Diffractive metasurface light-shaping from fiber endoscope probes for increased depth of field

Fei He[1], Rafael Fuentes-Dominguez[1], Richard Cousins[2], Christopher J. Mellor[3], Jennifer K. Barton[4,5], and George S. D. Gordon[1]

[1]Optics and Photonics Group, University of Nottingham, Nottingham
[2]Nanoscale and Microscale Research Centre, University of Nottingham, Nottingham
[3]School of Physics and Astronomy, University of Nottingham, Nottingham
[4]Wyant College of Optical Science, University of Arizona, Tucson, Arizona
[5]Biomedical Engineering, University of Arizona, Tucson, Arizona

ABSTRACT

In applications such as optical coherence tomography, there is a need both to achieve large depth of field by light shaping and to maintain ultracompact form factors. Flat metasurfaces on optical fibers can achieve such requirements, with designs such as encapsulated diffractive axicon masks. They have the advantages of simple fabrication and transfer, scalability to multi-layer structures and ability to wavelength and/or polarization control. We show a method to shape light from optical fibers via diffractive metallic metalenses bonded onto fiber facets. We discuss a novel process for fabrication and, as proof-of-principle, demonstrate Fresnel zone plates and diffractive axicons on optical fiber facets.

Keywords: fiber optics, nanofabrications, metasurfaces, Fresnel zone plates, axicon masks

1. INTRODUCTION

Shaping light at the facets of hair-thin optical fibers using flat optics has opened new paradigms in imaging,[1] nano-particle trapping[2] and optical coherence tomography (OCT).[3] Specifically, for OCT a large depth-of-field is desired in order to trade off spatial and axial resolutions, which can be achieved using axicon lenses. Previously, axicons have been made on fibers by polishing facets into conical shapes[4,5] or attaching metalens-integrated prisms[3] but more generally, flat optics can be fabricated directly on fiber facets by milling[6] or 3D printing.[2,7] In addition, similar functionalities can be achieved using diffractive lenses[8] bonded on fiber facets which have the advantages of being simpler to design, fabricate and transfer, and compatibility with multi-layer metasurface stacks increasingly finding use in advanced imaging systems,[9,10] although at the expense of reduced efficiency.

Metasurfaces (as well as the diffractive metalenses) have provided flexible ways to control light by engineering the spatial distributions of amplitude, phase and polarization responses with subwavelength resolution.[11–13] The conventional method to fabricate such nanostructures through top-down fabrication on millimeter-sized bulk substrates with electron-beam lithography (EBL) process is effective (as well as photo-lithography and nanoimprint technology), but needs certain adjustment to be easily transferable for fiber optics platform and

Further author information: (Send correspondence to Fei He)
F.H.: E-mail: Fei.He@nottingham.ac.uk, Telephone: +44 (0)778 42 78123
G.S.D.G.: E-mail: george.gordon@nottingham.ac.uk

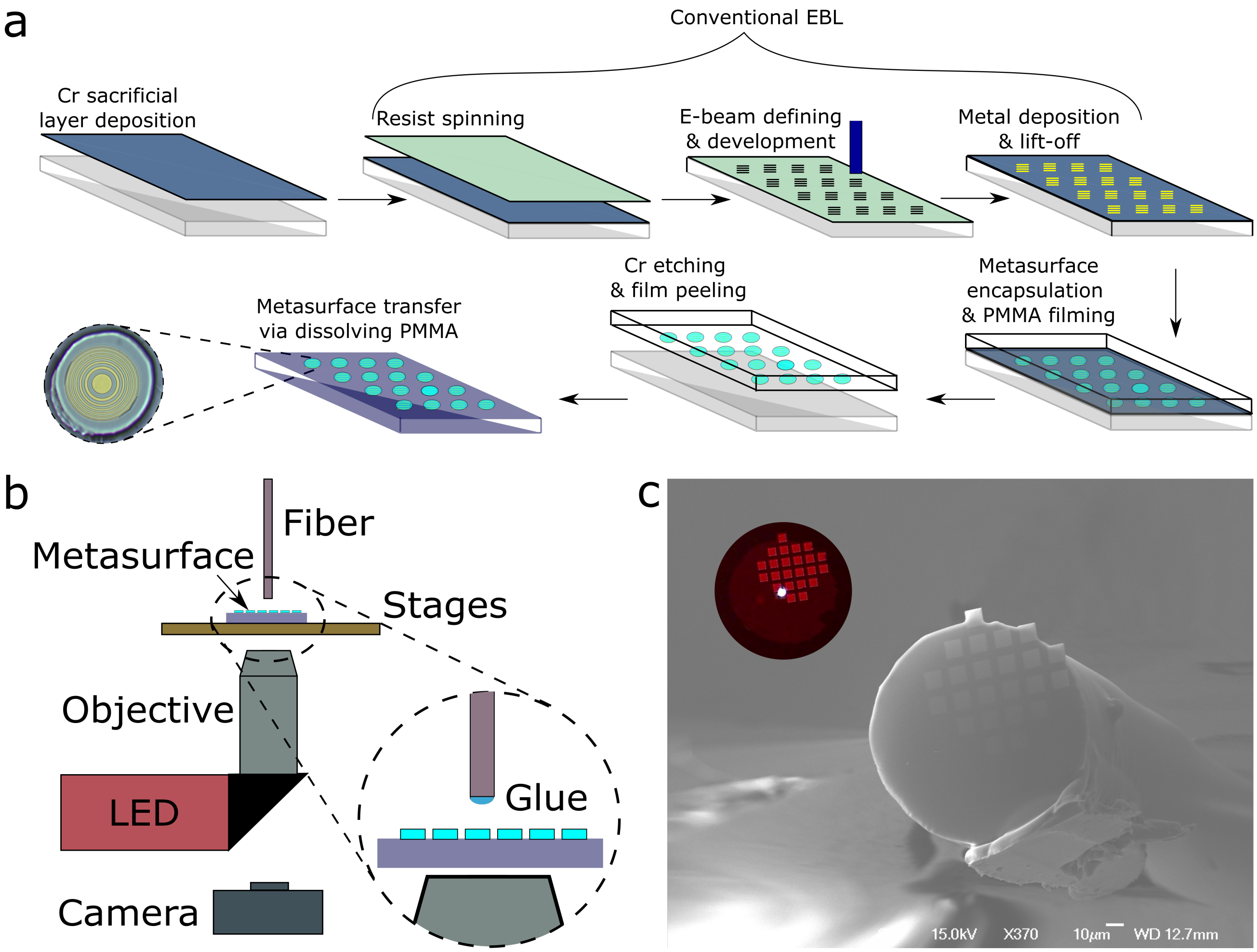

Figure 1. Fabrication of ultra-thin polymer-encapsulated metasurfaces onto fiber tips showing the steps to (a) separate encapsulated metasurfaces from the hosting substrate and to (b) transfer them onto optical fiber tips. (c) Scanning electron microscopy image of a polymerised metasurface attached to the tip of a single-mode fiber. Inset is the optical image showing the alignment between the fiber core and the metasurface pattern through the microscope in (b).

scalable for multi-layer structures. The solution is to peel off polymerised-nanostructures from the supporting substrate by etching a sacrificial layer, and to stick them onto fiber tips in sequence. As proof-of-principle, we demonstrate Fresnel zone plates and axicon binary masks on optical fiber facets shaping light into Gaussian foci and Bessel-like beams.

2. RESULT

As shown in Fig. 1(a), the first fabrication step is to deposit a thin Cr sacrificial layer (5-10 nm), followed by conventional EBL and lift-off processes to create metasurface patterns on the thin layer. A 10-20 μm layer of OrmoClear resist is then spin-coated, and align-patterned to disk shape via photo-lithography (125 μm disks, matching the fiber diameter) to encapsulate the metasurface patterns in polymer. Immediately after that, a thicker PMMA layer is uniformly coated onto the Si substrate to assimilate the polymer-encapsulated metasurfaces. The next step is to remove the Cr sacrificial layer via wet etching process, during which the PMMA film is gradually peeled off from the Si substrate and can float up to the surface of Cr etchant. The PMMA film is then dissolved via AR 600-71 remover to make them free-standing on glass coverslips which can be directly positioned onto the stage of a custom-built optical microscope (as shown in Fig. 1(b)).

In the next step, an inverted microscope is used to enable imaging through the coverslip by an objective underneath in order to locate both metasurfaces and fiber tips within the field of view. The live image at the coverslip-metasurface plane is formed by a camera capturing the reflection of LED illumination. The 2D horizontal translation of the electro-mechanical stage and the 3D movement of the fiber holder controlled by a micrometer allow accurate alignment between the metasurface and fiber tip (white light coupled into the fiber to help locating the core), with precision down to 1 µm. UV-curable optical adhesive is used to attach metasurfaces onto fiber tips, and the bonding can be solidified by UV-light illumination. As an example, Fig. 1(c) shows the optical image of a metasurface pattern bonded to a single-mode fiber tip (the alignment between the pattern and the white-light illuminated core is shown in the inset). It is noticed that due to the excessive use of adhesive this material is elongated along the fiber tip, which can be further improved by more careful control when transferring adhesive onto fiber tips.

As proof of principle, we transfer a Fresnel zone plate and a diffractive axicon mask onto fiber tips to shape the output light, via the fabrication steps described above. Single-mode fibers are used to guide red light (660 nm, diode laser), and 750 µm long multi-mode fiber (105 µm core diameter) are fusion-spliced onto the single-mode fiber tips so that the multi-mode endcaps can expand the beam size to illuminate the whole metalens apertures. The Fresnel zone plate (Fig. 2(a), with condensed rings) shapes the light into a Gaussian focus with 80 µm depth. The difference between the designed (250 µm to the fiber facet) and actual (205 µm) focal points as well the aberrated depth-of-focus can be attributed to the compromised metalens quality, variations on the endcap length and misalignment between the mode and rings. In comparison, an axicon mask (Fig. 2(b), with larger ring spacing) has the ability to shape the fiber light into a needle-like Bessel beam, with 400 µm depth-of-focus. The increased depth-of-focus compared to the zone plate makes the axicon a better candidate for any fiber-based OCT applications. The asymmetry of the field distributions in the XZ and YZ planes can be attributed to the asymmetrical design of the mask, and improvements can be made during nanofabrication process to improve the field quality.

3. CONCLUSION

To conclude, we have shown a method to fabricate diffractive metalenses onto optical fiber tips through direct bonding of encapsulated axicon mask with UV-curable optical adhesive. This method can be easily applied to fabricate multi-layer metasurfaces onto optical fiber tips. As a proof of principle, we designed, fabricated, transferred and optically characterised a Fresnel zone plate and an axicon mask attached to single-mode fibers to shape light into Gaussian focus and Bessel-like beam. The long depth-of-focus of the fiber-axicon device would be suitable for many fiber-based OCT applications.

ACKNOWLEDGMENTS

This work is supported by a UKRI Future Leaders Fellowship (MR/T041951/1) and a UNICAS Grant from the University of Nottingham. The authors would like to acknowledge the Nanoscale and Microscale Research Centre (nmRC) and Faculty of Physics at the University of Nottingham for providing access to cleanroom facilities.

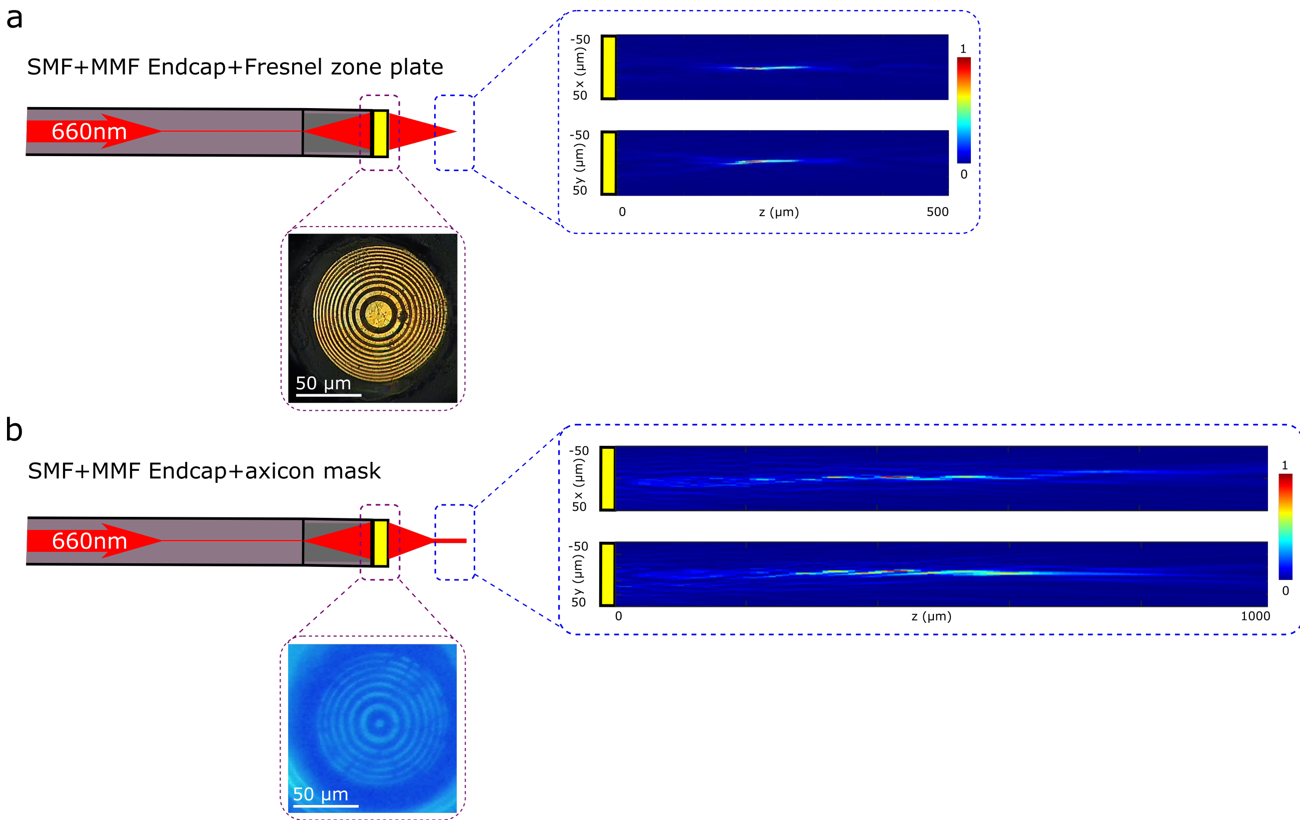

Figure 2. Experimental measurement result of (a) a Fresnel zone plate and (b) an axicon mask shaping light into Gaussian focus and Bessel-like beam. Inset images show microscope images of the attached zone plate and axicon. Cross-sections of experimentally measured beam profiles in the XZ and YZ planes are shown for each design.

REFERENCES

[1] Ren, H., Jang, J., Li, C., Aigner, A., Plidschun, M., Kim, J., Rho, J., Schmidt, M. A., and Maier, S. A., "An achromatic metafiber for focusing and imaging across the entire telecommunication range," *arXiv preprint arXiv:2201.07158* (2022).

[2] Plidschun, M., Ren, H., Kim, J., Förster, R., Maier, S. A., and Schmidt, M. A., "Ultrahigh numerical aperture meta-fibre for flexible optical trapping," *Light: Science & Applications* **10**(1), 1–11 (2021).

[3] Pahlevaninezhad, H., Khorasaninejad, M., Huang, Y.-W., Shi, Z., Hariri, L. P., Adams, D. C., Ding, V., Zhu, A., Qiu, C.-W., Capasso, F., et al., "Nano-optic endoscope for high-resolution optical coherence tomography in vivo," *Nature photonics* **12**(9), 540–547 (2018).

[4] Kuchmizhak, A., Gurbatov, S., Nepomniaschii, A., Vitrik, O., and Kulchin, Y., "High-quality fiber microaxicons fabricated by a modified chemical etching method for laser focusing and generation of bessel-like beams," *Applied optics* **53**(5), 937–943 (2014).

[5] Wang, W., Wang, G., Ma, J., Cheng, L., and Guan, B.-O., "Miniature all-fiber axicon probe with extended bessel focus for optical coherence tomography," *Optics express* **27**(2), 358–366 (2019).

[6] Rodrigues Ribeiro, R. S., Dahal, P., Guerreiro, A., Jorge, P. A., and Viegas, J., "Fabrication of fresnel plates on optical fibres by fib milling for optical trapping, manipulation and detection of single cells," *Scientific reports* **7**(1), 1–14 (2017).

[7] Lightman, S., Porat, O., Hurvitz, G., and Gvishi, R., "Vortex-bessel beam generation by 3d direct printing of an integrated multi-optical element on a fiber tip," *Optics Letters* **47**(20), 5248–5251 (2022).

[8] Vasara, A., Turunen, J., and Friberg, A. T., "Realization of general nondiffracting beams with computer-generated holograms," *JOSA A* **6**(11), 1748–1754 (1989).

[9] Avayu, O., Almeida, E., Prior, Y., and Ellenbogen, T., "Composite functional metasurfaces for multispectral achromatic optics," *Nature communications* **8**(1), 1–7 (2017).

[10] Gordon, G. S., Gataric, M., Ramos, A. G. C., Mouthaan, R., Williams, C., Yoon, J., Wilkinson, T. D., and Bohndiek, S. E., "Characterizing optical fiber transmission matrices using metasurface reflector stacks for lensless imaging without distal access," *Physical Review X* **9**(4), 041050 (2019).

[11] Chen, H.-T., Taylor, A. J., and Yu, N., "A review of metasurfaces: physics and applications," *Reports on progress in physics* **79**(7), 076401 (2016).

[12] Glybovski, S. B., Tretyakov, S. A., Belov, P. A., Kivshar, Y. S., and Simovski, C. R., "Metasurfaces: From microwaves to visible," *Physics reports* **634**, 1–72 (2016).

[13] Kamali, S. M., Arbabi, E., Arbabi, A., and Faraon, A., "A review of dielectric optical metasurfaces for wavefront control," *Nanophotonics* **7**(6), 1041–1068 (2018).