Chris Stanford
Fermilab

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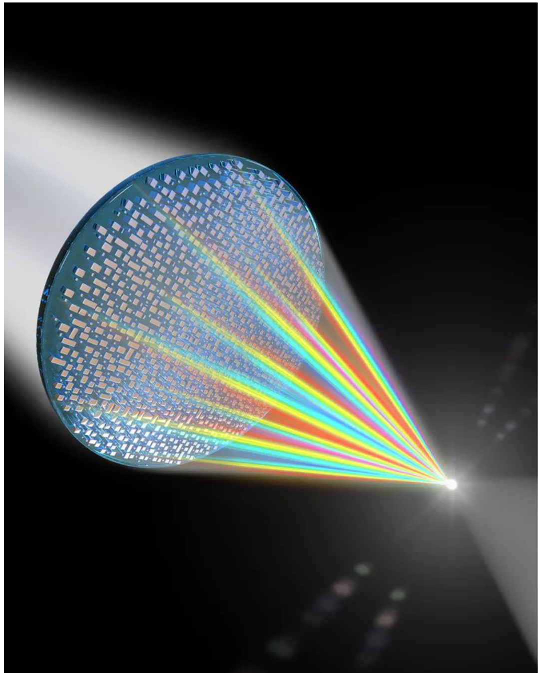
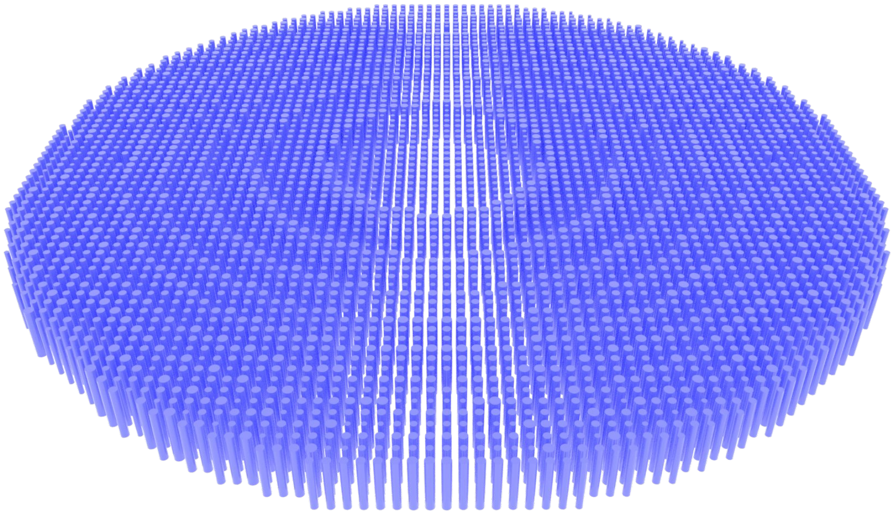
Assessing the performance of metalenses to enhance the light collection of silicon photomultipliers

Roxanne Guenette
Justo Martin-Albo
Augusto Martins
Taylor Contreras
Fabian Kellerer
Carlos Escobar
Adam Para
Michelle Stancari
Benjamin Lawrence-Sanderson

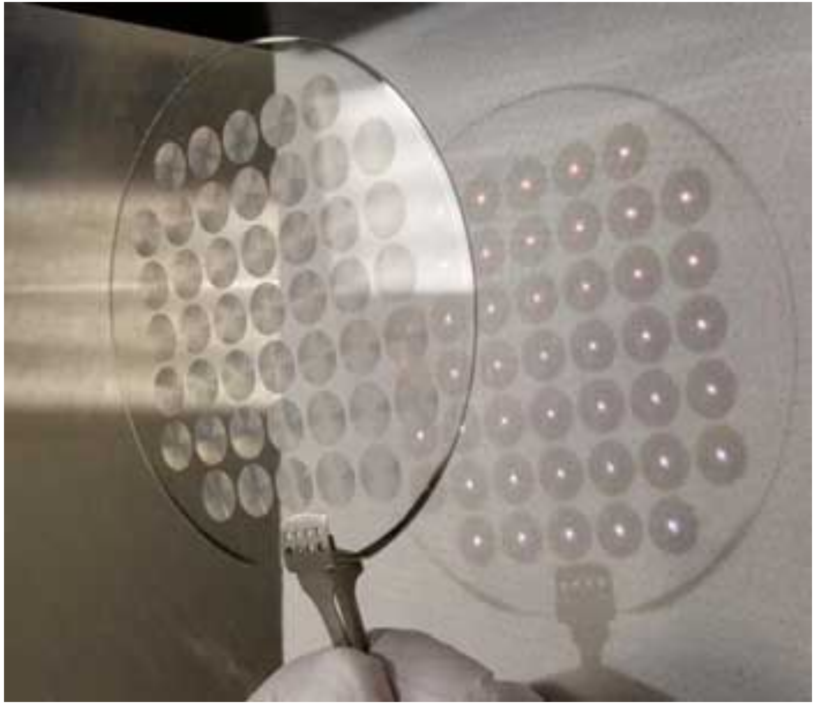
What are metalenses?

Metalenses are flat optics designed to focus light, much like traditional lenses


Capasso Group, Harvard University



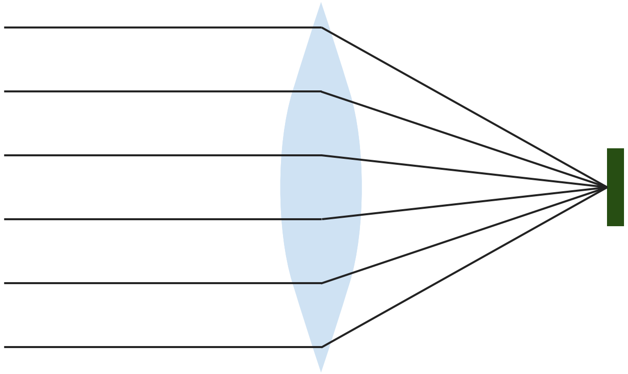
What are metalenses?

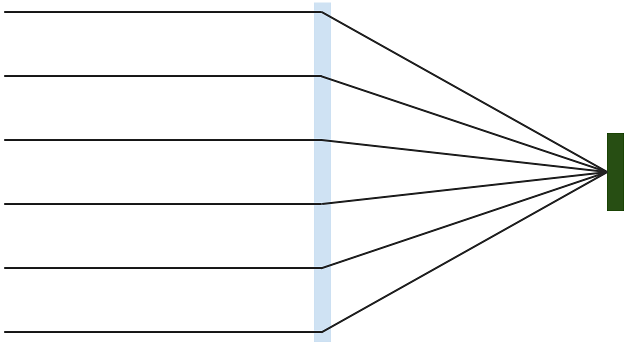


Capasso Group, Harvard University

Why “meta”?

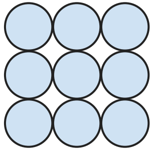
Traditional vs Meta





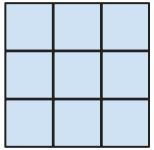
Traditional

- Bulky
- Expensive
- Optical limitations



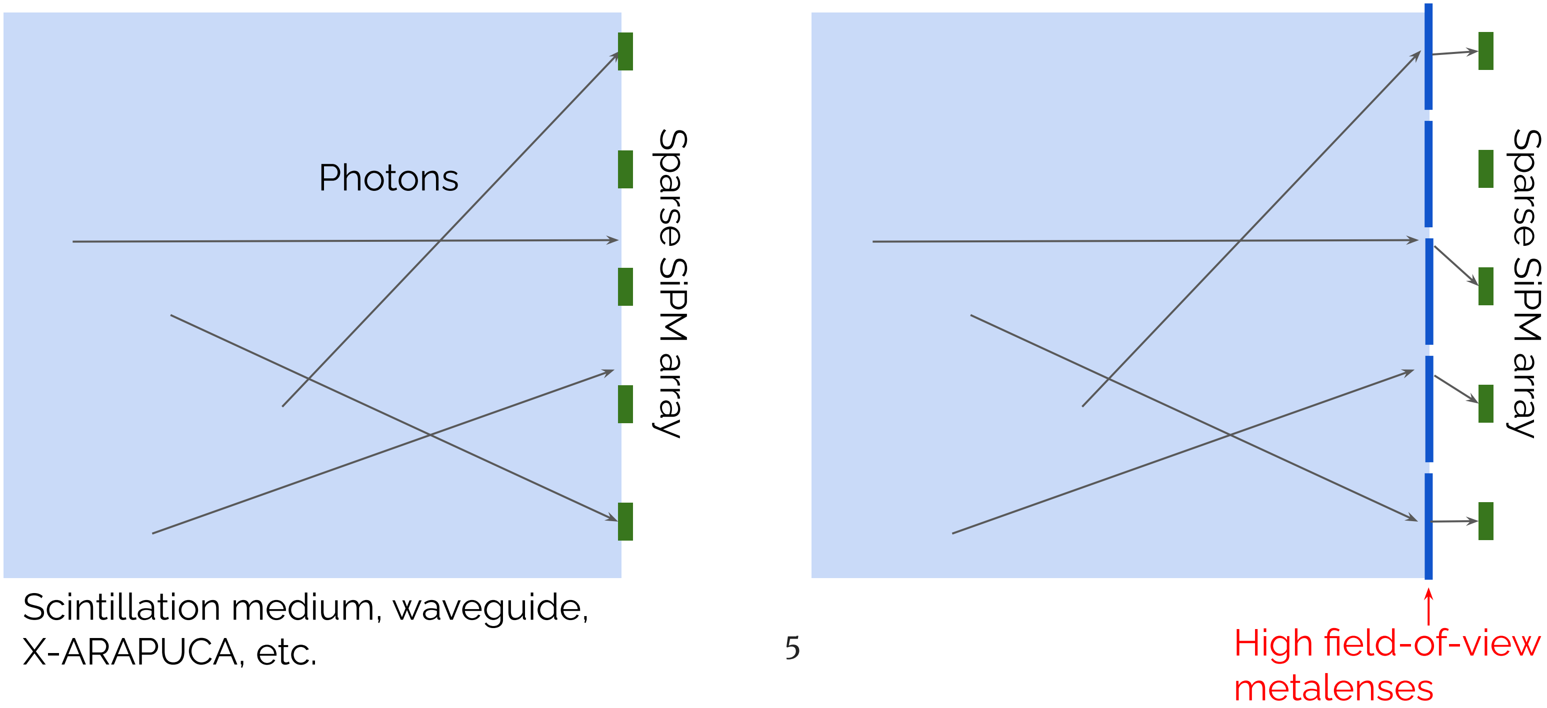
Meta

- Thin and lightweight
- Cheap, easy to mass-produce, $1/ea
- More flexible



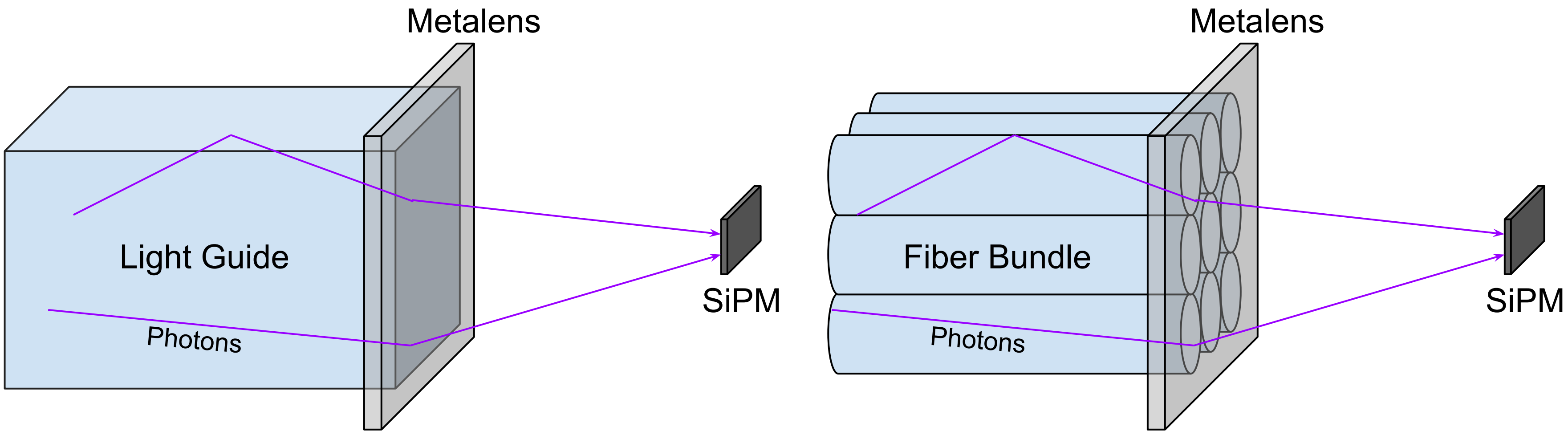
Applications in physics detectors

Metalenses could augment any proposal involving a sparse SiPMs to allow us to collect more light.



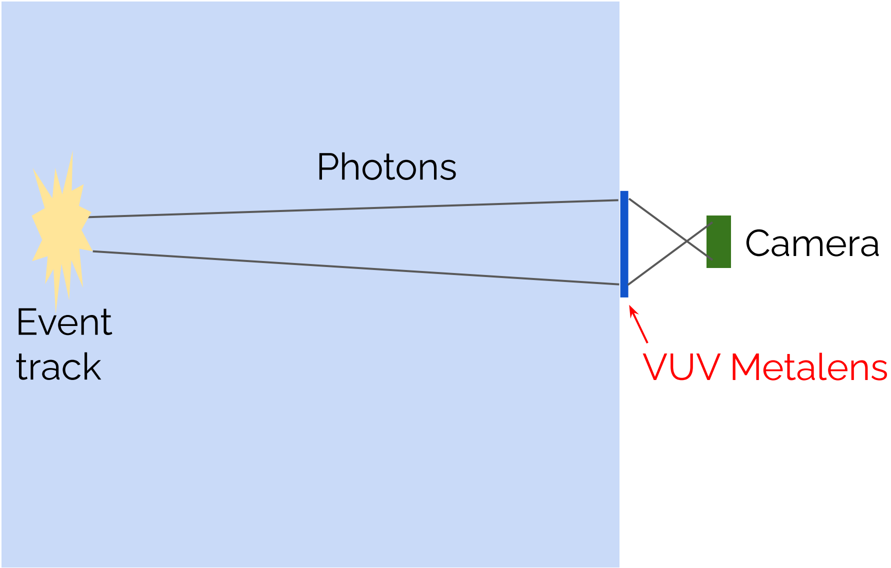
Applications in physics detectors

They could also be added to the end of a light guide to enhance the signal-to-noise

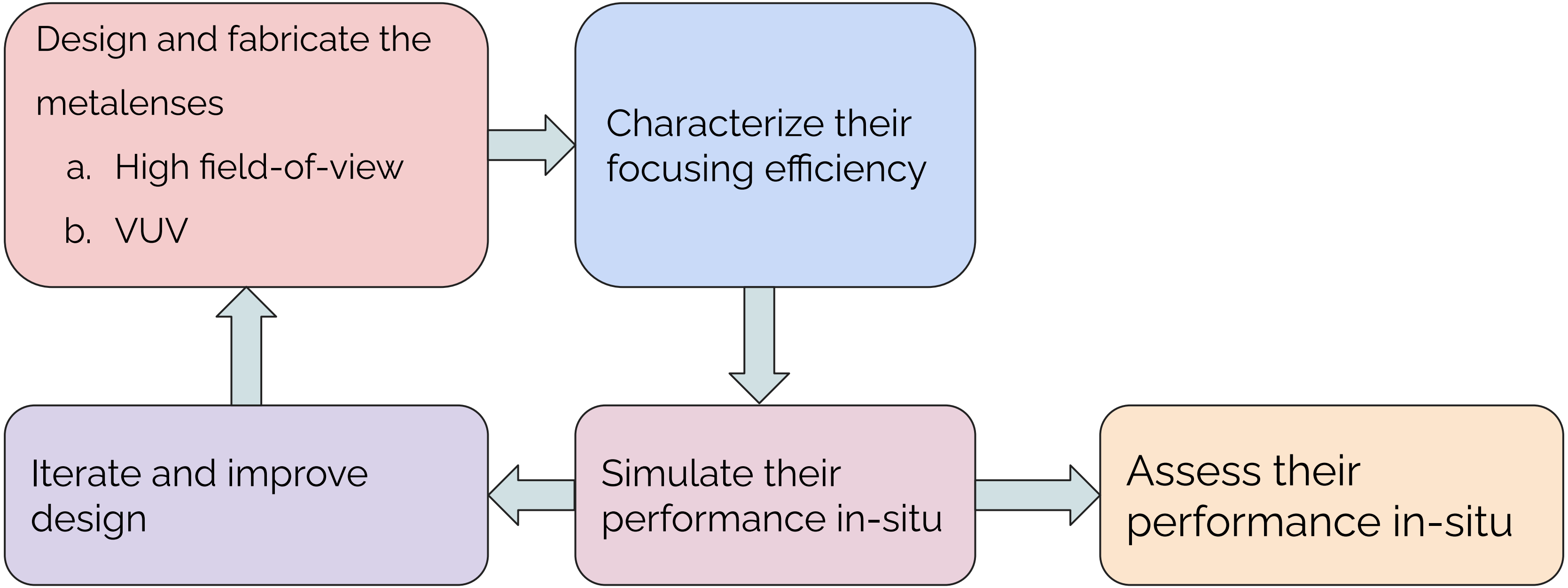


Applications in physics detectors

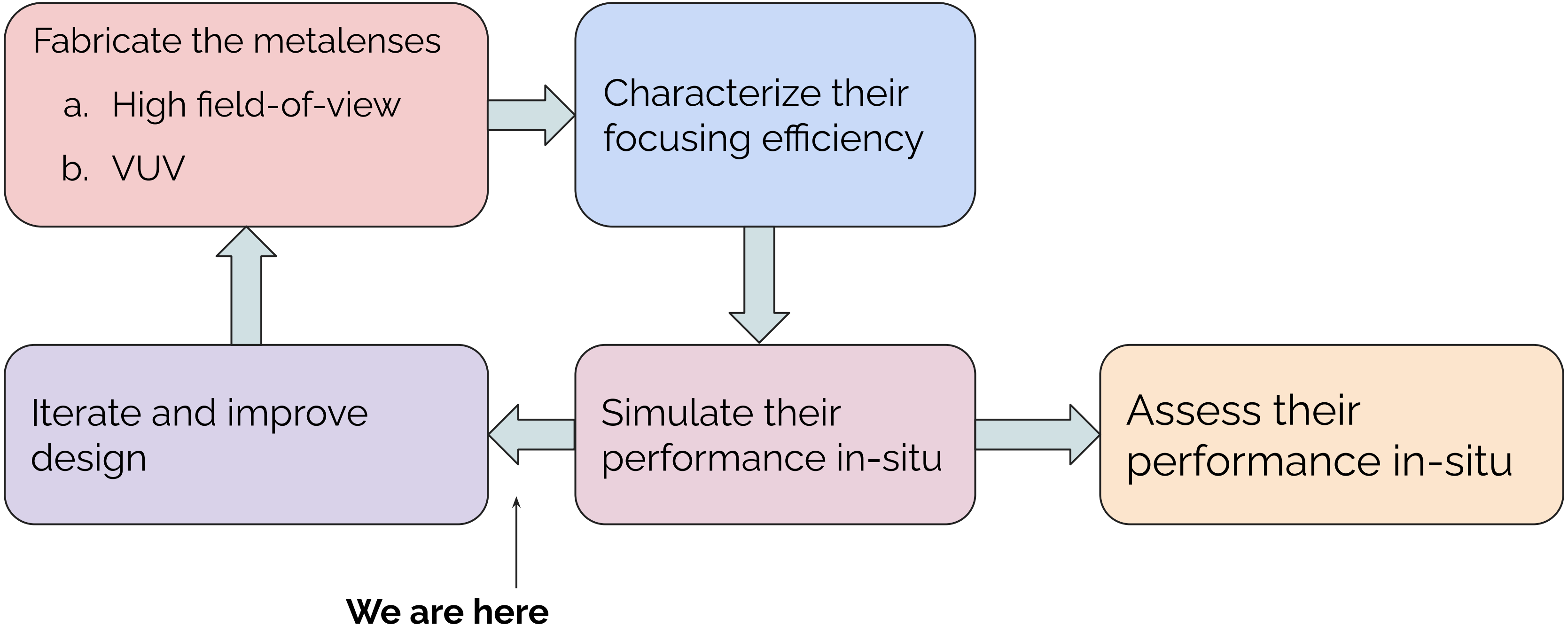
They could also be used for event imaging.



Procedure


Design and fabricate the metalenses
a. High field-of-view
b. VUV
Characterize their focusing efficiency
Simulate their performance in-situ
Assess their performance in-situ
Iterate and improve design

Procedure

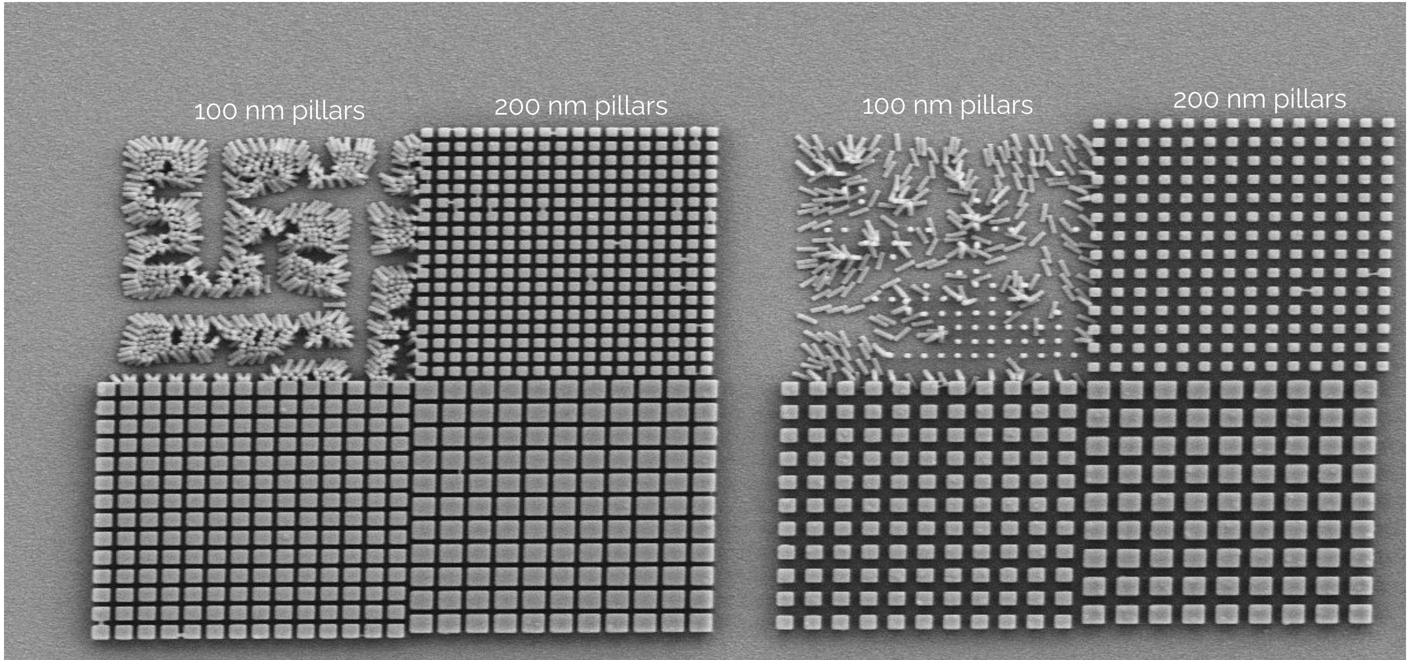

Fabricate the metalenses
a. High field-of-view
b. VUV
Characterize their focusing efficiency
Simulate their performance in-situ
Assess their performance in-situ
Iterate and improve design
We are here

Fabrication Results

by Augusto Martins

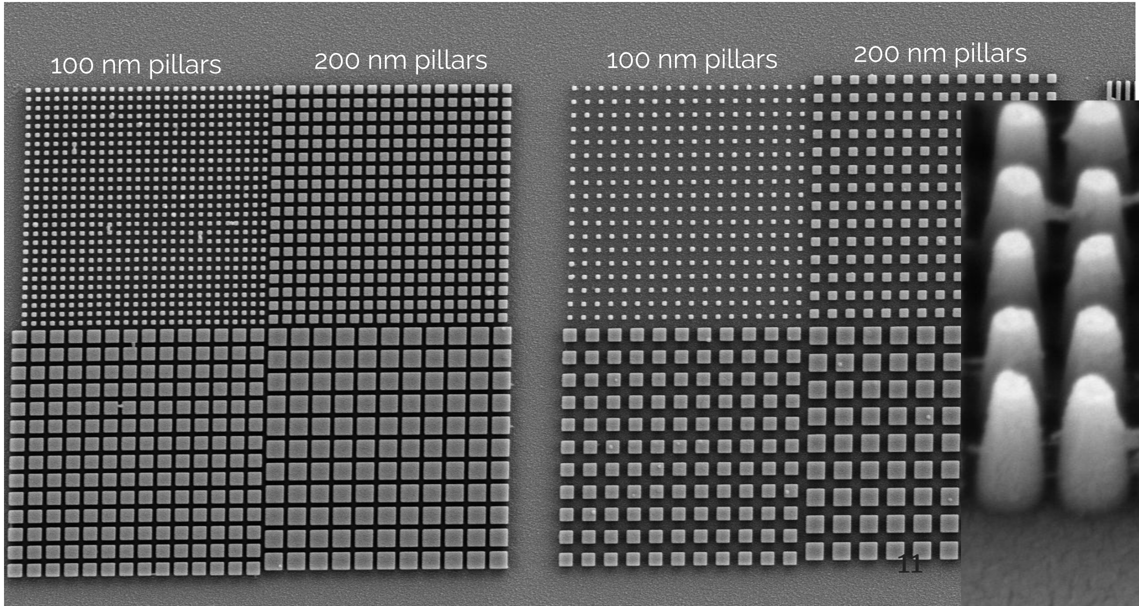
Metalenses require nanopillars that are significantly smaller than the wavelength of the light (~80 nm-wide pillars for 175 nm light).

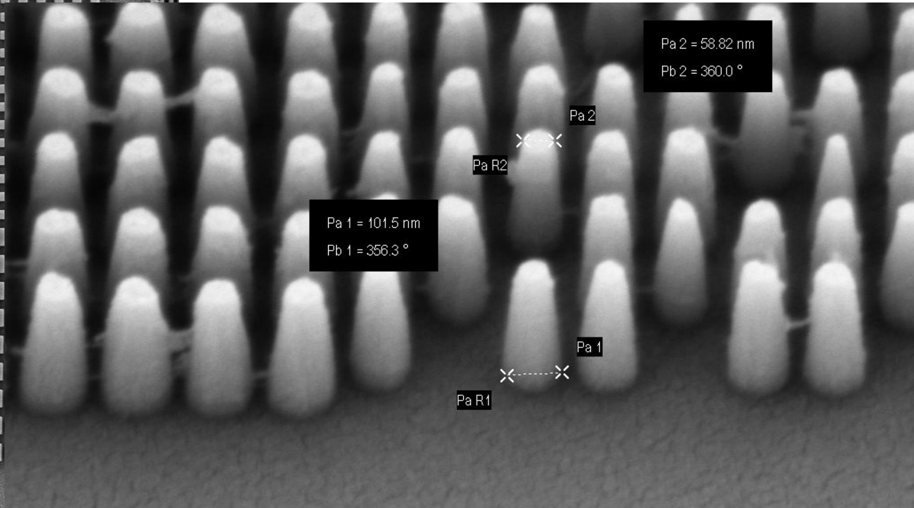
Due to the difficulties in fabricating such small pillars, this has never been achieved before.



Fabrication Results

With several months of improving the fabrication recipe, we have been able to push the minimum stable pillar size to new frontiers.





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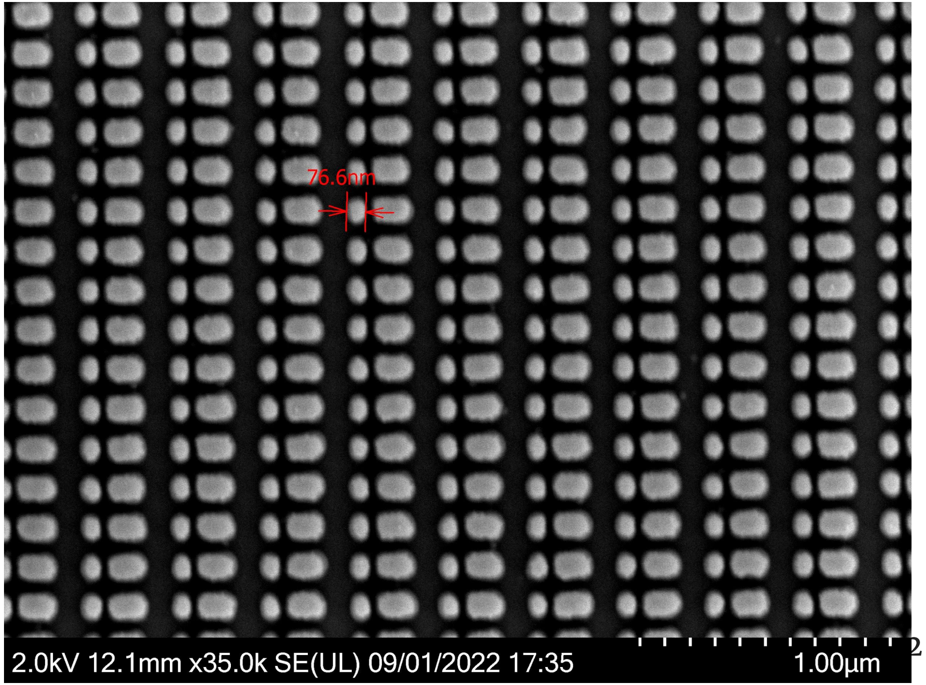
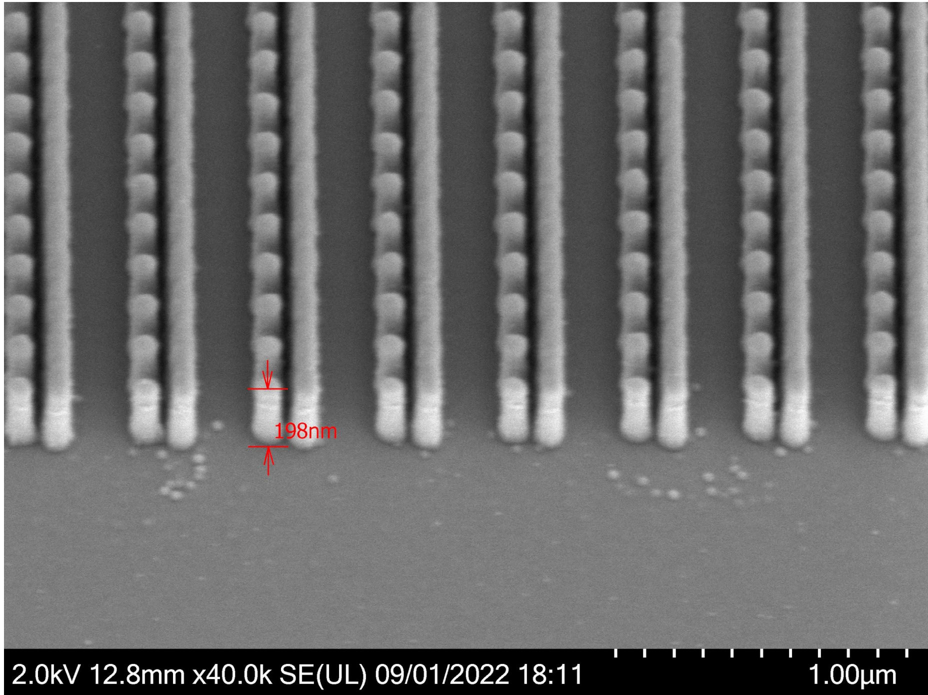
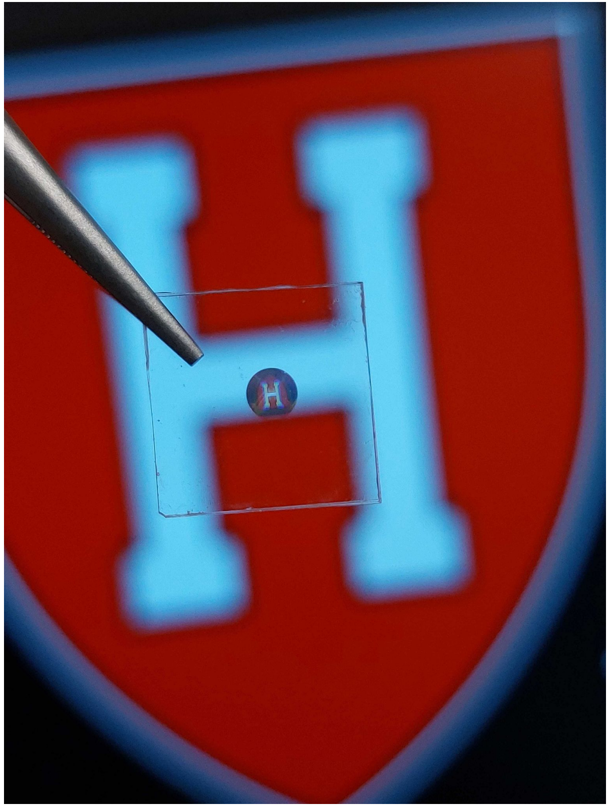




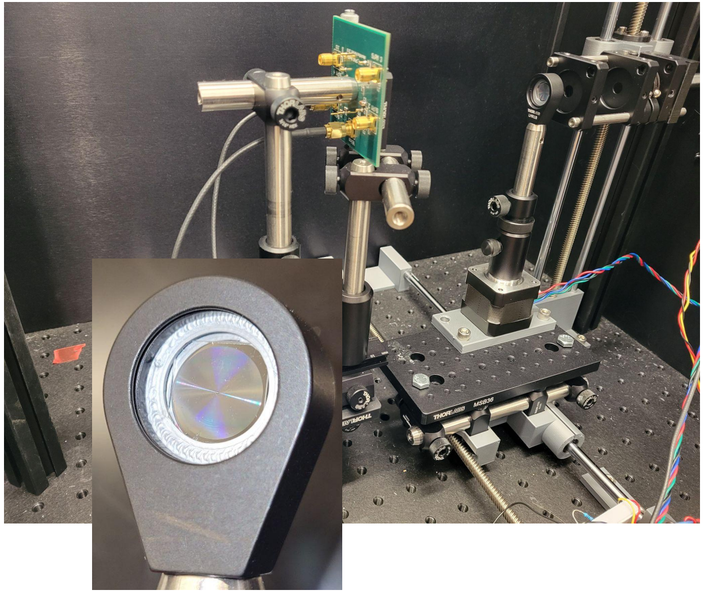
Fabrication

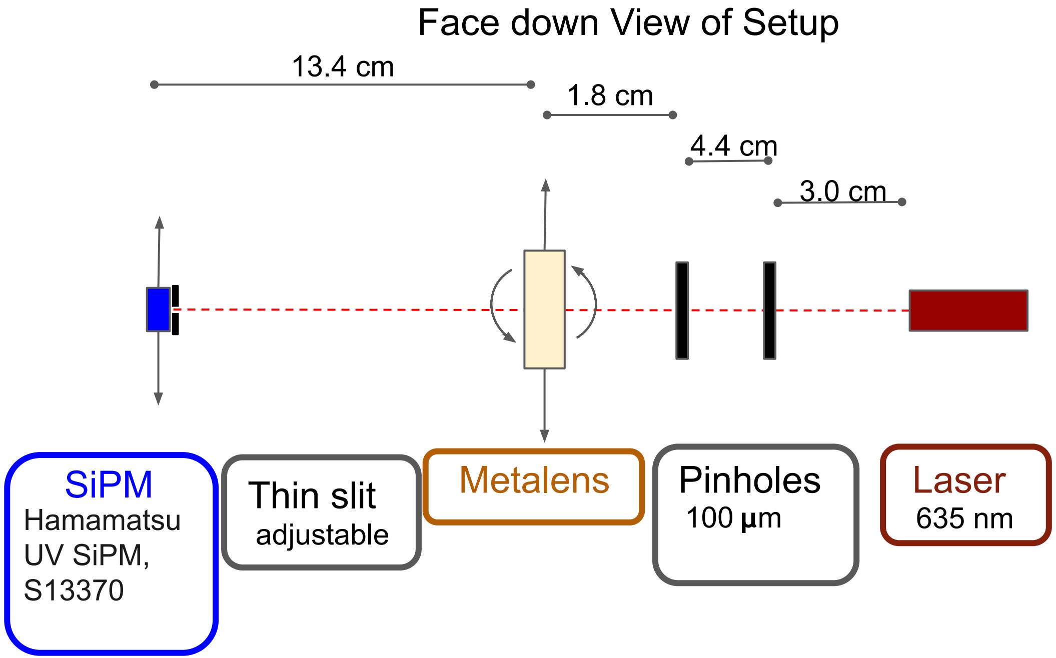
We have also achieved high field-of-view metalenses in the visible range, with NA > 0.5.



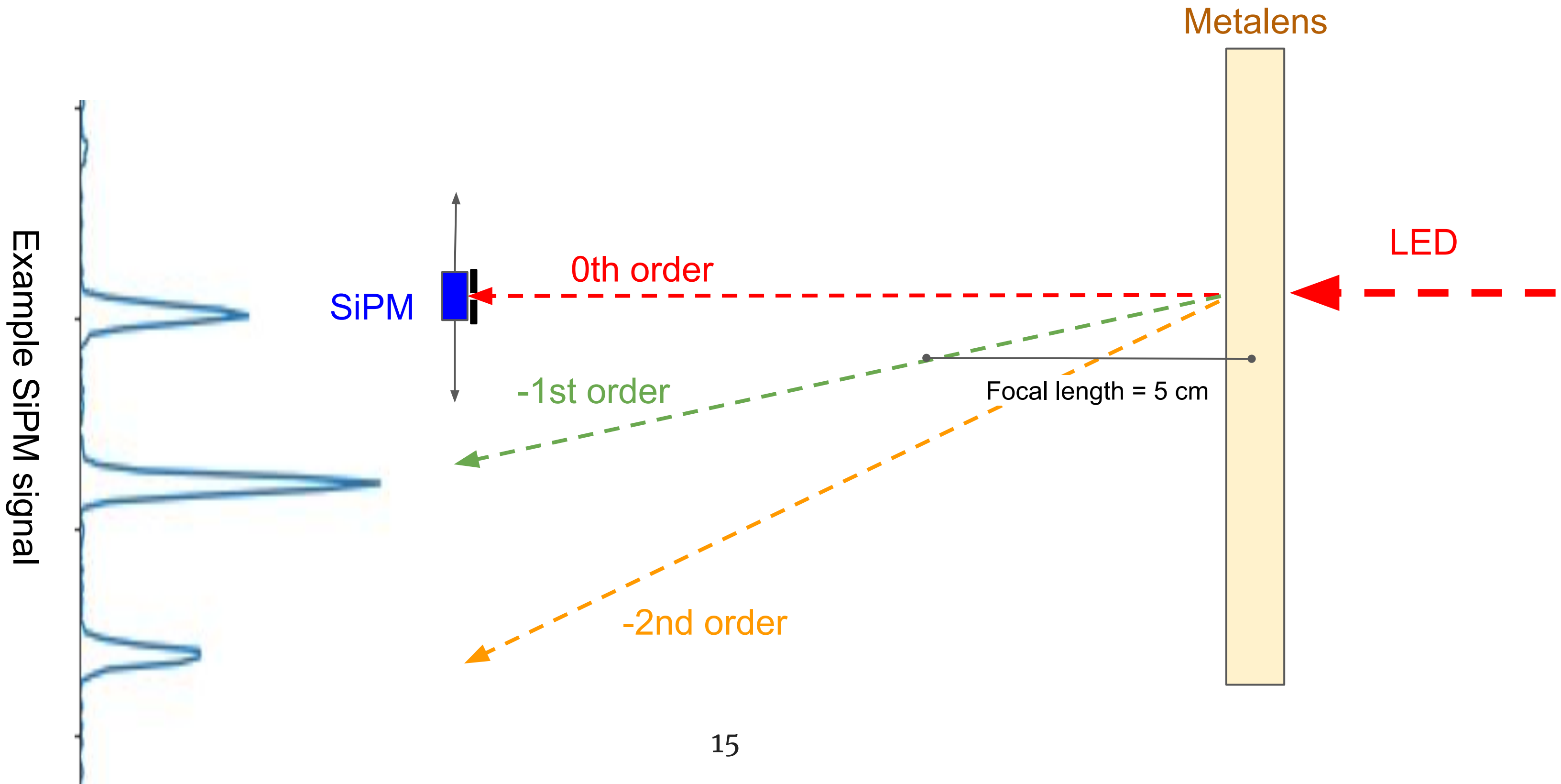
Metalens Characterization

By Taylor Contreras



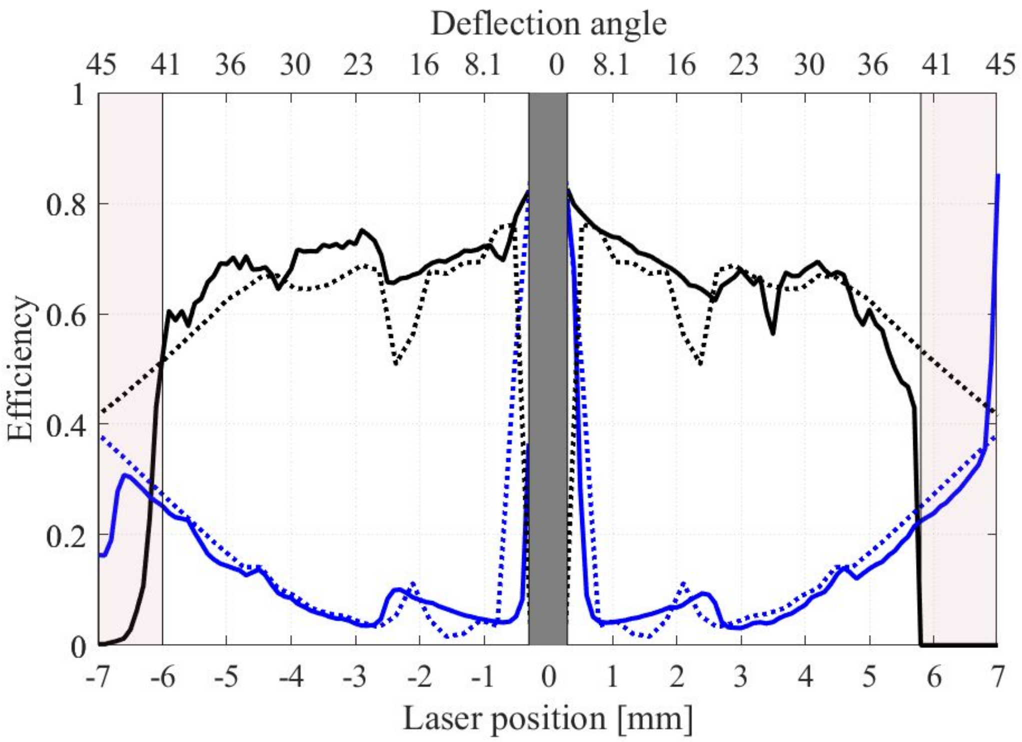


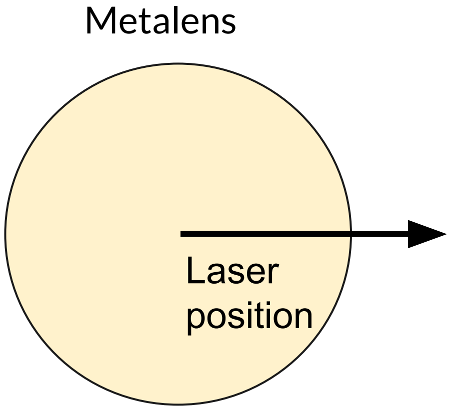
Metalens Characterization



Characterization Results

From latest high field-of-view metalens

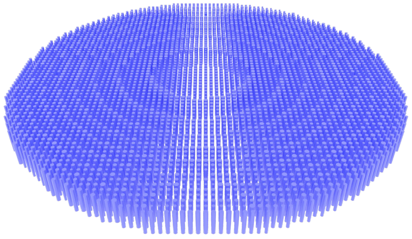




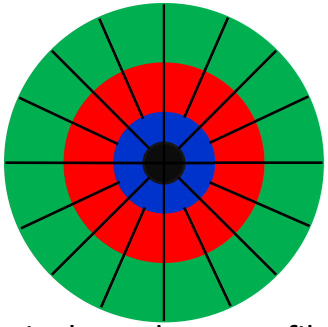
Simulated Performance

by Augusto Martins

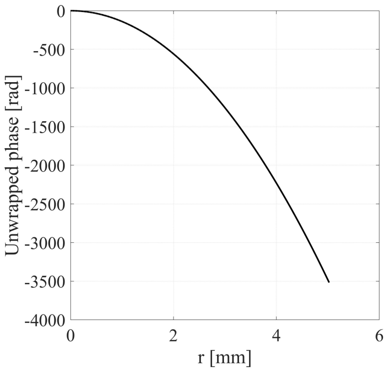
Metalens Ideal



Metalens model



Equivalent phase profile:



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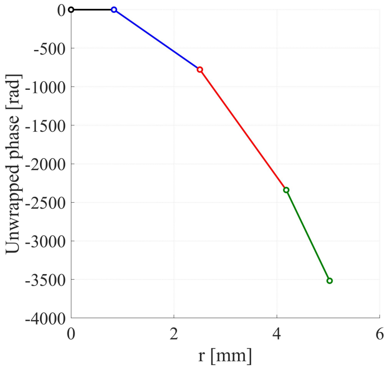


After we characterize a metalens, we would like to see how it would perform in a physics detector.

In a physics detector, light rays can come from all angles. Due to the time it takes to characterize a lens at one input angle, we are not able to directly characterize every metalens at every input angle.

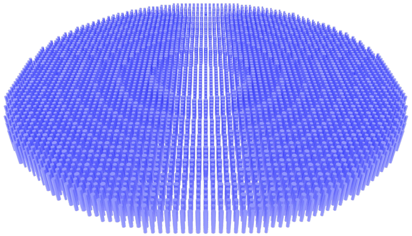
Traditional metalens simulation methods are used to simulating only one input angle, and take 10s of CPU hours. To simulate a metalens for a physics detector in this way would take weeks.

Instead, we use an approximation with a piece-wise linear phase profile.

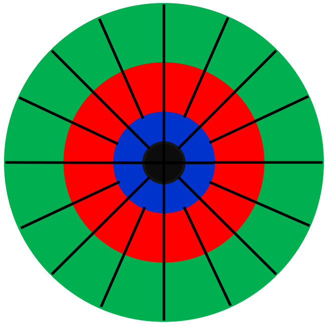
Simulated Performance

by Augusto Martins

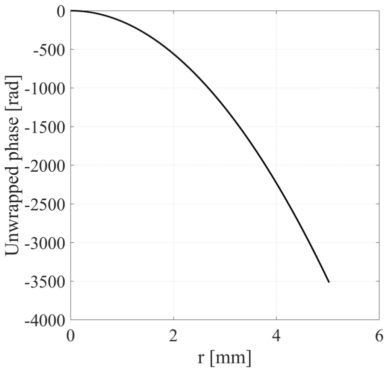
Metalens Ideal



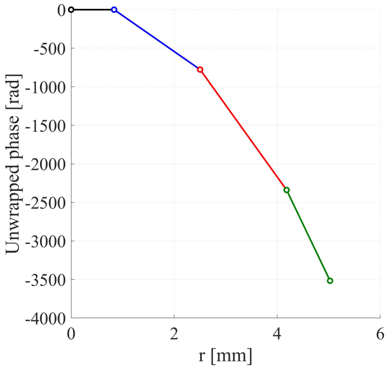
Metalens model



Equivalent phase profile:



Equivalent phase profile:



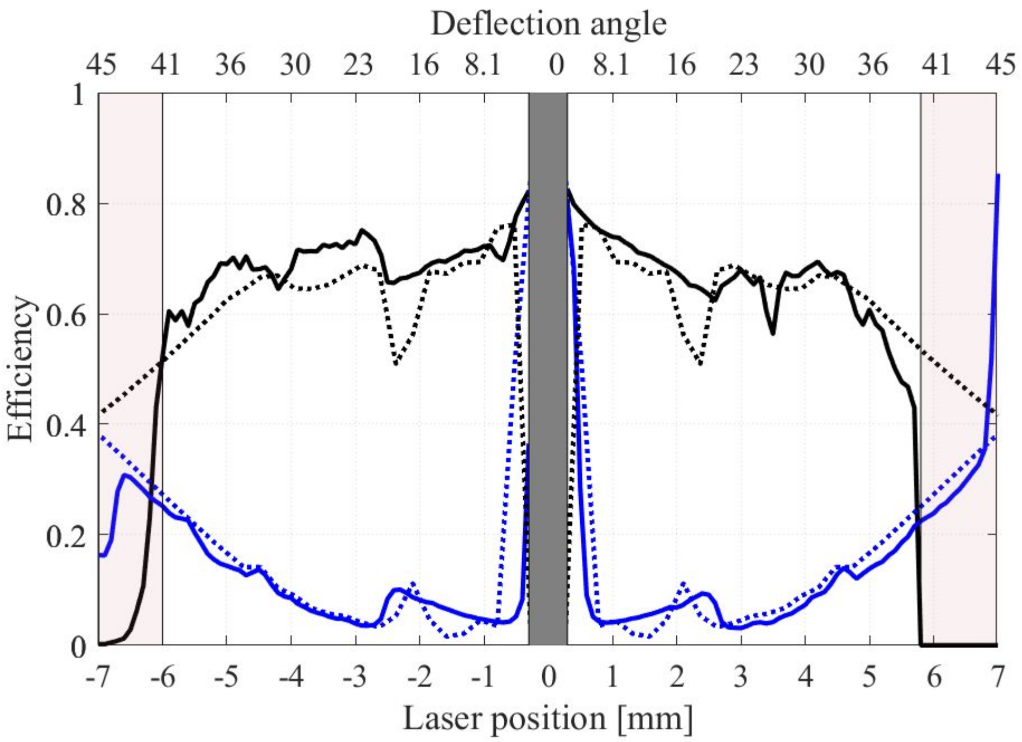
Each color represents a region with a radial blazed binary grating with constant period P.

Then we only need to rigorously simulate N parts to obtain the transfer function for each region.

Each transfer function contains the complex amplitude of all diffraction orders scattered by each piece as function of the angle of incidence for different polarization states.

Simulation Results

From latest high field-of-view metalens



0th order (goes straight through)

1st order (deflected toward focal point)

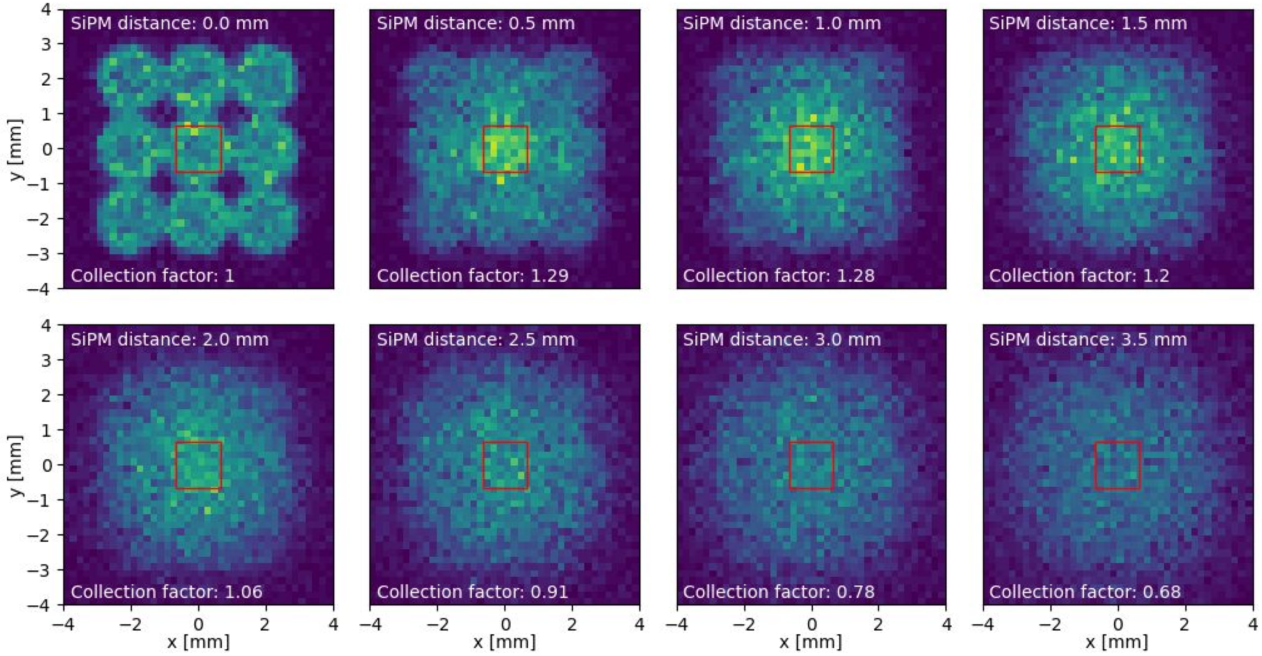
This approximation holds up very well with our characterization measurements.

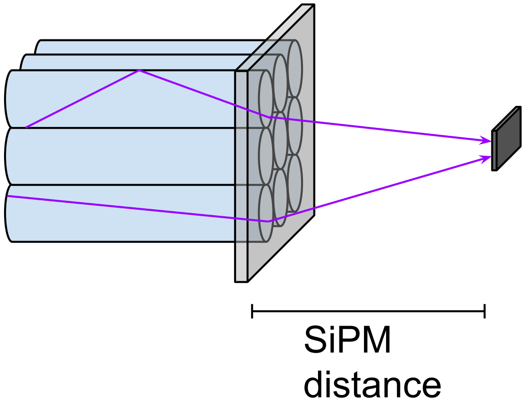
This gives us the confidence and ability to assess the efficiency of new metalens designs before we fabricate them.

Or current designs have 1st order efficiencies around 70-75%.

In-situ Simulation Results

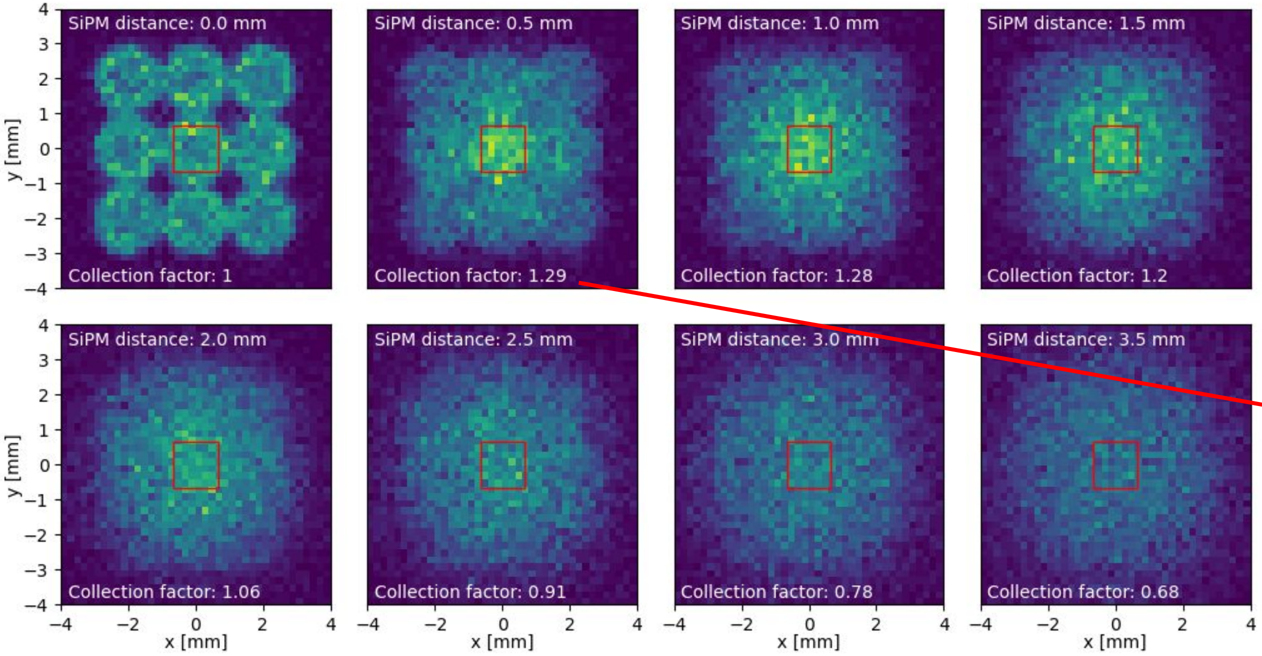
With an ideal metalens

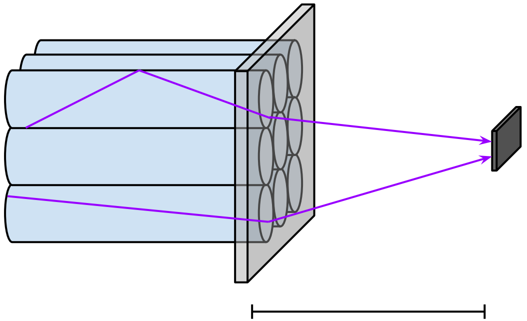




In-situ Simulation Results

With an ideal metalens

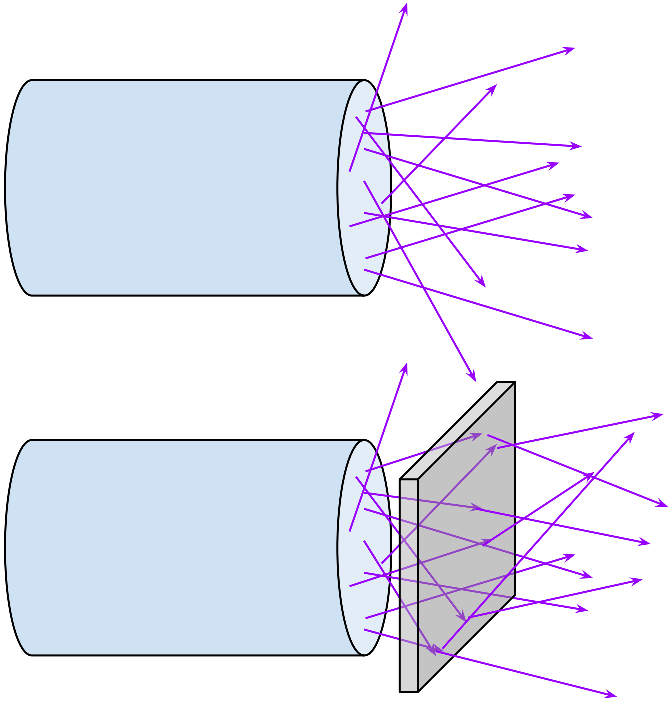


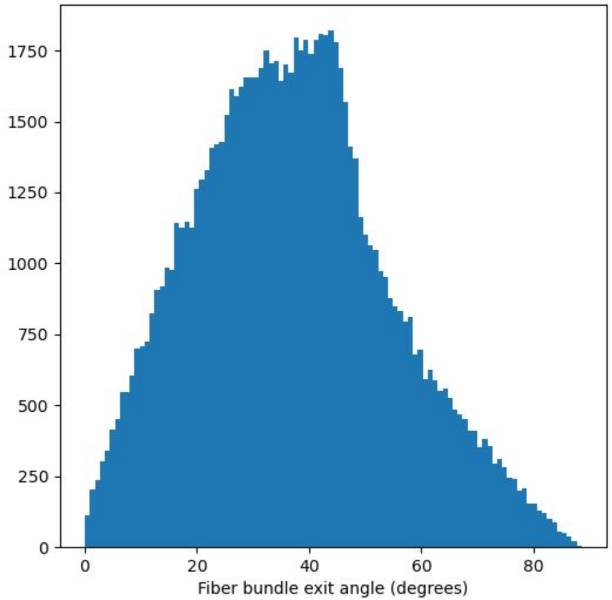


Unfortunately, an ideal metalens only produces a modest 30% increase in the signal-to-noise. After including the 75% efficiency of our metalenses, we have no appreciable gain.

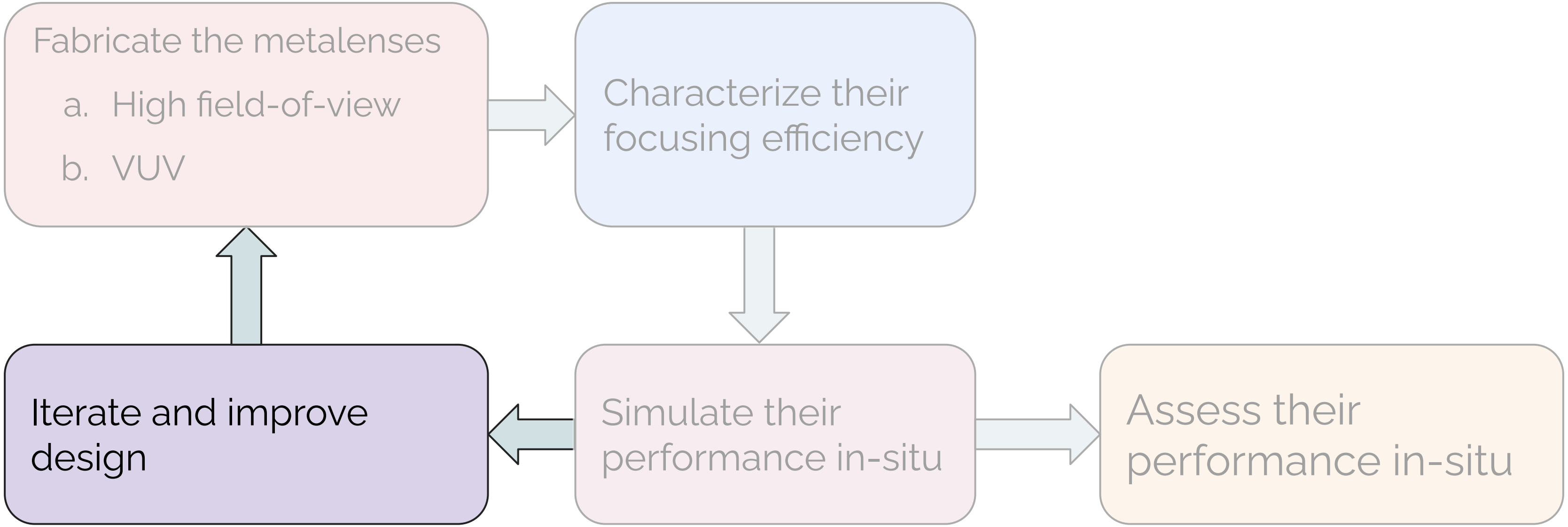
In-situ Simulation Results

The etendue of the system limits how effective lenses can be. The exit angles from the light guide peak around 40 degrees, which is not ideal for focusing.





Next steps



Fabricate the metalenses
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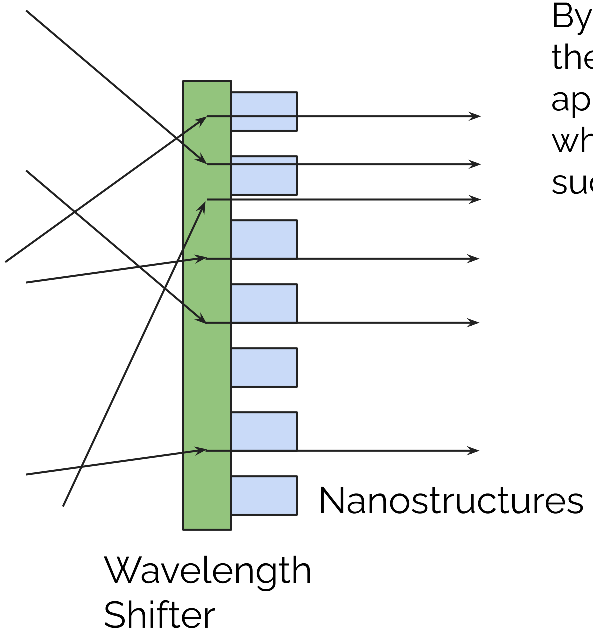
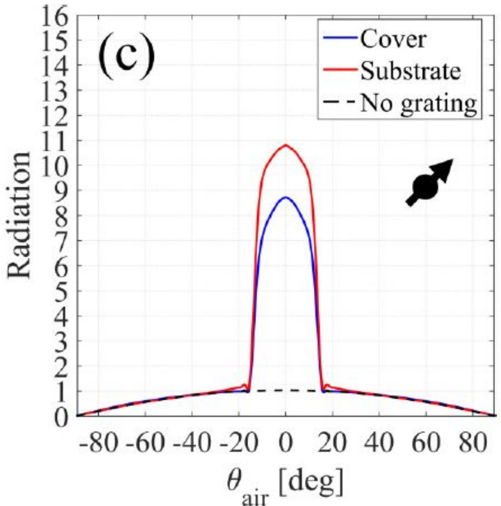
Resonant enhancement



By coupling the nanostructures with an emitter, it is possible to enhance the decay modes that result in emission in a certain direction. This is appealing because many detectors already use a wavelength shifter, which can act as the emitter. We are currently building simulations for such systems and exploring fabrication options.

"Band shaping and emission control via waveguide plasmon polaritons"
Phys Rev B, **103**, 205423 (2021)



See also:

Nanoscale, 2014, 6, 9223–9229
ACS Photonics 2018, 5, 1359–1364
Science, 329(5994), 930-933.
ACS Photonics 2018, 5, 1951–1959

Summary

- Metalenses are cheap diffractive lenses that can be used in place of traditional lenses.
- We have refined our fabrication recipe and are now able to produce VUV and high field of view metalenses.
- We have developed a technique for the rapid characterization and simulation of metalens designs, and confirmed its accuracy via experiment.
- We determined that raw metalenses would not be capable of significantly increasing light collection due to the diffuse angles involved.
- We are now exploring ways forward in using metasurfaces with wavelength shifters to create directed emission for efficient focusing.

Thank You