University of Glasgow

THE AWARDS 2020 | UNIVERSITY OF THE YEAR

CEOI

Nanostructured Ultra-Lightweight Lenses for Earth Observation

Thomas S. Nowack, Mitchell Kenney, James Grant,

Danni Hao, David R. S. Cumming

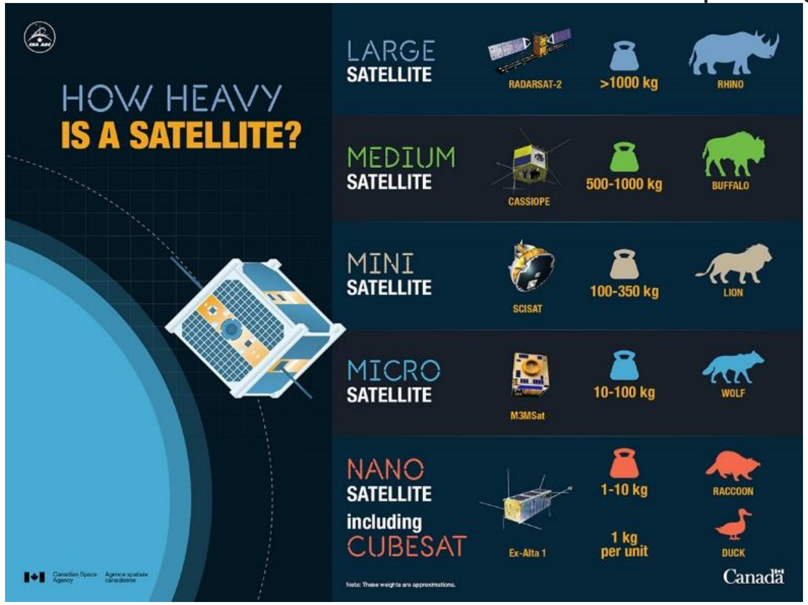
WORLD CHANGING GLASGOW

Satellite optic – Design considerations & important metrics

Weight

→ 5-20 k$/kg

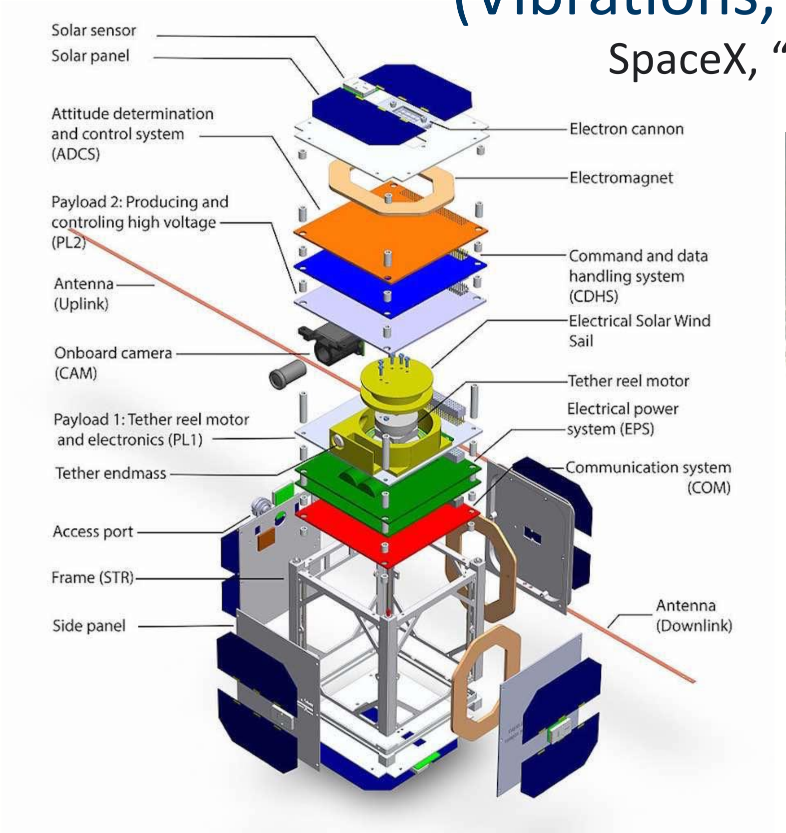
©Canadian Space Agency



Compactness

i.e. CubeSat

1U →11.35cm x 10cm x 10cm



The structure of cubesat ESTCube-1

Kuuste, Henri, et al. "Imaging system for nanosatellite proximity operations." *Proceedings of the Estonian Academy of Sciences* 63 (2014).

Stability & Reliability

(Vibrations, Temperature, Radiation, etc.)

SpaceX, "Falcon User's guide", (April 2020)

Slavinskis, Andris, et al. "ESTCube-1 in-orbit experience and lessons learned." *IEEE aerospace and electronic systems magazine* 30.8 (2015): 12-22.

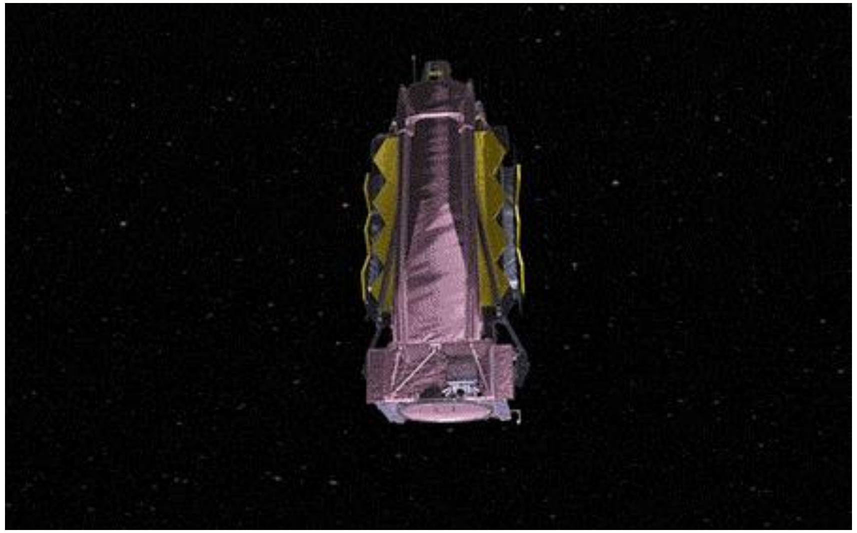
Performance

e.g. aperture size, efficiency, image acquisition time, image quality

Satellite optic – State of the art technologies

(Foldable) Au mirrors

- Medium to large apertures
- Good ratio weight ↔ area
- Only compact when folded
- Reflection imaging (larger volume)
- Moving parts (less robust/reliable)



©NASA: James Webb Space Telescope

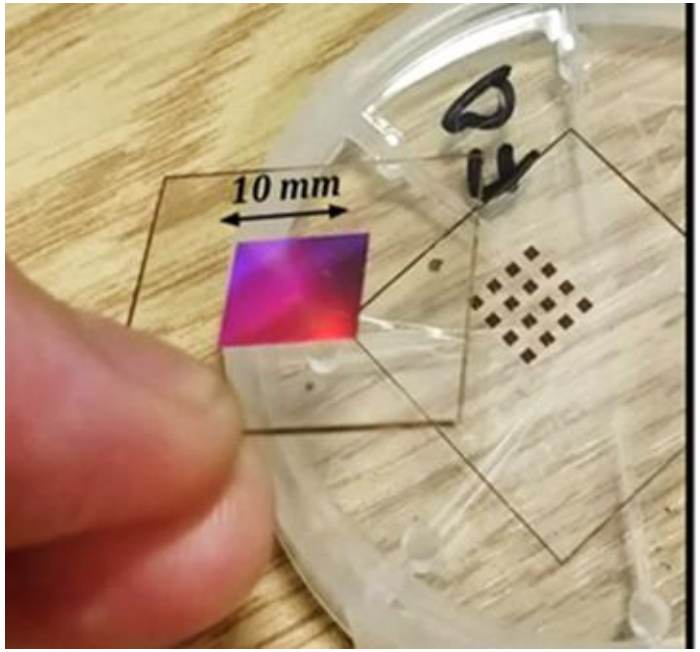
© TH Swiss, Irix
https://space.irixlens.com
(last accessed 23/06/21)

Classic (bulk) optic

- Small to medium apertures
- Heavy, i.e. for large NA/aper. [250 g, aperture: 70mm]
- Bulky lens (Transmission)
- Comparably robust
- Very mature technology

Metasurfaces

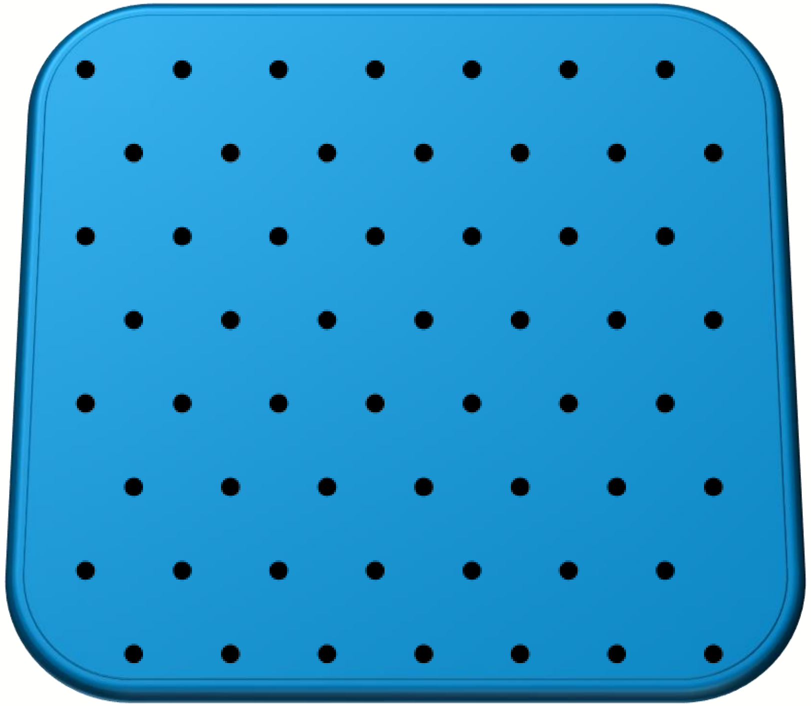
- Previously only small apertures
- Ultra Lightweight aperture 70mm→2.2 g (quick math)
- Ultra-compact (planar, Transmission)
- Robustness given by substrate
- Rich, ever advancing capabilities (multiplexing, achromatic, etc.)



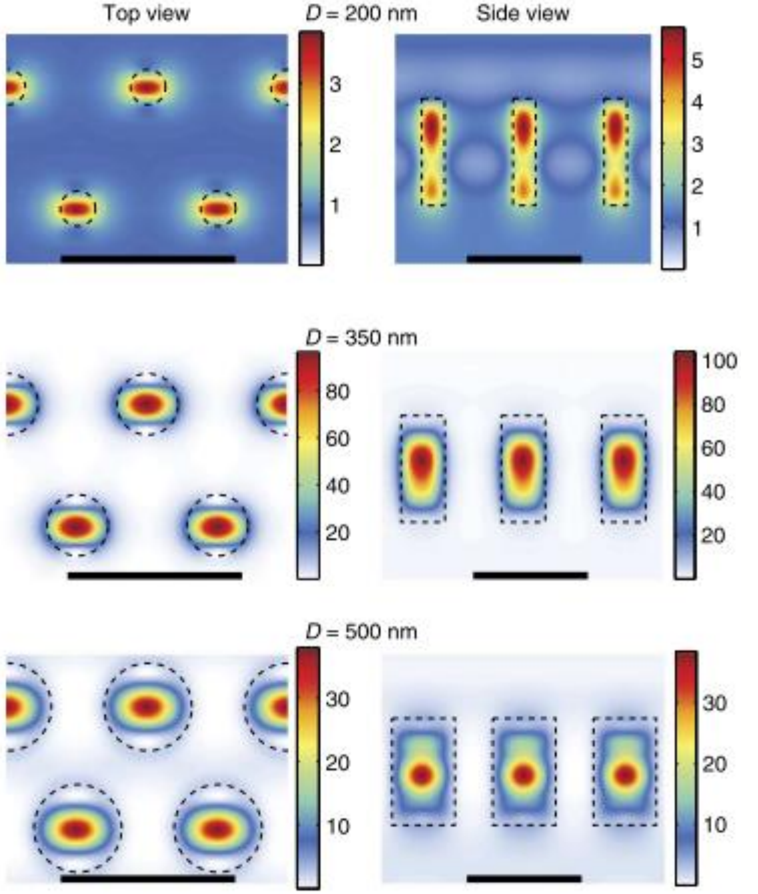
MetaLens - Design and Physics - I

1. Choice of materials:
Mech. Support (SiO_2), as thin as possible
+ active layer (a-Si), d ≈ 0.5-1 λ
(MWIR: 3300 nm, SWIR: 1064 nm)

2. Divide continuous surface into discrete, periodic lattice points (sub-λ spacing)



E-field confined in Pillars



Arbabi, Amir, et al. "Subwavelength-thick lenses with high numerical apertures and large efficiency based on high-contrast transmitarrays." *Nature communications* 6.1 (2015): 1-6.

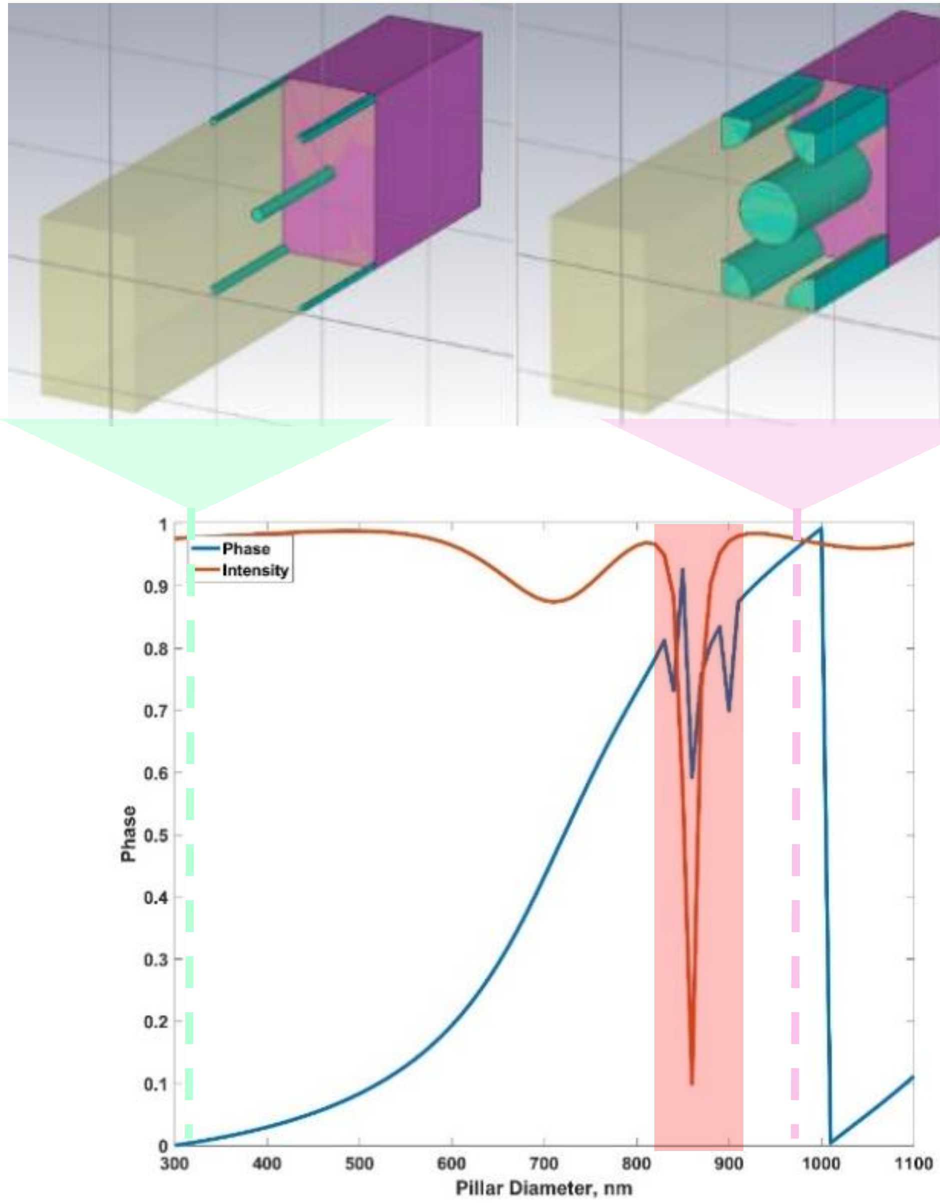
MetaLens - Design and Physics (MWIR) - II

1. Choice of materials:
Mech. Support (SiO_2), as thin as possible
+ active layer (a-Si), d ≈ 0.5-1 λ
(MWIR: 3300 nm, SWIR: 1064 nm)

2. Divide continuous surface into discrete, periodic lattice points (sub-λ spacing)

3. Simulate Transmitted Phase & Intensity as function of pillar diameter

4. Choose X Pillar dimensions that span phase-shifts 0-2π with high transmitted intensity



Pillar Diameter	Phase shift [rad]	Transmission [%]
450	0.11	99
600	0.40	96
650	0.58	92
700	0.87	88
750	1.18	90
800	1.41	96
900	1.71	97
1000	1.98	99

MetaLens - Design and Fabrication - I

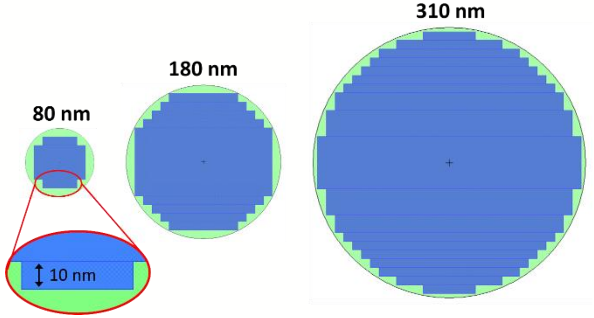
5. Develop manufacturing capabilities:

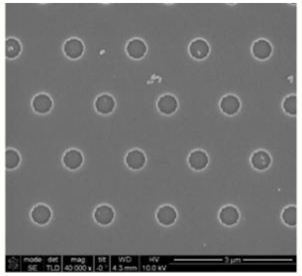
I. E-beam lithography (PMMA)

II. NiCr hardmask (lift-off)

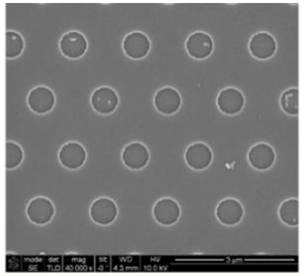
III. Dry-etching (C_4F_8:SF_6 plasma)

⇒ "Look-up table"

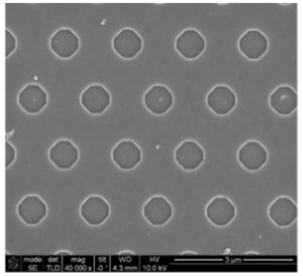




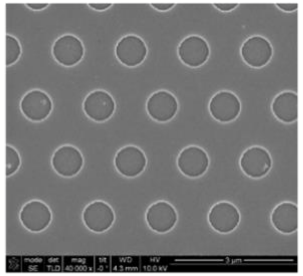
Pillar 1 – 450 nm



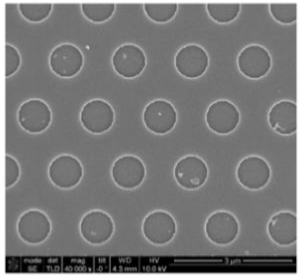
Pillar 2 – 600 nm



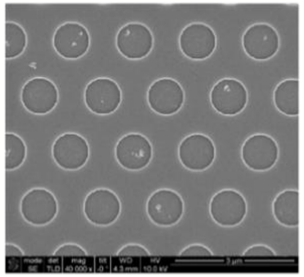
Pillar 3 – 650 nm



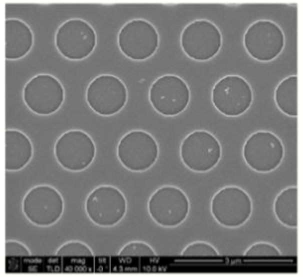
Pillar 4 – 700 nm



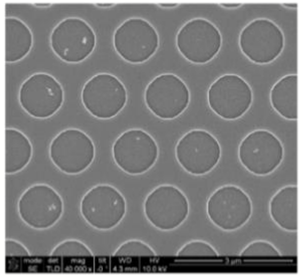
Pillar 5 – 750 nm



Pillar 6 – 800 nm



Pillar 7 – 900 nm



Pillar 8 – 1000 nm

Desired fabricated diameter	Digital diameter (nm)	Exp. Dose ($\mu C/cm^2$)
450	450	395
600	600	395
650	600	596
700	650	520
750	700	520
800	750	520
900	800	684
1000	900	596

MetaLens - Design and Fabrication - II

6. Define desired Phase function (λ, f, D):
Spherical lens with focal length f

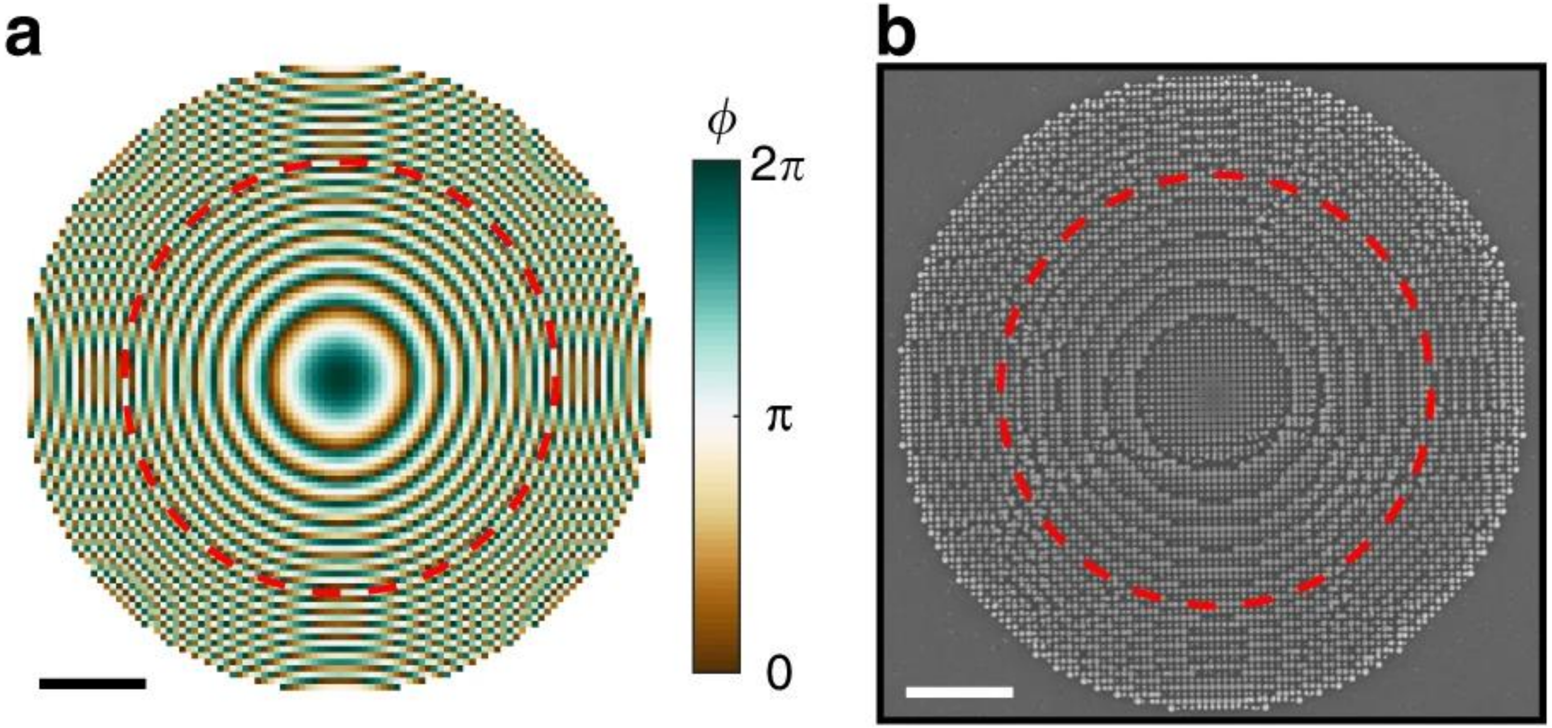
$$\varphi_{theo}(x,y) = \frac{2\pi}{\lambda}\left(\sqrt{f^2+x^2+y^2}-f\right) + X$$

At each lattice point:
Find closest match

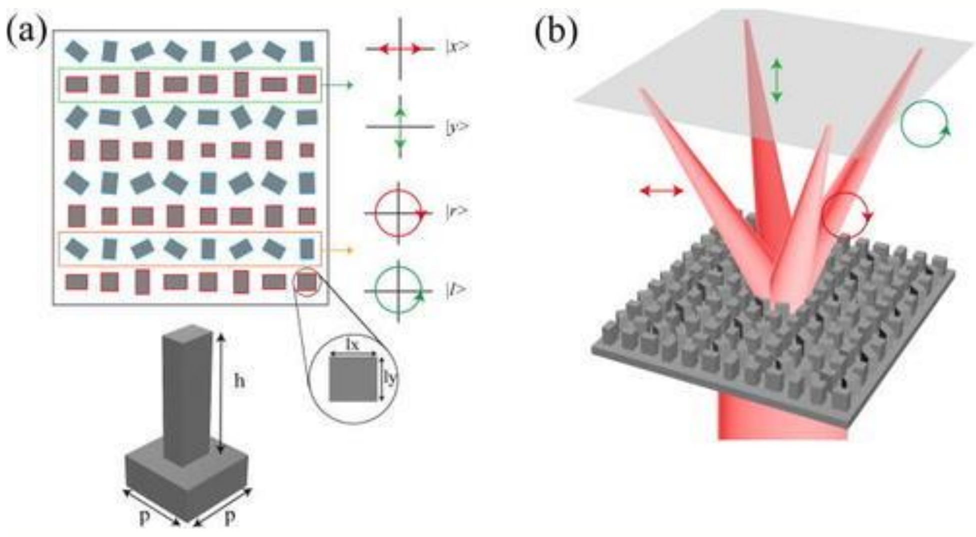
$$\varphi_{theo}(x,y) \leftrightarrow \varphi_{pillar}(x,y)$$

Potential for Multiplexing Components:

X= e.g. Vortex Phase, diffraction grating, (waveplate, polarimeter), etc.



Huang, Tzu-Yung, et al. "A monolithic immersion metalens for imaging solid-state quantum emitters." *Nature communications* 10.1 (2019): 1-8.

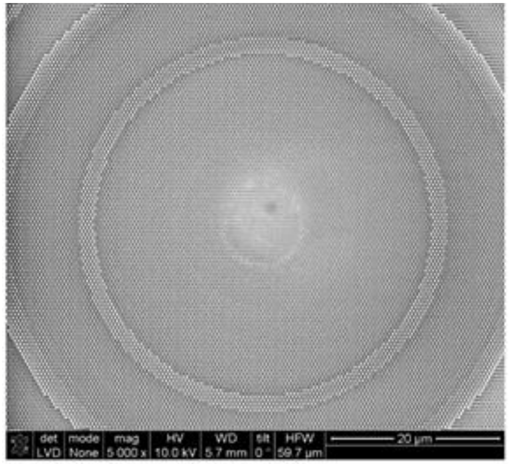


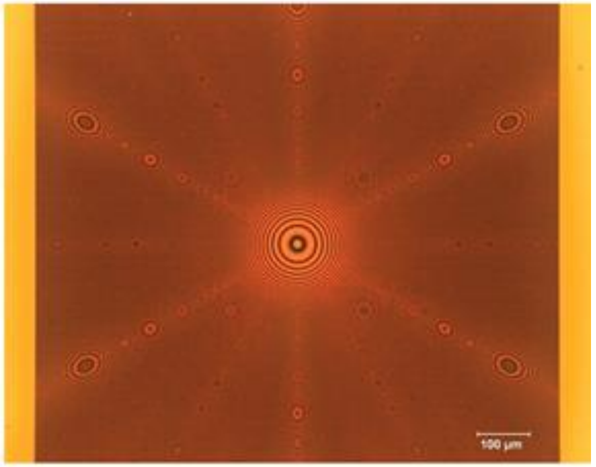
Yan, Chao, et al. "Midinfrared real-time polarization imaging with all-dielectric metasurfaces." *Applied Physics Letters* 114.16 (2019): 161904.

MetaLens - Design and Fabrication - III

7. Generate pattern file for EBL:
- **.txt file with lattice point (x,y), .gds Cell and Dose**
  - **100x 1mm x 1mm areas (stiching)**
- **Sequential exposure of pattern pillar dimensions**

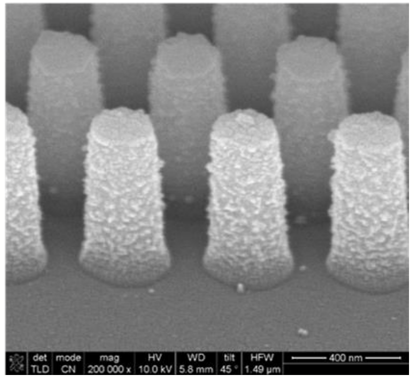
8. Manufacture MetaLenses

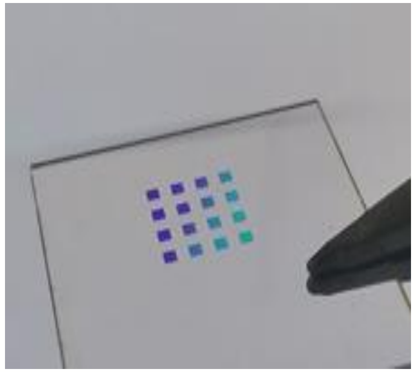


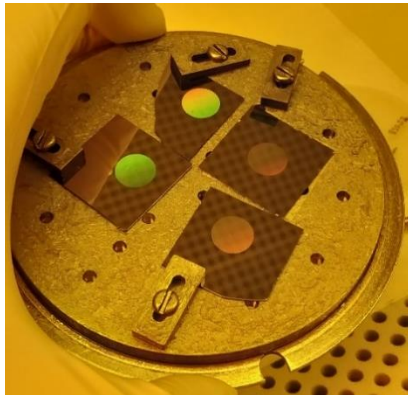


Number of Elements ∞D^2 !

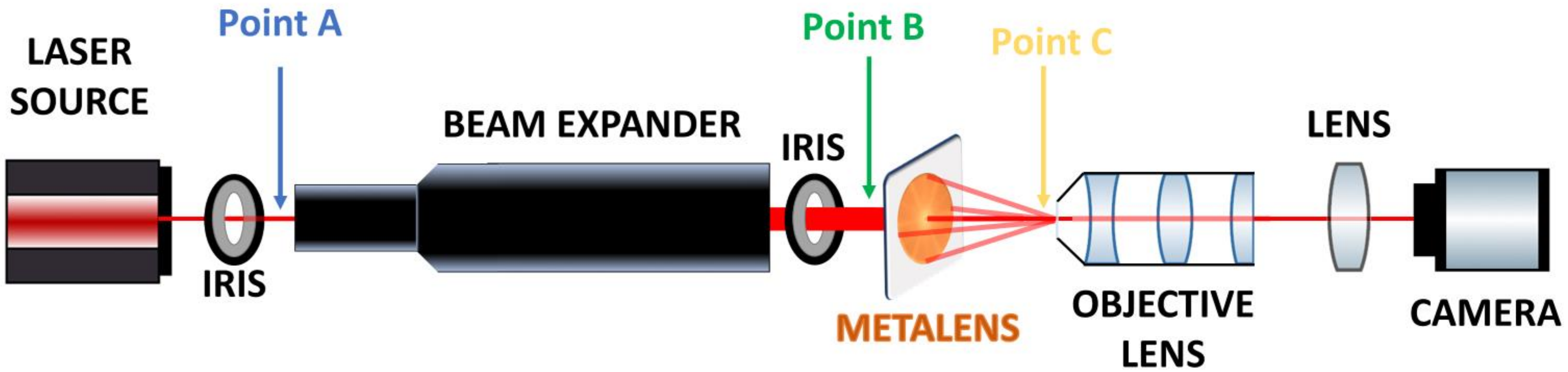
Aperture (A), mm	Focal length (f), mm	Number of elements	File Size	Time to calculate
1	**5**	**8’552’478**	**293 MB**	**Few hrs**
10	50	855’324’780	28.6 GB	2.5-3days
Below after Code Optimisation (MWIR)				
5	**5**	**8’864’385**	**311 MB**	**3m 29s**
10	10	35’445’295	1.24 GB	13m 58s
20	20	141’733’709	4.98 GB	1hr 2mins







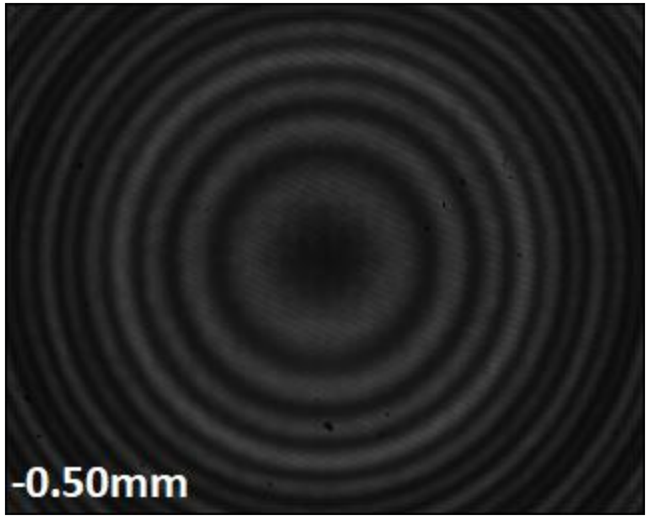
Metasurfaces – Optical Testing SWIR Lenses– I Efficiency determination



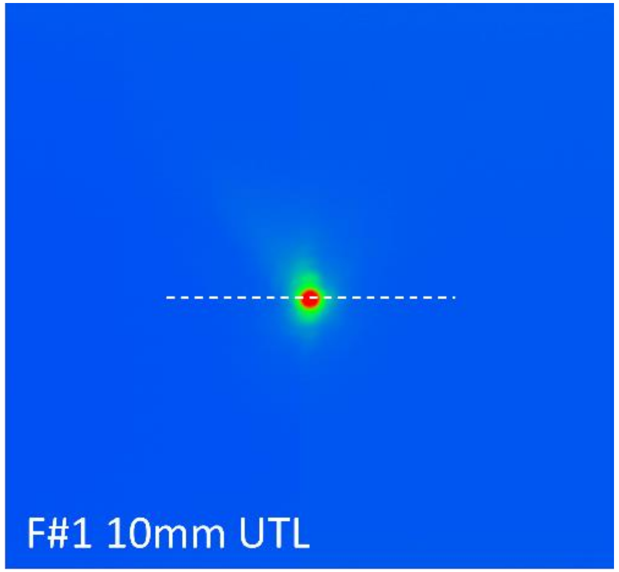
	Averaged Power Values [mW]				Efficiencies [%]	
Lens	Point A	Point B	Point C Substrate	Point C Metalens	Absolute	Relative
F#1 (10 mm)	0.765	0.298	0.287	0.207	69.7	73.4
F#2 (10mm)	0.765	0.306	0.287	0.201	65.8	69.3

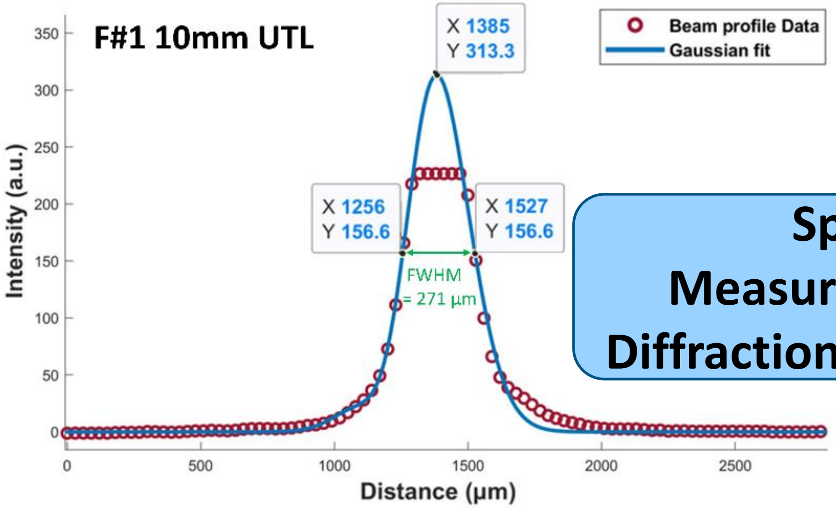
Metasurfaces – Optical Testing SWIR Lenses – II focal Length and spot size

F = 2 mm (1mm aperture)

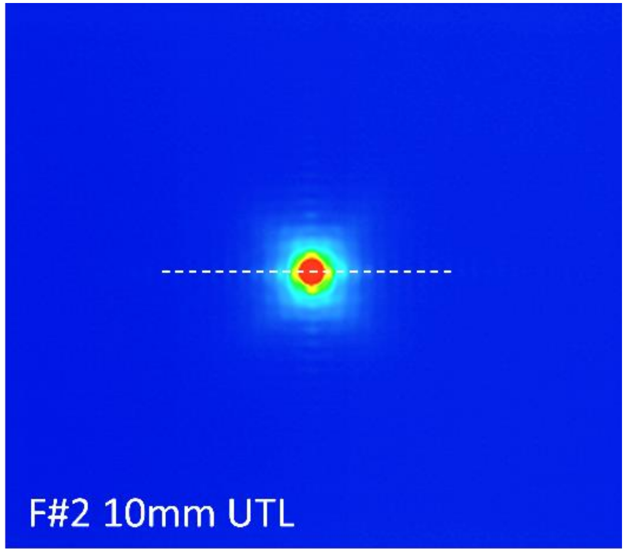


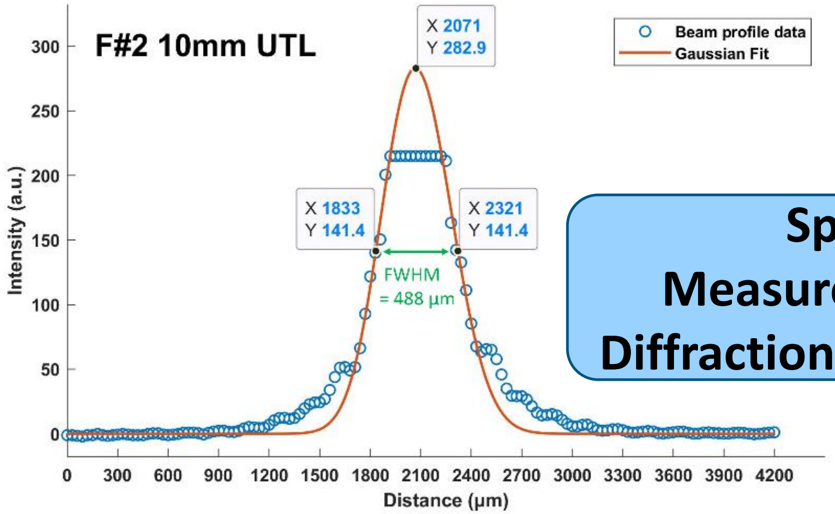
$$SpotSize = \lambda/(2 \cdot NA)$$





Spotsize
Measured: 2.07 μm
Diffraction limit: 1.19 μm





Spotsize
Measured: 3.73 μm
Diffraction limit: 2.19 μm

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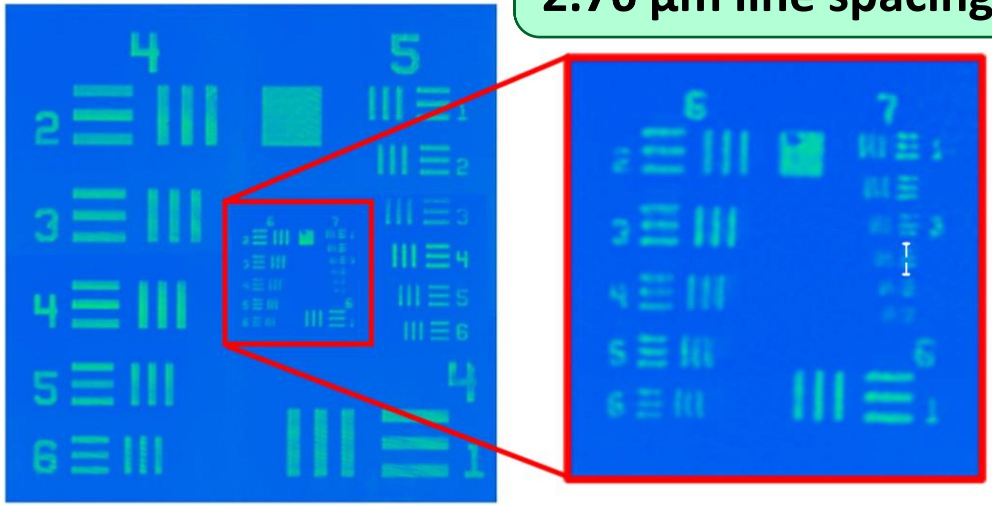
Metasurfaces – Optical Testing – I
Imaging with 1951 USAF target

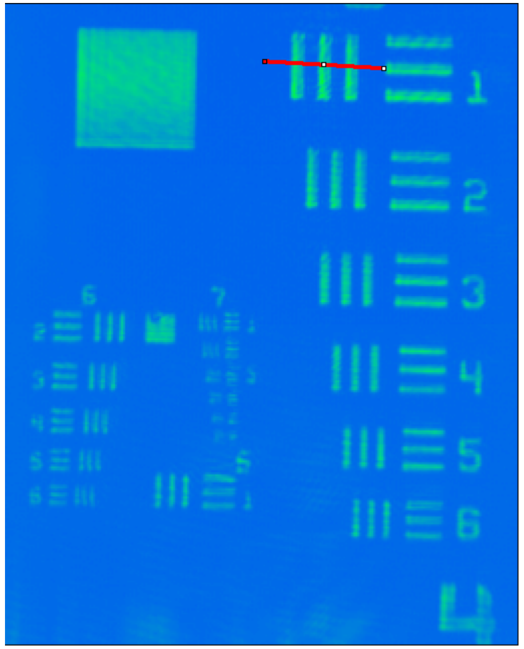
F#1 (10mm aperture)
2.76 µm line spacing

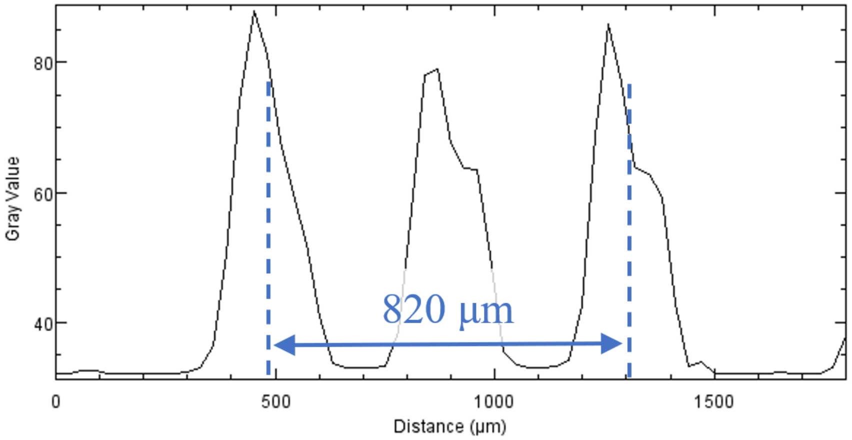


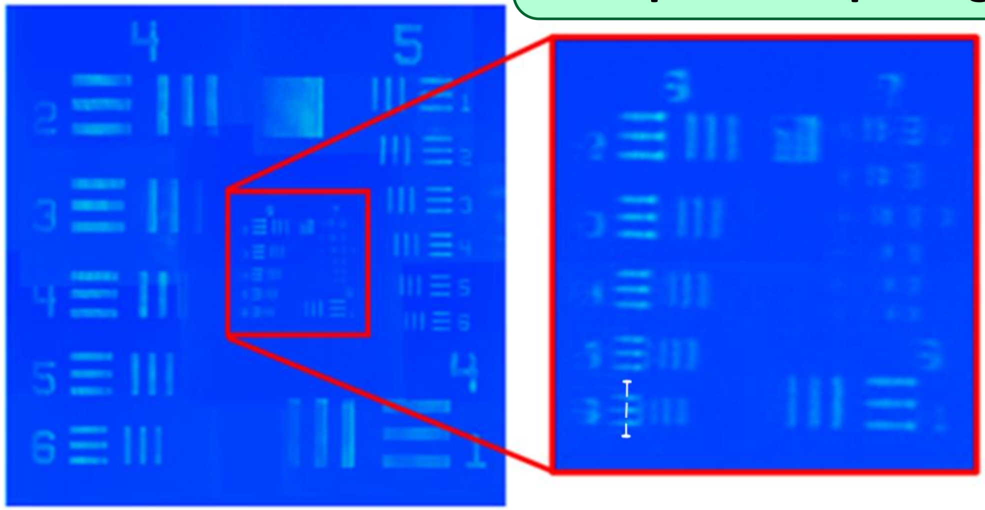
1: Calibrate System magnification (µm/pixel) with line pair of known dimension

F#2 (10mm aperture)
4.39 µm line spacing

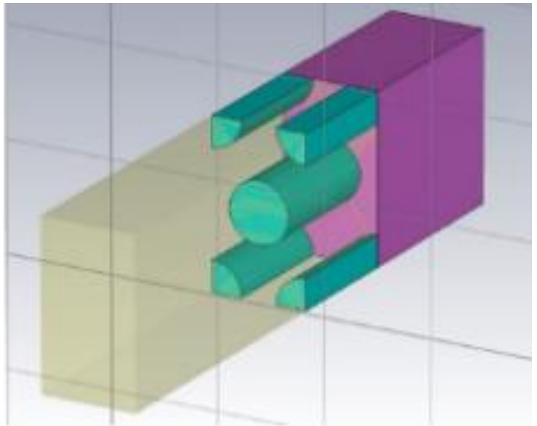
2: Determine max. resolution of MLens via smallest resolvable line pair

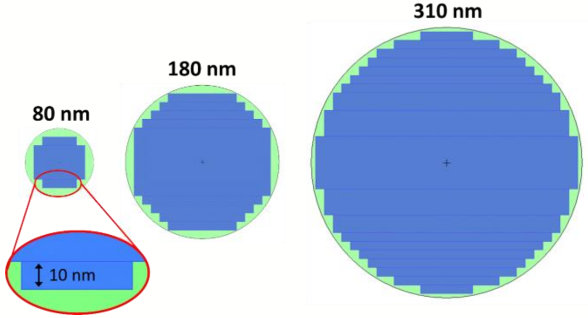






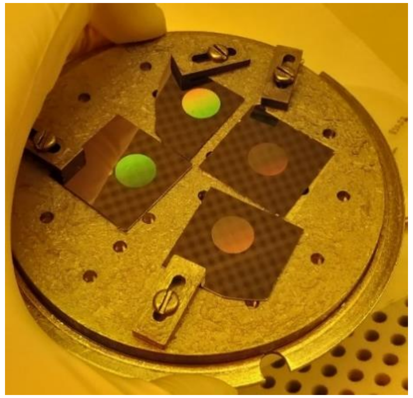
Achievements and conclusions of the project

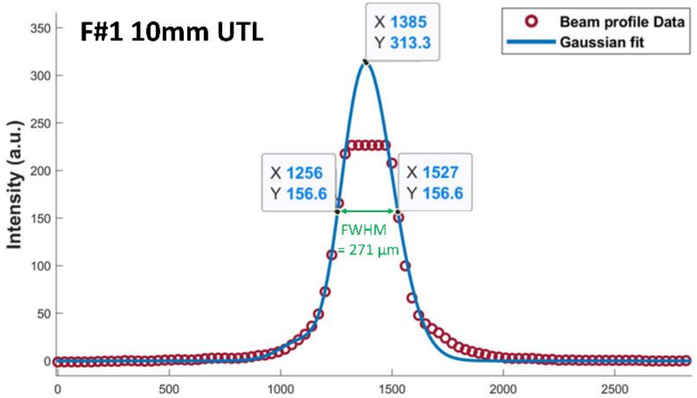




1: Successfully designed & simulated highly efficient MetaLenses for SWIR (1064 nm) & MWIR (3300 nm)

2: Developed and optimised software for fast, large-area pattern generation compatible with commercial EBL technology

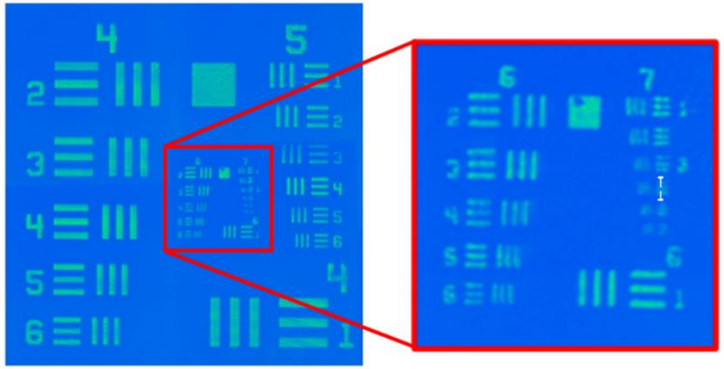




3: Developed and optimised manufacturing protocol for large area MetaLenses, incl. Quality Assurance

4: Experimentally confirmed close to diffraction-limited & highly efficient optical performance of manufactured MetaLenses

5: Demonstrated imaging with high spatial resolution (few µm) employing manufactured MetaLenses



Kenney, Mitchell, et al. "Large area metasurface lenses in the NIR region." *Modeling Aspects in Optical Metrology VII*. Vol. 11057. International Society for Optics and Photonics, 2019.

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Thank you for your attention!

Any Questions?

M.Sc. Thomas Nowack – PhD candidate in MSCA “TeraApps”
E-mail: thomas.nowack@glasgow.ac.uk

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