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Cite as: Appl. Phys. Lett. 117, 021106 (2020); https://doi.org/10.1063/5.0013823
Submitted: 14 May 2020 . Accepted: 06 July 2020 . Published Online: 16 July 2020

G. H. Yuan ☯, Y.-H. Lin ☯, D. P. Tsai ☯, and N. I. Zheludev ☯
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G. H. Yuan,1,a) Y.-H. Lin,2 D. P. Tsai,2,3 and N. I. Zheludev1,4

AFFILIATIONS
1Centre for Disruptive Photonic Technologies, The Photonics Institute, SPMS, Nanyang Technological University, Singapore 637371
2Taiwan Instrument Research Institute, NARLabs, Hsinchu, Taiwan
3Department of Electronic Information Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
4Optoelectronics Research Centre & Centre for Photonic Metamaterials, University of Southampton, Southampton SO17 1B3, United Kingdom

a)Author to whom correspondence should be addressed: ghyuan@ntu.edu.sg

ABSTRACT

We report super-resolution high-numerical-aperture and long-working-distance superoscillatory quartz lenses for focusing and imaging applications. At the wavelength of $\lambda = 633$ nm, the lenses have an effective numerical aperture of 1.25, a working distance of 200 $\mu$m, and a focus into a hotspot of 0.4 $\mu$m. Confocal imaging with resolution determined by the superoscillatory hotspot size is experimentally demonstrated.

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https://doi.org/10.1063/5.0013823

However, the radius $R$ of previously reported SOLs was limited to a few tens of micrometers and focal distances to about less than 20 wavelengths, which limited their wider applications. The short working distance (typically 10–15 $\mu$m) prohibits the use of conventional coverslips, and great care is required to safely position the lens at close proximity of objects without damaging either the lens or the object, and therefore imaging of complex volume structures is prohibited.

Here, we report large SOLs with dimensions comparable with conventional commercial high-NA lenses. The SOLs with diameter $2R = 1.2$ mm are fabricated in quartz by optical lithography that allows low-cost mass-production. At a wavelength of 633 nm, the SOLs with a working distance of up to $f = 200$ $\mu$m focus light into superoscillatory hotspots with a full-width at half-maximum (FWHM) of 0.4 $\mu$m. This corresponds to an effective $NA = 1.25$. A conventional singlet lens with such focal distance and diameter would have $NA = 0.95$ and will focus into a hotspot of $ \approx 0.53 \lambda$.

The SOLs reported here are binary phase masks, a concentric set of rings etched into a 1 mm thick quartz substrate. The required depth of etching depends on the targeted operation wavelength. It is selected such that the light passing through the ring gains an additional phase shift of 180° with respect to the light directly passing through the substrate. The SOL is designed as a set of 30 rings with the multi-objective particle swarm optimization algorithm that optimizes the targeted hotspot using two circular prolate spheroidal wavefunction decompositions and vectorial diffraction theory, see Table I.
The fabrication procedures of the quartz SOLs are shown in Fig. 1(a), while Figs. 1(b)–1(d) show the detailed optical and scanning electron microscope (SEM) images of the SOL and its height profile, respectively. The prevailing nanofabrication techniques, including electron beam lithography and focused ion beam milling, are not suitable for mass production. Instead, we used the CMOS compatible optical lithography on a highly transparent quartz wafer that is suitable for the in-parallel fabrication of multiple optical components on a single-crystal. The simulated field intensity profiles of the SOL in the propagation cross section (yz plane near the designed focus) and transverse plane at the focus (xy plane, \( z = 200 \mu m \)) are shown in Figs. 2(a) and 2(b), respectively. The FWHM of the superoscillatory focus is \( 0.4 \) \( \mu m \), corresponding to an effective NA \( 1.25 \). The ratio of intensities \( k / (2NA) \) used a confocal arrangement with circularly polarized illumination at \( \lambda = 633 \) nm, a 100\( \times \) objective lens, and a pinhole aperture at the detector plane, as shown in Fig. 3(a). Circularly polarized light is used to generate a more rotationally symmetric hotspot and mitigate the depolarization effect. We first tested the limit of resolution of the quartz SOL and compared with a conventional diffraction-limited objective (NA \( = 0.95 \)).

Performance of such lenses was characterized experimentally and tested in imaging experiments. Since the superoscillatory field is formed by the interference of free-space propagating waves, its intensity profile can be directly mapped by the optical microscope with no loss of resolution.\(^6\) For experimental characterization, we used a high-NA objective (Nikon CFI LU Plan APO EPI 150\( \times \), NA \( = 0.95 \)). The overall magnification of the microscope equipped with an sCMOS camera with a pixel size of 6.5 \( \mu m \) was 500\( \times \). The experimentally measured intensity profiles are in good agreement with theoretical predictions; see Figs. 2(c) and 2(d); the attainable spot size of \( 0.41 \) \( \mu m \) at \( z = 200 \mu m \) is slightly larger than the simulation value of \( 0.4z \) due to fabrication and incident wavefront imperfections. The axial intensity profiles and spot sizes show good agreement between the simulation and experiment, as seen from Figs. 2(e) and 2(f). We also evaluated the Strehl ratio defined as the intensity ratio between the designed superoscillatory hotspot and the Airy disk at the same total power of incident light. The throughput to focus efficiency of the SOL is somewhat lower than that of conventional diffraction-limited lens: the expected (simulated) and actual (measured) Strehl ratios are 0.266 and 0.126, respectively (the actual value is lower due to fabrication imperfection), approaching the upper limit of the Strehl ratio at a given hotspot size.\(^7\)

To demonstrate the imaging capabilities of the quartz SOL, we used a confocal arrangement with circularly polarized illumination at \( \lambda = 633 \) nm, a 100\( \times \) objective lens, and a pinhole aperture at the detector plane, as shown in Fig. 3(a). Circularly polarized light is used to generate a more rotationally symmetric hotspot and mitigate the depolarization effect. We first tested the limit of resolution of the quartz SOL and compared with a conventional diffraction-limited objective (NA \( = 0.95 \)). The first set of test objects were pairs of nanoholes (diameter of 160 nm) with varying distance from 210 nm to 390 nm with a step of 30 nm fabricated by a focused ion beam milling in a...
shown in Fig. 3(c): the smallest hole-to-hole distance of 264 nm arranged in “Ursa Major” and “Ursa Minor” constellation layouts, as be seen with more complex objects comprising nanohole arrays tance of 330 nm (valley to peak ratio of 0.969) and above using the limited objective (NA = 0.584 to 0.495, respectively. In comparison, a conventional diffraction-limited objective, where the valley to peak ratio is 1/4 = 0.25, can only resolve holes spaced by a dis- 100 nm-thickness gold film on a glass slip; see Fig. 3(b). With the SOL, a hole center-to-center distance of 240 nm can be nearly resolved according to the Abbe criterion, where the valley to peak ratio is around 0.974. For distance from 270 nm, 300 nm, 330 nm, 360 nm to 390 nm, the valley to peak ratio decreases from 0.876, 0.788, 0.734, 0.584 to 0.495, respectively. In comparison, a conventional diffraction-limited objective (NA = 0.95) can only resolve holes spaced by a dis- tance of 330 nm (valley to peak ratio of 0.969) and above using the same criterion. A considerable image resolution improvement can also be seen with more complex objects comprising nanohole arrays arranged in “Ursa Major” and “Ursa Minor” constellation layouts, as shown in Fig. 3(c): the smallest hole-to-hole distance of 264 nm (0.42λ) can be resolved by the SOL but cannot be distinguished by diffraction-limited objective.

In summary, we report quartz superoscillatory lenses fabricated in a CMOS compatible high-throughput optical lithography process. The lenses, with only 1 mm thickness and having an effective NA of 1.25 and a focal distance of 316λ, were fabricated. Designed for the wavelength of 633 nm, they focus light into the hotspot of 253 nm (∼4λ) such compact and powerful lenses can find applications in confocal imaging and metrology instruments.

This work was supported by the Singapore Ministry of Education (Grant No. MOE2016-T3-1-006), the Agency for Science, Technology, and Research (A*STAR) Singapore (Grant No. SERC A1685b0005), and the Engineering and Physical Sciences Research Council UK (Grant Nos. EP/N00762X/1 and EP/M009122/1).

DATA AVAILABILITY

The data that support the findings of this study are openly available in the University of Southampton ePrints research repository at https://doi.org/10.5258/SOTON/D1381, Ref. 19.

REFERENCES