Refractive free-form micro-optical elements and phase plates in lithium niobate by high-current focused Xe ion beam milling

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Refractive micro-optical components are typically limited in their surface profiles to focusing lenses (spherical or parabolic) and axicons (conical). Here, we demonstrate the fabrication and optical characterization of complex refractive optical elements not constrained to a particular shape. The fabricated devices, such as angularly modulated parabolic lenses and static spiral phase plates, do not have a particular axis of symmetry.

The fabrication of such complex three-dimensional surface reliefs in hard substrates is challenging, however with the advent of focused ion beam milling systems with high-brightness inductively-coupled plasma sources rapid prototyping of optical devices without a constraint on the surface profile is becoming possible. Furthermore, we fabricated the micro-optical elements directly in single-crystal lithium niobate - an exciting piezo- and opto-electrical material with a high refractive index of >2.2. Due to its high inertness and resistance to most etchants, lithium niobate has the reputation of being difficult to use for the realization of photonic micro- and nanostructures, however, its gray-scale patterning by direct milling with noble and heavy Xe ions is straightforward. Focused ion beam (FIB) systems based on high brightness plasma ion sources provide more than an order of magnitude increase in milling rates with noble gas ions (e.g., Xe) compared with more conventional metallic Ga FIBs. Here, we demonstrate the feasibility of a rapid, direct milling of refractive 230-μm in diameter free-form phase-plates in lithium niobate using >200 nA of Xe ion current (Figure 1).

We analyzed the optical performance and beam-shaping properties of the fabricated micro-optical components by collecting series of intensity profiles at various planes (Figure 2) and compared the experimental results with the numerical simulations. The results indicate the applicability of the plasma focused ion beam systems for rapid fabrication of high-quality free-form optical elements directly in even such challenging hard substrates for microfabrication like lithium niobate.

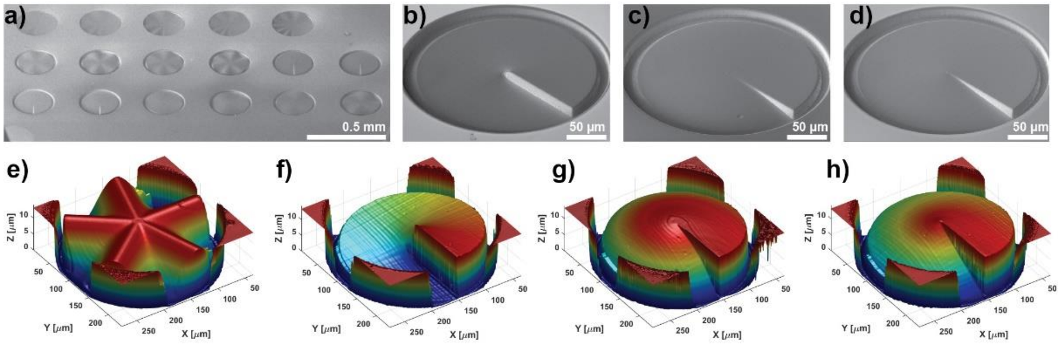

Figure 1: Micro-optical components milled in lithium niobate: a) SEM image of an overview of multiple components on the same chip (stage tilt 52°). b) Static spiral phase plate with a constant phase with the radius, while (c) has a parabolic phase and (d) linear phase variations with the radius. (e-h) White light interferometry of micro-optical phase plates in lithium of a focusing lens with angular sag height modulation, spiral constant phase plate, spiral parabolic phase plate and linear phase, respectively.

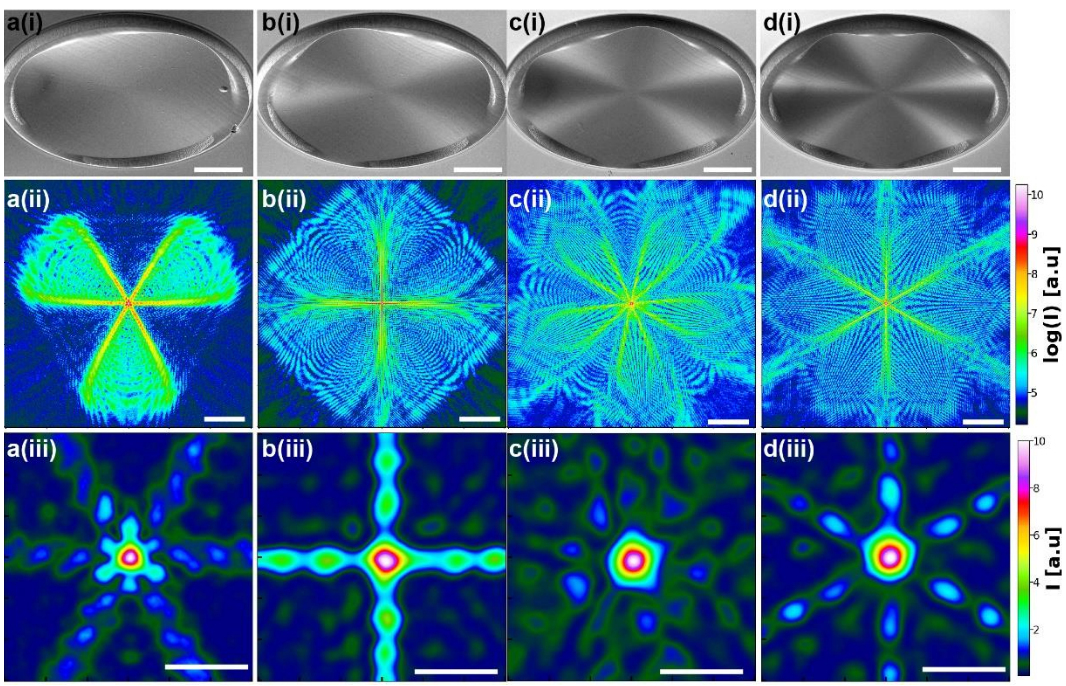

Figure 2: Microlenses with angular modulation of their sag height: Lithium niobate 12-µm-deep, 230-µm microlenses with (a-d) 3-, 4-, 5- and 6-fold angular modulation of the sag height. (i, top) Scanning electron microscope image of the milled lenses. Scale bar 50 µm. Stage tilt 52°. (ii, middle) Overview of the light intensity on log scale at the focal plane. Scale bar 50 µm. (iii, bottom) Magnified regions from (ii) around the focal spot. Scale bar 4 µm.