Monolithic Metalens Integrated with Fiber for Miniaturized Endoscopic Imaging

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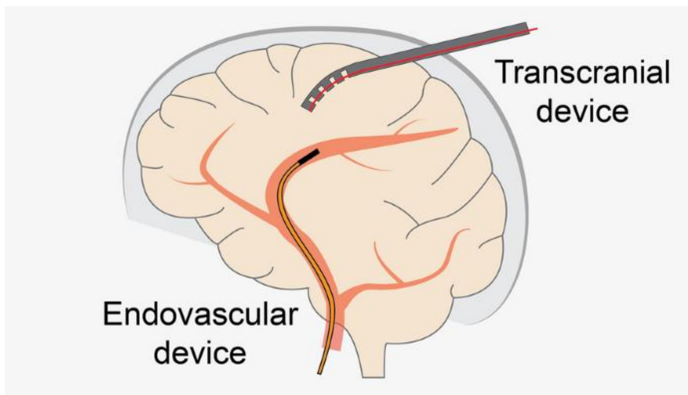
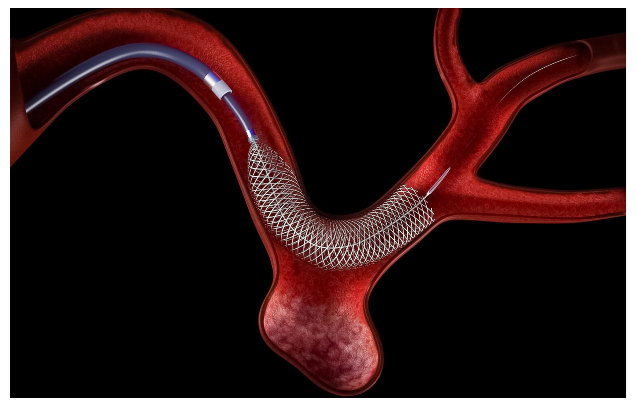
Introduction

➢ Endoscopy

Medical procedure that employs a slender, flexible or rigid instrument with integrated optics to visualize internal body structures

➢ Miniaturized endoscope

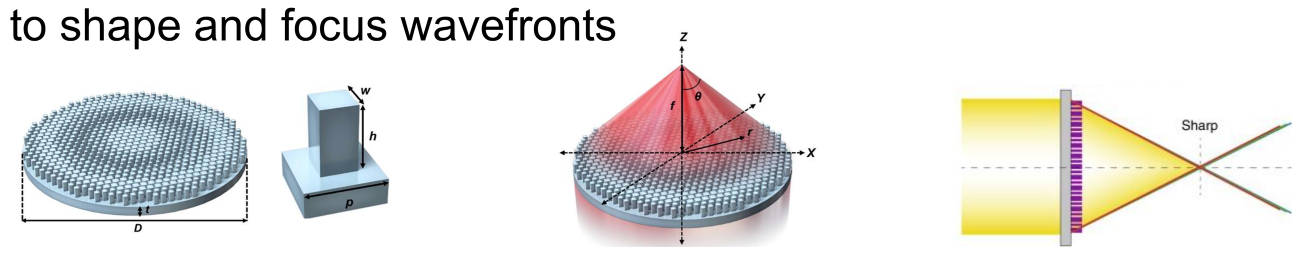




- Diameter: sub-millimeter (< 1 mm)
- Target region: Blood vessels, brain tissue, fine cavities
- Challenge 1) small aperture → limited resolution
  2) short optical path → chromatic aberration

➢ Metalens

Flat optical lens (< 1um) made of a dense array of subwavelength nanostructures (meta-atoms) that locally control the phase of light to shape and focus wavefronts



Ultrathin & Compact   Wavefront control   Aberration correction

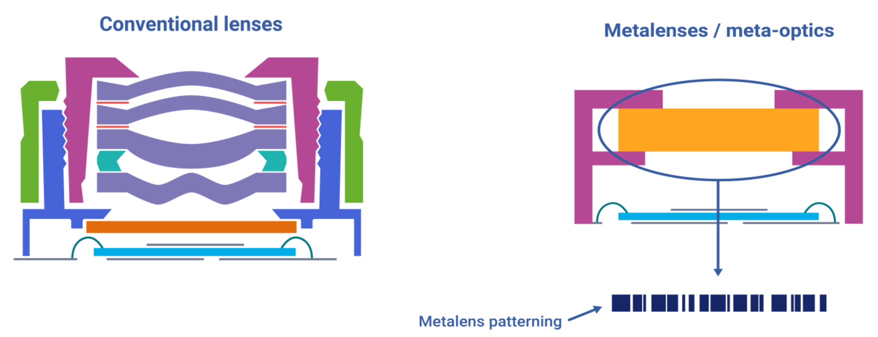
$$\phi(r) = -\frac{2\pi}{\lambda}\left(\sqrt{r^2+f^2}-f\right)$$

$\phi(r)$: required phase at radius r
λ: operating wavelength
r: radial distance from lens center
f: focal length

1) Extremely thin form
→ enables a **shorter distal tip and smaller probe**, ideal for compact endoscopic designs

2) Wavefront control
→ controls the phase, amplitude, and polarization of light, allowing **high-resolution** imaging in confined spaces

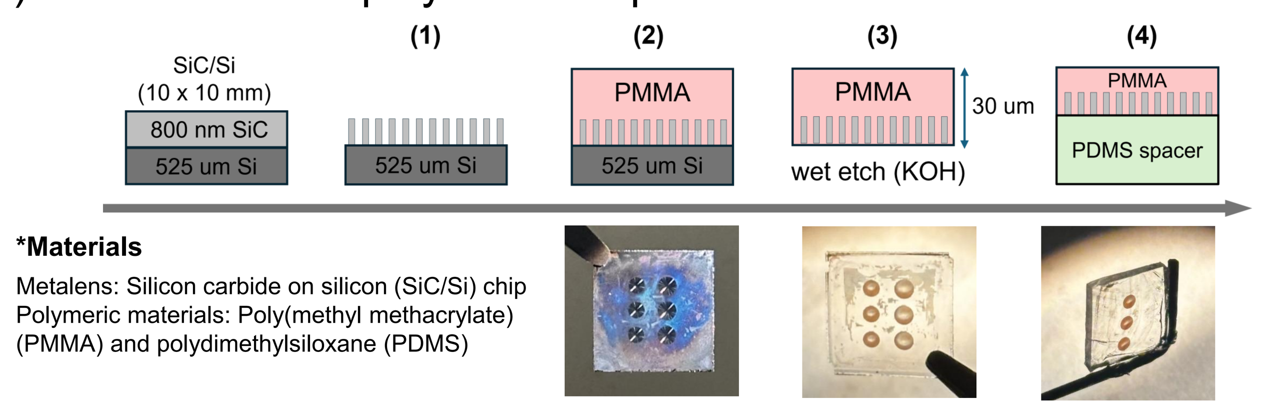
3) Aberration correction
→ Reduces distortions and improves image **accuracy**



Methodology

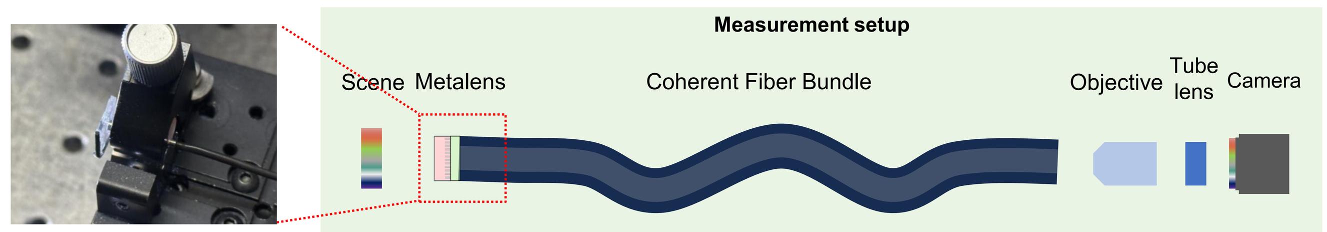
➢ Fabrication flow

1) Fabrication and polymer encapsulation of metalens



(1) Pattern writing through E-beam lithography
(2) Polymer (PMMA) integration via spin coating
(3) Etch back the substrate silicon via wet etching
(4) Polymer encapsulation of freestanding SiC metalens with a spacer

2) Matalens integration with coherent fiber bundle (CFB)



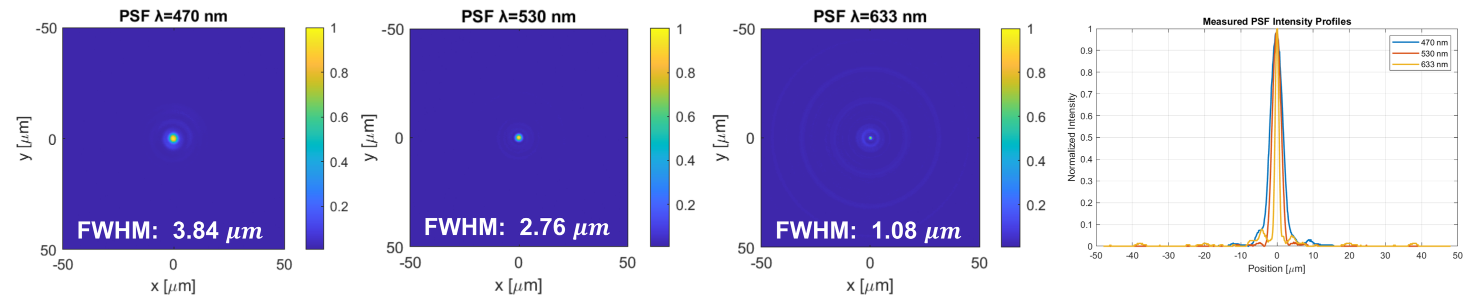
Result

➢ Characterization

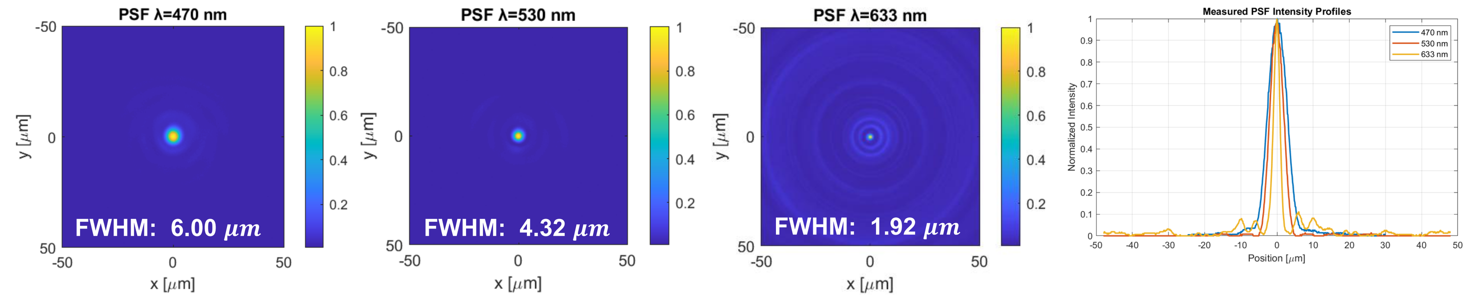
1) Point spread function (PSF)

The PSF represents spatial intensity distribution at the image plane generated by an optical system for a point source, quantifying the system's focusing performance and resolution.

- Focal length: 1 mm

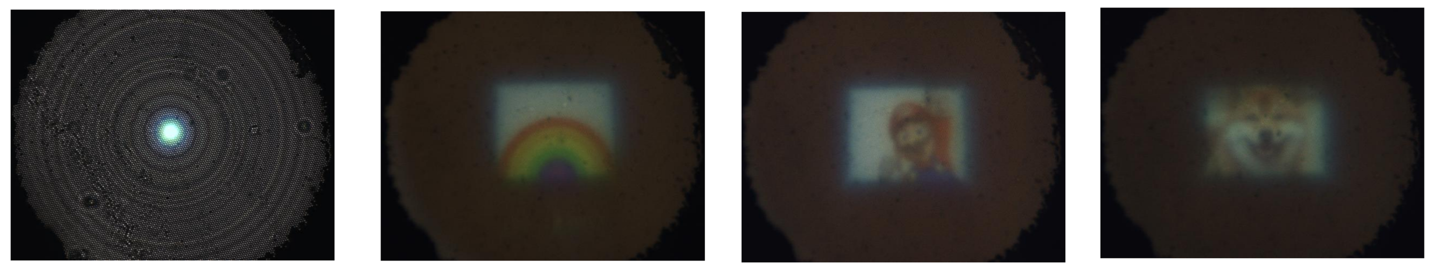


- Focal length: 2 mm

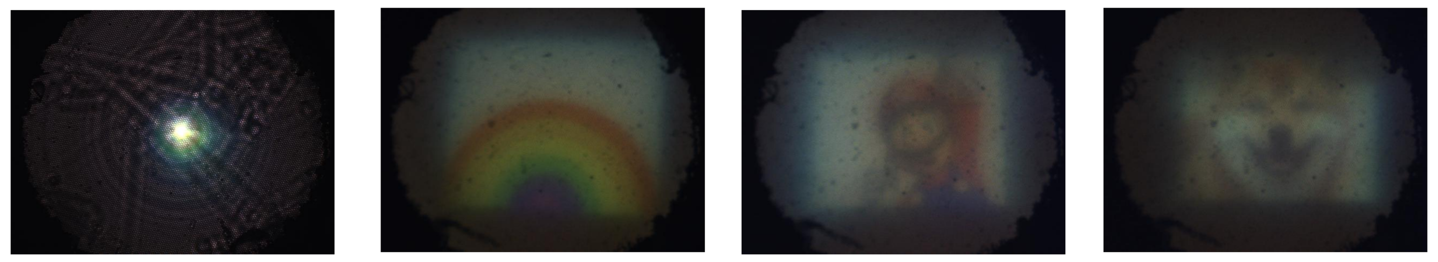


➢ Test Imaging

- Focal length: 1 mm / Field of view: **87** °



- Focal length: 2 mm / Field of view: **64** °



- Real-time acquisition of full-color images across the visible spectrum
- Wide field-of-view imaging with minimal optical distortion

Discussion

➢ Key Findings

- Developed a **full visible range SiC metalens** encapsulated in polymers and integrated with fiber optics.
- Achieved **real-time, full-color imaging without computational reconstruction**.
- Enabled a **wide 87° field of view** with **direct fiber coupling** for compact imaging architectures.
- Polymer encapsulation enhances mechanical **durability** and enables **access to tortuous cavities** in endoscopic applications.

➢ Future Work

- Optimize encapsulation and bonding for image clarity and maintain precise optical alignment.
- Integrate advanced fiber bundles to achieve higher resolution and enable high-quality imaging of biological samples.
- Develop tunable metalens designs for adaptive focusing in next-generation endoscopic imaging system,

References

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