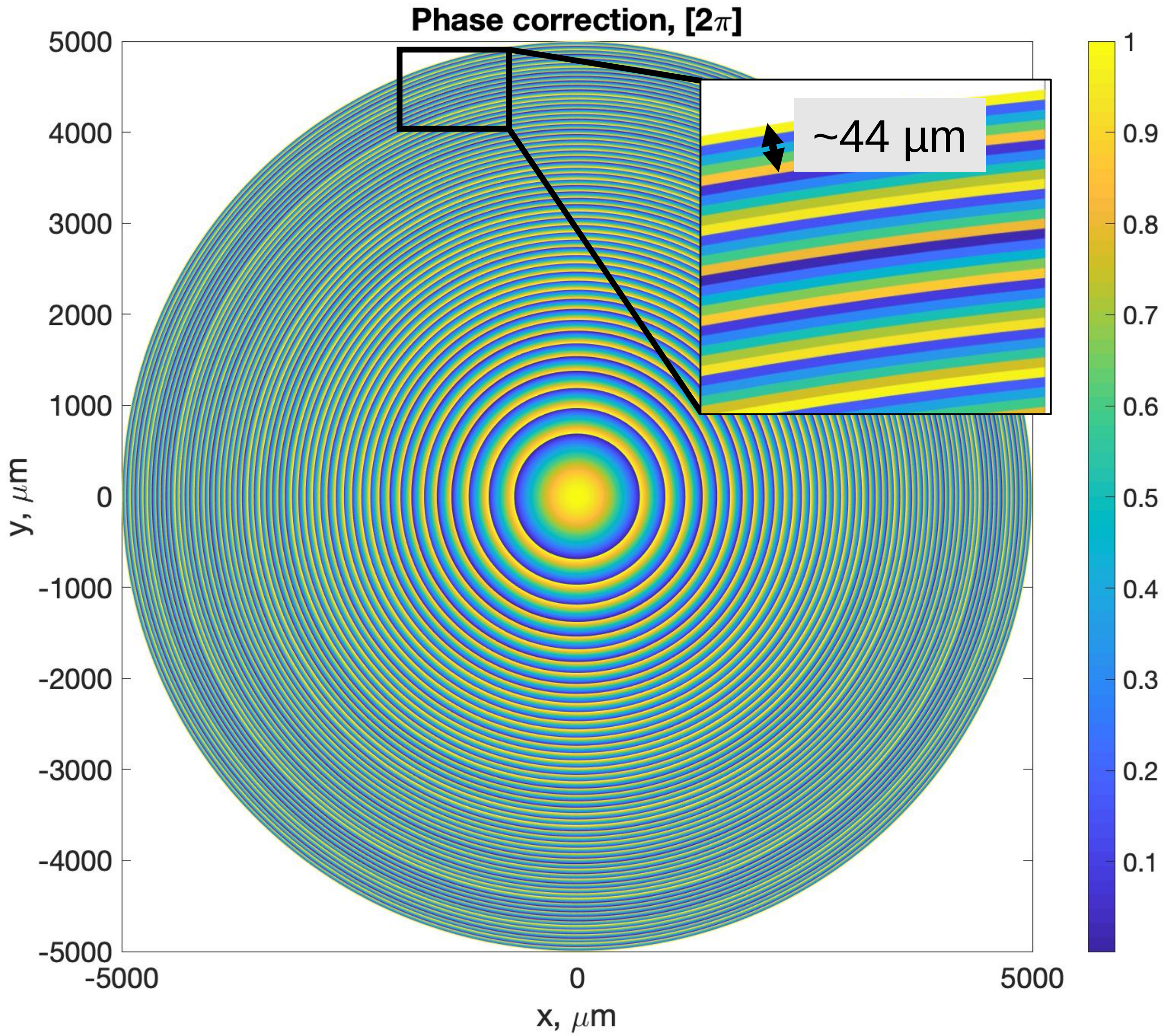
- **Efficiency of an optimized set of meta-elements remained high (> 80%) for both TE and TM polarization out to 10°**

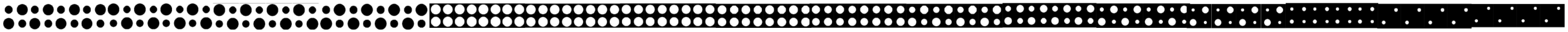


Layout of a 1 cm meta-corrector

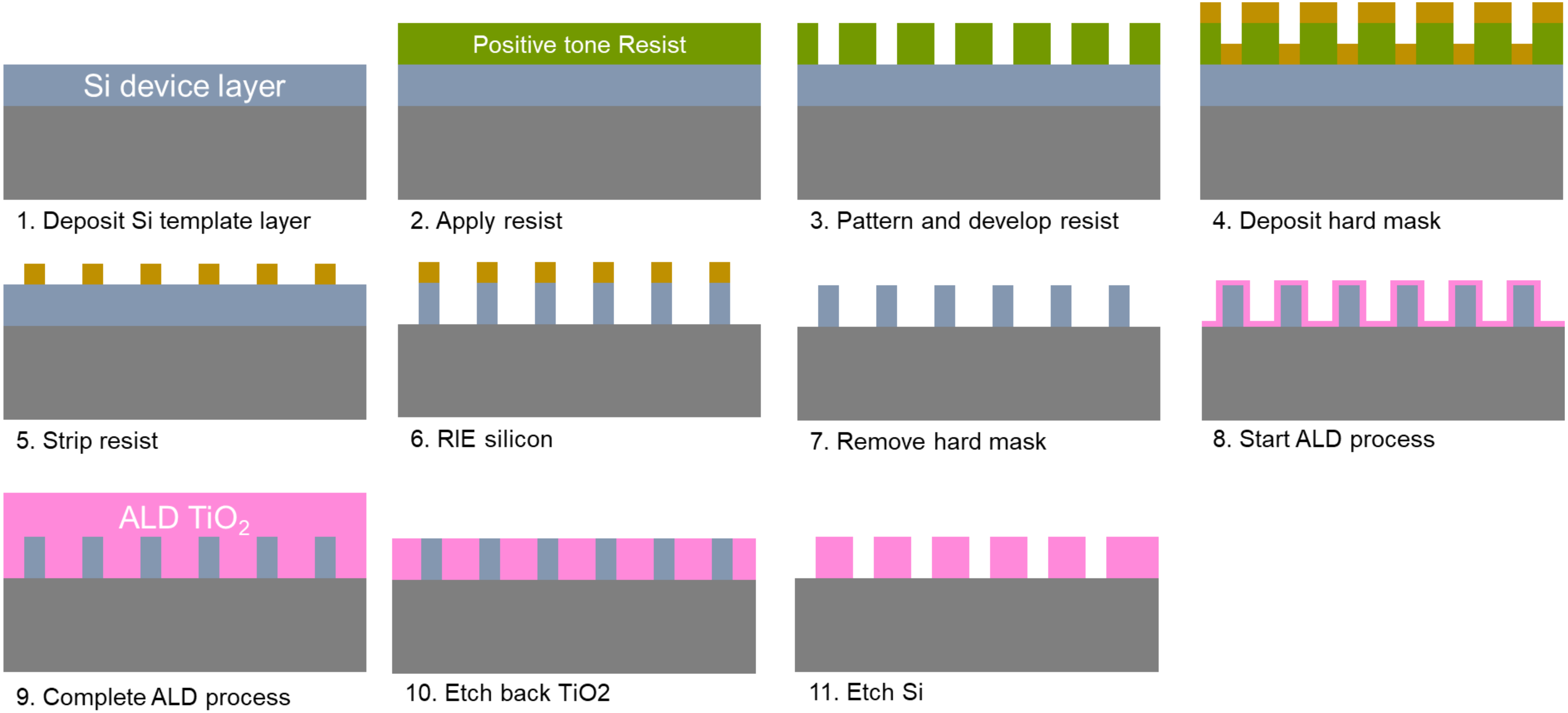
- **Design of a 1 cm diameter meta-lens**
  - Performed in Zemax
  - Central zone radius: 600 um
  - Outermost zone width: 44 um

- **Device works on three length scales**
  - Meta-atom:
    - 300 nm
    - 
  - Meta-grating:
    - 3-30 um
    - 
  - Fresnel zone:
    - 44-600 um

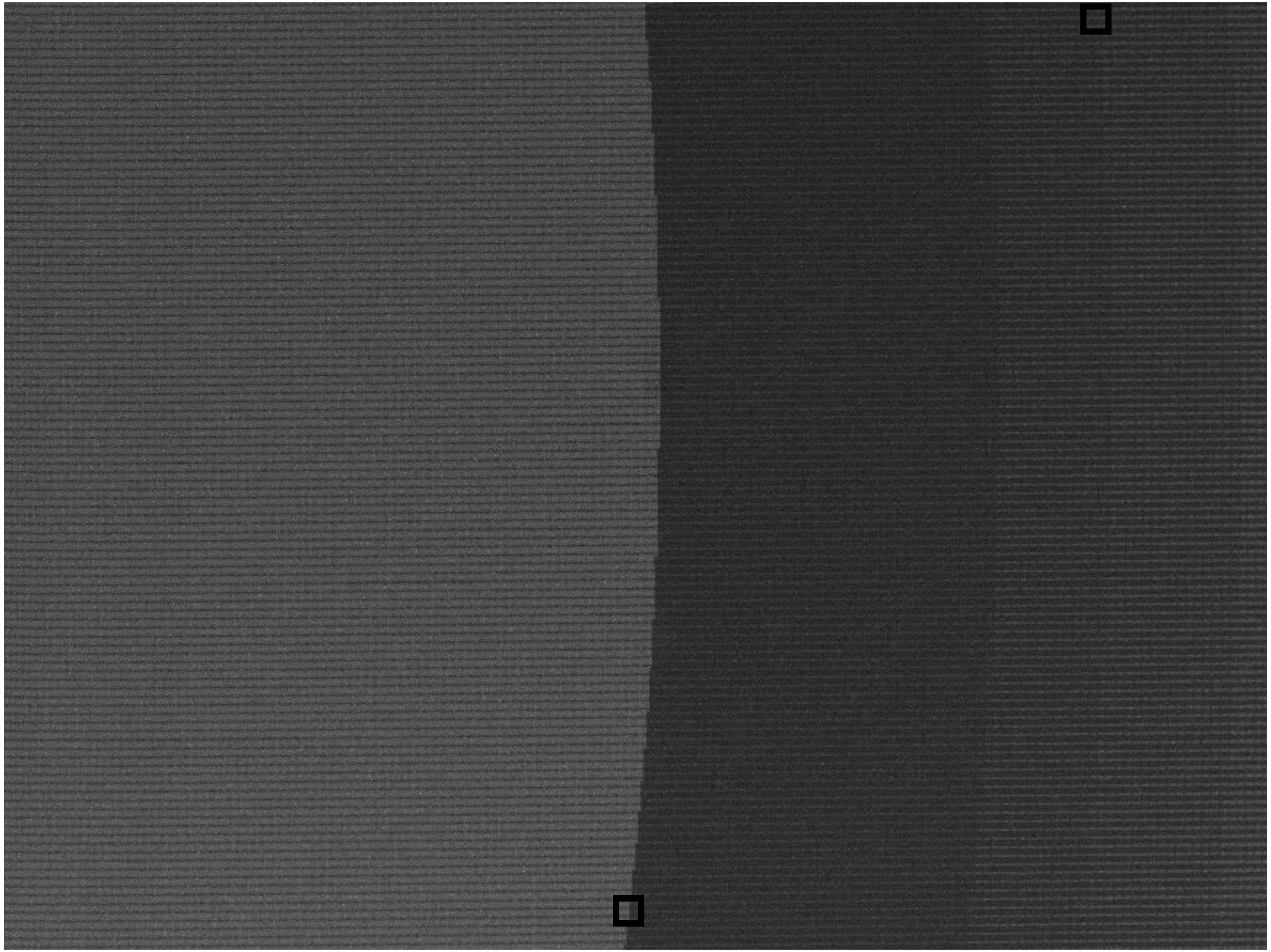




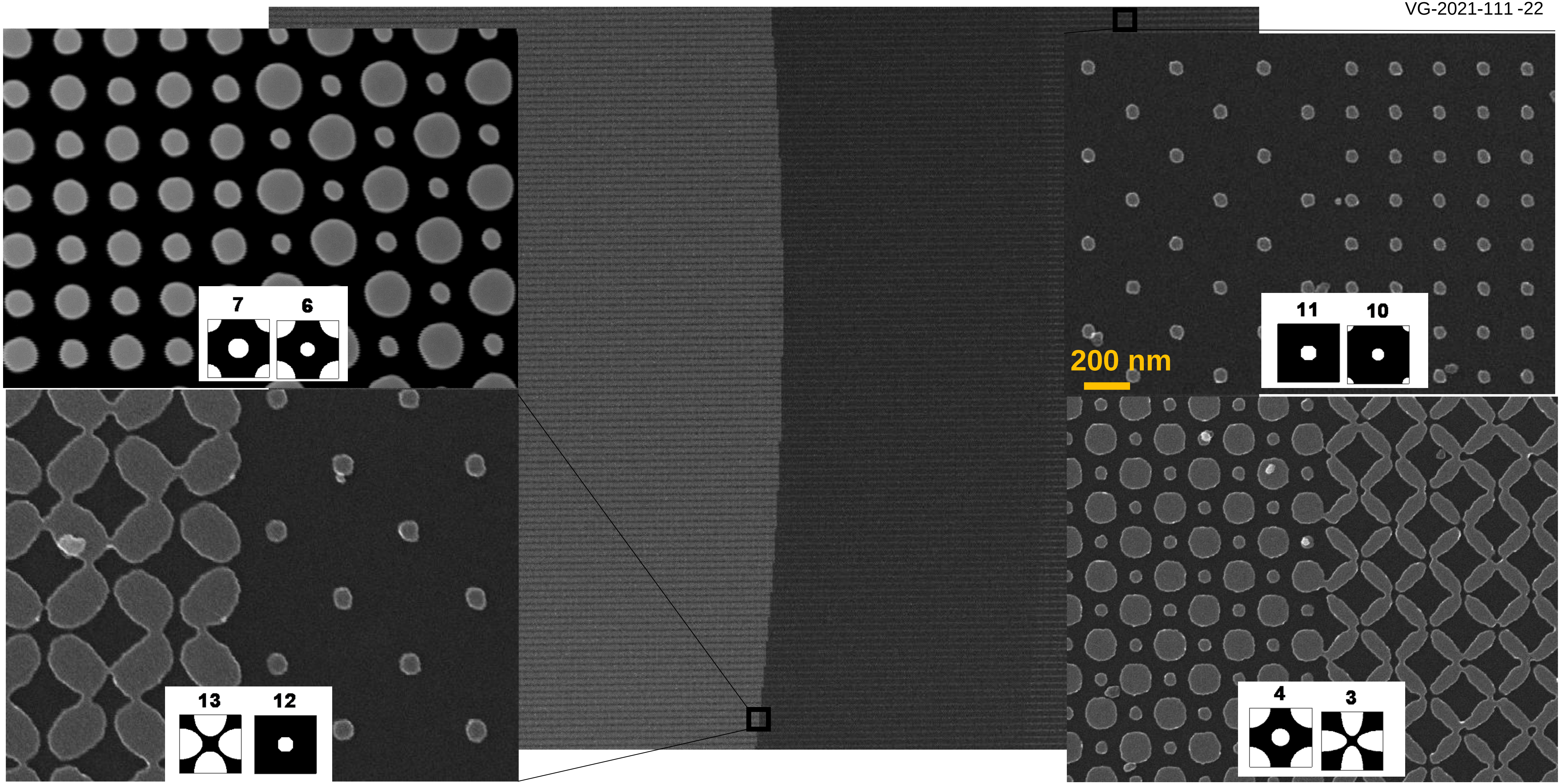
Fabrication process



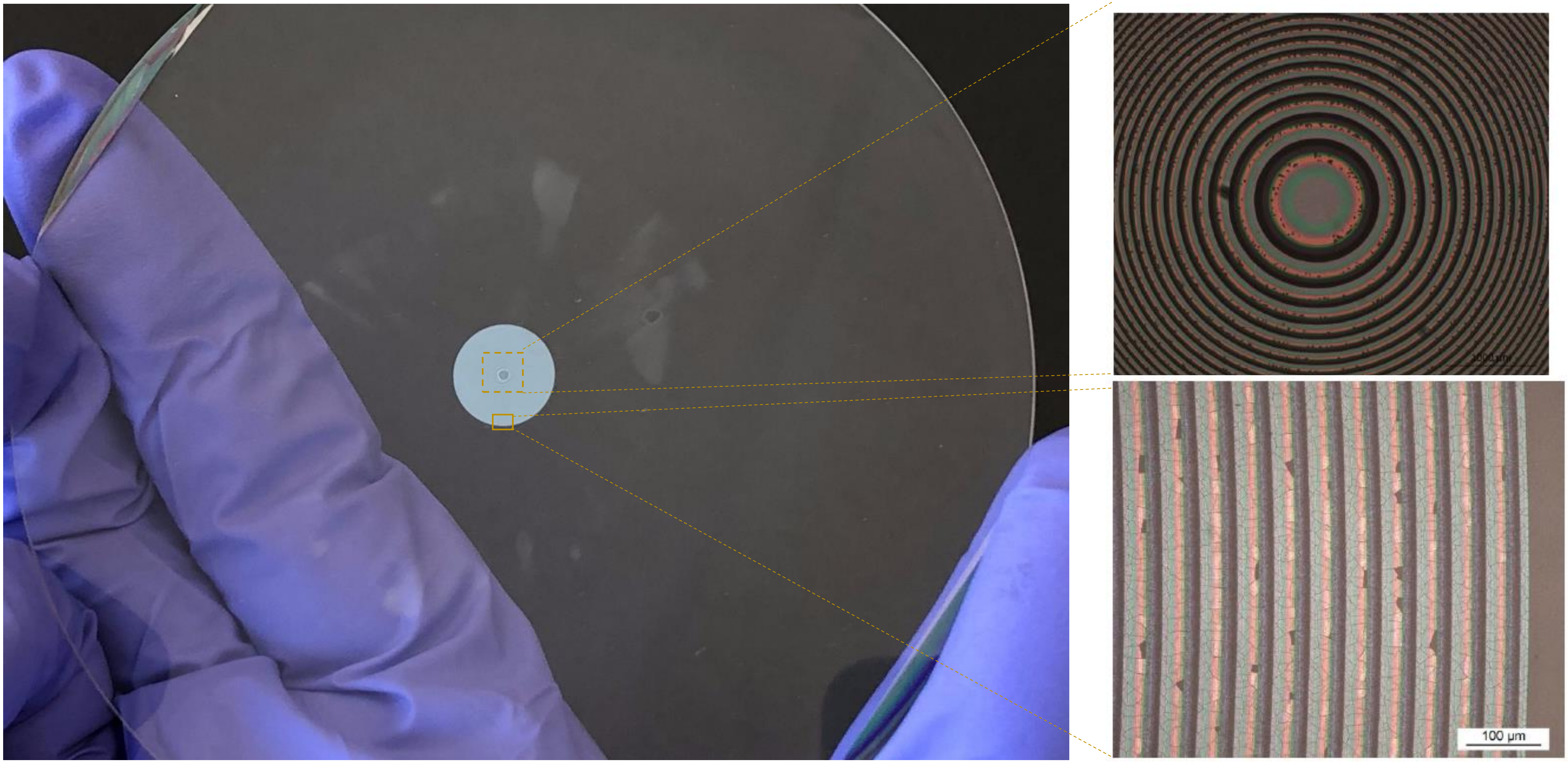
Fabrication of Si Template



Fabrication of Si Template



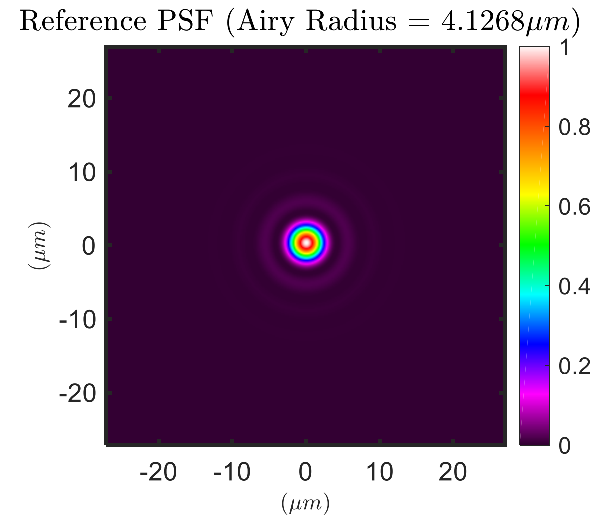
Fabricated Lens

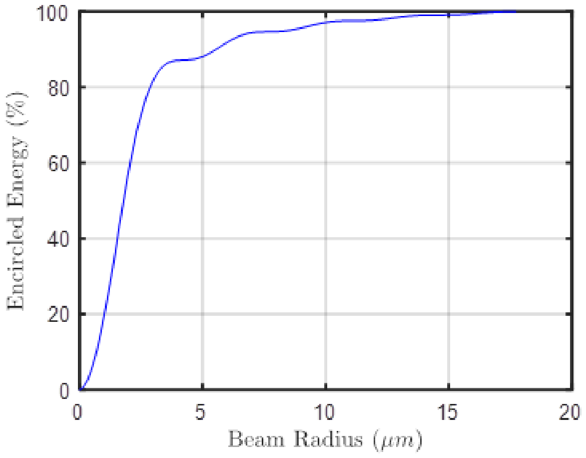


Physical Sciences Inc.

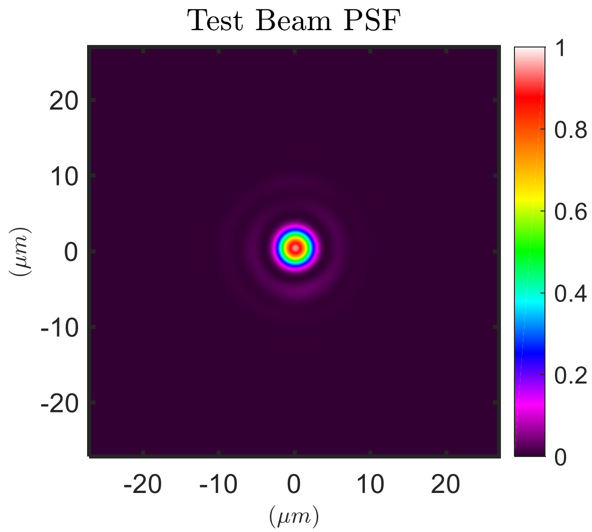
Performance @ 632 nm

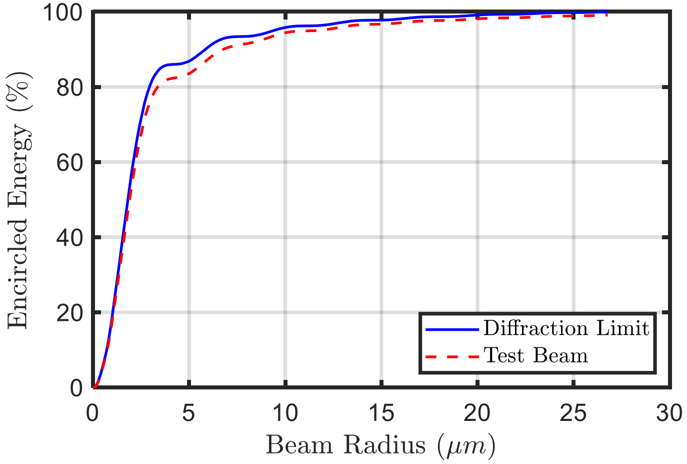
Ideal lens



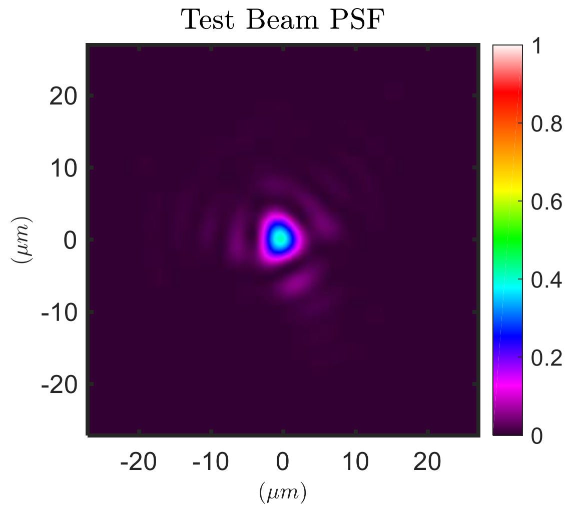


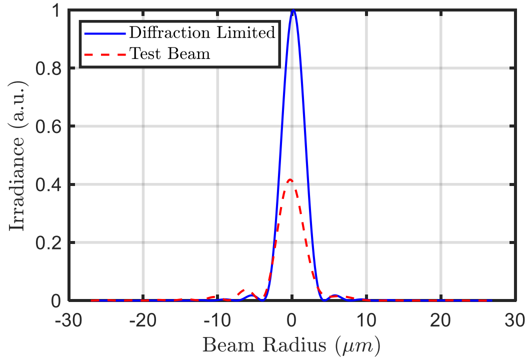
Asphere

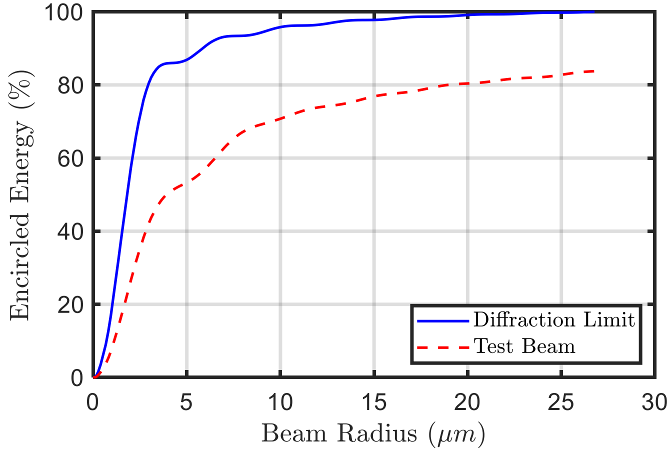




Asphere/metalens doublet



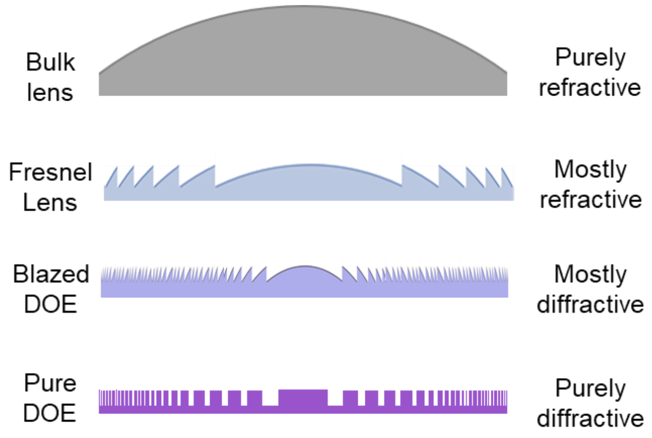




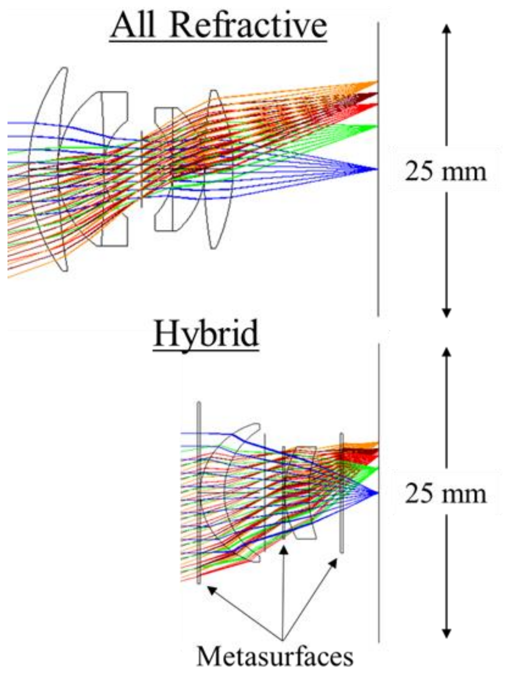
Current device limited because of out-of-spec height and stress-related cracking

Conclusions

- **We developed a design for a high-efficiency, broadband metalens**
  - Used a heuristic approach, based on mature diffractive optic design methods
  - > 90% transmission efficiency in each of the red, green and blue color bands
  - Maintains performance out to > 10° AOI



- **Metalens can be used to correct aberrations in multi-element optical systems**
  - Corrective doublets
  - Multi-element imaging systems



- **Fabricated a proof of concept, 1-cm diameter metalens**
  - Currently working on stress-minimizing approaches

- **Demonstrated focusing when hybridized with a commercial asphere, limited by fabrication errors in prototype device**
  - Integrating diffractive optics into multi-element systems can drastically decrease size and weight of optical systems

Physical Sciences Inc.

Thank you

PSI Team

David Woolf

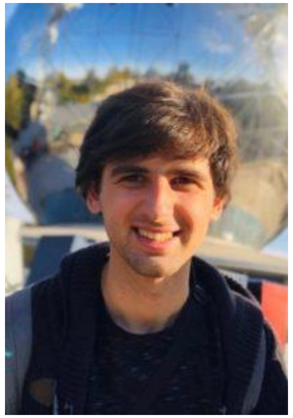
Joel Hensley

Joe Goodwin

Stanford Team

Jon Fan

Anton Ovcharenko

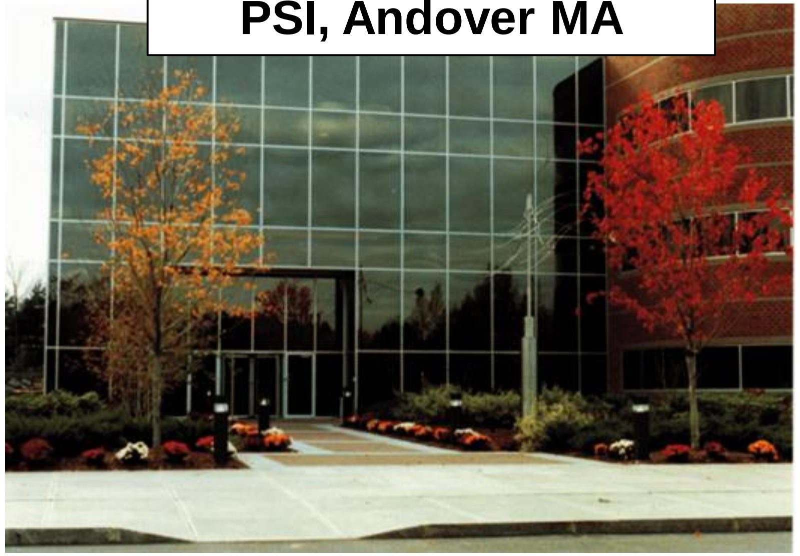


Peter Phan

Mingkun Chen

Foundry fabrication by NILT

PSI, Andover MA



About PSI: PSI is a small business with $80M annual revenue (~200 employees) with >45 year track record of developing and transitioning technologies, include space payloads

Currently hiring for photonics and materials science!

www.psicorp.com

Questions: contact dwoolf@psicorp.com