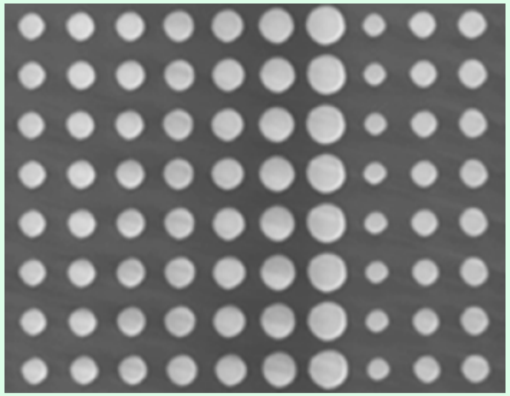
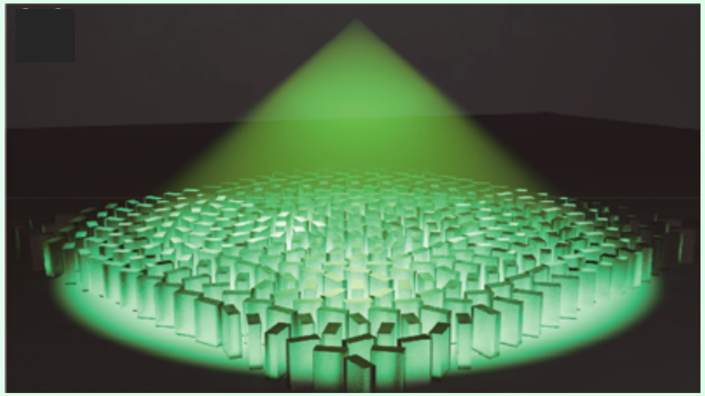
Metalens by Nanophotonics

Thomas F Krauss, Kezheng Li, Chris Reardon
Department of Physics, University of York
thomas.krauss@york.ac.uk

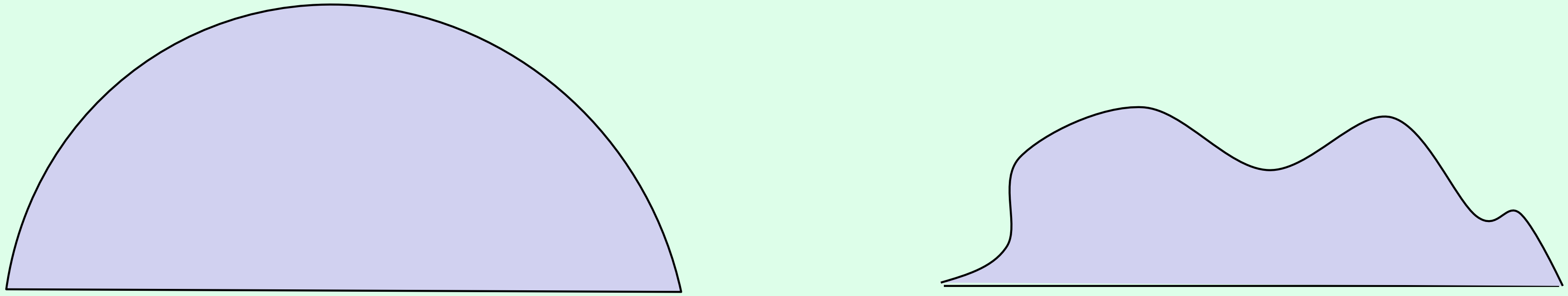
Augusto Martins, Emiliano Martins, University of Sao Paolo, Brazil
Juntao Li, Sun Yat-Sen University, Guangzhou, China



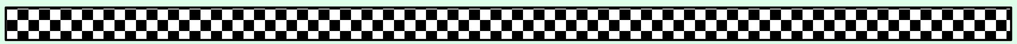


UKRI Engineering and Physical Sciences Research Council

What is a metalens?



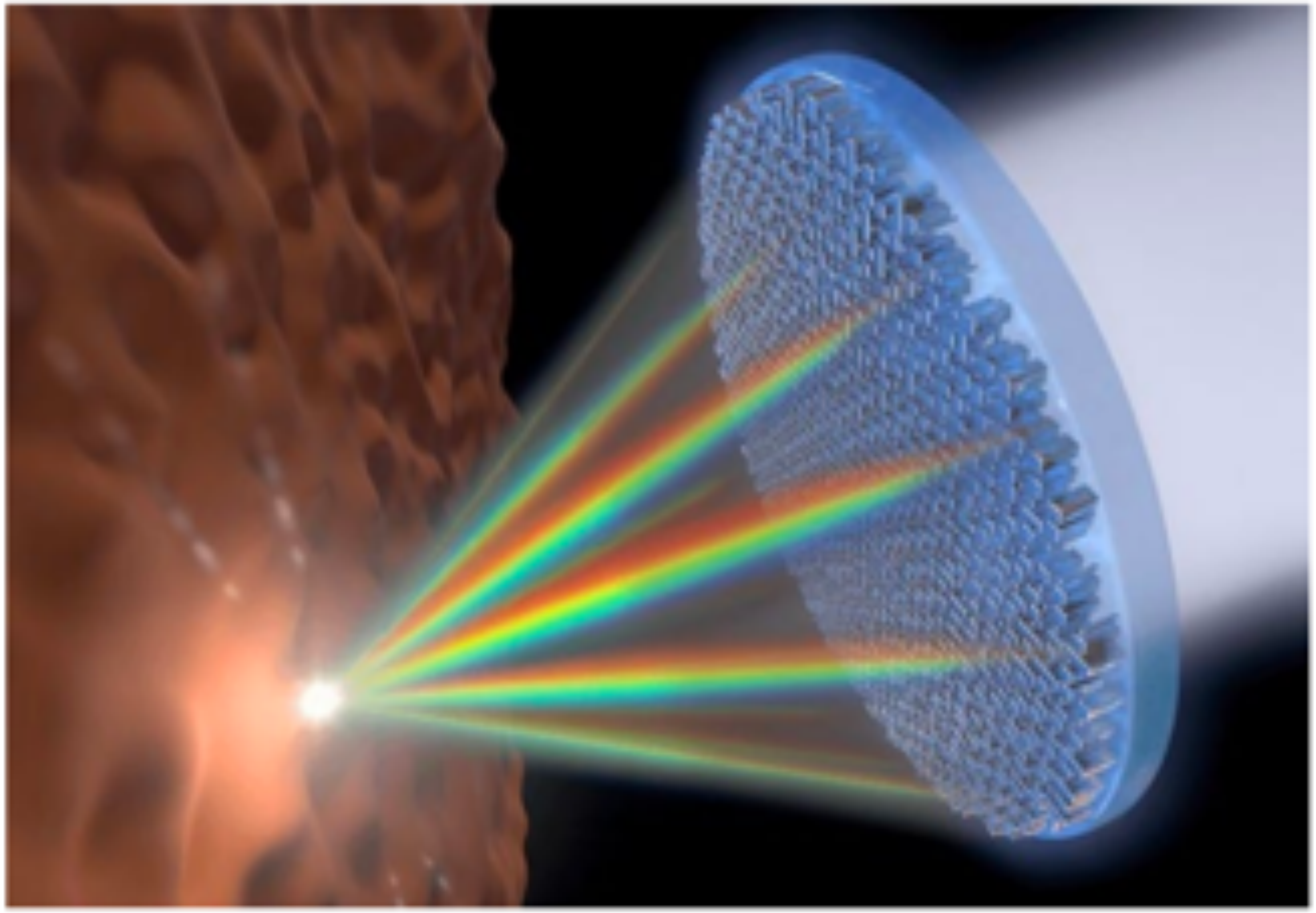
It is a lens. But a very fancy lens. And it is flat.



1. Replace bulk optics
2. Do something you cannot do otherwise

Top 10 Emerging Technologies (3): Tiny Lenses

3 min



Metalense © Harvard

Posted by Bart Brouwers | Aug 13, 2019 | Tags: asml, Metalenz, tiny lense, tiny lenses, WEF, WEF emerging, Zeiss

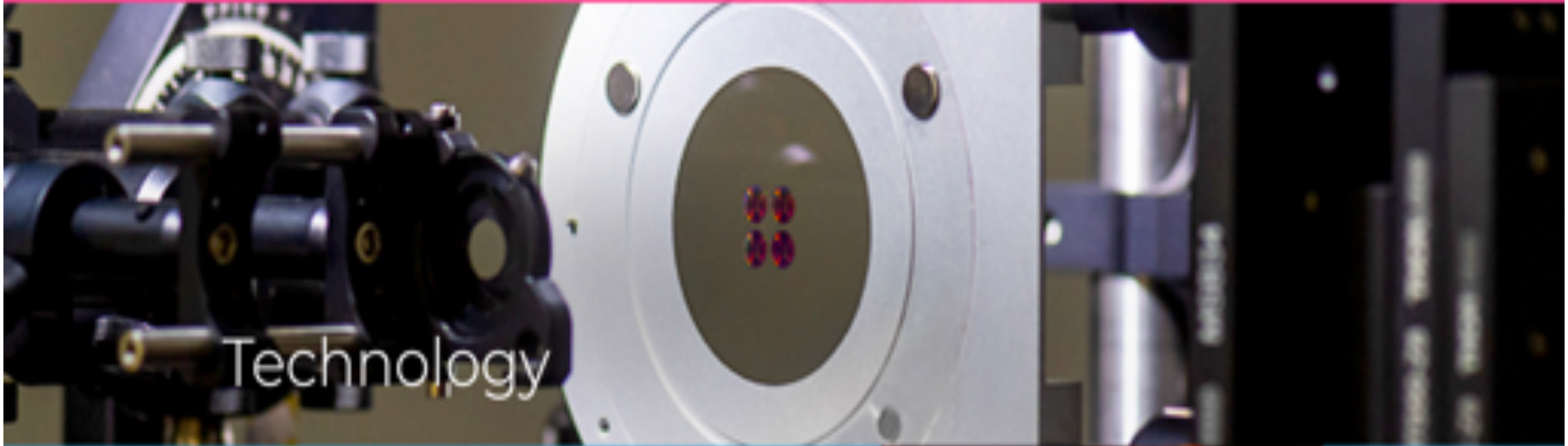
World Economic Forum (WEF) asked a group of international technology experts to identify this year's Top 10 Emerging Technologies. After soliciting nominations from additional experts around the globe, the group evaluated

Search Contact

metalenz

Transforming light via breakthrough flat-lens technology

About Us | Technology | Products | Markets & Applications | News and Publications

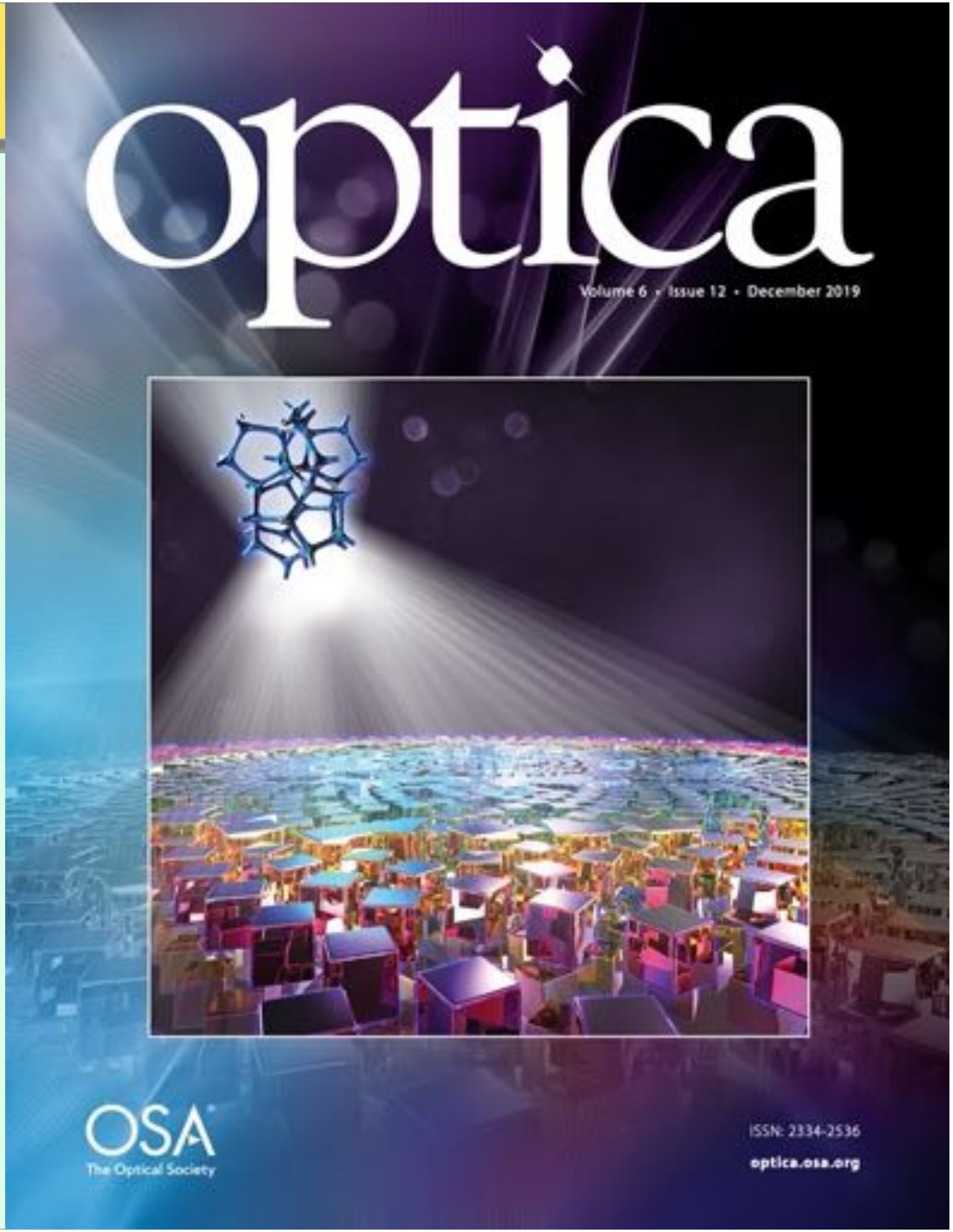


Technology

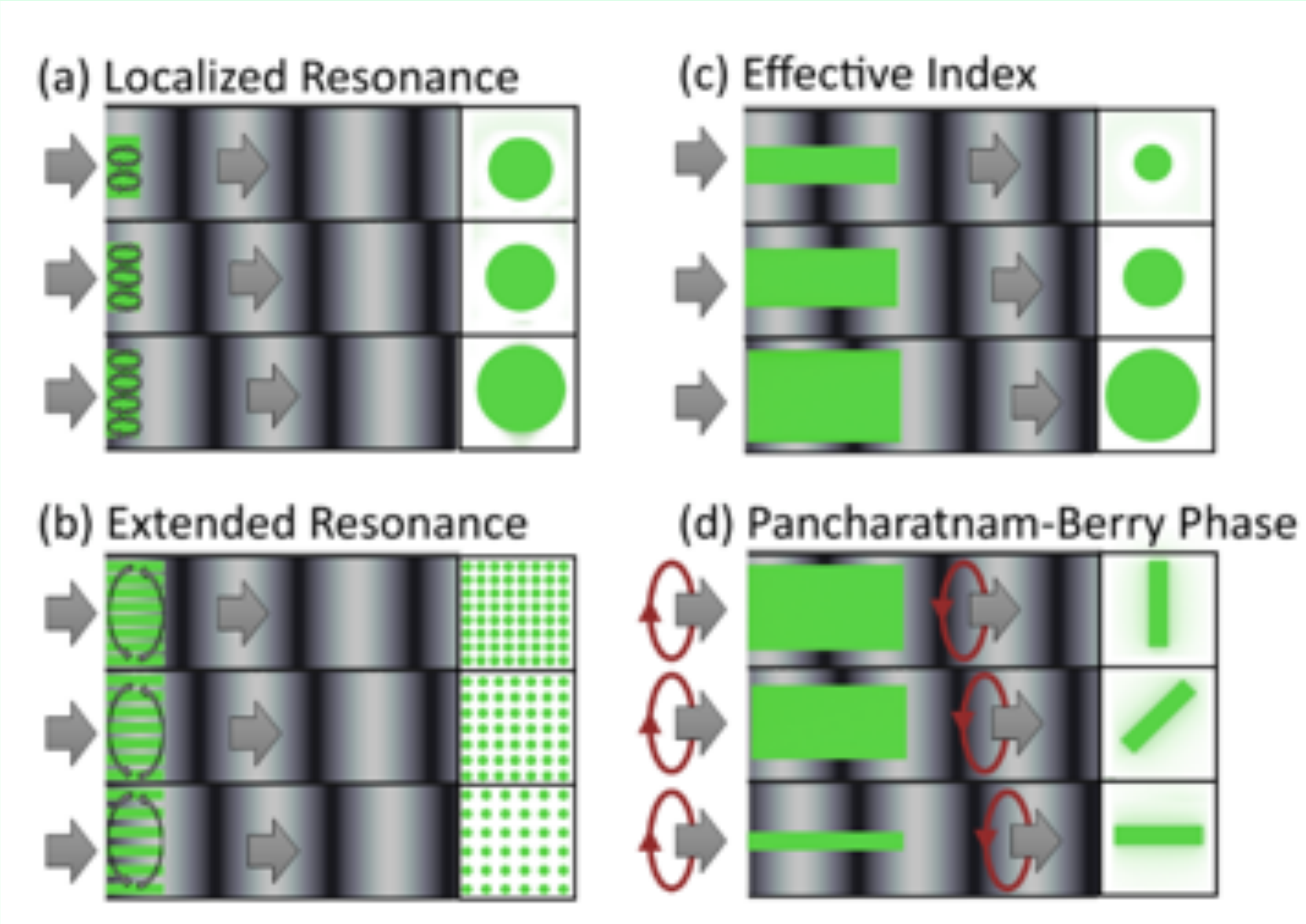
Home » Technology

Meta-optics use planar surfaces consisting of sub-wavelength structures with uniform height of several hundred nanometers.

Part 1: On-axis



How to achieve phase control ?

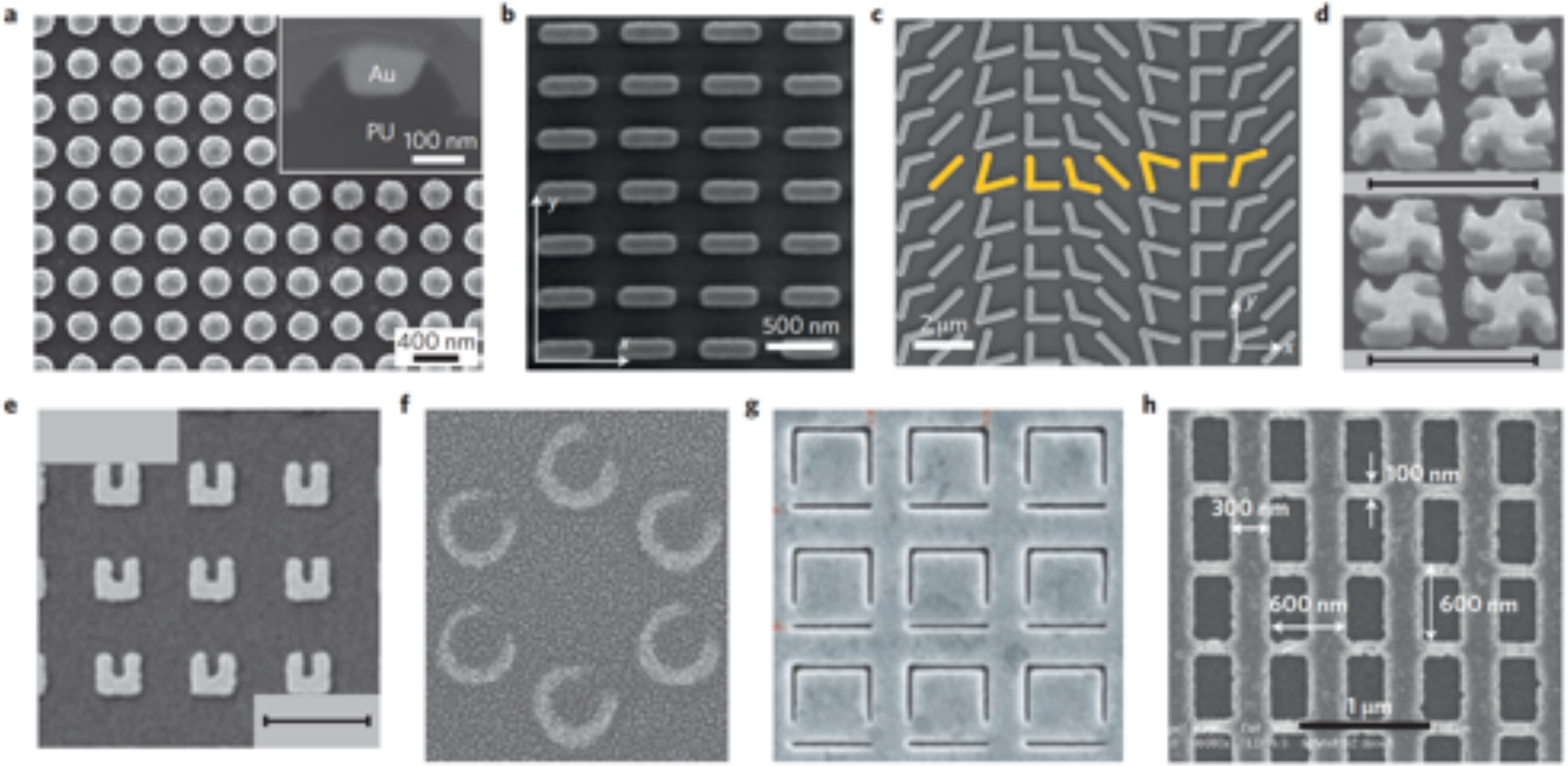


NB there is a mistake in one of the panels.
Please email thomas.krauss@york.ac.uk if you spot the mistake

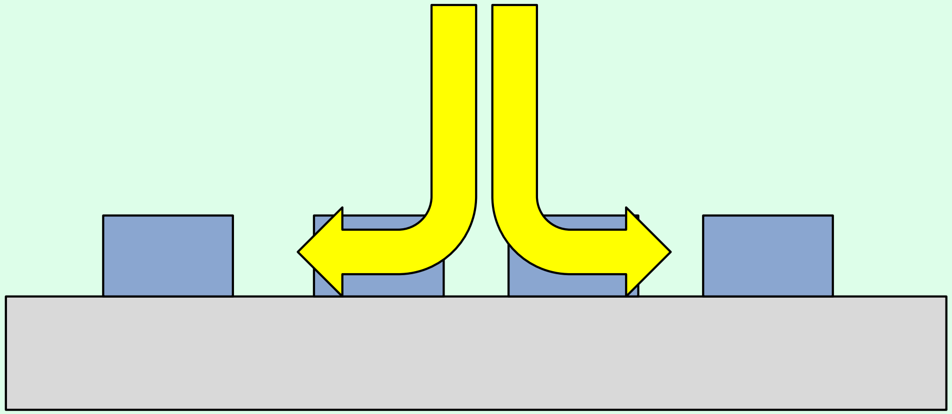
nature photonics
FOCUS | REVIEW ARTICLE
PUBLISHED ONLINE: 27 NOVEMBER 2014 | DOI: 10.1038/NPHOTON.2010.247

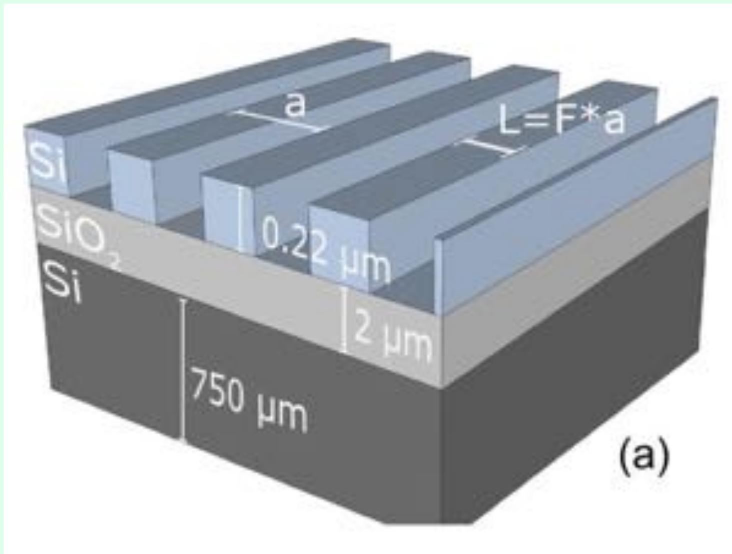
Plasmonic meta-atoms and metasurfaces

Nina Meinzer, William L. Barnes* and Ian R. Hooper

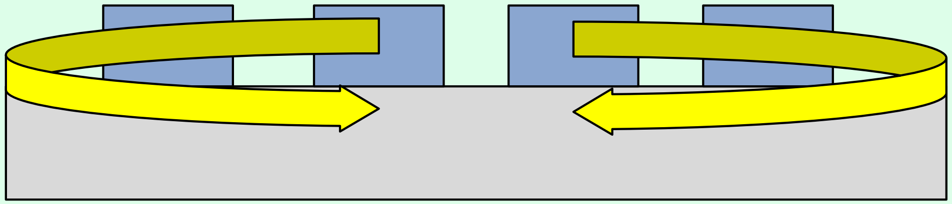


Guided mode resonance

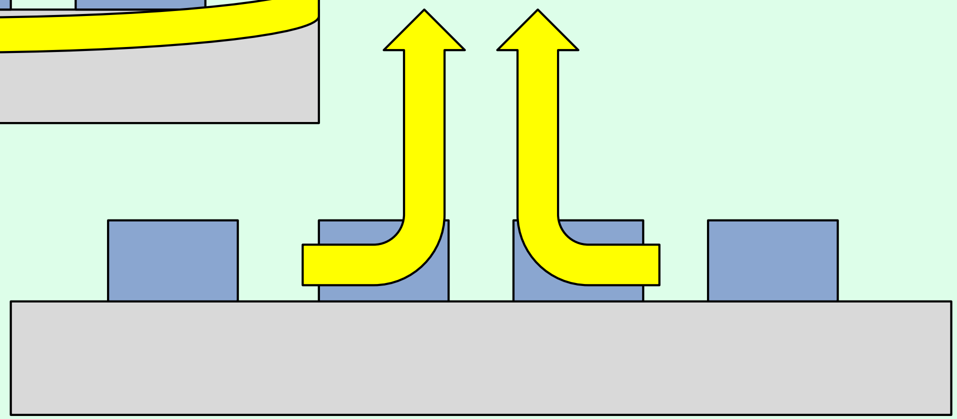




1. Light couples into the grating

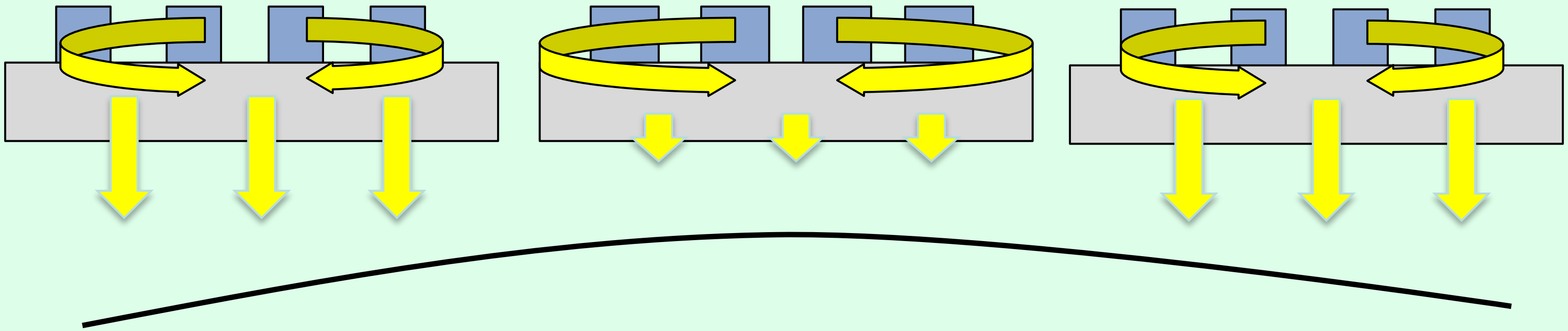


2. Light is Bragg-reflected.



3. Light couples out again. The phase of the Bragg reflected light and the thickness of the high index layer determine whether the outgoing light is reflected or transmitted.

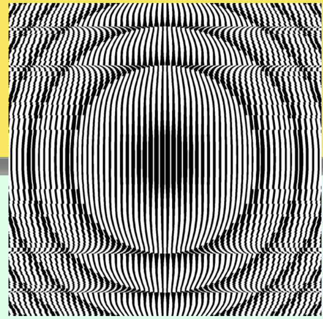
Phase control



Klemm et al., Optics Letters **38** (17), 3410-3413 (2013)

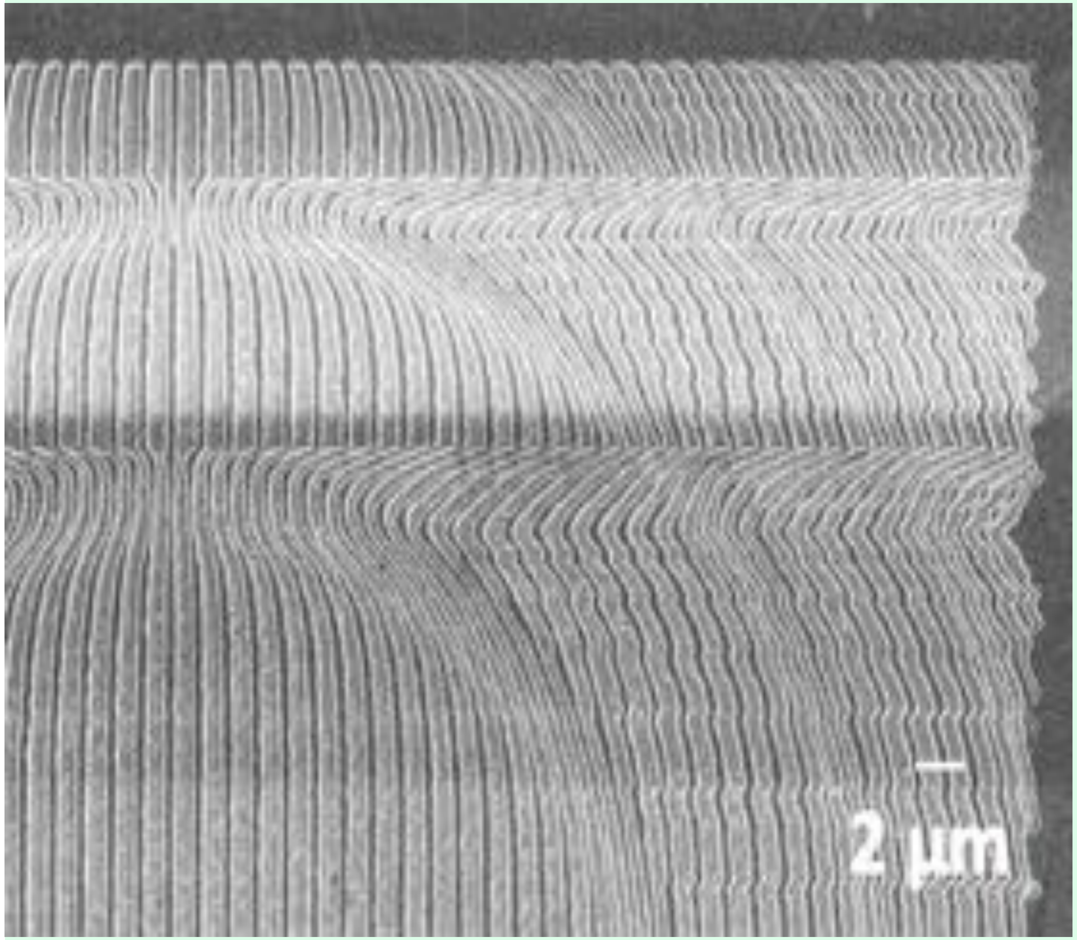
See also: Fattal et al., Nature Photonics 2010

Realisation



¼ Pattern

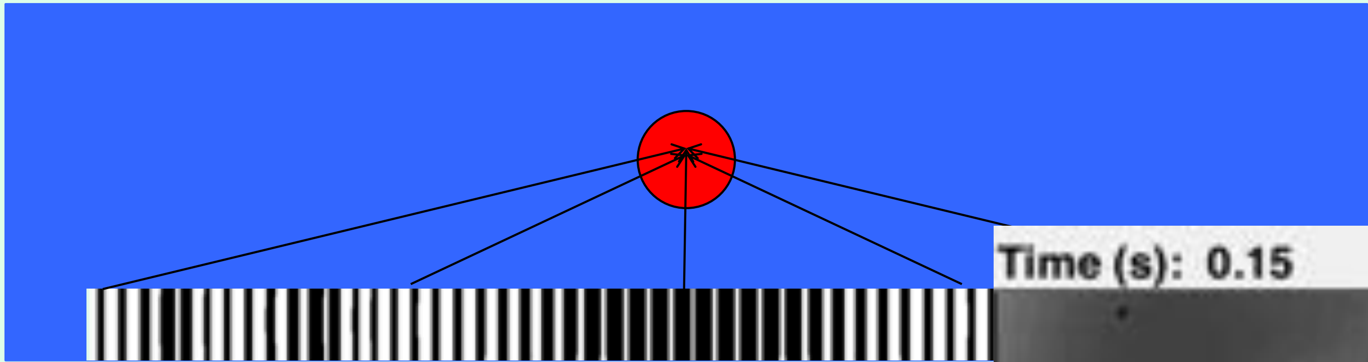
SEM Micrograph

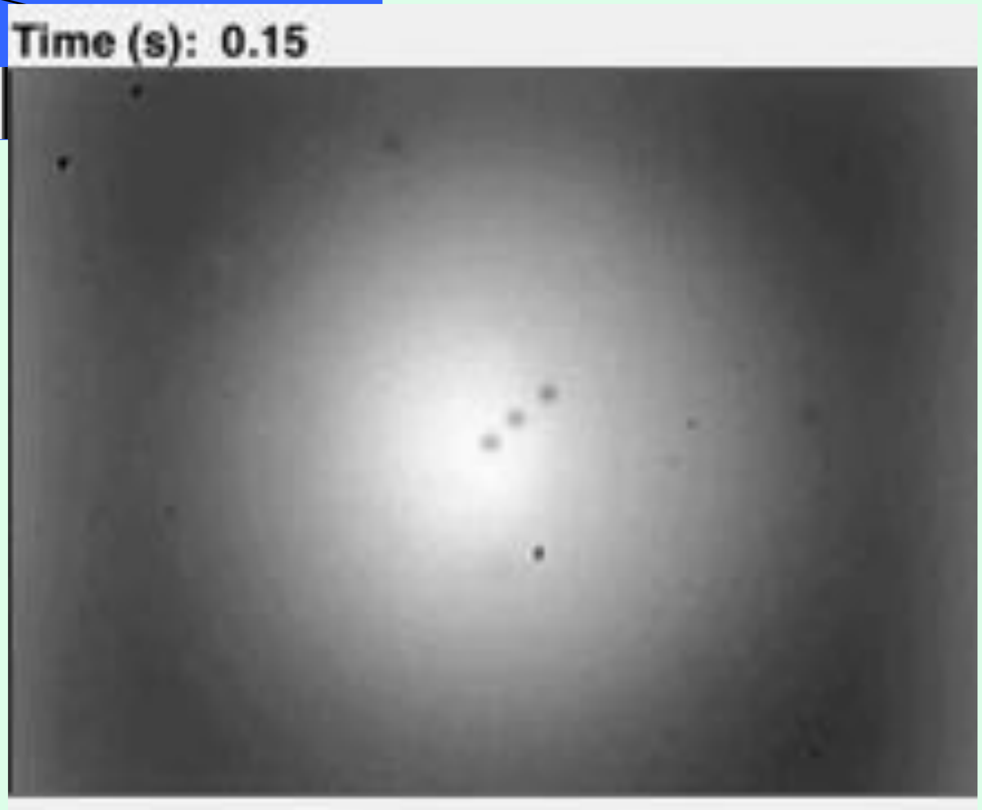


Klemm et al., Optics Letters **38** (17), 3410-3413 (2013)

Optical trapping with metalens

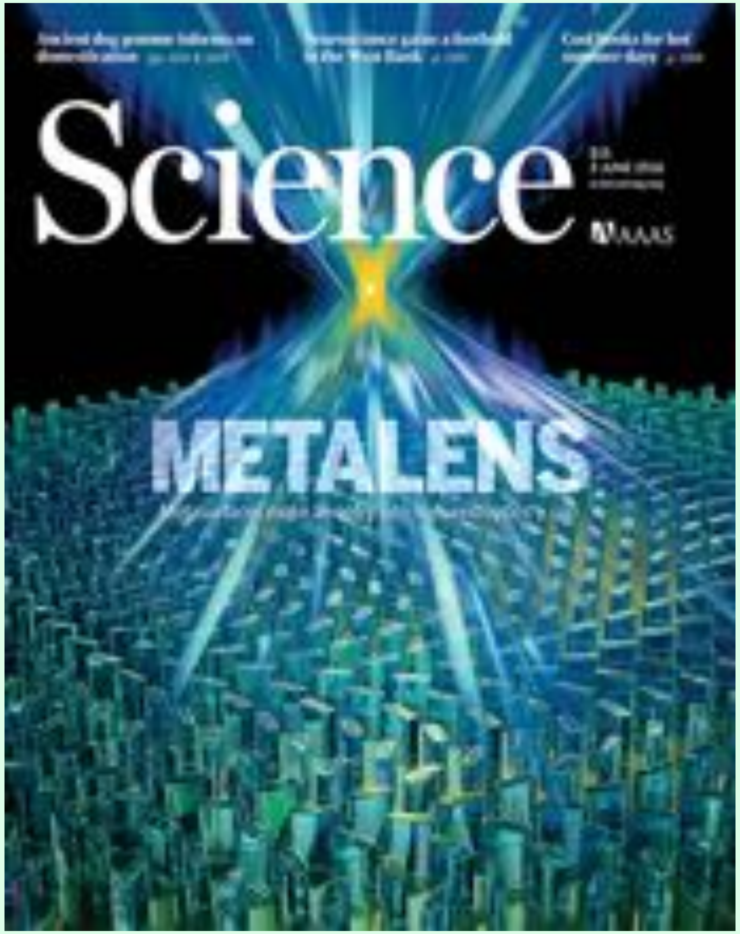
Ideal compatibility with microfluidics

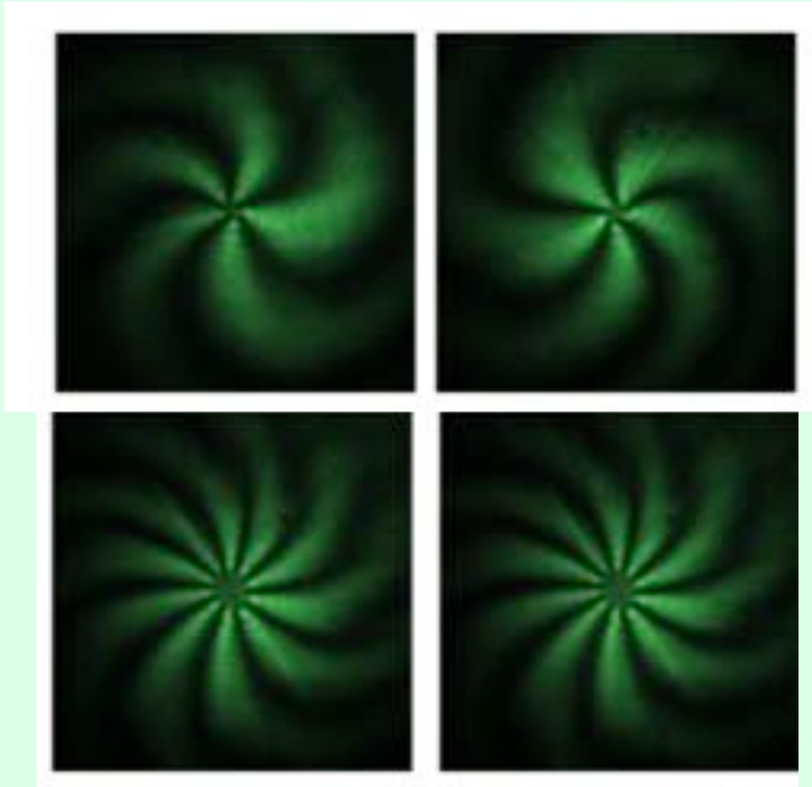




Krauss, Dholakia et al., Opt. Lett 2018

Pancharatnam-Berry phase metalens





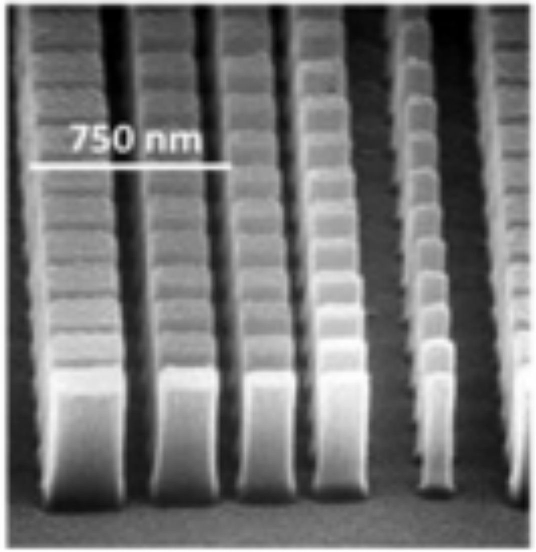
Mobile phone application a huge driver

M. Khorasaninejad et al., (Capasso) *Science* **352**, 1190 (2016)

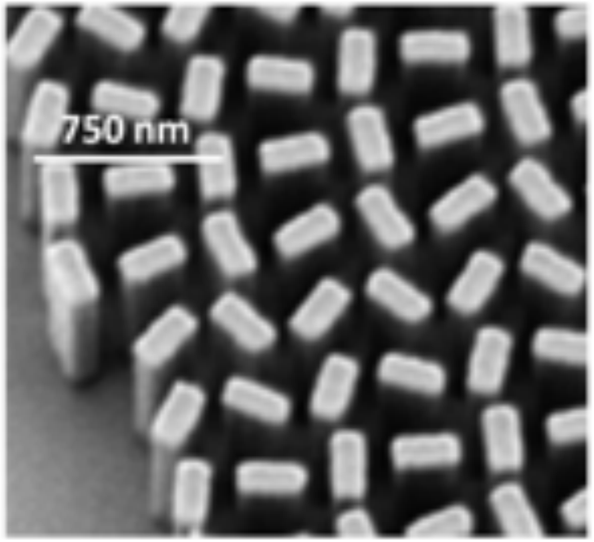
Comparison

Lalanne et al. Capasso et al.

Blazed binary elements [19]



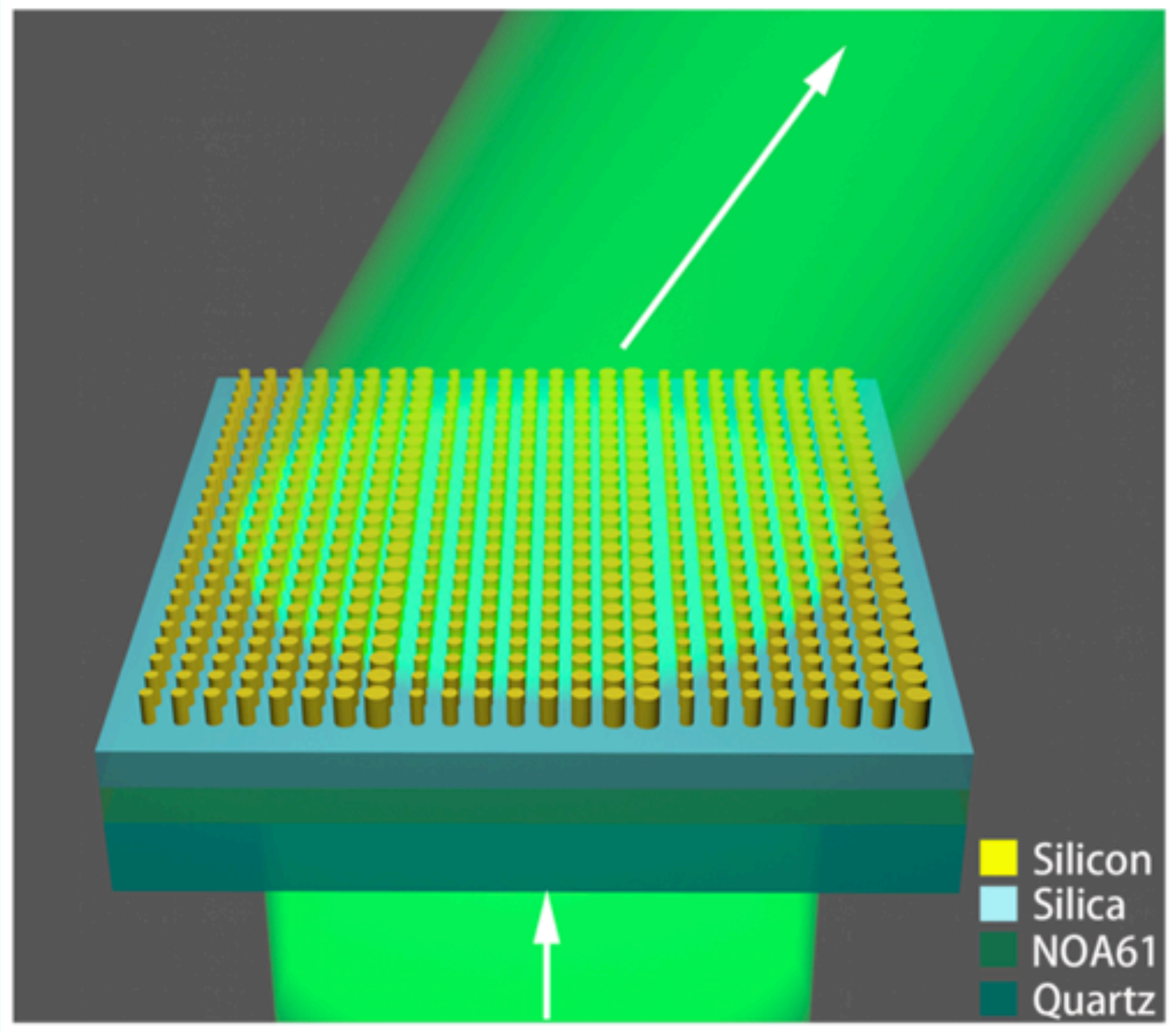
Metalenses [4]



Material	TiO_2	TiO_2	
Wavelength (nm)	633 – 860	405 (blue)	532 (green)
Spacing S/λ	0.47	0.49	0.61
Efficiency	80% (absolute)	86%	73%
Polarization	Insensitive	Circular (cross)	
NA	0.64	0.8	

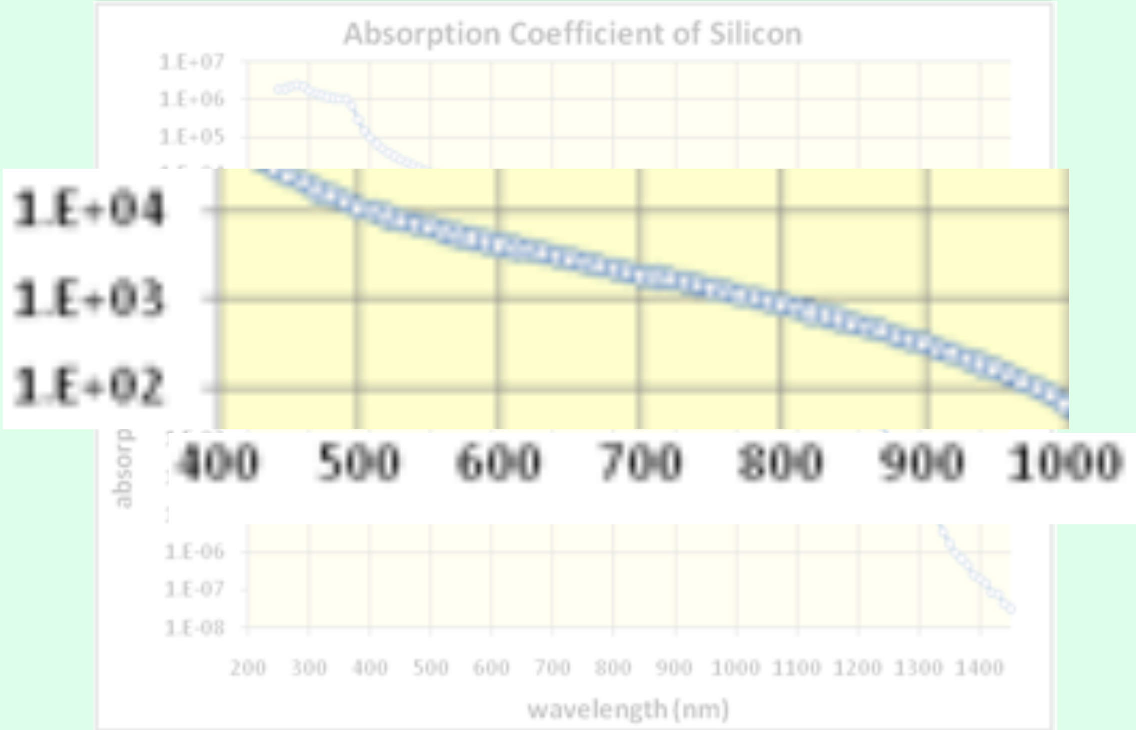
Both structures require bespoke material and high aspect ratio etching

Silicon metalens



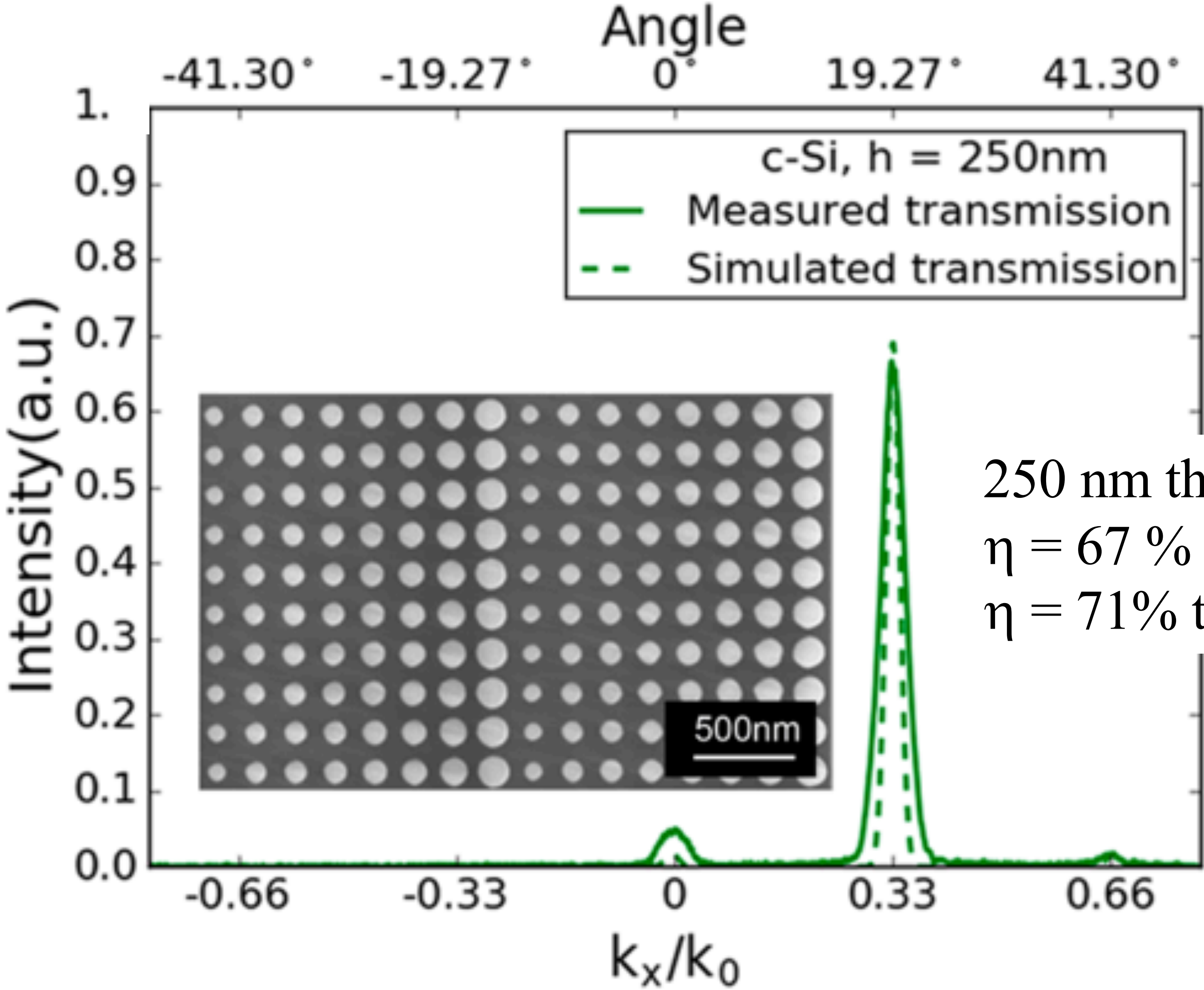
Z. Zhou et al., “Efficient Silicon Metasurfaces for Visible Light”, ACS Photonics 4, 544-551 (2017)

Silicon in the visible ?



The absorption of silicon in the visible range appears prohibitive.

10^4/cm!!!



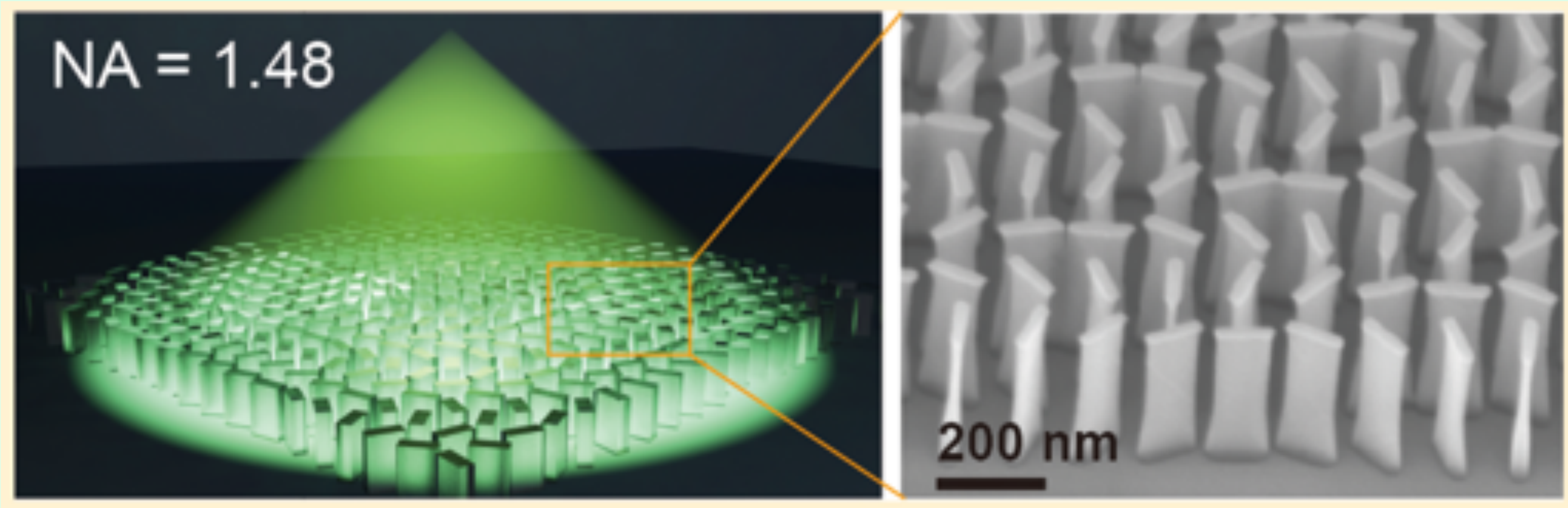
250 nm thick silicon
η = 67 % expt.
η = 71% theory

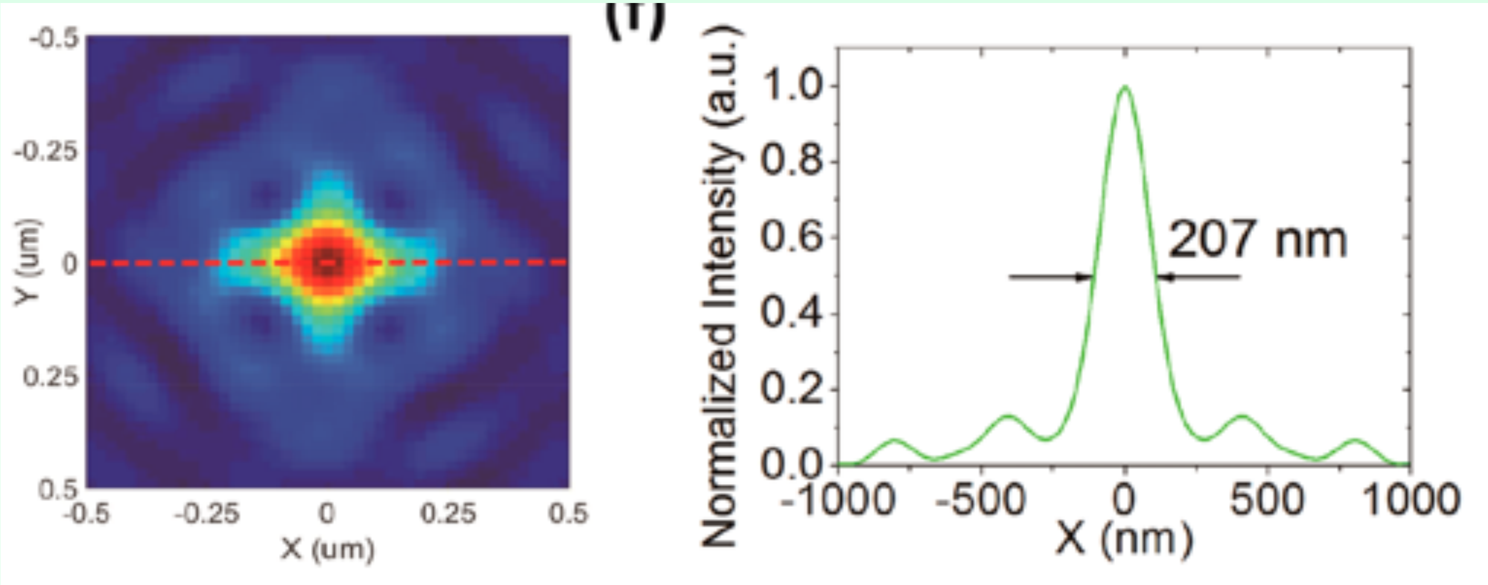
Z. Zhou et al., "Efficient Silicon Metasurfaces for Visible Light", ACS Photonics 4, 544-551 (2017)

NANO LETTERS
Letter
Cite This: Nano Lett. 2018, 18, 4460−4466
pubs.acs.org/NanoLett

Ultrahigh Numerical Aperture Metalens at Visible Wavelengths

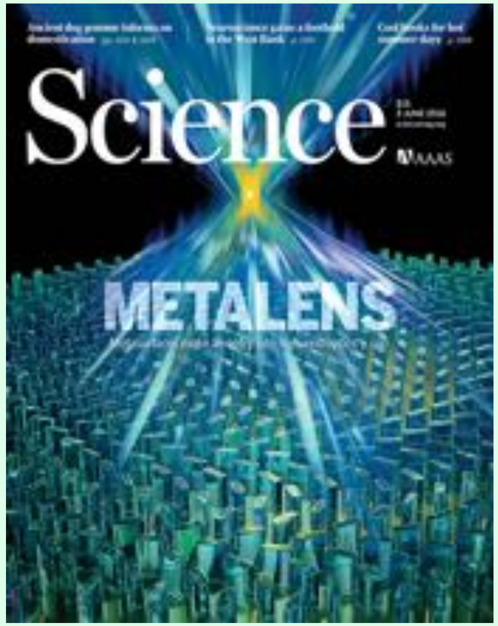
Haowen Liang,[†] Qiaoling Lin,[†] Xiangsheng Xie,[‡] Qian Sun,[†] Yin Wang,[†] Lidan Zhou,[†] Lin Liu,[†] Xiangyang Yu,[†] Jianying Zhou,[†] Thomas F Krauss,[§] and Juntao Li*[,†]





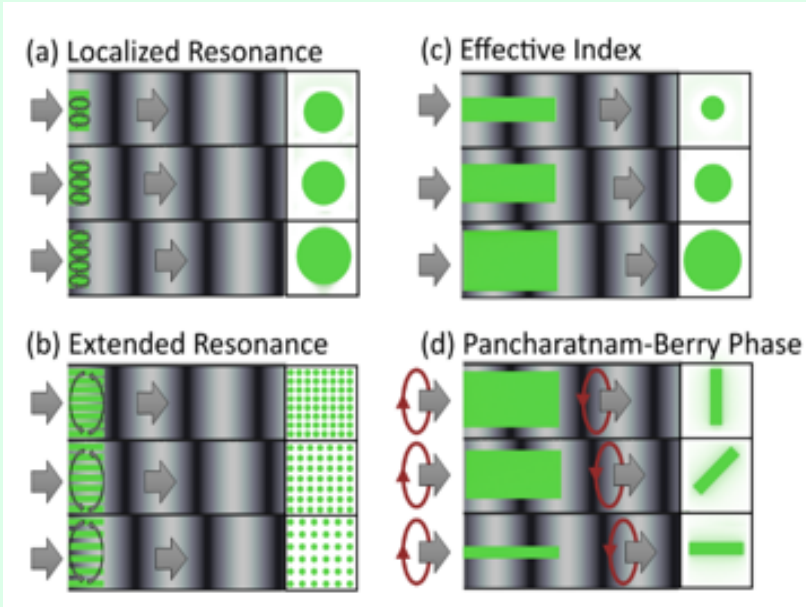
67% Transmission efficiency into the focal spot at 532 nm. Max NA=1.48

Comparison TiO_2: Same transmission; max NA=1.1

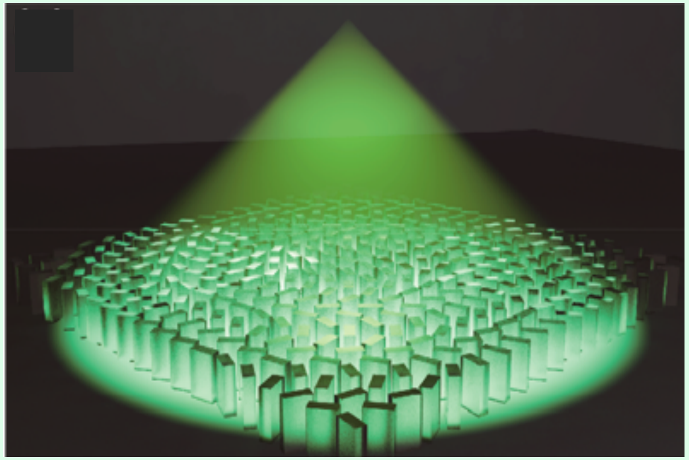


What have we learned ?

There are multiple ways to achieve the phase control necessary for a metalens. Effective index and P-B phase have been the most successful, although P-B requires polarization control.

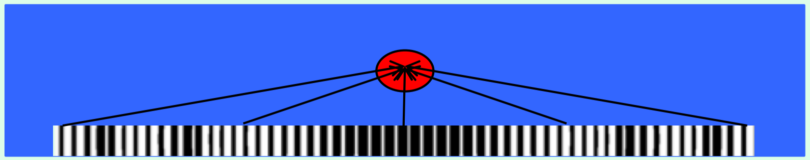


Silicon can compete in terms of efficiency, even in the visible, and is much easier to fabricate. The high index affords larger numerical apertures.

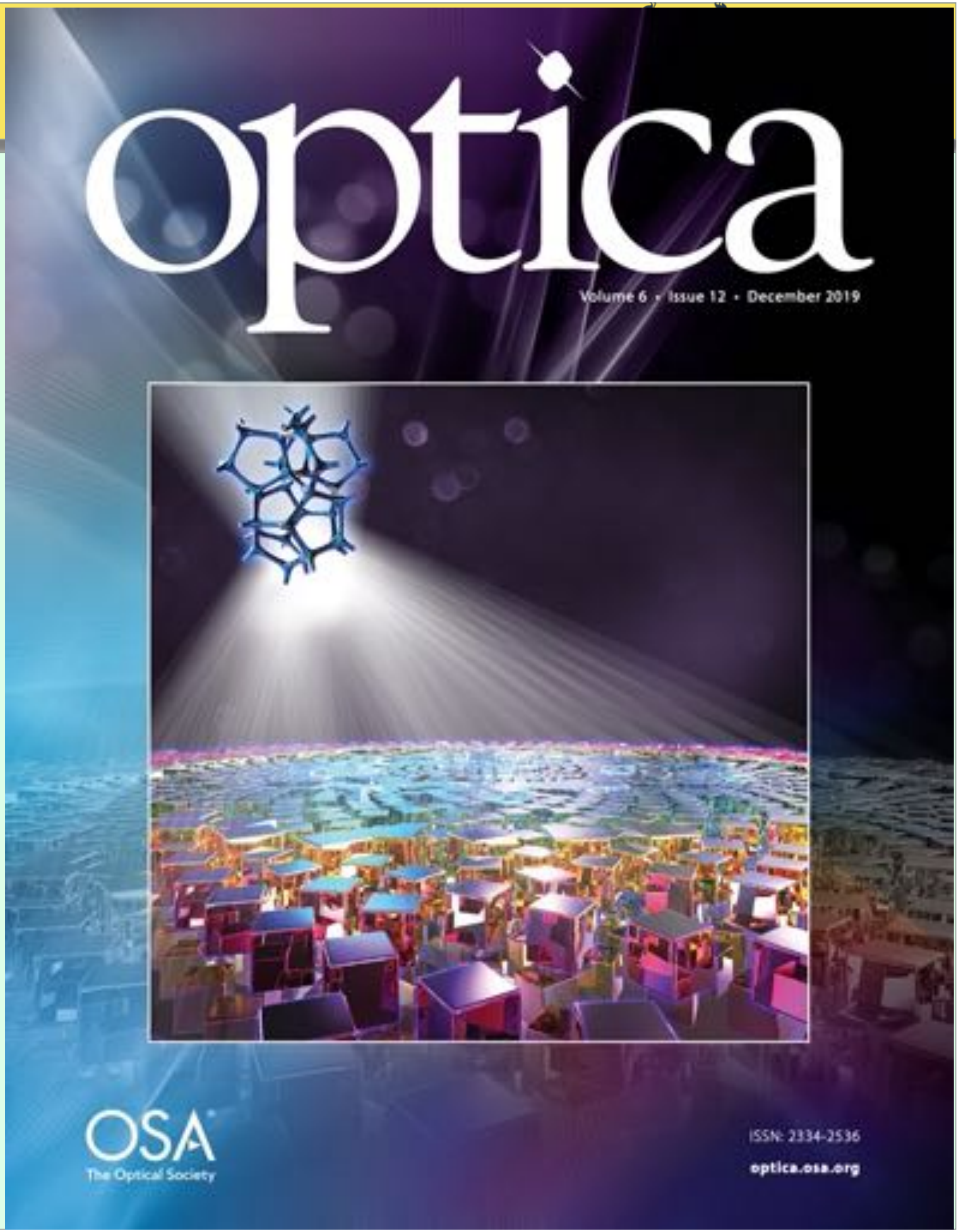


η≈67% @ 532nm, NA=1.48

The flat nature affords integration into a microfluidic channel for optical trapping.



Part 2: Off-axis



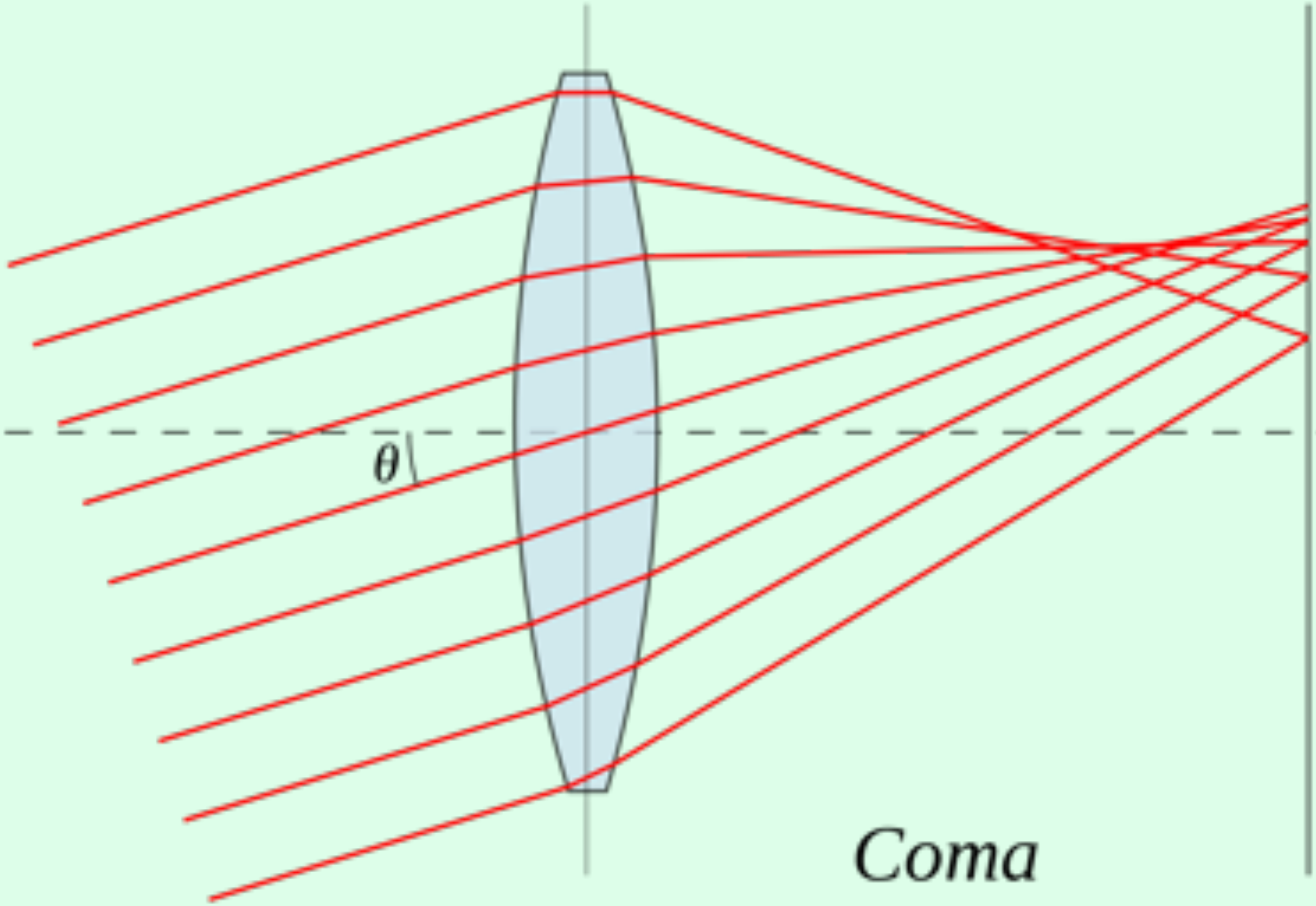
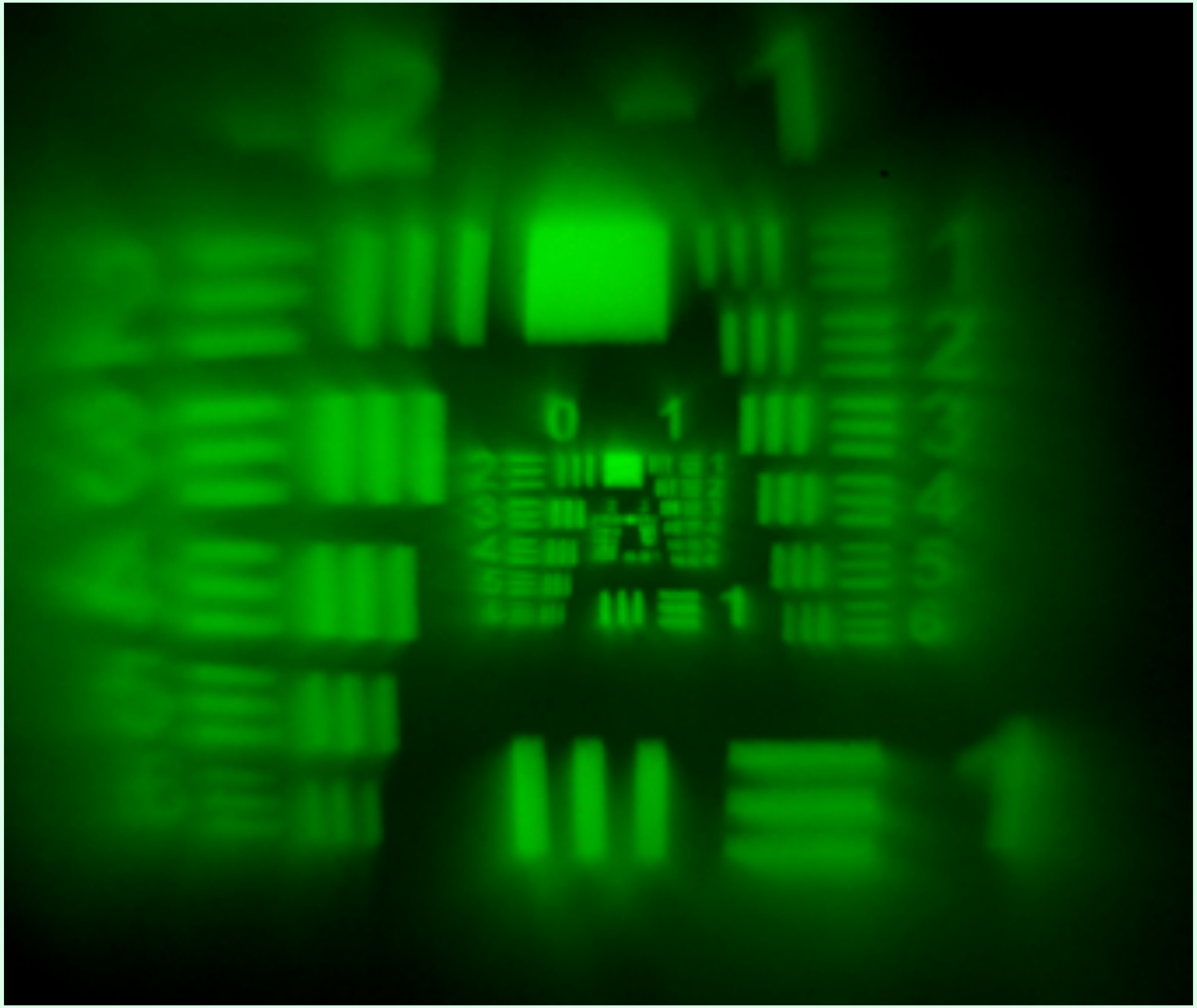
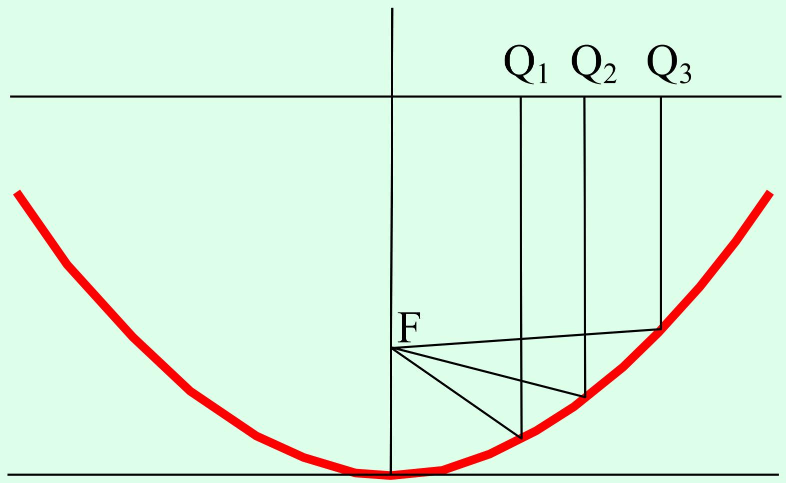
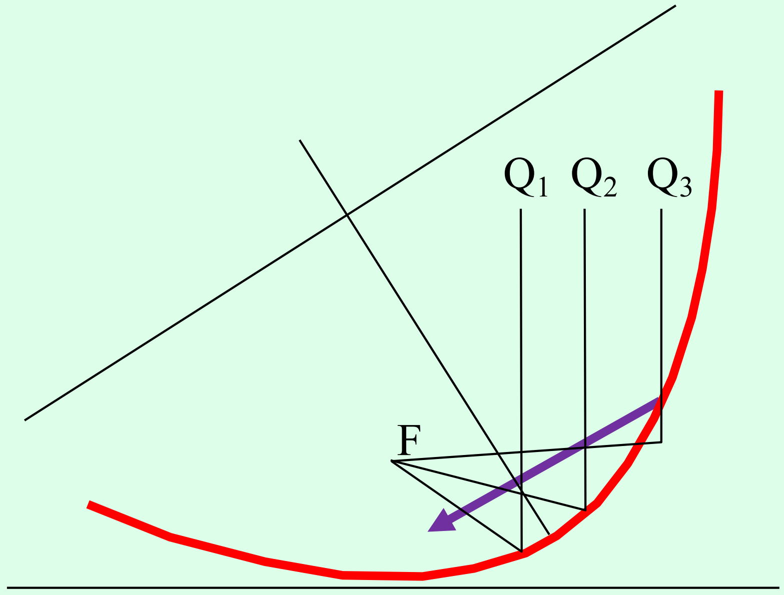


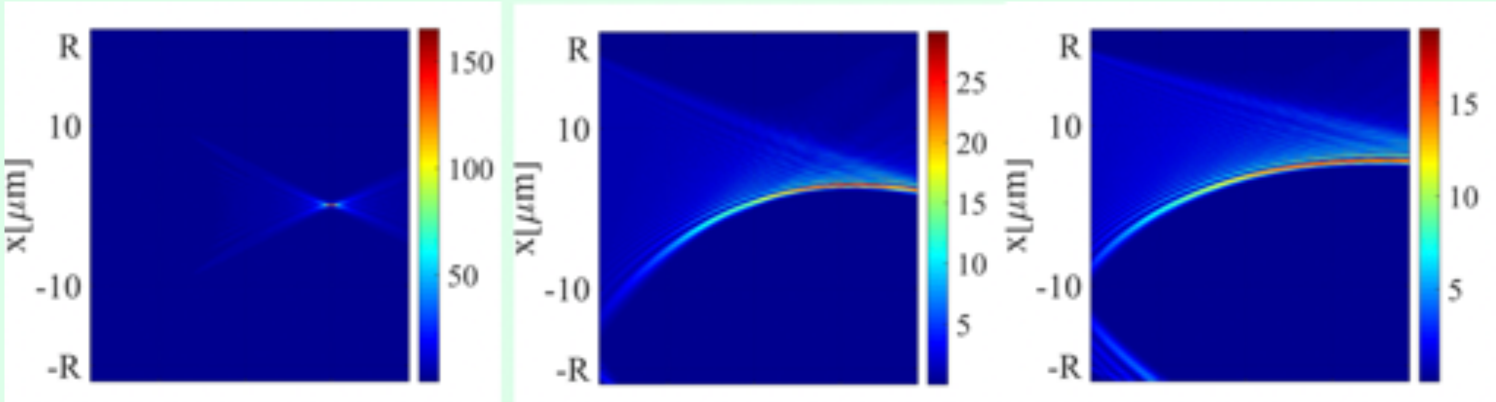
Image
θ
Coma

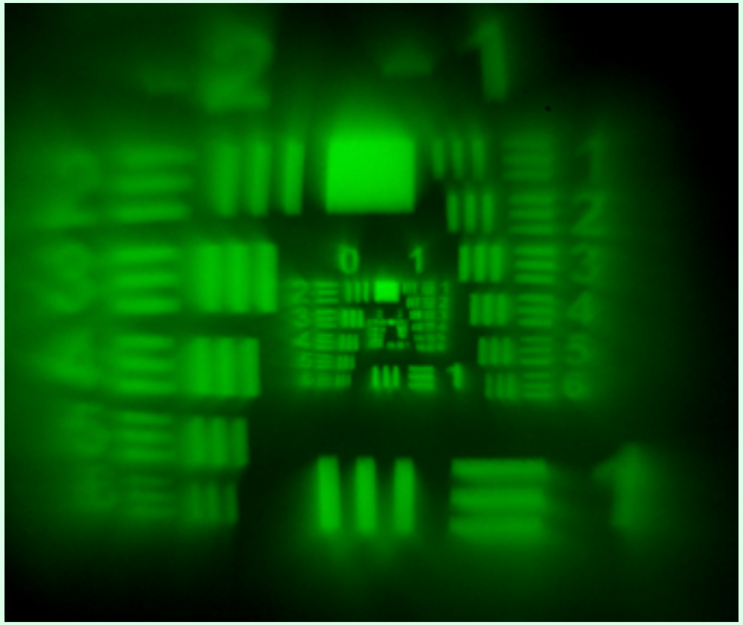


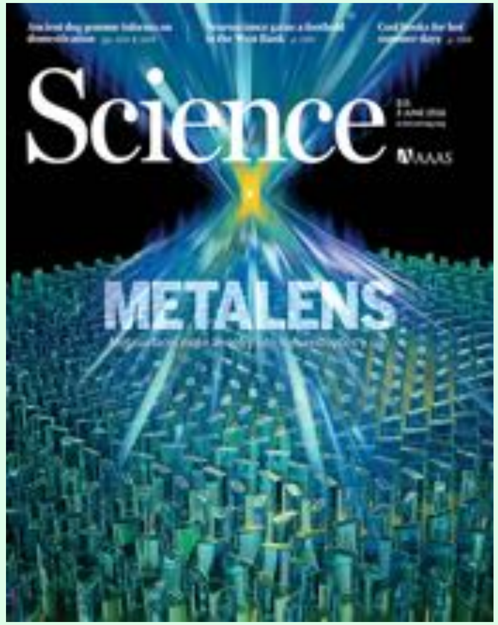

Q1 Q2 Q3
F


Q1 Q2 Q3
F

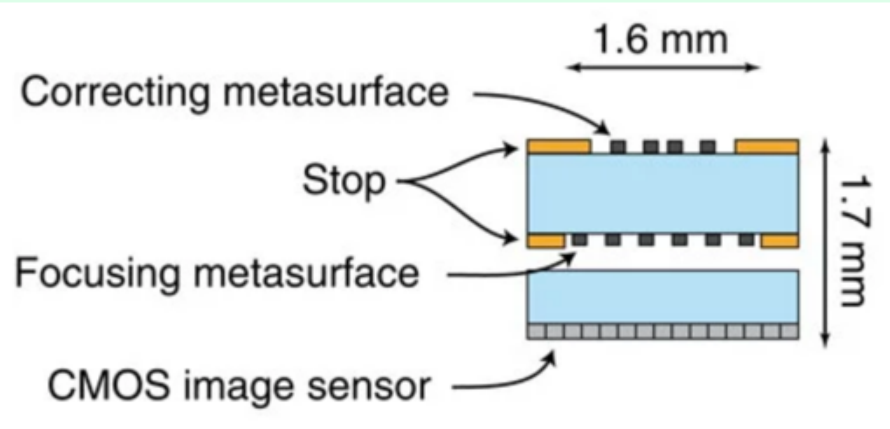
Normal incidence   15˚   35˚

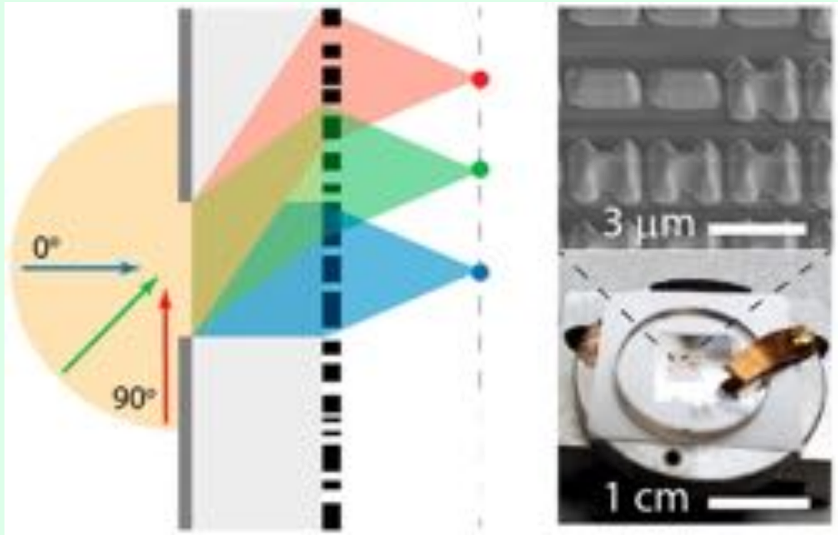






Some people have solved the problem by adding an aperture or a phase-correcting second surface (doublet)

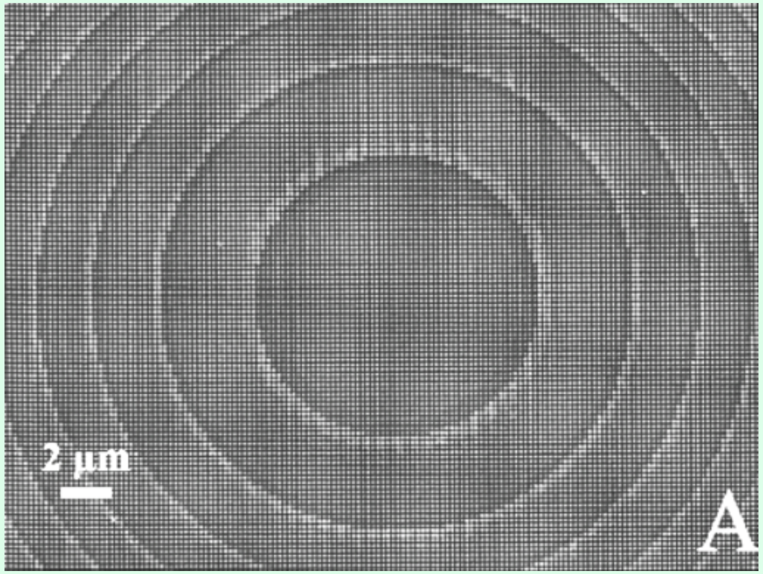


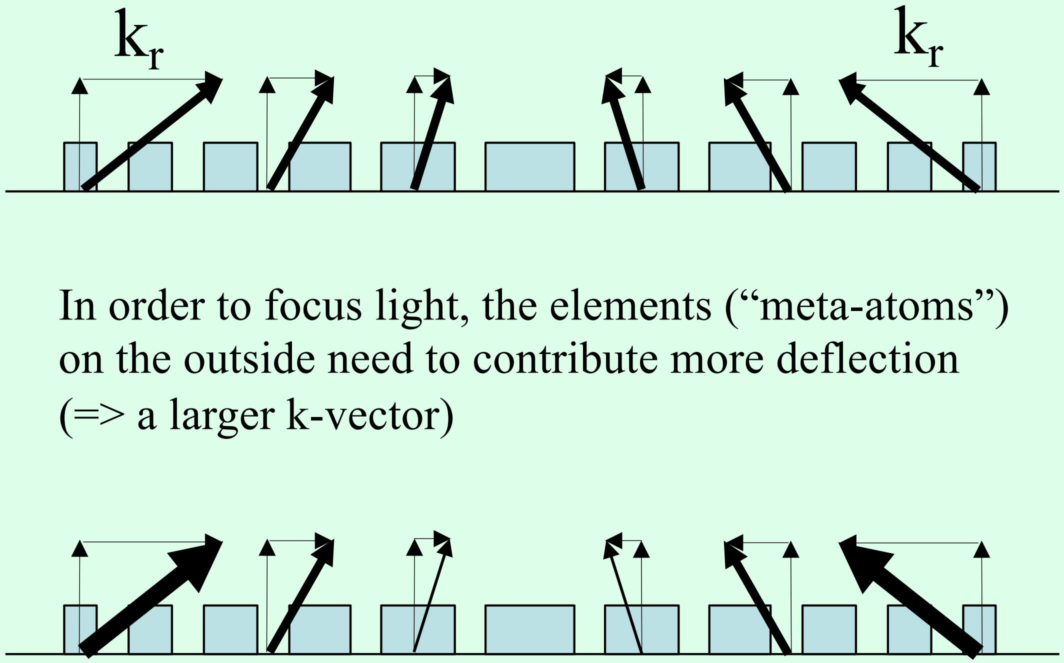


Caltech: Nat Commun 7, 13682 (2016)

MIT: Nano Lett. 2020, 20, 10, 7429–7437

k-space

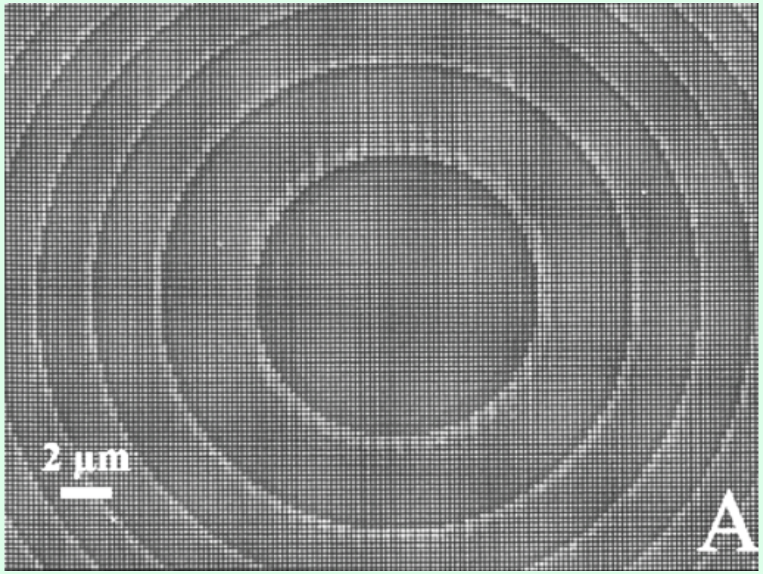


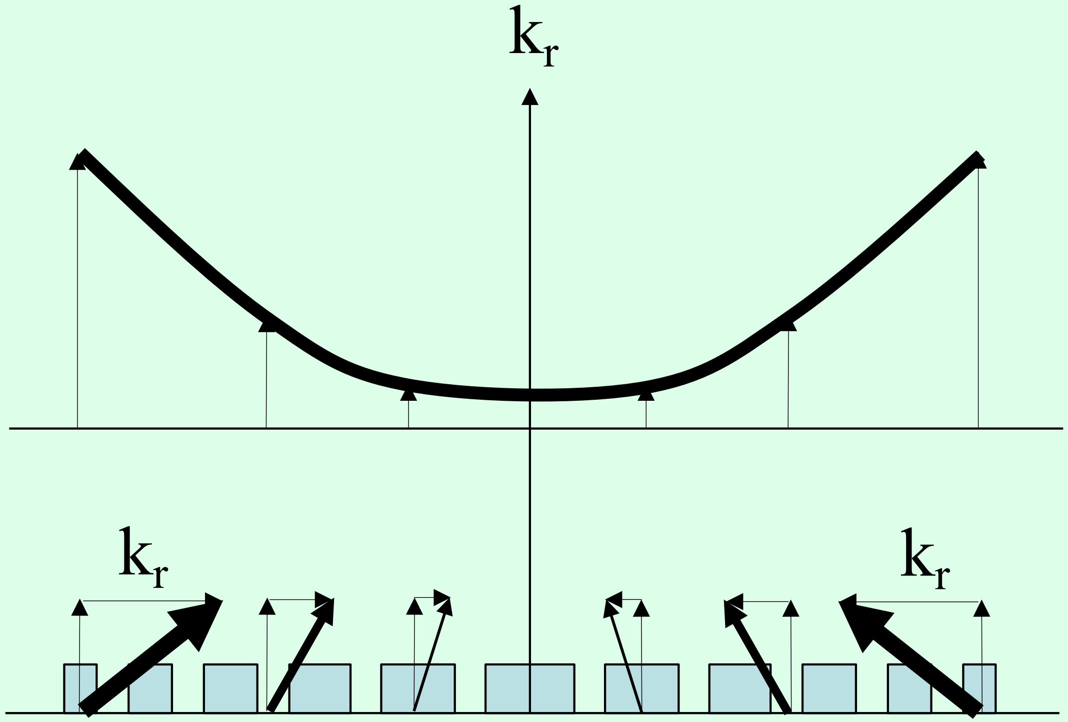


In order to focus light, the elements ("meta-atoms") on the outside need to contribute more deflection (=> a larger k-vector)

The high k-vectors on the outside provide the sharpness. That's why you want to make them stronger. This is exactly what Capasso's hyperbolic metasurface does, and that's why it provides such good focussing.

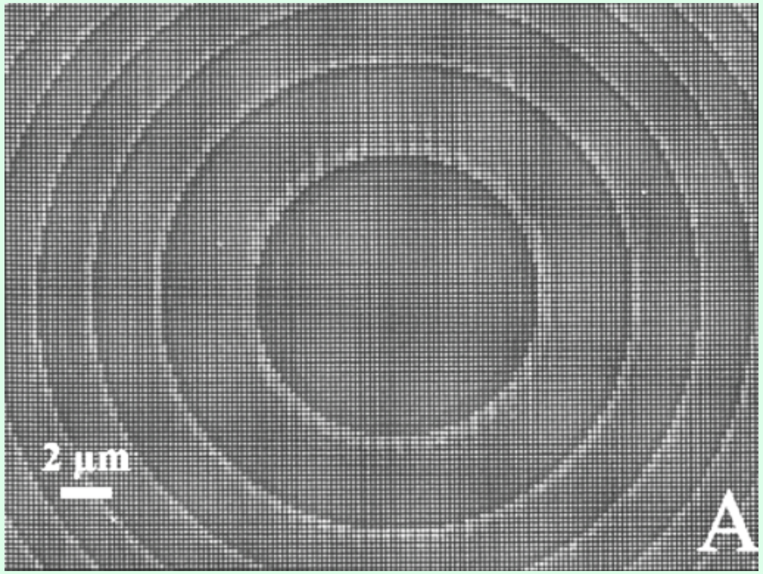
k-space

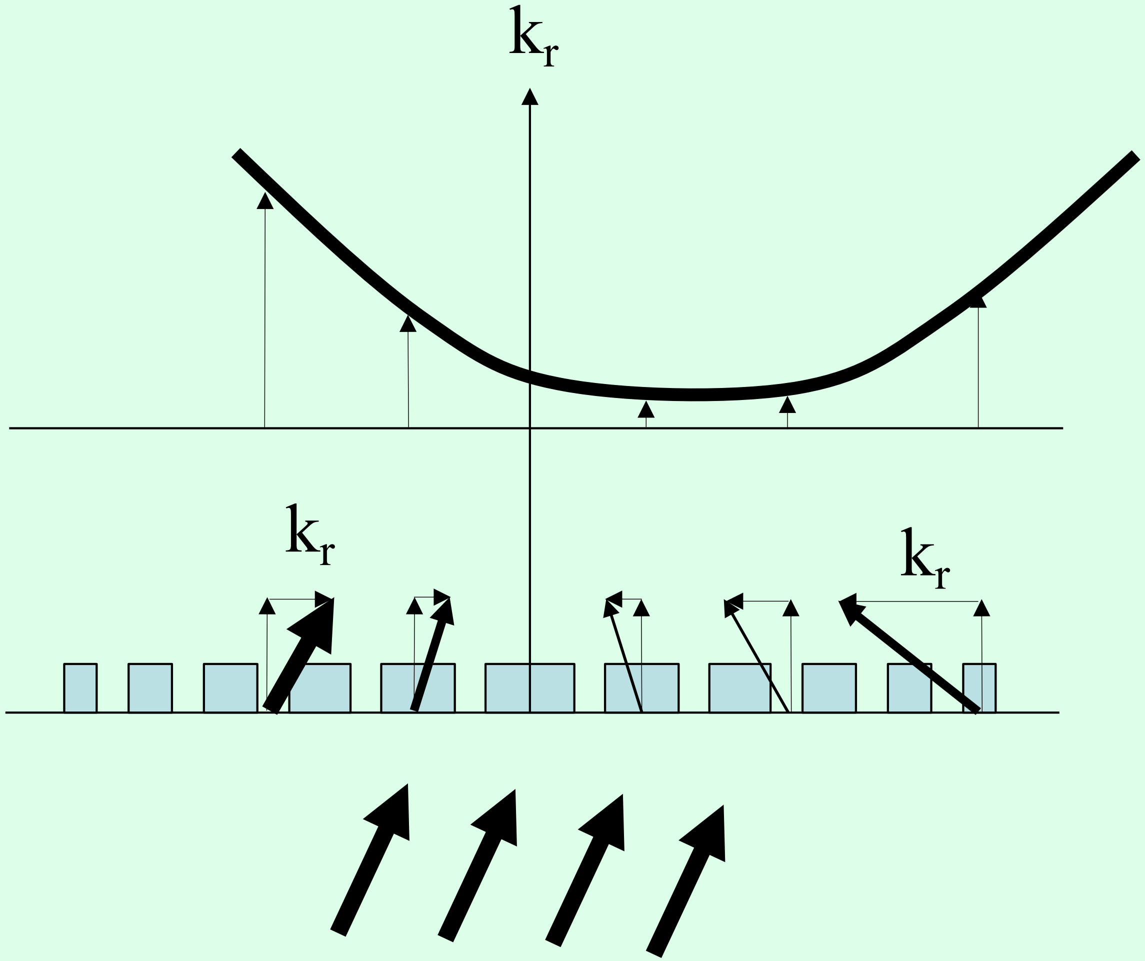




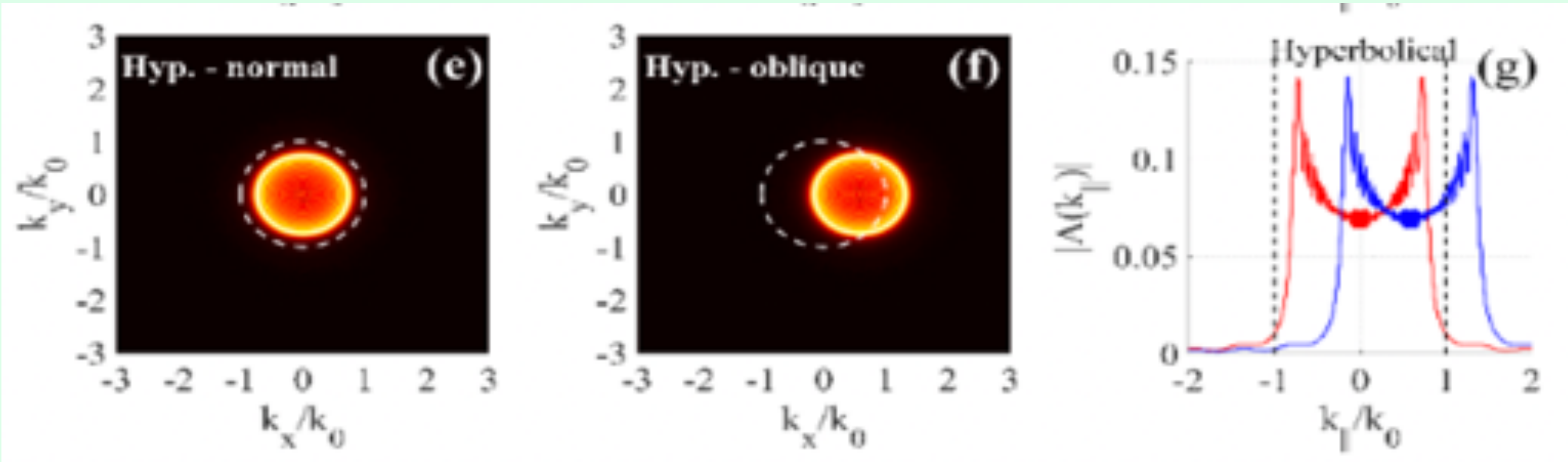
The high k-vectors on the outside provide the sharpness. That's why you want to make them stronger. This is exactly what Capasso's hyperbolic metasurface does, and that's why it provides such good focussing.

k-space

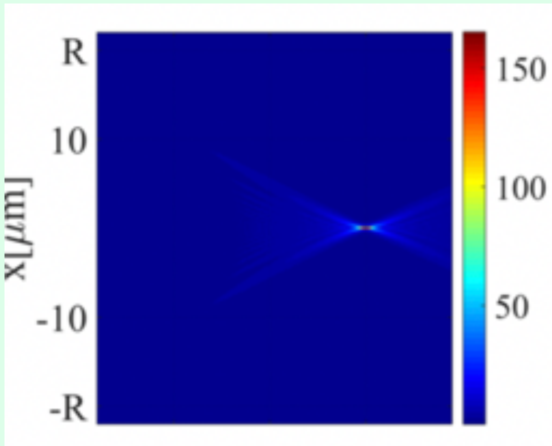




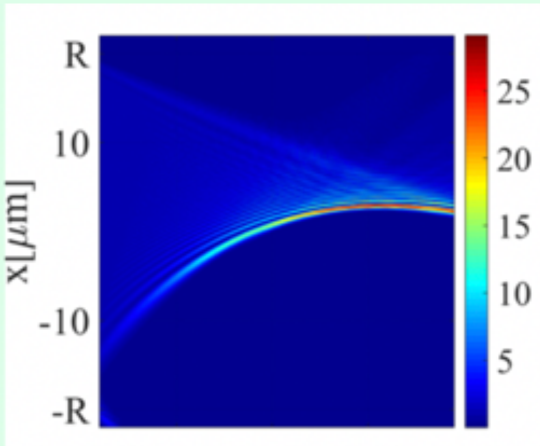
Off-axis incidence shifts phase profile; it becomes asymmetric



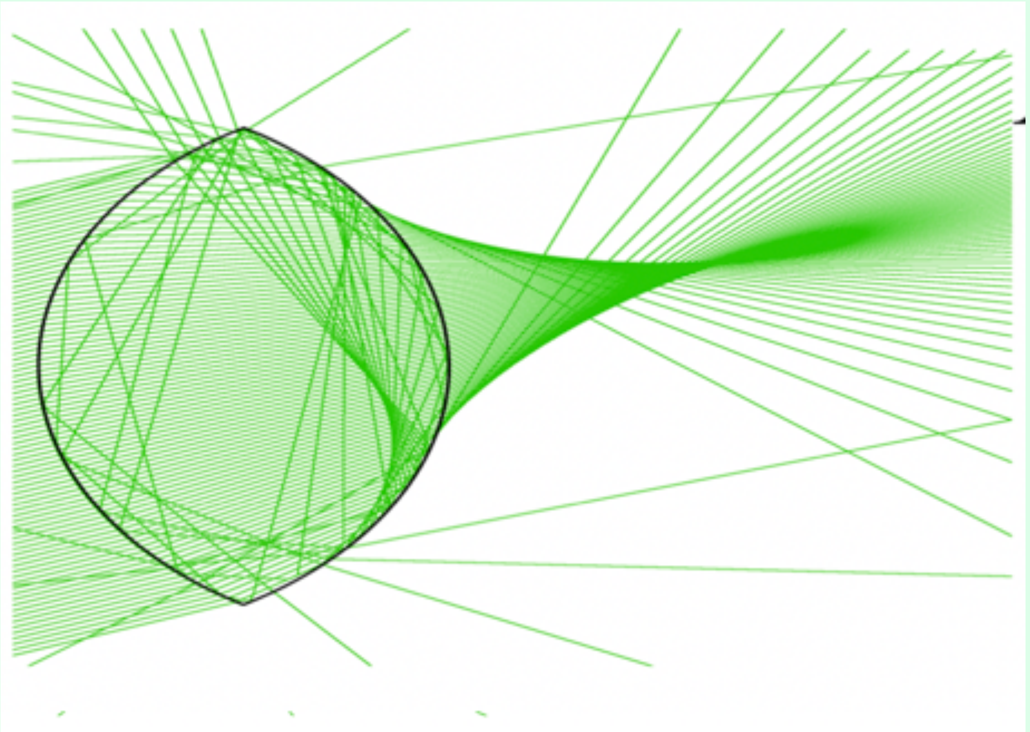
Normal incidence

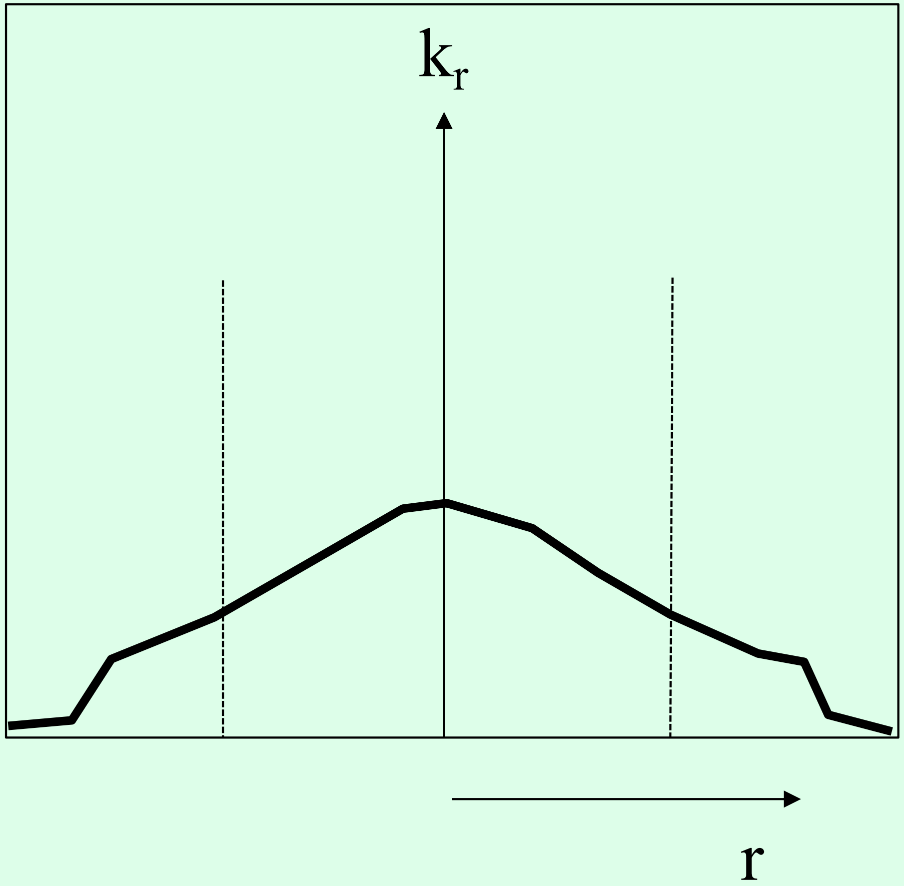


15°



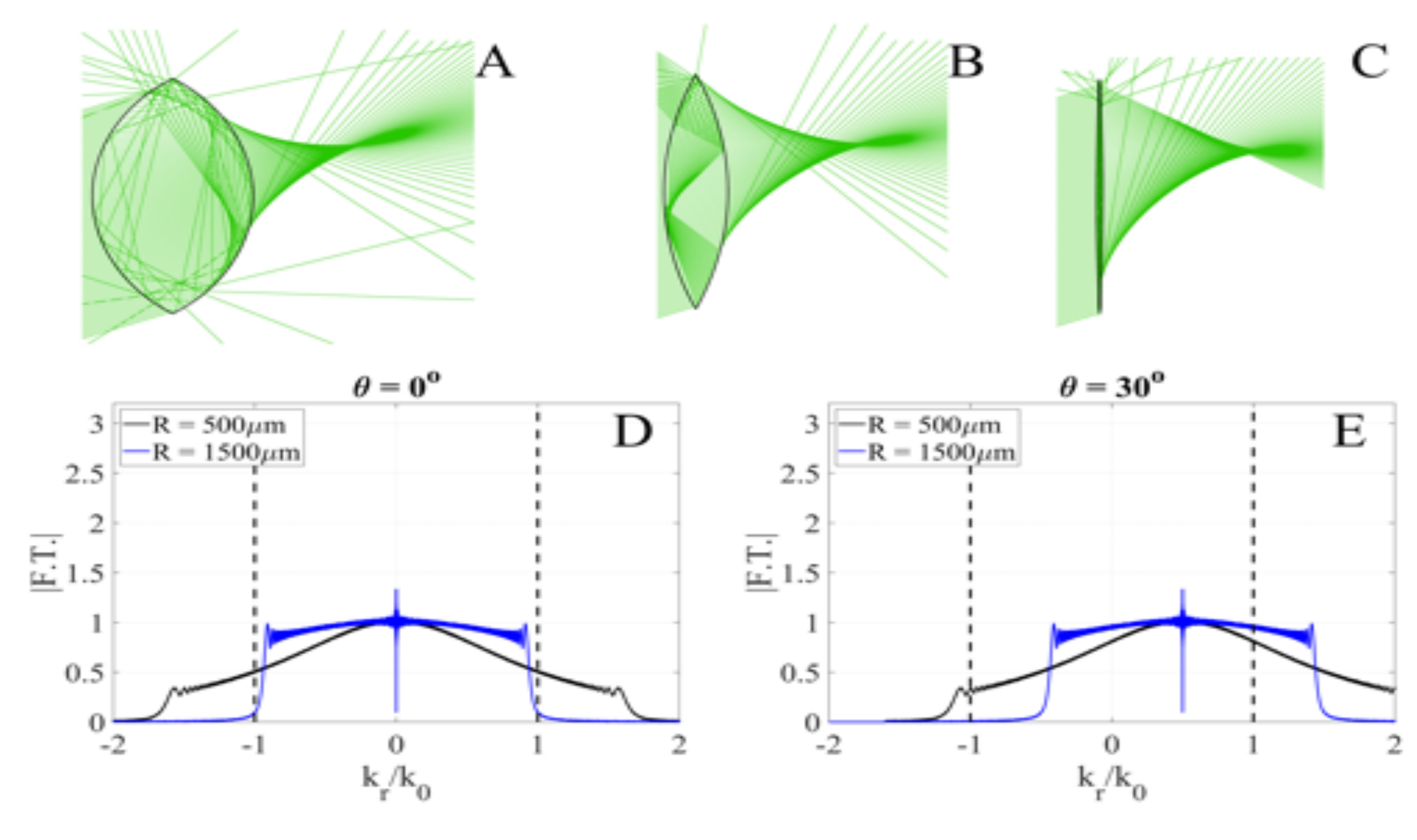
Back to the spherical lens





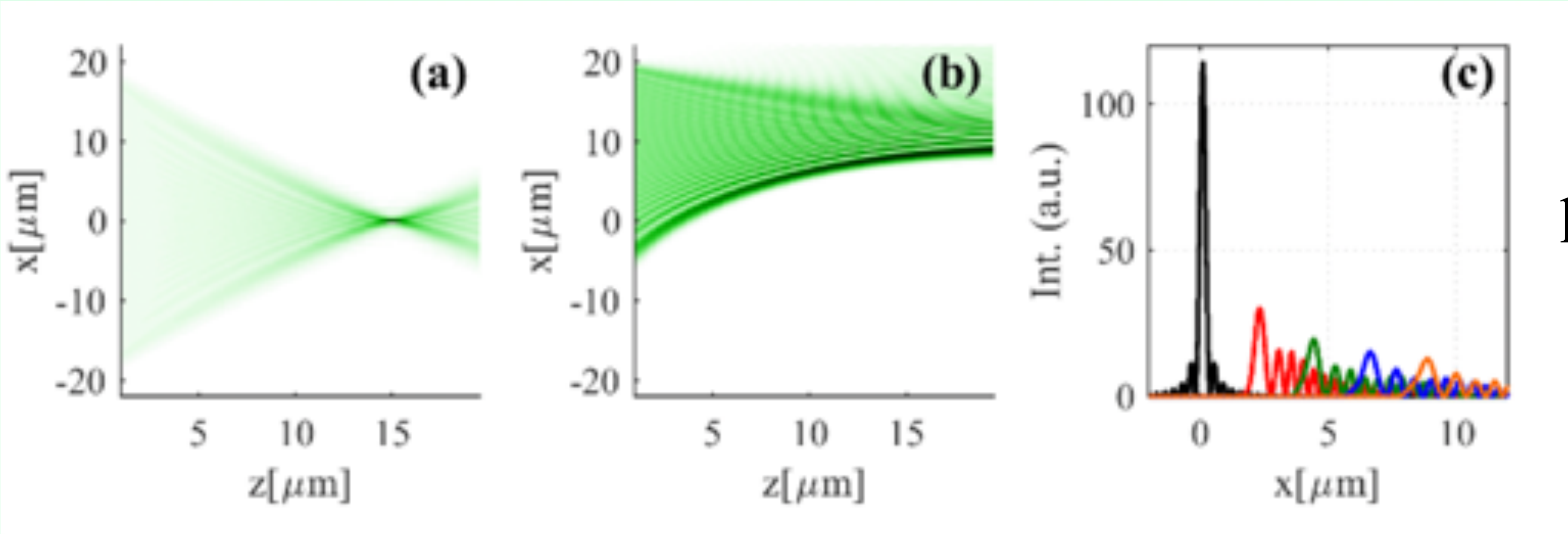
The spherical lens has a much flatter k-space than the hyperbolic lens
That means it is more tolerant to angular incidence.
Can we improve on this?

The "impossible" lens, $r \rightarrow \infty$ and $n \rightarrow \infty$

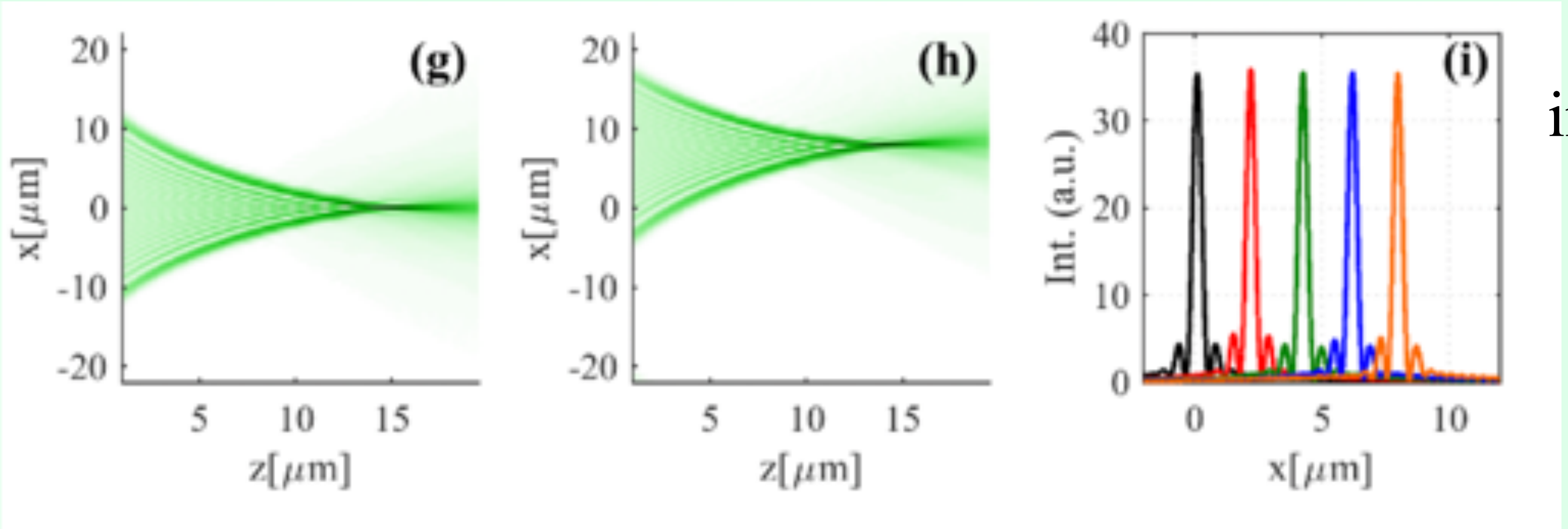


Martins et al., "On metalenses with arbitrarily wide field of view", ACS Photonics 7, 8, 2073-2079 (2020)

Point spread function



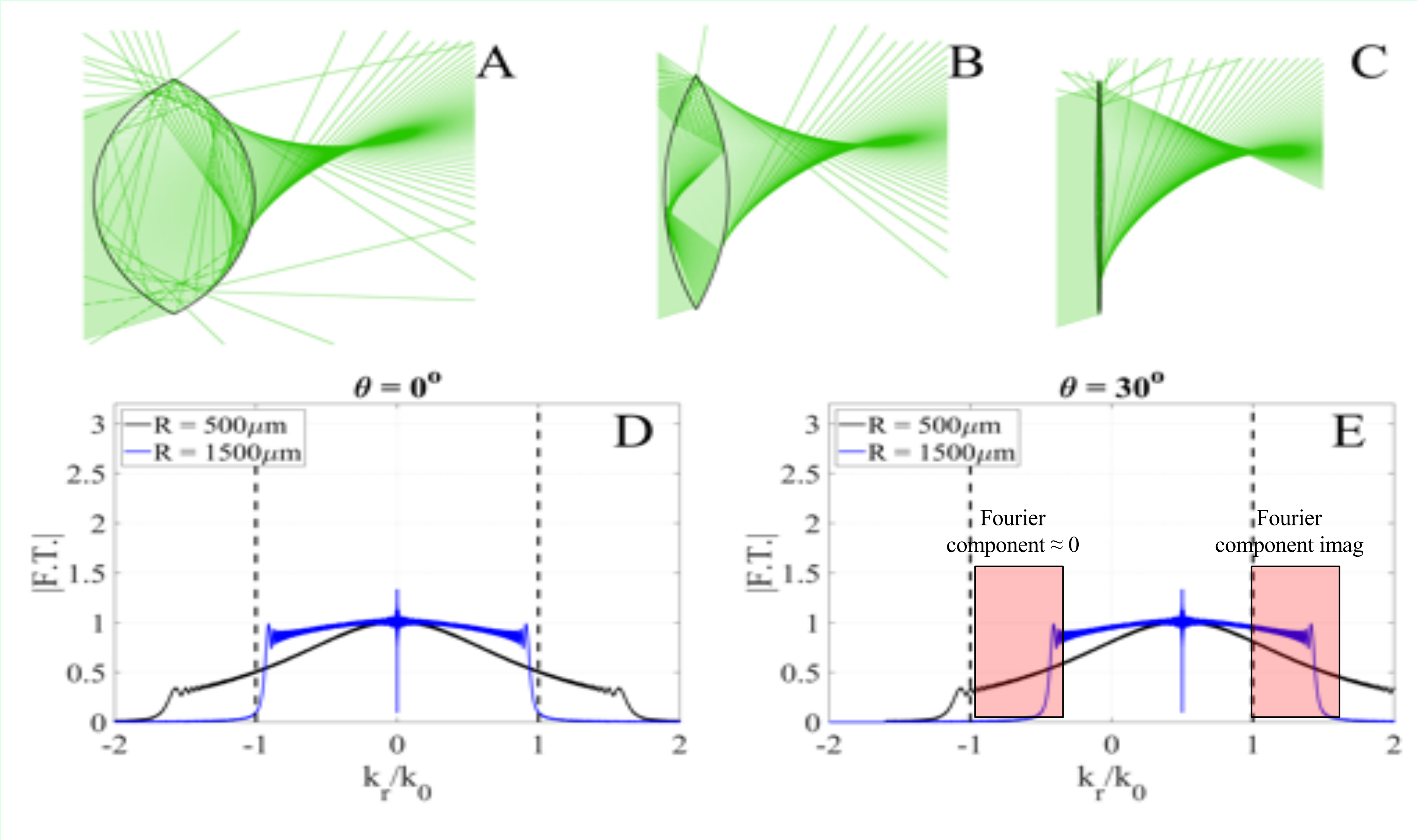
hyperbolic



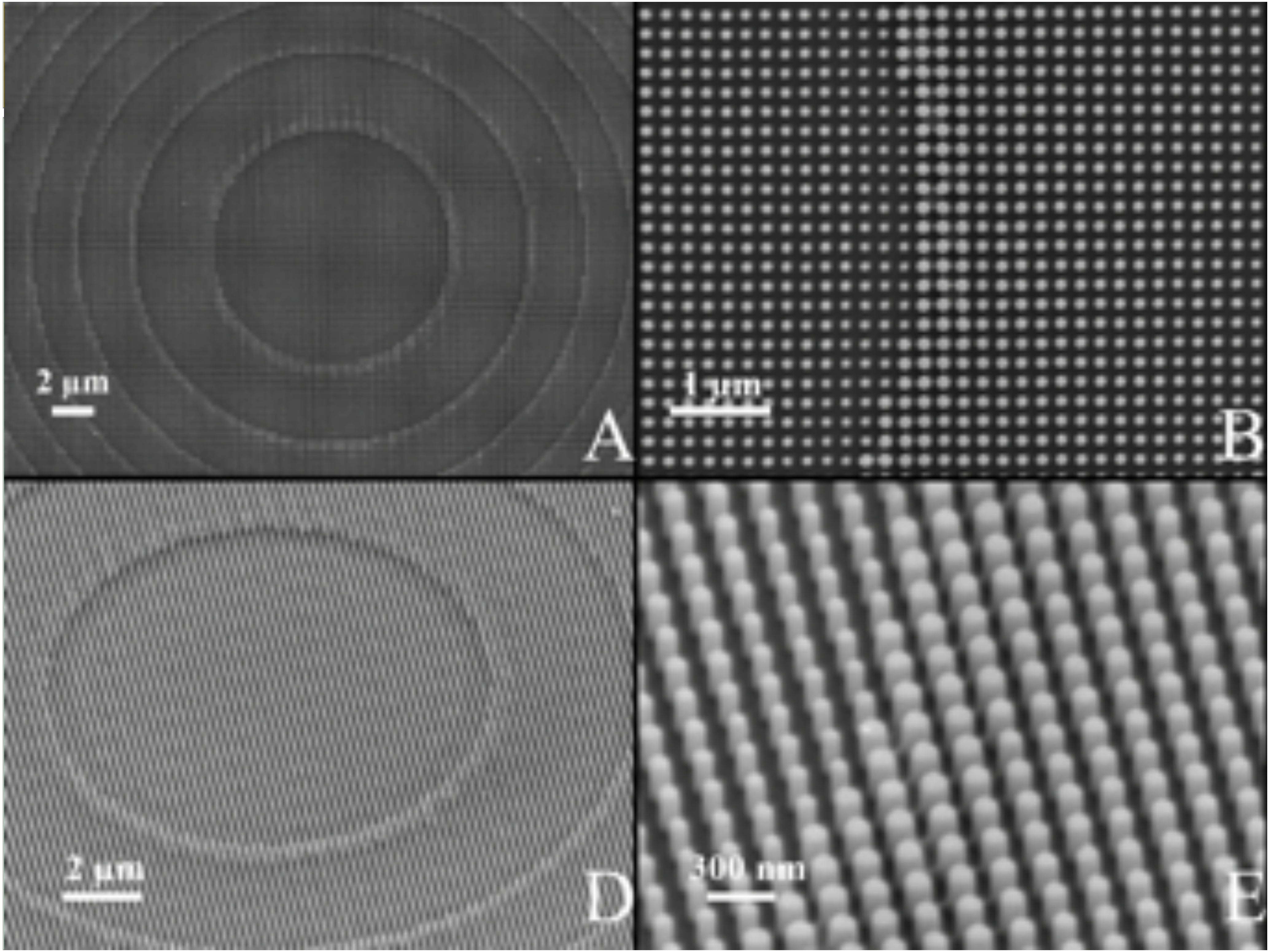
impossible

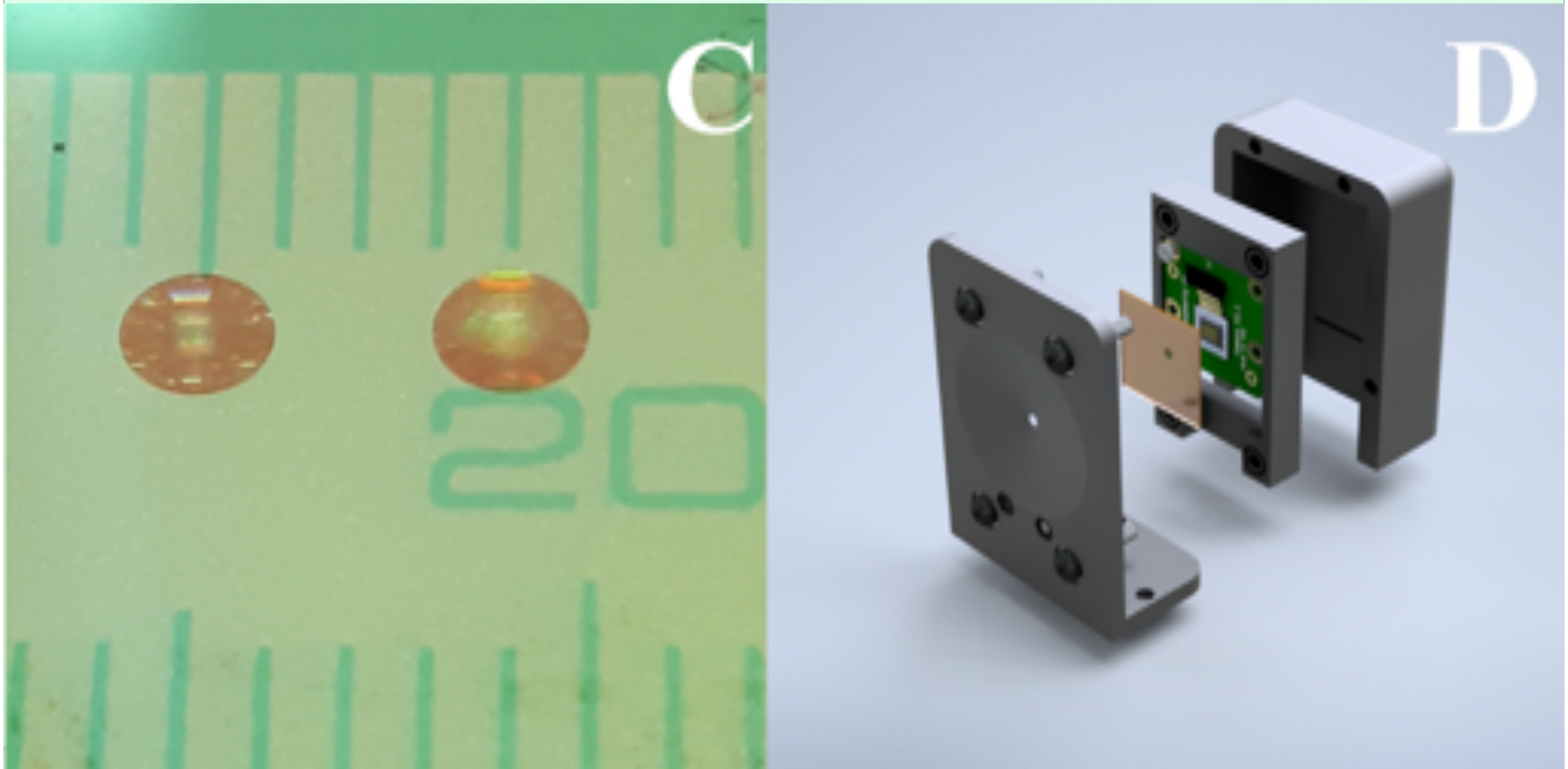
Martins et al., "On metalenses with arbitrarily wide field of view", ACS Photonics 7, 8, 2073-2079 (2020)

The “impossible” lens, $r \to \infty$ and $n \to \infty$

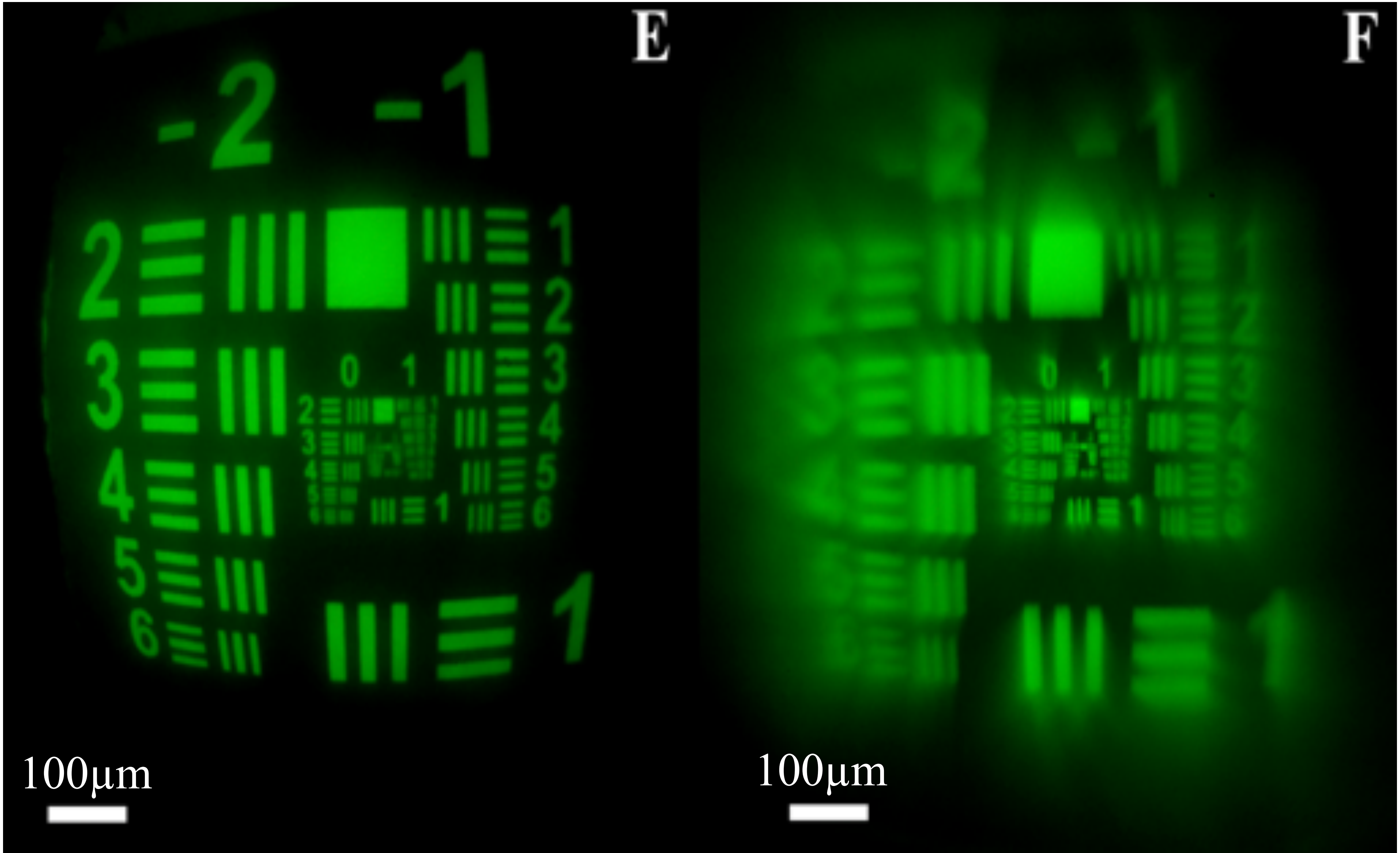


Martins et al., “On metalenses with arbitrarily wide field of view”, ACS Photonics 7, 8, 2073-2079 (2020)

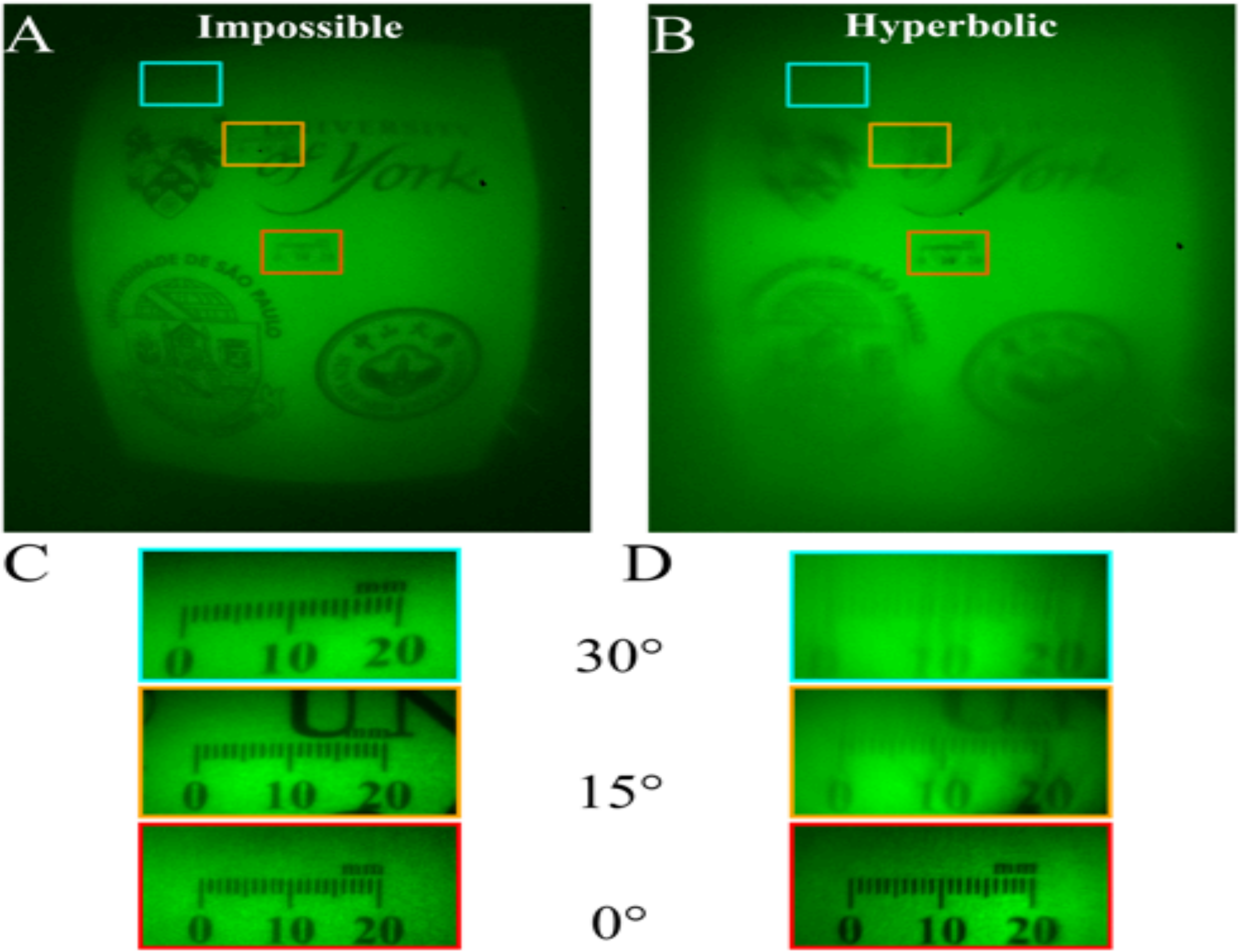

2 μm
A
1 μm
B
2 μm
D
300 nm
E



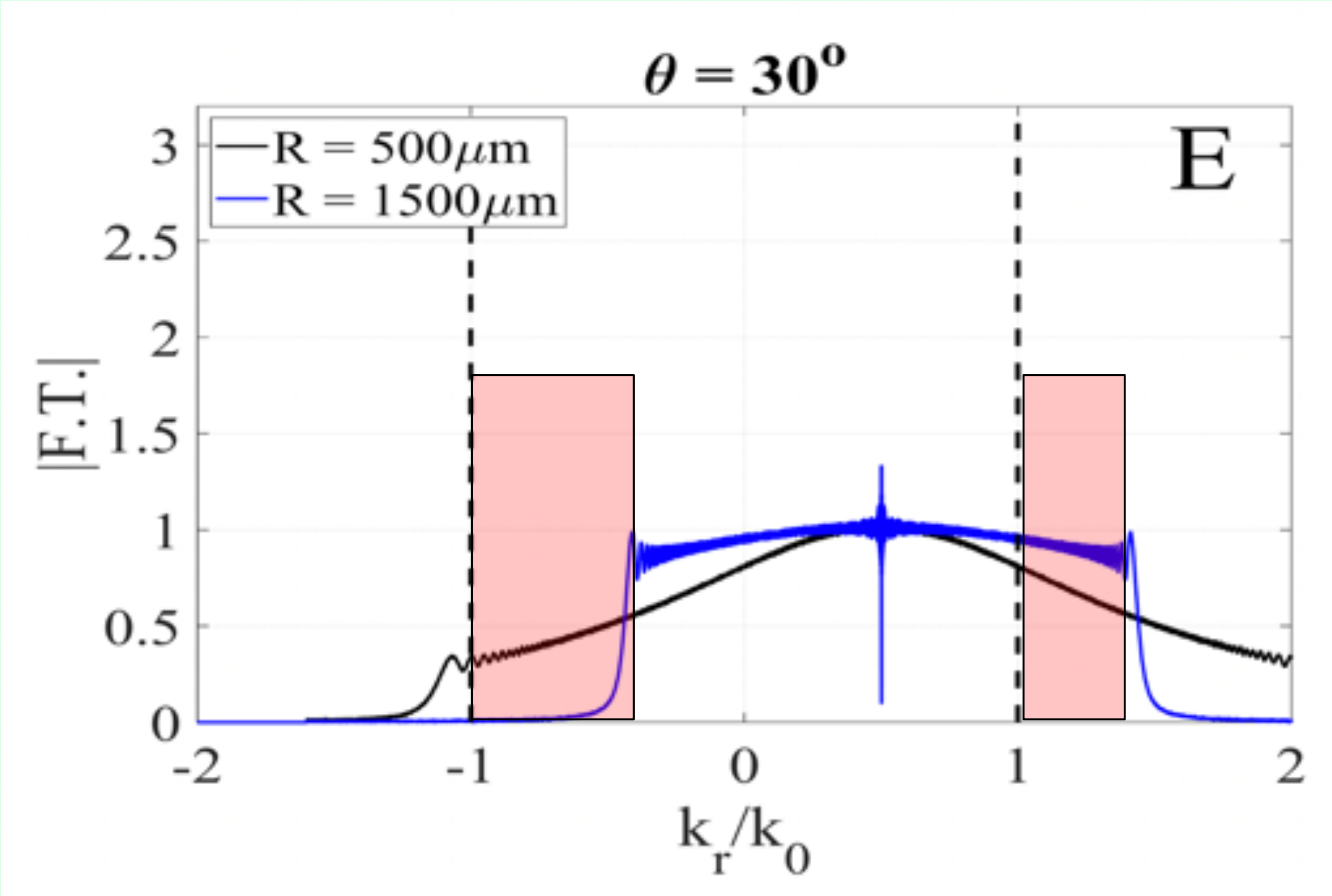
Martins et al., “On metalenses with arbitrarily wide field of view”, ACS Photonics 7, 8, 2073-2079 (2020)



Martins et al., “On metalenses with arbitrarily wide field of view”, ACS Photonics 7, 8, 2073-2079 (2020)

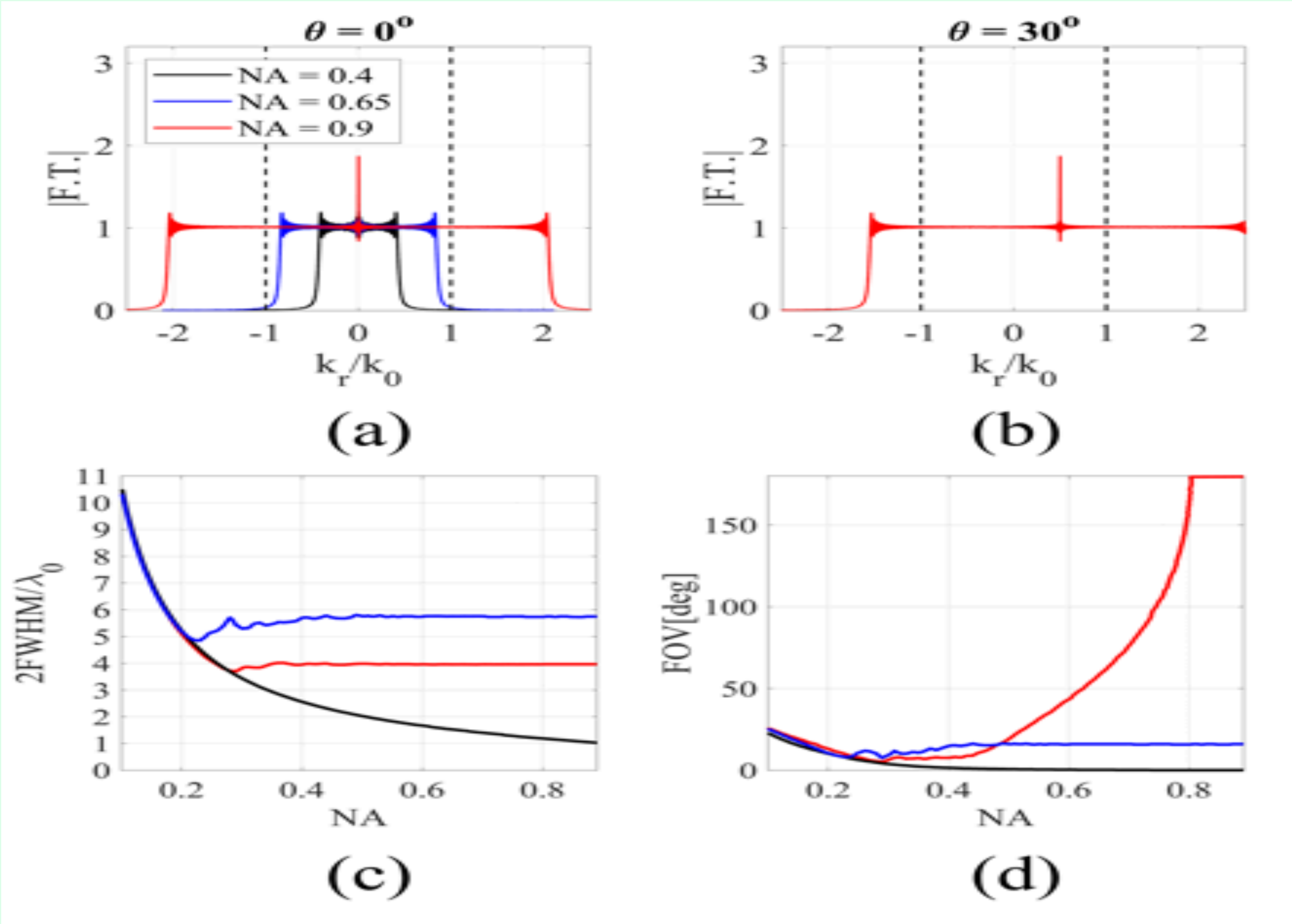

A
Impossible
B
Hyperbolic
C
D
30°
15°
0°
0 10 20
mm

What does the NA do?



Getting a flatter distribution in k-space is good, but can we avoid the red boxes?

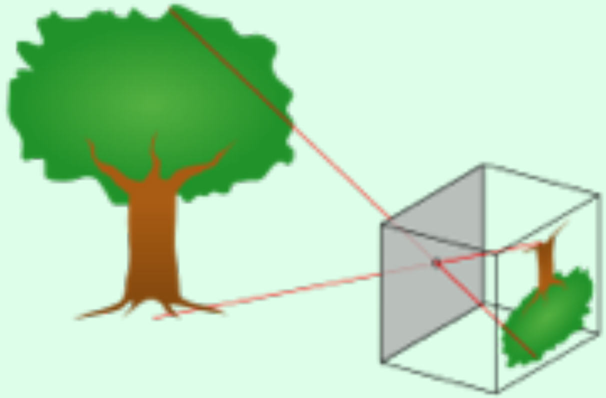
Field of view vs. NA



For the impossible lens, NA controls FoV, less so spatial resolution.
You pay for the FoV with a loss in spatial resolution.

Your lens is very small – does it not just work as a pinhole camera?

$d = 2\sqrt{f\lambda}$ ➔ f=750 µm, λ=550 nm ➔ $d \approx 50\mu m$

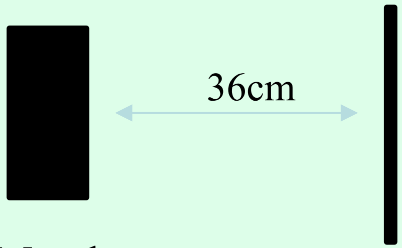


Metalens vs pinhole camera

Metalens

Pinhole

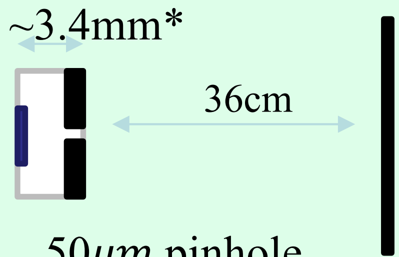
Notice that the metalens focuses the green and the red in different positions. That's why only the green numbers are shown in this image.



Metalens camera
(f= 0.75mm)

Metalens:

- Focal length: 0.75 mm
- Magnification: $\sim \frac{1}{484.7}$
- Exposure time: <1s



$50\mu m$ pinhole

Pinhole:

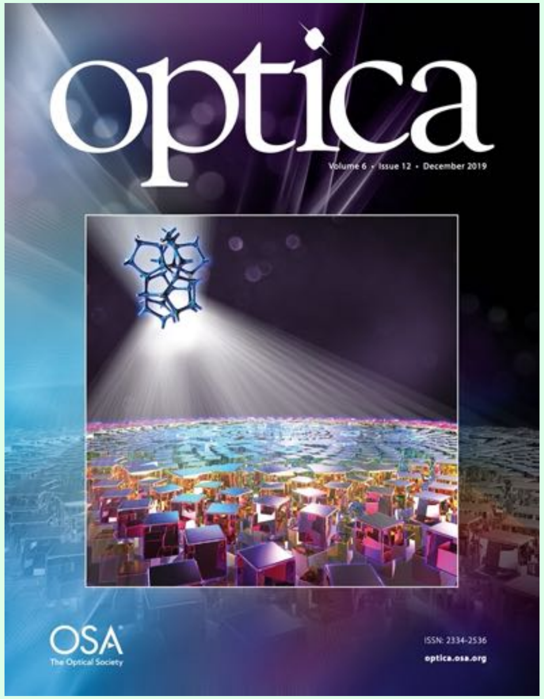
- Distance from the CCD: ~3.4mm
- Magnification: $\sim \frac{1}{107}$
- Exposure time: 50s

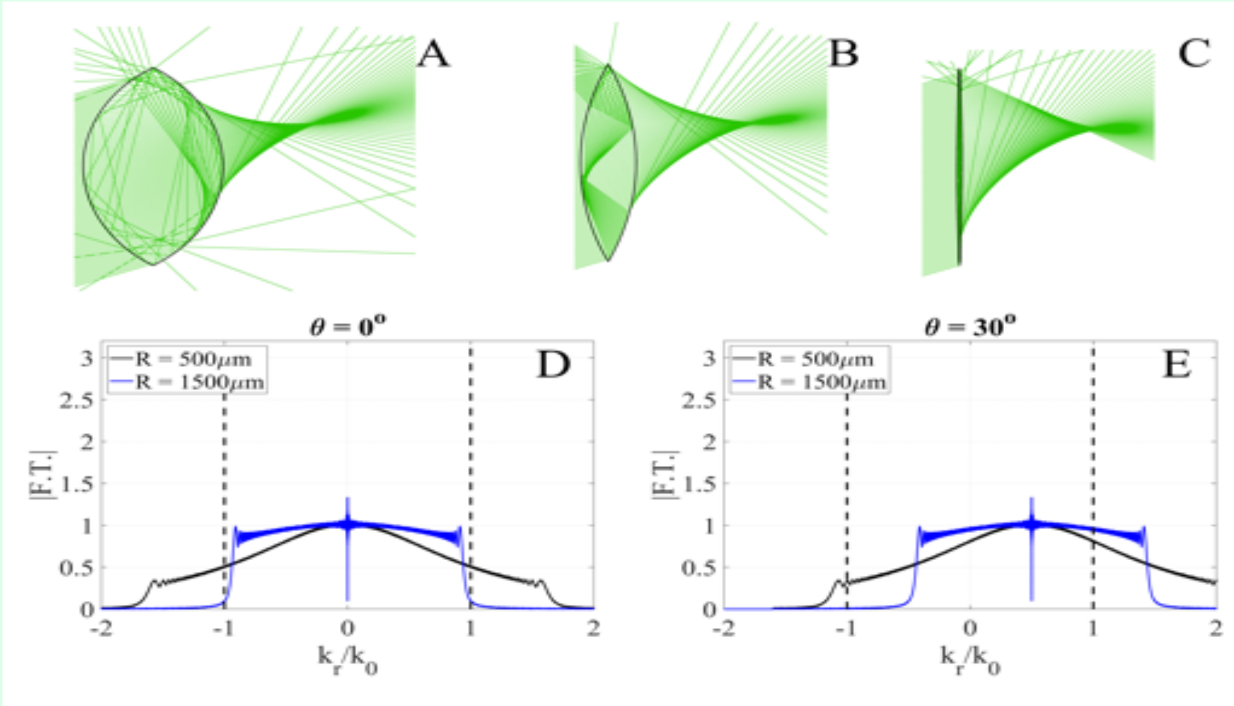
Metalens focusses much more light than a pinhole, but it introduces chromatic aberration

Conclusion

The hyperbolic phase profile used by many researchers gives excellent on-axis performance, but it is poor off-axis, with significant coma aberration.

The "impossible" metalens addresses this in the limit of $r \to \infty$ and $n \to \infty$. The performance becomes independent of angle, and you pay with a reduced spatial resolution. NA mainly controls field of view, less so the spatial resolution. The "impossible" lens has no equivalent in bulk optics, hence the name.





Martins et al., "On metalenses with arbitrarily wide field of view", ACS Photonics 7, 8, 2073-2079 (2020)

Opportunities

Achromatic metalens: Most metalenses work best for a limited wavelength range. Existing achromatic designs are either low efficiency or low numerical aperture or small field of view.

New Functions: Polarisation? Polarisation-dependent functions are difficult with classical optical elements, but are easy to do with metalenses.

Point spread function