Stitching-free 3D printing of millimeter-sized highly transparent spherical and aspherical optical components

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Abstract: We fabricate and characterize spherical and aspherical polymer lenses on the millimeter scale by stitching-free 3D printing via two-photon polymerization. The imaging quality is excellent, being comparable to commercially available glass lenses. © 2021 The Author(s)

1. Introduction

Optical elements with millimeter size are nowadays standard components in many technical devices, ranging from smartphone cameras over medical endoscopes to numerous optical sensors used in the automotive industry. It is, however, often challenging to fabricate complex lens systems on this scale by conventional techniques such as grinding or milling. Therefore, polymer lenses fabricated by 3D printing based on two-photon polymerization are an interesting alternative. This technique is not only able to create arbitrary free-form surfaces but also offers excellent intrinsic alignment of multi-component lenses. The diameter of 3D printed optical elements fabricated by this technique usually ranges from tens of micrometers to several hundreds of micrometers. The challenge thus is pushing the size of the printed structures from the micrometer into the millimeter realm. This is in principal possible by dividing a larger lens into smaller units which are printed sequentially, however, the stitching marks between adjacent units deteriorate the imaging quality. Furthermore, the increased size and volume of the lenses reveals one of the downsides of the commonly used materials: they often retain a yellow color after polymerization, resulting in reduced imaging quality. In this work, we overcome these challenges with the help of two distinct advances: The use of a novel microscope objective with a large writing field in combination with a new commercially available photoresist with low absorption and low luminescence in the visible wavelength range. This combination enables us to 3D print millimeter-sized lenses without stitching marks and unprecedented optical clarity.

2. Fabrication

The 3D printer used for the fabrication is a Nanoscribe Photonic Professional GT with a 10x objective (numerical aperture: 0.3). A liquid photoresist is hardened by laser-induced two-photon polymerization. The laser is focused by a microscope objective, generating a small polymerized region called a voxel (volume pixel). By moving the voxel through the resist, arbitrary 3D structures can be created. An overview of the printed lenses under investigation is displayed in Fig. 1(a). The aspheric lens on the left is designed to demonstrate the superior focusing ability of non-spherical lenses with free-form surfaces. The lens diameter is 1 mm. The half-ball lenses in the middle and on the right have diameters of 1 mm and 2 mm and are printed to compare them to commercially available glass lenses with the same shape and size. The resist used for the lenses is called IP-Visio (Nanoscribe GmbH) and was recently introduced. Compared to other resists for two-photon polymerization, e.g., IP-S (Nanoscribe GmbH), the yellow color is significantly reduced. This is particularly obvious in Fig. 1(b), where cubes with 1 mm side length fabricated from IP-S (left) and IP-Visio (right) are displayed side-by-side.

3. Aspherical focusing lens

Being able to create non-spherical lens shapes is one of the crucial advantages of 3D printing, especially when it comes to more complex optical systems. In order to demonstrate this, we fabricate an aspherical focusing lens with a diameter of 1 mm and a center thickness of 227 µm. It is essential that deviations of the printed lens from the optical design caused by shrinking of the polymer are minimized. Therefore, we use an iterative optimization procedure to improve the shape fidelity. The surface profile after two iterations (blue) in Fig. 1(c) matches the optical design (red) much better than the first printed lens (black). A laser with a wavelength of 550 nm is focused 880 µm behind the lens, matching the designed focal length of 873 µm very well. The laser spot in Fig. 1(d) has beam radii of 0.760 µm in x direction and 0.711 µm in y direction, which is close to the simulated Airy disk radius of 0.762 µm.
4. Comparison with glass lenses

While our aspherical lenses emphasize the design freedom of our 3D printing technique, it is impracticable to compare them directly to similar lenses made from glass, which is the ultimate benchmark material for polymer optics. Aspherical glass lenses with 1 mm diameter cannot be obtained easily, therefore we print a spherical half-ball lens with 1 mm diameter and compare it to a readily available equivalent glass lens (Edmund Optics). Scanning electron microscopy (SEM) is used to examine the surface of the printed lens, which looks very smooth in general (Fig. 1(e)). Only at the very top the discretized layer structure is slightly visible. The radius of curvature (ROC) of the lens is determined by confocal surface mapping ($\mu$surf expert, Nanofocus AG) to be 496 µm, which is very close to the ROC of 500 µm of the glass reference lens. Images of a USAF 1951 resolution test target placed in front of both lenses can be seen in Fig. 1(f) and Fig. 1(g). The general color impression and contrast is very similar, however, the glass lens shows a slightly better imaging quality, when examining elements 4 to 6 of group 7. Reasons for this could be residual deviations from the spherical shape and the surface roughness. Overall, these measurements underline the excellent optical quality and performance of our 3D printed lenses as well as of the lens material.

5. Conclusion

We have successfully fabricated aspherical and spherical singlet lenses with diameters up to 2 mm. The focal length and measured spot size of the aspheric lens match the design parameters very well. Compared to a commercially available glass lens, the imaging quality of our printed half-ball lens is only slightly reduced. Although the lenses studied in this work are basic optical components with a single curved surface, the knowledge of the underlying fabrication process is a crucial first step towards more complex optical systems, e.g., free-hanging lenses with two surfaces or multi-lens objectives for smartphone cameras. Furthermore, we expect the new resist to have a high damage threshold due to its high transparency, which is crucial for high-power applications, e.g., customized optical instruments for medical surgery.

6. Funding

Bundesministerium für Bildung und Forschung (PRINTOPTICS, PRINTFUNCTION), European Research Council (AdG COMPLEXPLAS, PoC 3DPRINTEDOPTICS), Deutsche Forschungsgemeinschaft (SPP1839, SPP1929), Baden-Württemberg Stiftung (OPTERIAL), IQST

7. References

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