Quartz superoscillatory lenses with NA > 1

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Abstract: We developed design algorithms and manufacturing processes for quartz visible-range superoscillatory lenses. Lenses with focal spot size of 0.4λ, effective numerical aperture of 1.25 in air and working distance of 1 mm are demonstrated.

Large-scale and high-numerical-aperture (NA) planar optical lenses with long working distance, efficient optical throughput and high resolution are highly desirable for applications in mobile devices, camera lenses, and super-resolved imaging. Conventional diffractive optical elements and more advanced optical metasurface lenses are existing solutions by utilizing properly designed optical masks. However, their resolution is still diffraction limited, giving NA less than 1 in free space. On the other hand, the requirement on the long working distance, high NA and high resolution can be fulfilled by the recently developed superoscillatory lenses (SOLs) using the fact that band-limited functions can oscillate much faster than its highest Fourier component over arbitrarily large intervals. By delicate interference of propagating waves, SOL can form sub-diffraction spatial features in the optical far-field without any evanescent wave contributions, thus inspiring far-field super-resolution imaging applications. In this work, we fabricate large-scale SOL using optical lithography followed by dry etching. Binary-phase (0/π) SOLs with diameters ranging from 0.9 mm to 2 mm are fabricated and characterized, showing the great advantages of high transparency, low cost and mass-production capability. At a selected wavelength of 633 nm, superoscillatory hotspots with full width at half maximum (FWHM) of 0.4λ are firmly observed in the experiment, giving rise to working distance ranging from 0.15 mm to 1 mm and an effective numerical aperture as high as 1.25 in air.

Figure 1(a) shows the real images of massive SOLs etched into a 1 mm-thickness and 4 inch-diamter single crystal quartz wafer. Then each SOL is cutted into 6 mm diameter using laser dicing for ease of integration and characterization, see Fig. 1(b). An optical image of SOL with a diamter of 1.2 mm is given in Fig. 1(c) and the SEM image of the central region is shown in the inset. Both illustrate good uniformity and high fabrication quality, and the etching depth is around 703 nm for generating a π phase delay at 633 nm. The simulated focusing performance is shown in Fig. 1(d) and the FWHM of the superoscillatory focus is around 0.4λ, corresponding to an effective NA=0.5λ/FWHM. The intensity profiles in the focal plane show reasonable agreement between the simulation and experiment.

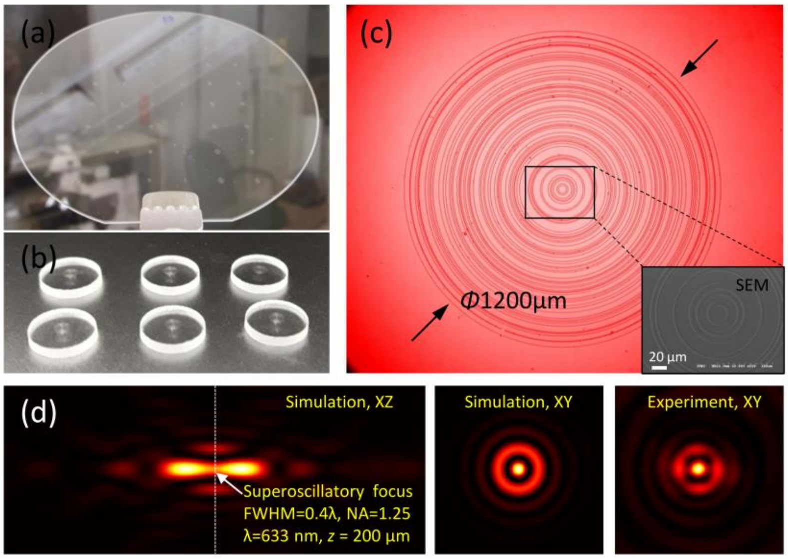

Fig. 1 Quartz superoscillatory lenses with NA > 1. (a) Super-oscillatory lenses (SOLs, white spots) etched into 1 mm-thickness quartz wafer. (b) After laser dicing into 6 mm diameter, and the SOLs are centered. (c) Optical image of an SOL with diameter of 1.2 mm. Inset shows the SEM image of the central area. (d) Focusing performance of the SOL shown in (c): (left) the superoscillatory focus is generated at a propagation distance of 200 μm, and the FWHM of the spot is 0.4λ corresponding to an effective NA=1.25. (middle) the simulated intensity profiles in the transverse plane (*xy*) where the central hotspot and first sideband are clearly visible. (right) experimental results. λ=633 nm.