

Metasurface Enhanced Lensless Endoscopy

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Abstract. We integrate a metasurface with a multicore fiber in a lensless two-photon endoscope. The fiber's transmission matrix is measured using an SLM, and its phase corrections are transferred to the metasurface to enable beam focusing. Our ongoing work suggests that integrating tip-tilt scanning could eventually allow point-by-point image reconstruction, paving the way toward truly miniaturized endoscopic imaging.

1 Introduction

Recent advances in lensless endoscopy have opened new avenues for non-invasive, in vivo imaging of deep biological tissues-especially in the brain-by eliminating the need for bulky distal optics. However, challenges persist in enhancing imaging resolution, scanning capabilities and reducing the footprint of the endoscopes. Conventional approaches rely on optical fibers paired with spatial light modulators (SLMs) to control the output wavefront via wavefront shaping from the input. Although SLMs provide flexible phase compensation to correct the phase delays among individual fiber cores, their bulky nature and the need for extra optical components limit overall efficiency and field of view. Metasurfaces present a compact, versatile alternative for wavefront shaping [1]. In our ongoing work, we integrate a metasurface with a multicore fiber (MCF) to replace the SLM in a two photon lensless endoscope. This integration transfers the phase corrections measured in the fiber's transmission matrix (TrM) onto the metasurface, thereby enabling precise beam focusing and illustrating a promising pathway toward fully miniaturized endoscopic imaging systems.

2 MCF Transmission Matrix Compensation

In this study, we use a tapered multicore fiber (MCF) [Fig. 1(a)] as a flexible probe owing to its many advantages, [2]. Our setup [Fig. 1(i)] generates a speckle field [Fig. 1(g)] in a plane δz away from the MCF end face, which becomes a focal spot [Fig. 1(h)] after correcting for the MCF's TrM. We measure the TrM of the MCF, which then guides our metasurface design. The metasurface we made is an effective-index device composed of GaN nanopillars on a sapphire substrate [Fig. 1(d)], operating in transmission without polarization dependence. Detailed FDTD simulations and fabrication procedures are provided in a previous study on a similar metasurface [3]. In our design [Fig. 1(b), 1(c)], each segment has a size of about

48 μm laterally and produces a focal spot at 600 μm , which corresponds to the MCF core pitch and mode field diameter when scaled by 4 \times magnification. Characterization, including intensity [Fig. 1(f)] and phase measurements [Fig. 1(e)] and SEM imaging [Fig. 1(d)] are performed to validate the metasurface design post-fabrication [4]. Finally, scanning mirrors control the focal spot by adding a tip and tilt, enabling point-by-point imaging over a defined field of view (FoV) at the fiber's working distance.

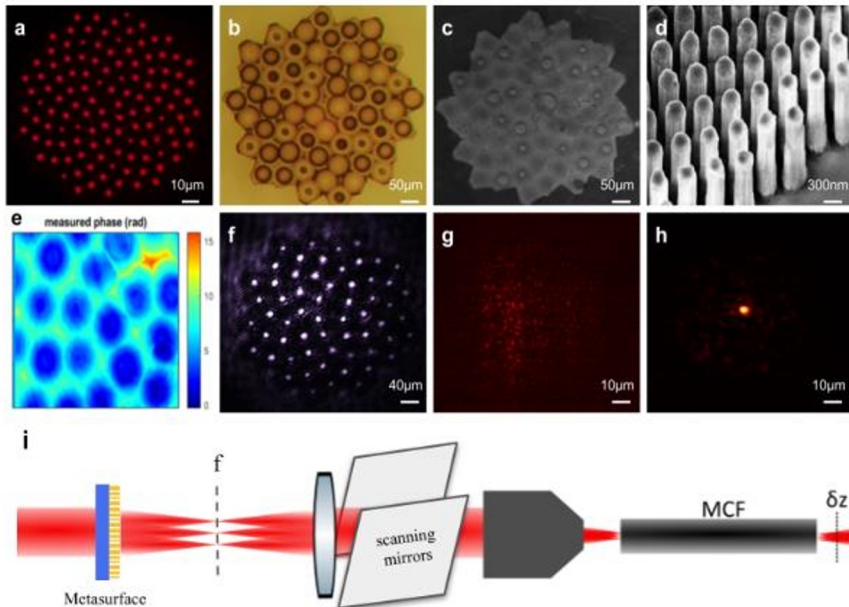


Fig. 1. (a) Image of the cores of the aperiodic MCF used in the setup; (b) Optical microscope image and (c) SEM image of the fabricated metasurface; (d) High-magnification SEM image showing the meta-atoms; (e) Phase image of selected segments of the metasurface; (f) Intensity image of the spots produced by the metasurface at a distance $f = 600 \mu\text{m}$; (g) Intensity image at a working distance δz from the MCF end face before and (h) after correcting for the TrM, showing a clear focus. (i) Schematic of the optical setup: a collimated beam passes through the metasurface, which generates spots matching the MCF core sizes and pitch at a focal distance f . The phase pistons for each core are compensated. Scanning mirrors then add tip and tilt, injecting the spots into the MCF. At the output, interference, as shown in (g) and (h), is observed at δz .

References

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