Ultra-deep micro-axicons in lithium niobate by focused Xe ion beam milling

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Refractive axicons are conically shaped optical devices that are capable of generating non-diffracting Bessel-like beam over extended depths-of-focus (DOFs). In addition to the substantially longer DOF compared to those produced by parabolic focusing lenses, the axicons generate beams with a better resolution (~25%) for the same form-factor of the optical element, e.g., its diameter and sag height. These properties make the axicon useful in numerous applications[1] in imaging, particle trapping and many others. Miniaturized refractive axicons[2] or micro-axicons are challenging to realize in hard substrates due to the lack of sufficiently precise and rapid fabrication technologies. The direct-write focused ion beam (FIB) milling has the flexibility to produce complex three-dimensional reliefs in practically any substrate, however it is inherently slow due to the serial nature of the pattern transfer.

The next generation of FIB systems with inductively coupled plasma ion sources allows to reduce the fabrication times by 10-20× or more. The reduction of the ion milling times are due to the availability of heavier ion beam chemistry (e.g. noble Xe) and significantly higher ion beam currents (up for 4 µA compared to conventional metallic Ga-beam-based instruments). Micro-axicons with 230-µm diameter with ultra-deep sag heights between 21 and 48 µm (Figure 1) were milled using 200 nA of beam current. Furthermore, the axicons were milled in single-crystal lithium niobate – a material with high refractive index of >2.2 but which inertness makes it a challenging material in microfabrication. The performance of the lenses was characterized by mapping the transmitted intensity at different positions (Figure 2). The measured spot sizes (full width at half maximum) of the produced beams are in excellent agreement with the theoretical expectations and range from 750 nm for the shallowest micro-axicon in this study and down to 250 nm (~$\lambda/2$) beam spot size for the deepest micro-axicon with a 48-µm sag height. The corresponding DOFs are from ~500 µm and down to ~50 µm for the ultra-deep micro-axicon. The results verify the applicability of high-current milling with a focused Xe ion beam for the fabrication of high-performance optical elements.

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[1] D. McGloin, K. Dholakia, Contemp. Phys. **46**(1), 15–28 (2005)
[2] S. Gorelick, A. de Marco, Optics Express **26**(24), 32324 (2019)

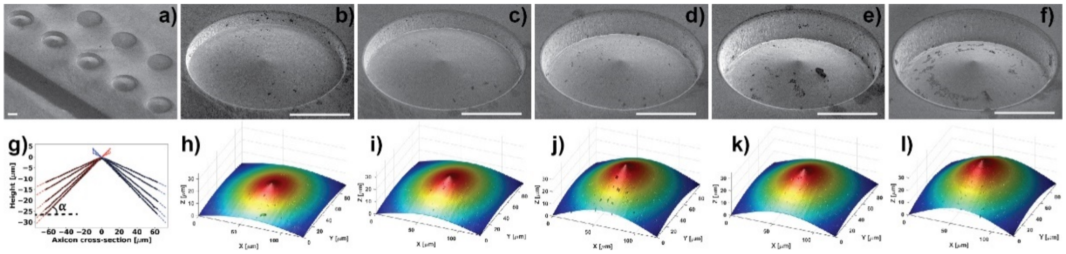

Figure 1: Ultra-deep micro-axicons in lithium niobate: a) Scanning electron microscopy (SEM) overview of multiple micro-axicons with different sag height. (b-f) Micro-axicons with 21 µm, 27 µm, 37 µm, 44 µm, and 48 µm sag height, respectively. Scale bar is 100 µm. g) Surface profile cross-sections with corresponding linear fits. (h-l) White light profilometry characterization of the tip regions of the corresponding micro-axicons from (b-f).

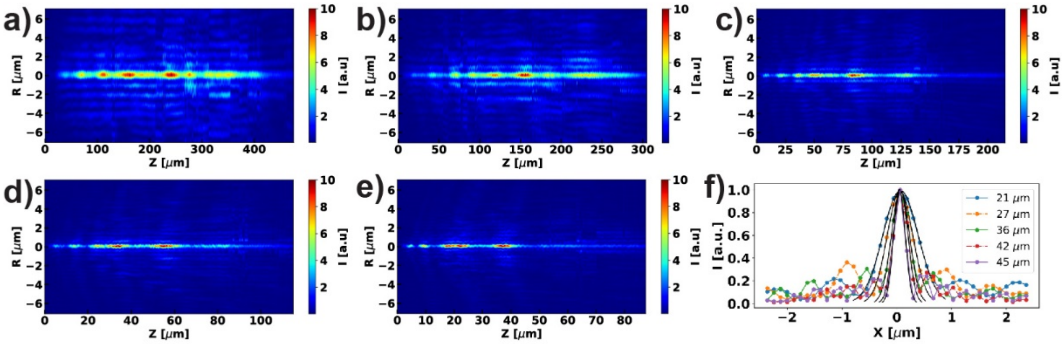

Figure 2: Optical characterization of lithium niobate micro-axicons: (a-e) Intensity maps (cross-section) of the areas of maximal intensity along the optical axis from axicons with the 21 µm, 27 µm, 37 µm, 44 µm, and 48 µm sag height, respectively. f) Beam profile cross-sections with Gaussian fits of the central peak. The beam spot sizes at full width half-maximum are 750 nm, 552 nm, 389 nm, 312 nm, and 252 nm.