Non-line-of-sight imaging via wavefront shaping

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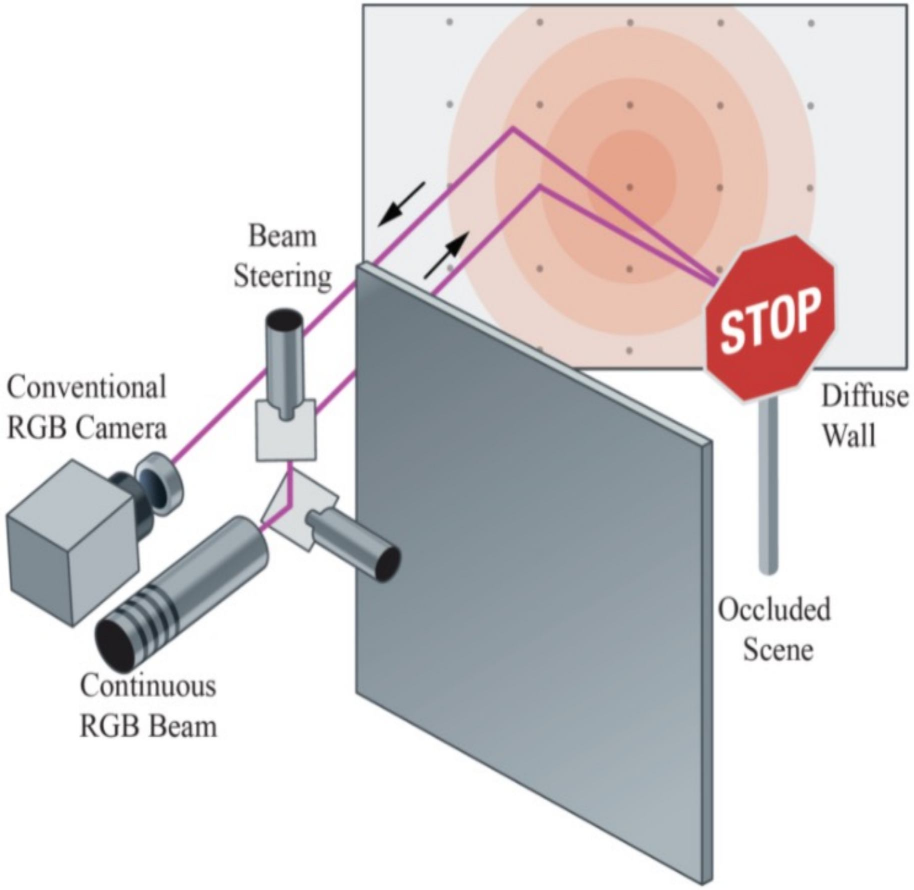
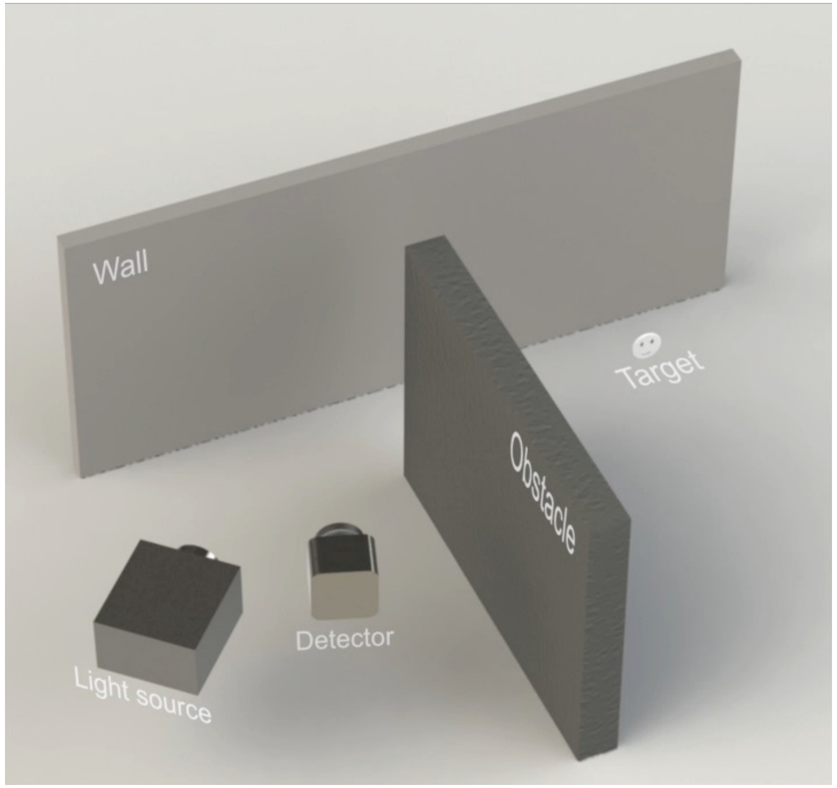
Non-line-of-sight (NLOS) imaging



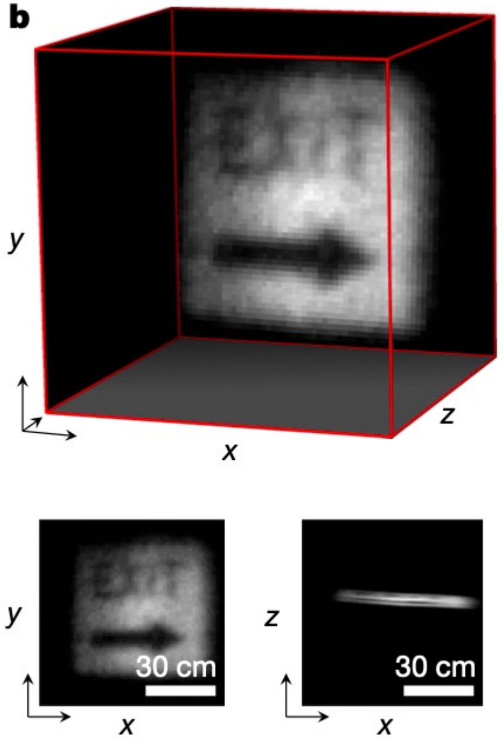
https://www.cs.princeton.edu/~fheide/steadystatenlos

Goal:
Want to image an object whose direct line-of-sight is blocked

State-of-the-art methods for NLOS imaging

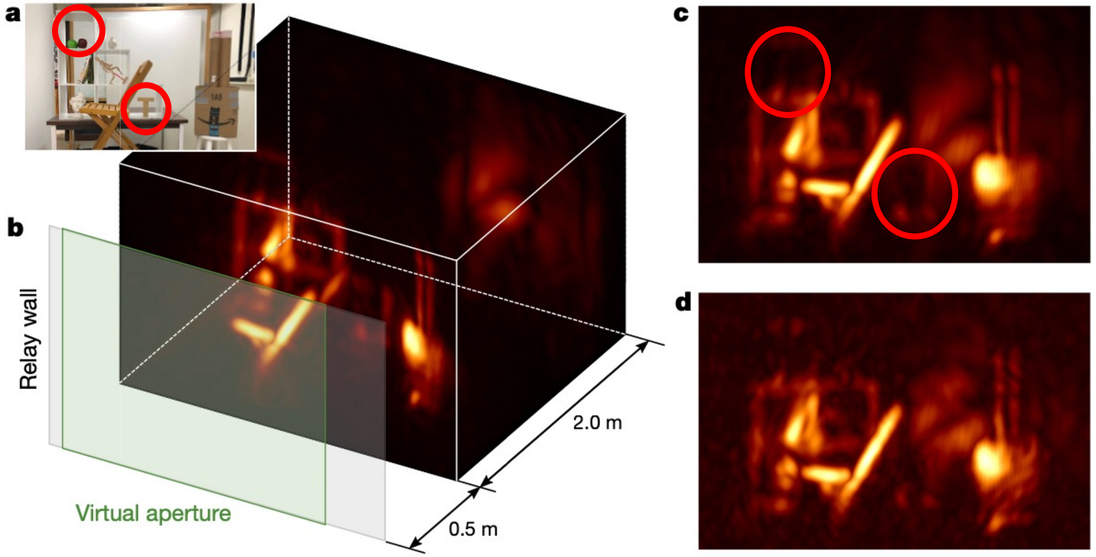


Time of Flight (ToF)



O'Toole, M., Lindell, D. & Wetzstein, G. *Nature* **555,** 338–341 (2018).

Phasor field



Liu, X., Guillén, I., La Manna, M. *et al. Nature* **572,** 620–623 (2019).

Two main problems:

- Lateral resolution (distance-to-resolution ratio) is still low compared with optical resolution
- Reconstruction artifacts overwhelm dark objects

Distance between the wall and object: ~ 1 m

Resolution: ~ 1 cm

Distance-to-resolution ratio ~100

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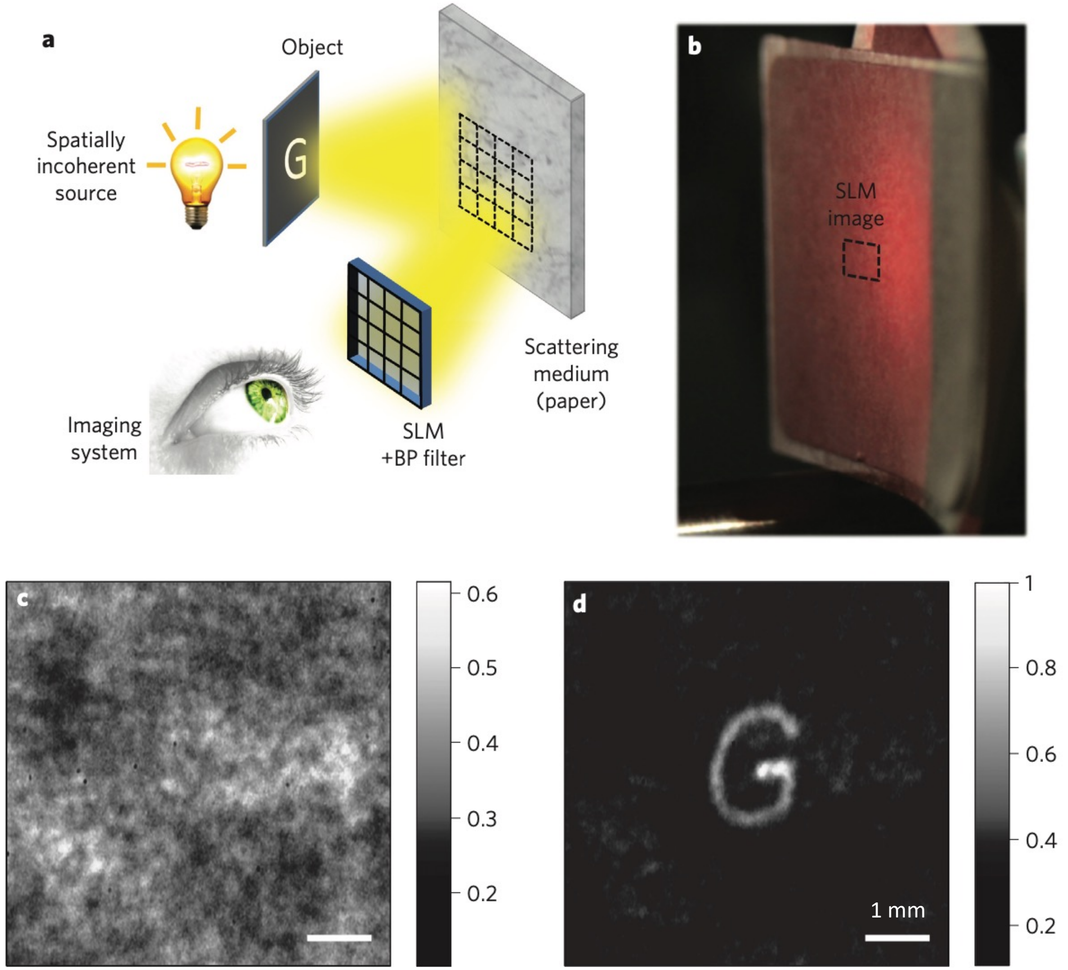
NLOS imaging via wavefront shaping (uses priors)



Katz, O., Small, E. & Silberberg, Y. Nature Photonics 6, 549–553, (2012).

After performing the correction for a point source (pre-calibration), the reflecting medium is effectively transformed into a 'scattering mirror'

Wavefront shaping:

- achieves high resolution,
- focuses light onto the target and produces image directly without using reconstruction algorithm (thus less artifact)!

Can we use wavefront shaping in NLOS without using priors?

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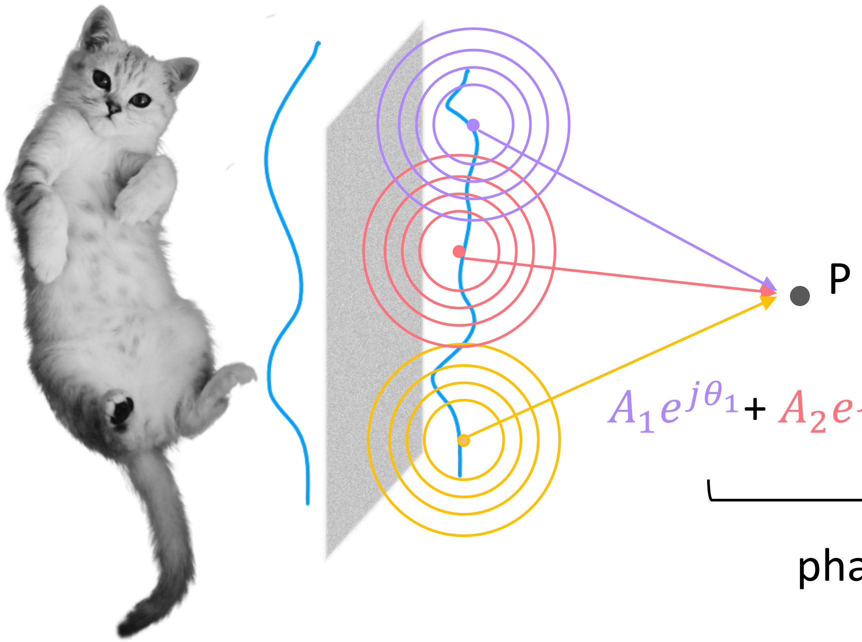
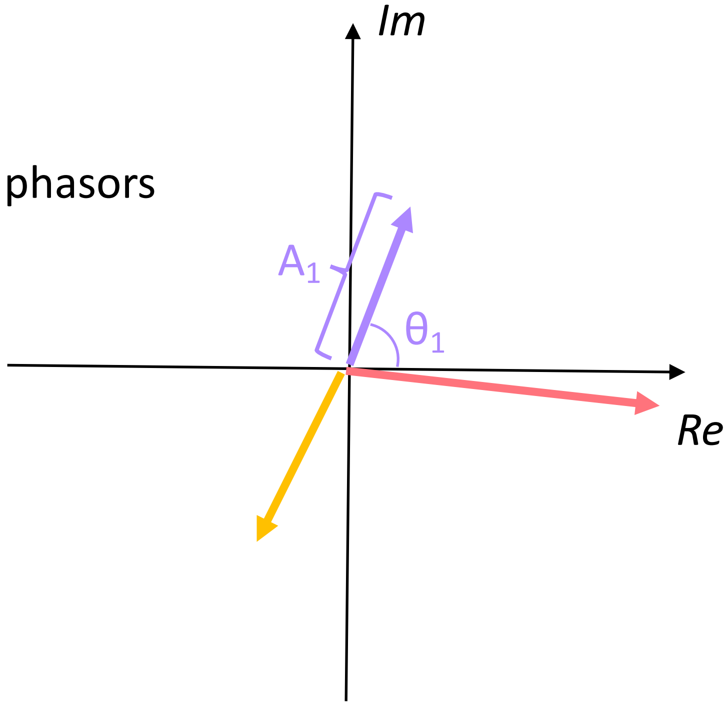
Speckle field and phasors



$A_1 e^{j\theta_1} + A_2 e^{j\theta_2} + A_3 e^{j\theta_3} + \dots$

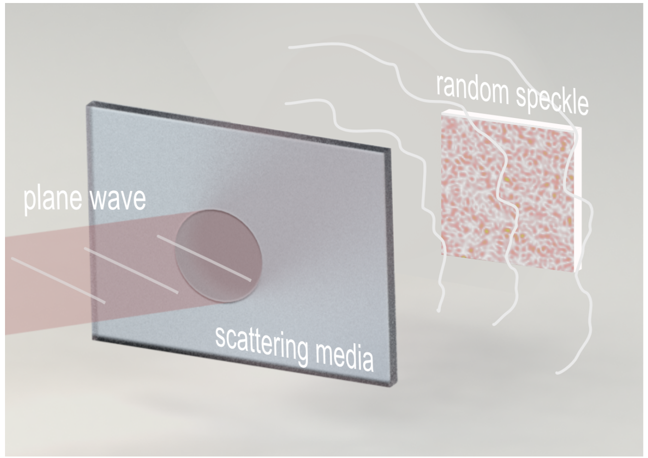
phasors



Complex plane

This random phasor sums generates speckle field

Random phasor sums



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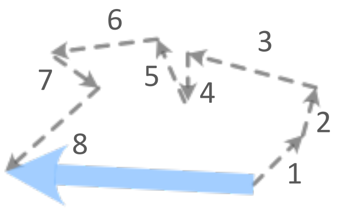
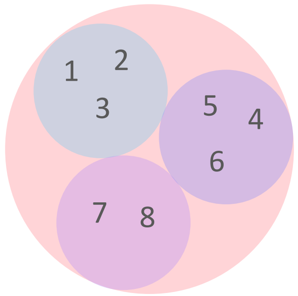
How to focus through a scattering medium?

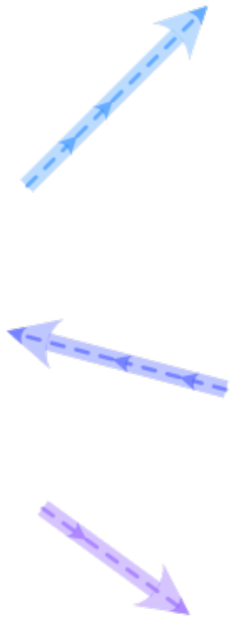
Random phasor sums



Phasor set



Align phasors in a smaller phasor set

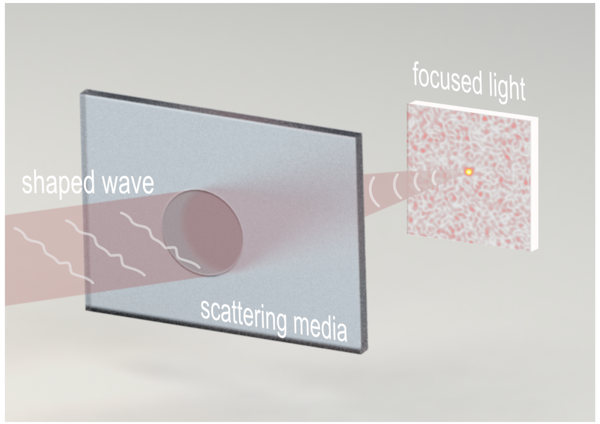


“macro” phasors

Align “macro” phasors

Combine multiple “macro” phasors

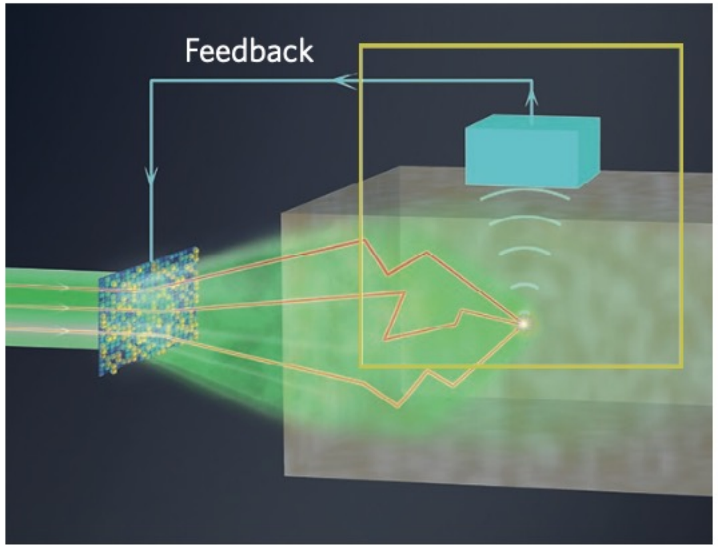
Aligned phasor sums



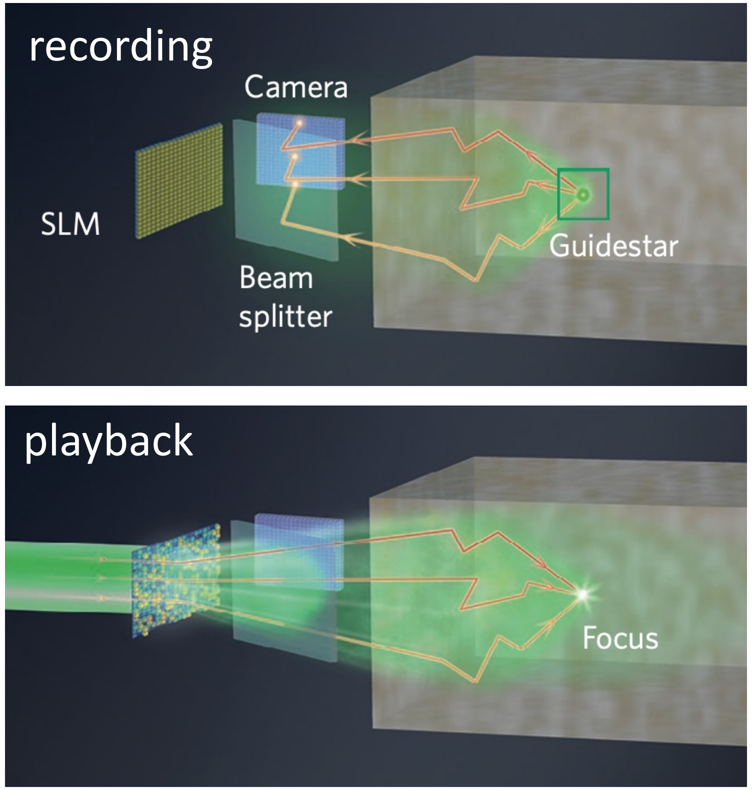
Aligning the phasors (uses guidestar)

Two popular wavefront shaping methods

Feedback



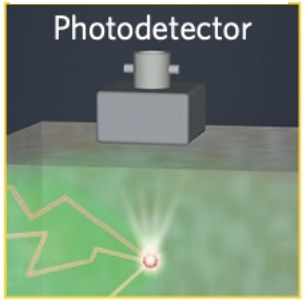
(Digital) Optical Phase Conjugation



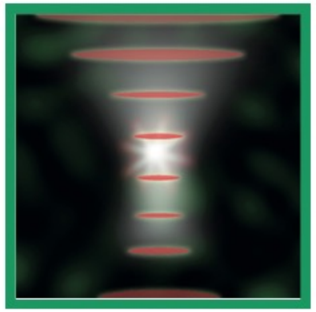
Horstmeyer, R., Ruan, H. & Yang, C. *Nature Photon* **9,** 563–571 (2015).

Popular Guidestars

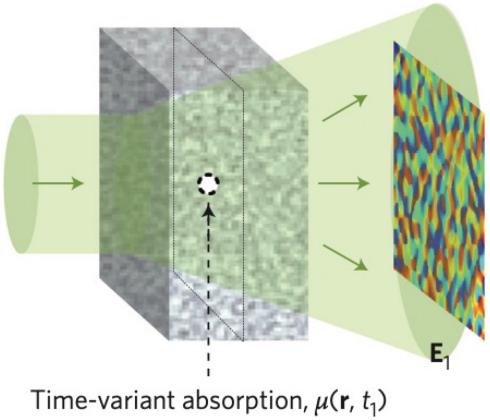
Fluorescence



Ultrasound



Horstmeyer, R., Ruan, H. & Yang, C. *Nature Photon* **9,** 563–571 (2015).



Ma, C., Xu, X., Liu, Y. *et al. Nature Photon* **8,** 931–936 (2014).

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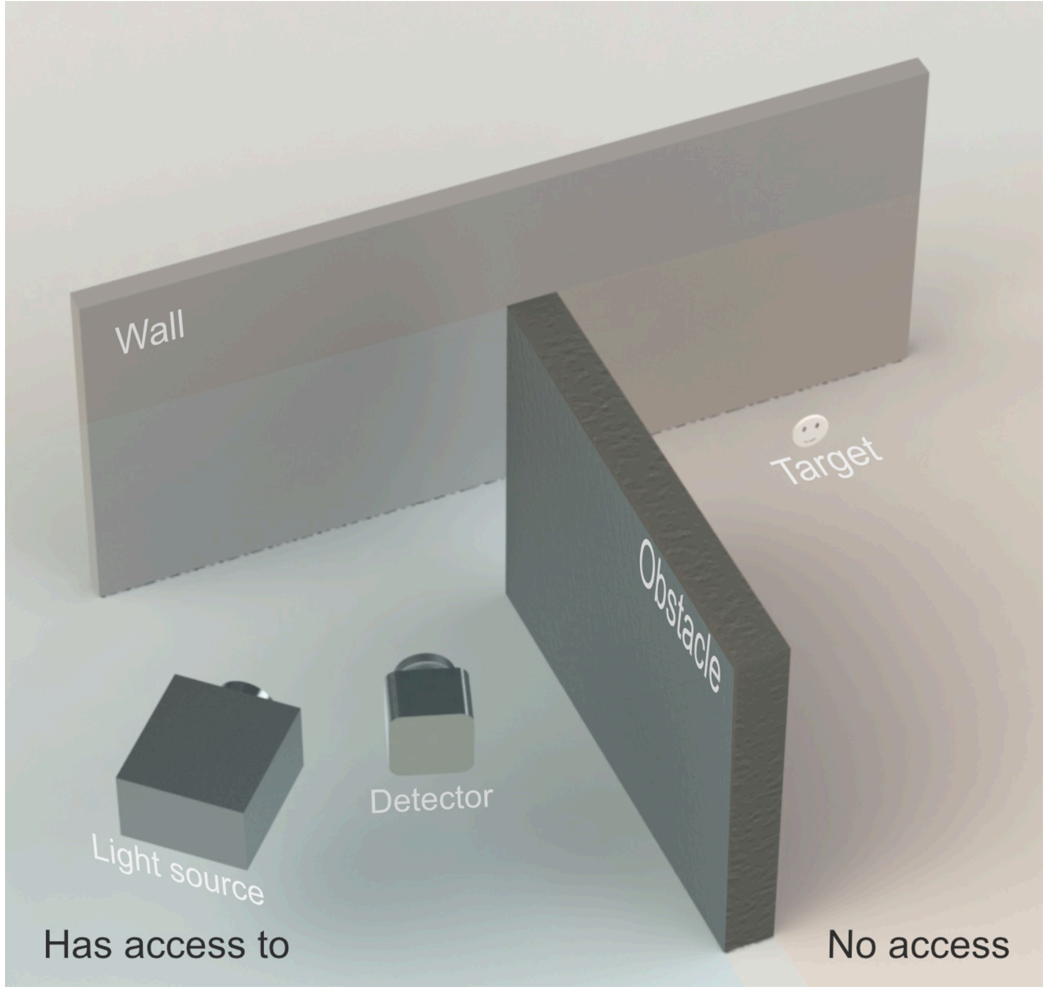
The challenge in NLOS imaging



No access on the target's side: cannot modulate the target.

Can we use the target itself as the guidestar?

Idea: If the target is "small", then we can use the target as a guidestar.

- How small should the target be?
- What kind of resolution can you get using the target itself as the guidestar?

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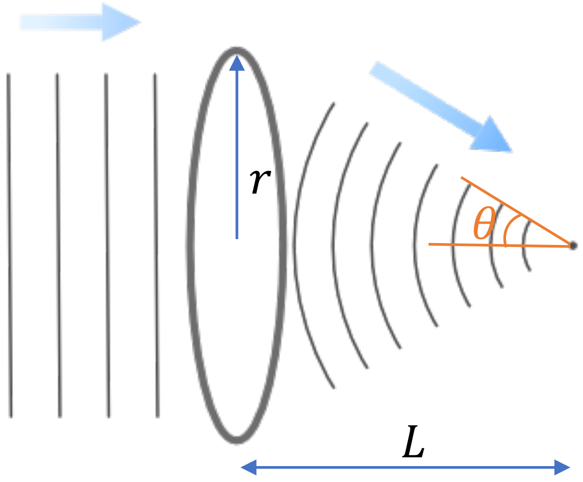
How small should the target be?

Intuition: the target should be smaller than the speckle size

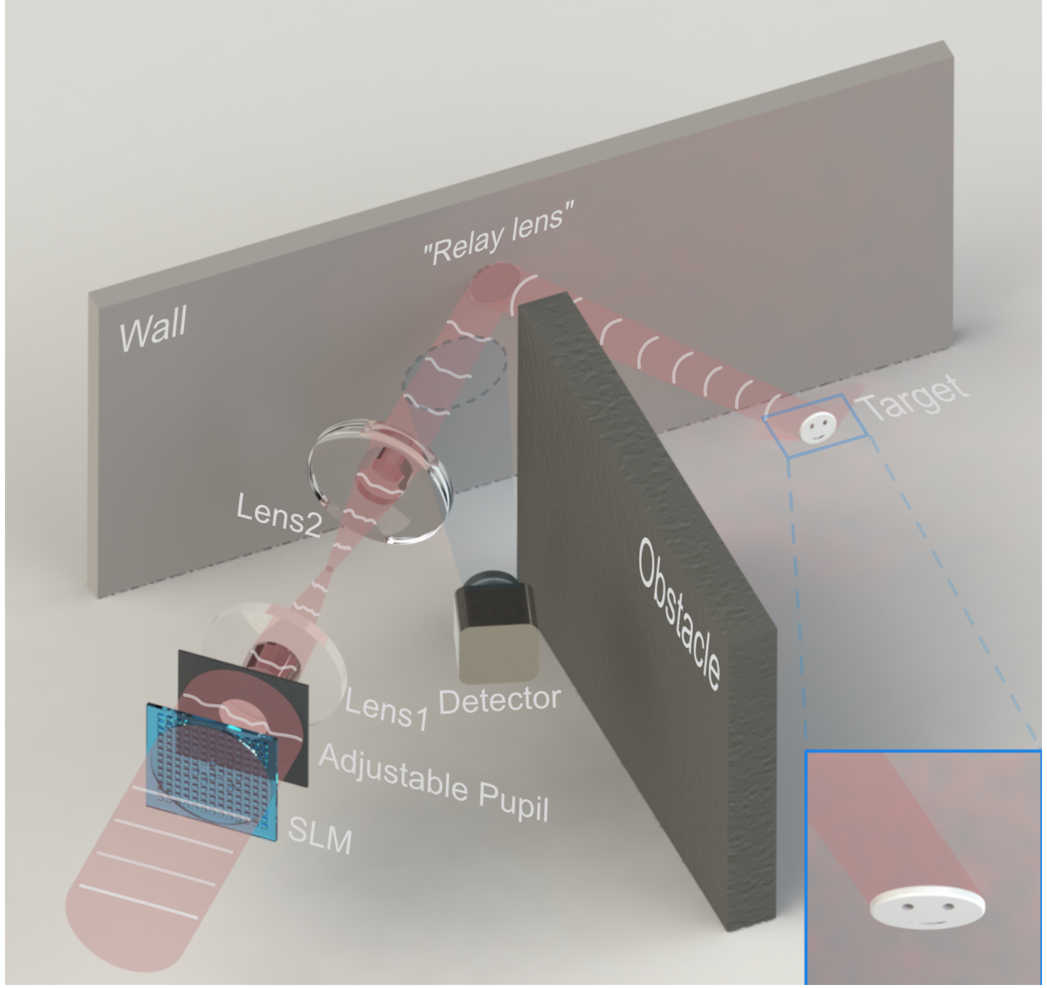
Speckle size ≈ focus size ∝ resolution



Optical resolution (intensity)

$$Resolution = \frac{\lambda}{2n\ \sin\theta}$$

For fixed L, a larger r gives a larger θ, thus a better resolution



Limit the radius of the “relay lens” such that Speckle size > target

Then, we can use feedback-based wavefront shaping.

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What kind of resolution can we achieve?

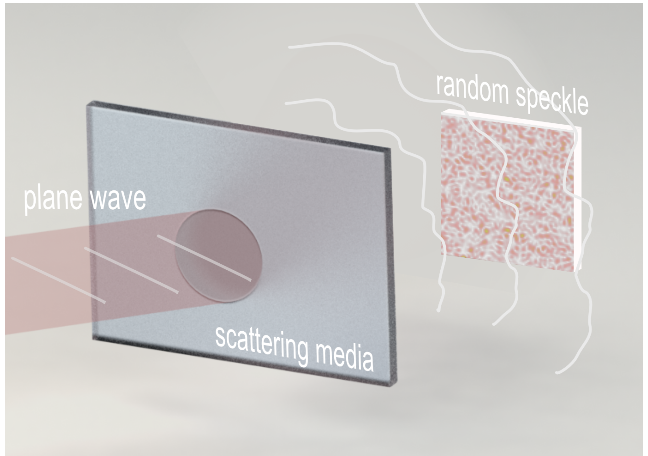
Speckle Size ≈ Focus Size & Speckle Size > Target ⇒ Resolution > Target

To image the object:
Resolution < Target
(Focus < Target)

Use a bigger "relay lens"?

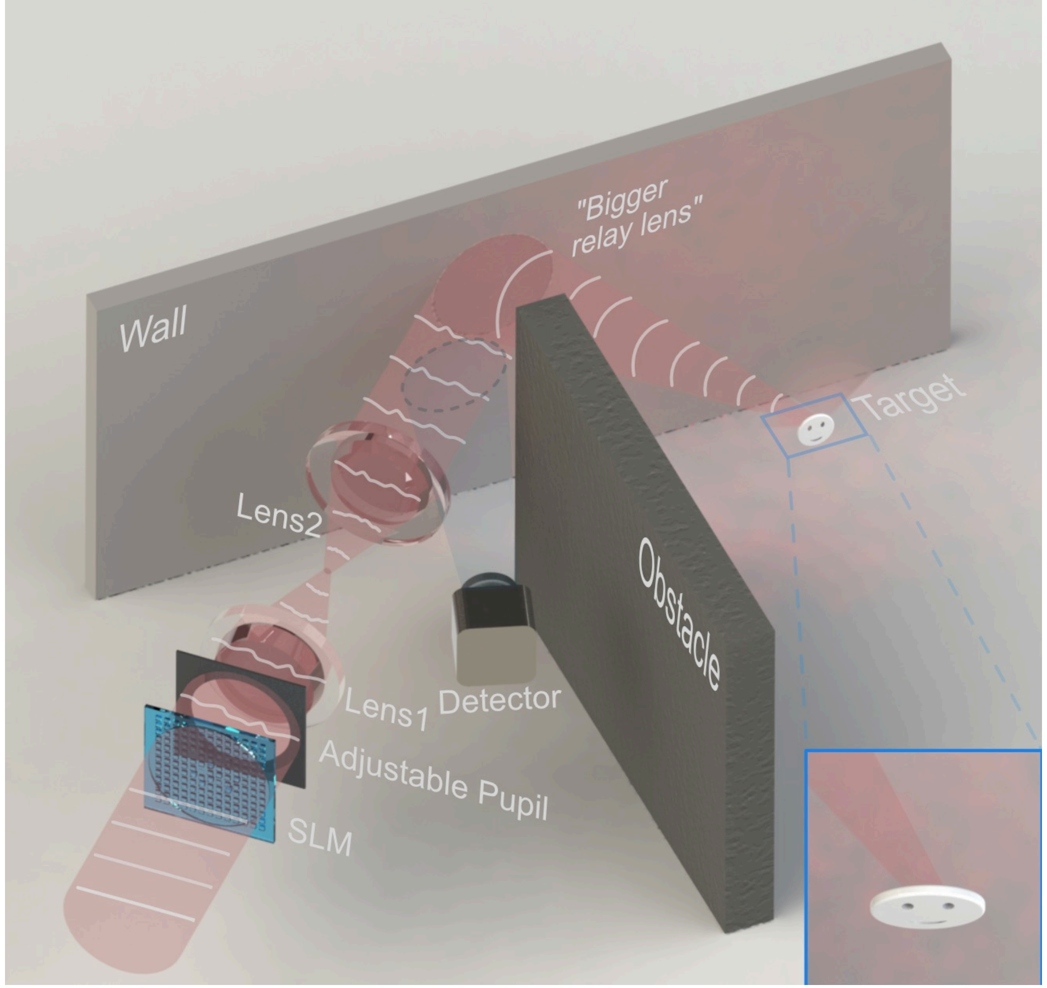
?

However, it's impossible to start from "big lens"



?

Combine small relay lenses -> Big relay lens



How do we combine small lenses?
/How do we combine the macro phasors corresponding to the small lenses?

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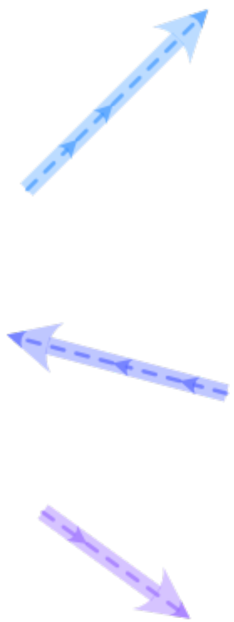
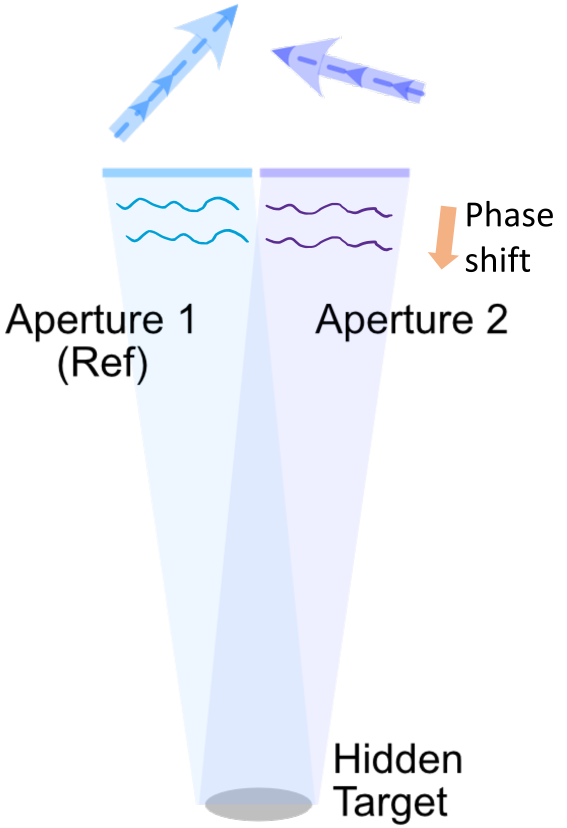
"Combining" the macro phasors

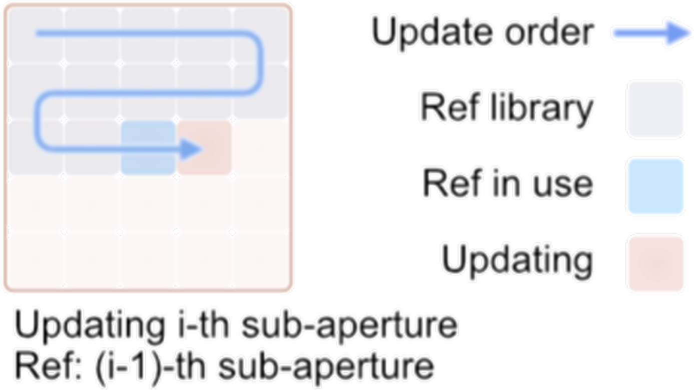
Want to align "macro" phasors using the feedback signal



Idea: make the intermediate focus larger than the object in optimizing the phase offset of "macro" phasors at any instant



Strategy of using pairs:
Optimize the phase offset using pairs consisting of two "macro" phasors
(Here, the *i*-th sub-aperture corresponds to the *i*-th "macro" phasors)



It can be proven that the center of the optimized focus is fixed (independent) with respect to the choice of "macro" phasors

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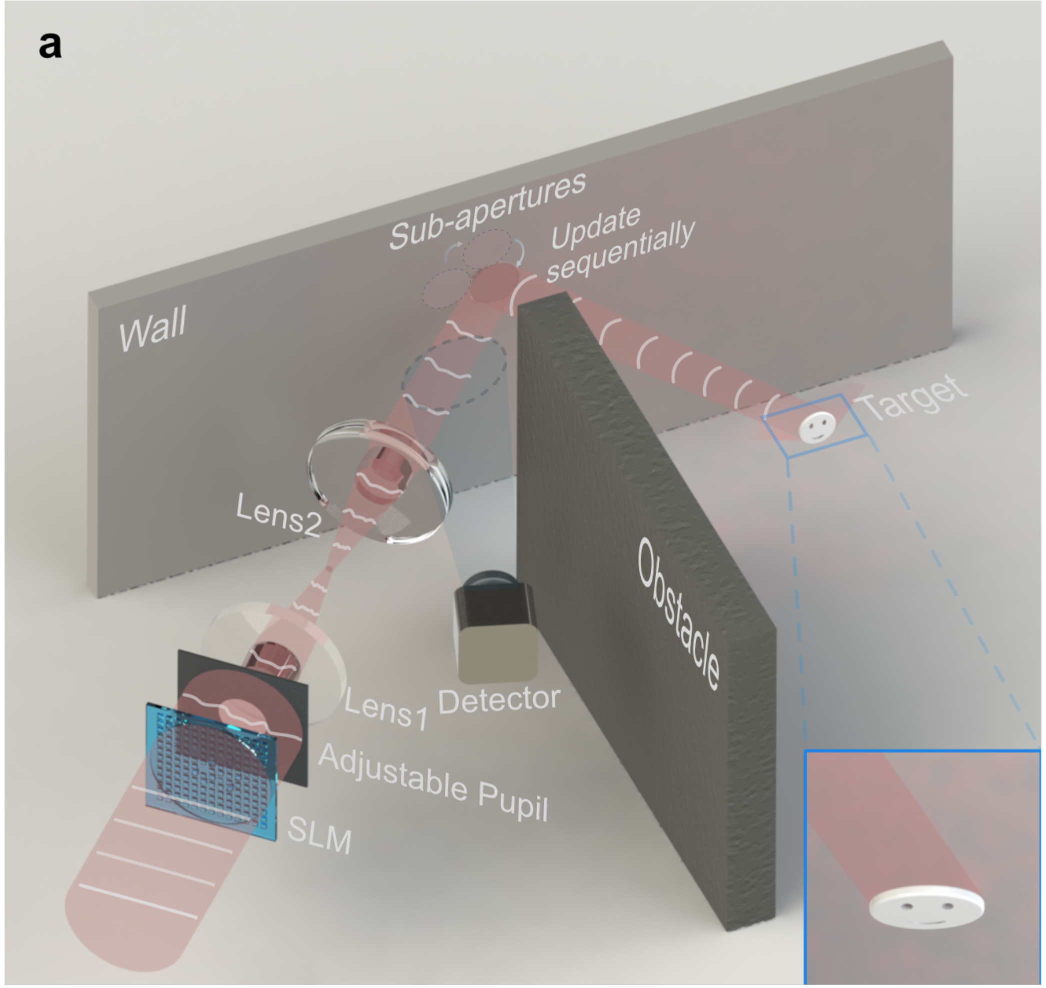
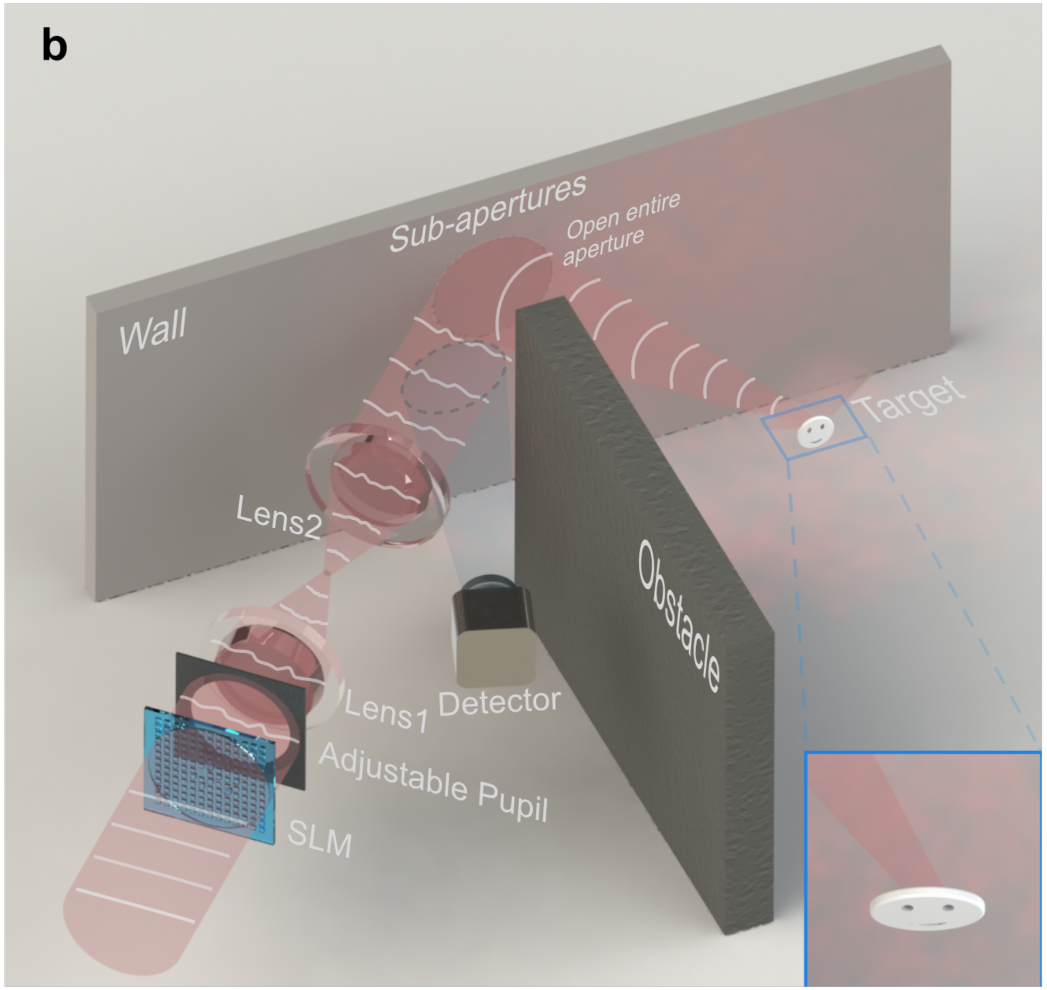
Our Method

Can be shown that n^2 sub-apertures -> n-fold isotropic resolution improvement

Optimize the phase for each sub-aperture sequentially

Synthesize all the sub-apertures using pairs





Small NA -> low resolution

large NA -> high resolution

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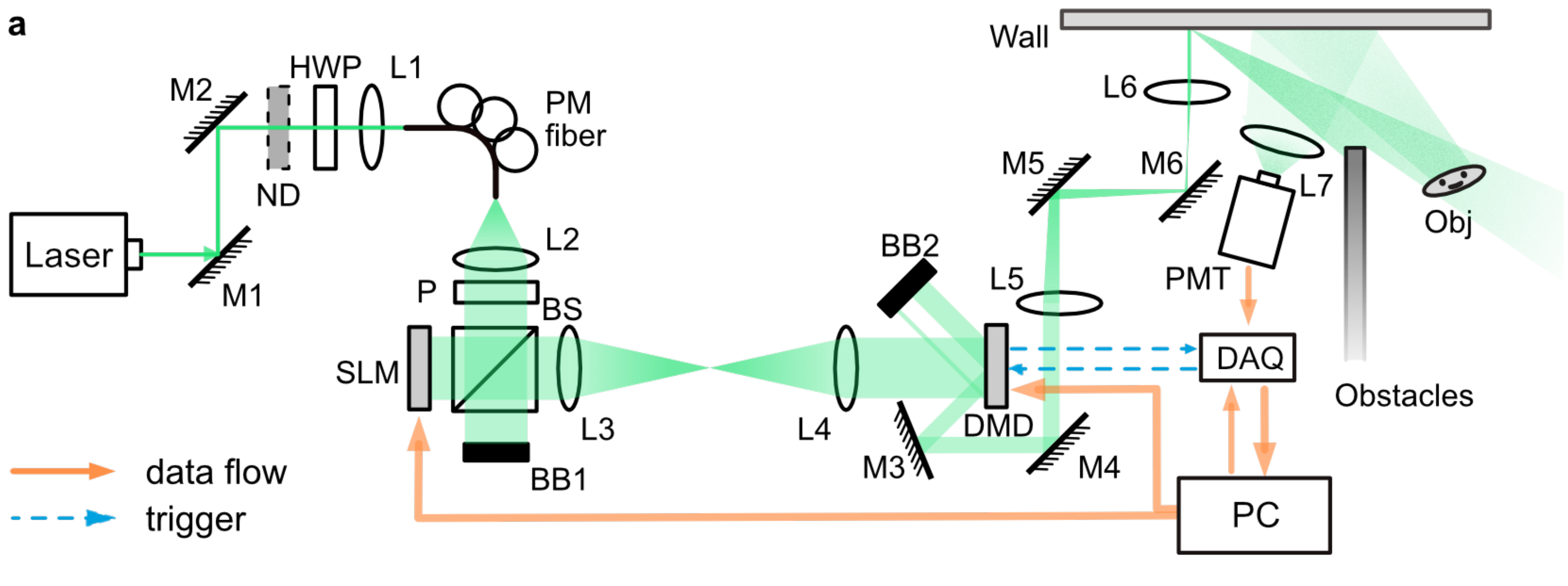
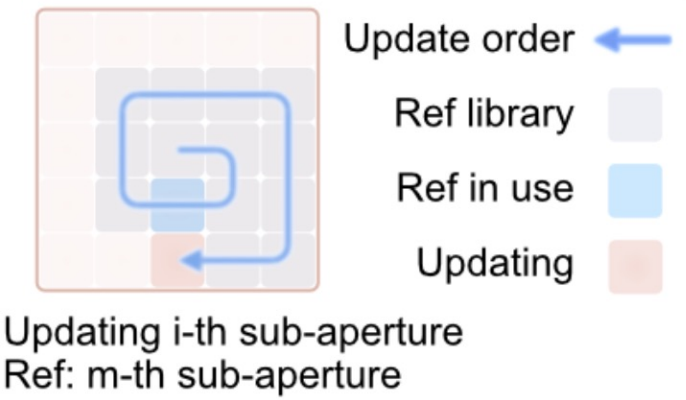
System setup

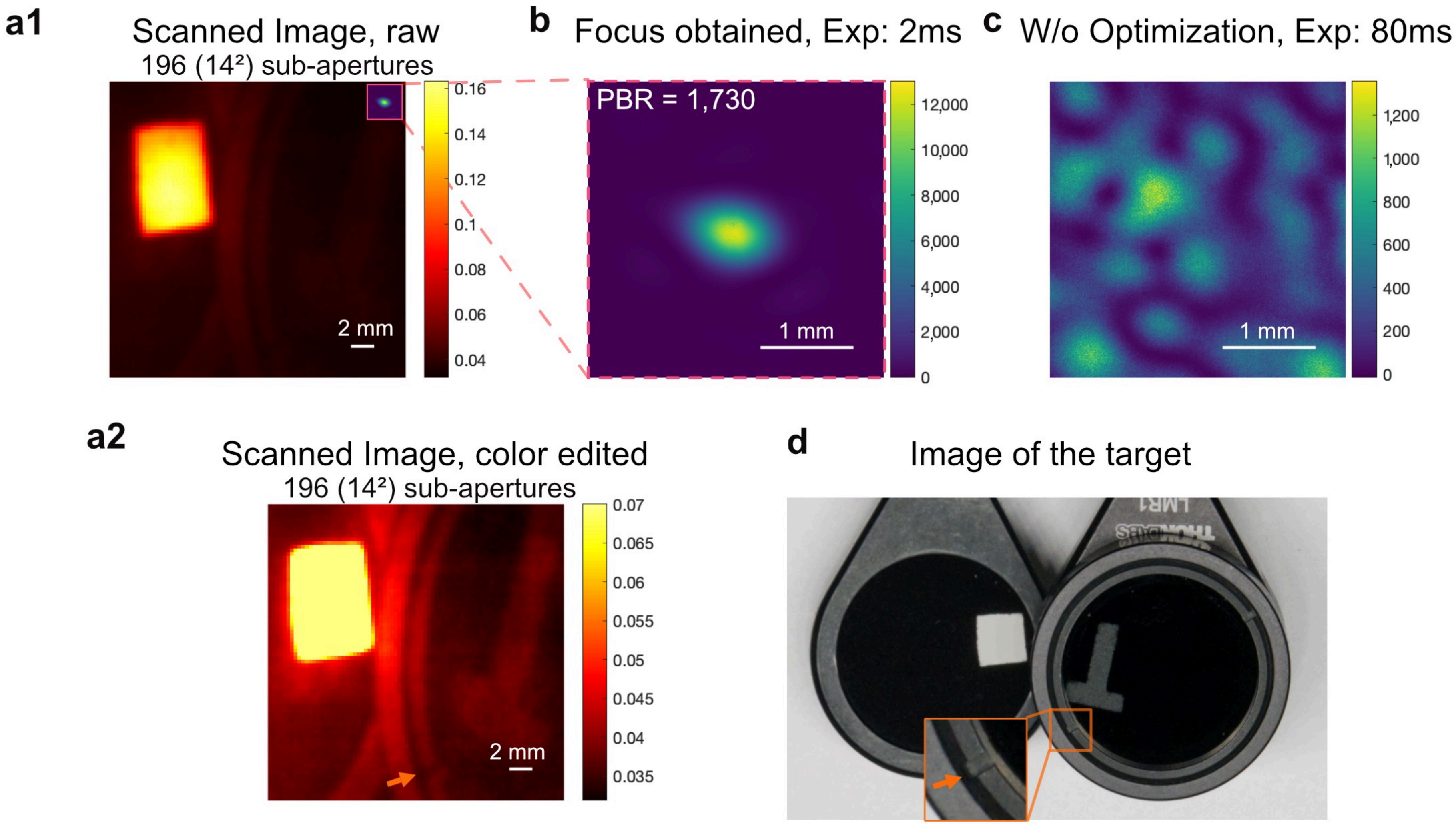


PM fiber: polarization maintaining fiber, DMD: digital micro-mirror device, L: lenses, M: Mirrors, HWP: half-wave plate, ND: neural density filter, BS: beam splitter, L: lens, BB: beam block, Obj: object, PMT: photomultiplier tube, and DAQ: data acquisition device.

Aperture synthesis
- the "combining" strategy



Experiment results – improved distance-to-resolution ratio



Wall proxy: reflective ground glass diffuser

Distance between the wall and the hidden object : 0.55 m

Resolution (FWHM): 0.58 mm

Distance-to-resolution ratio ~900

(In ToF, the number is around 100)

“T” is 97% weaker than the square

PBR: peak-to-background ratio

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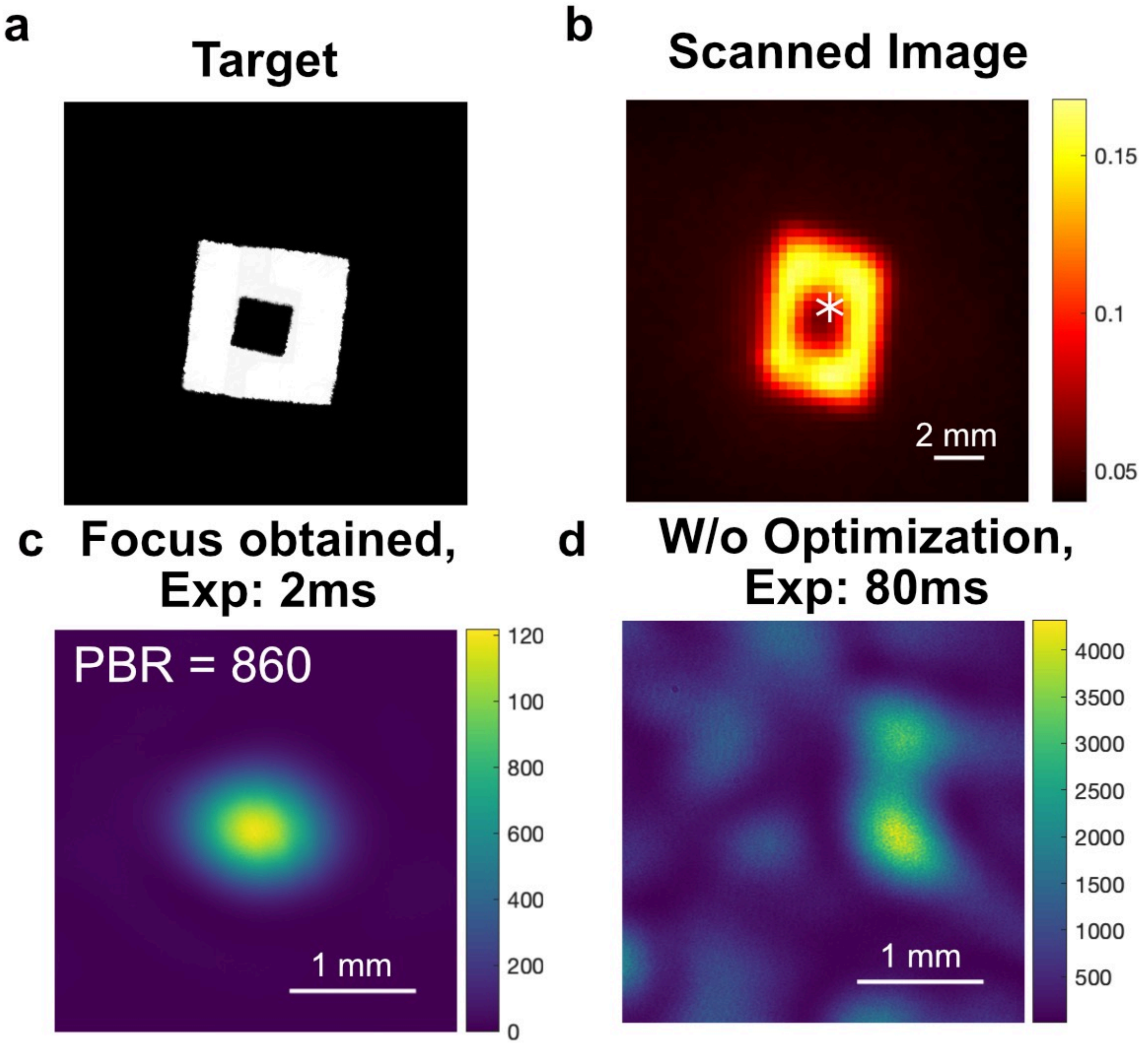
Imaging a hollow object



196 sub-apertures (14×14) were used

A square of side length ≈ 0.61 mm is illuminated when using the full aperture.

The focus was initially formed at the white asterisk ∗

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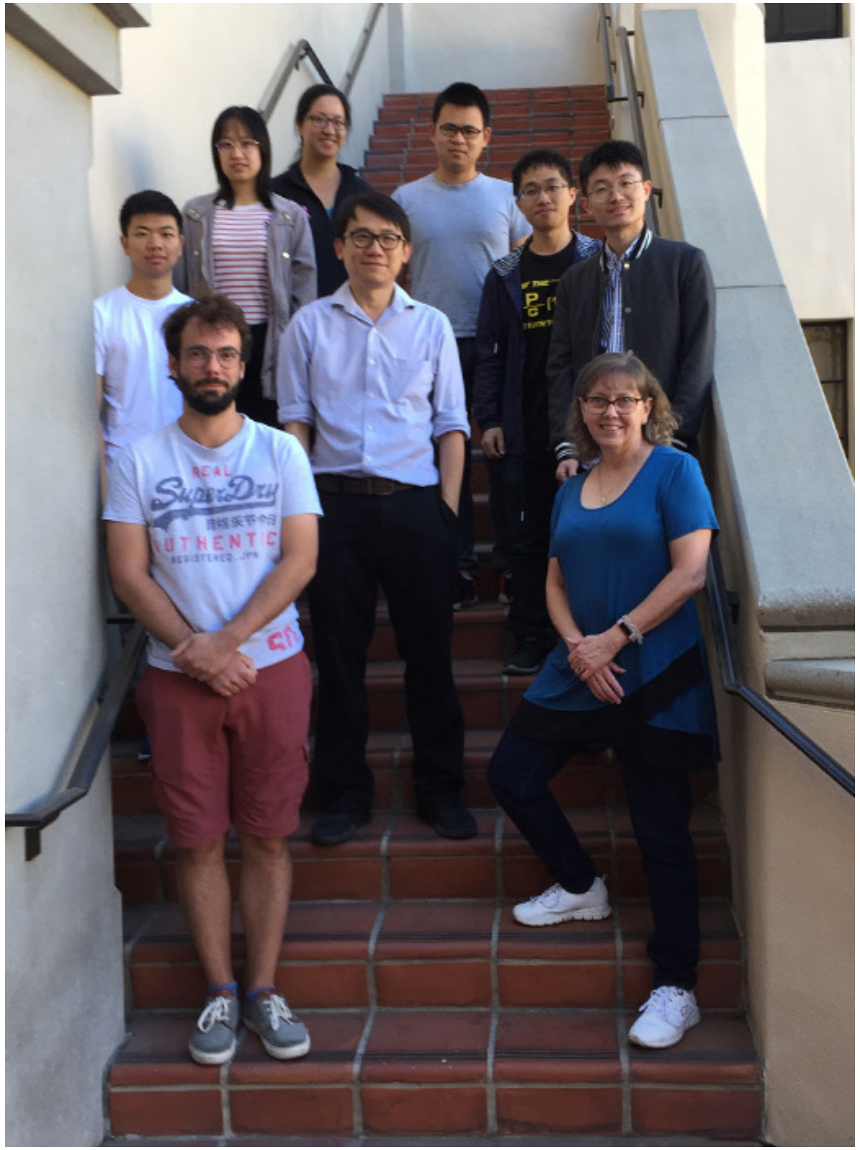
Acknowledgement



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