

From Two-Photon Grayscale Lithography to Scalable Replication: Enabling Complex Aspherical Micro-Optics for Mass Production

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The evolution of complex micro-optics from prototyping to scalable manufacturing is a key challenge for modern imaging, sensing, and photonic systems. Two-photon polymerization grayscale lithography (2GL) revolutionized the fabrication of micro-optics by combining aspherical lenses with micro-features enabling performance increases, weight reduction, aberration correction, and beam shaping. Its scalability for mass production, however, remains a key limitation. In this study, the replication and integration of 3D printed optics are demonstrated through electroplating and injection molding processes, enabling high-volume production without sacrificing precision. Advancements in replicating complex micro-optics fabricated via 2GL are presented by designing and 3D printing a diffractive, aspherical micro-lens array. In relation to their size, these optics are almost impossible to produce with common techniques such as precision turning. The topography, beam profiles, and imaging quality of the 3D printed master are compared to the replicated lens array. By combining 2GL 3D printing and injection molding, micro-optical mass production of arbitrary geometries is enabled. It is highlighted how this approach unlocks new opportunities for scalable production, addressing disparities between rapid prototyping and industrial manufacturing of micro-optics.

1. Introduction

In recent years, two-photon polymerization (2PP) emerged as one of the most promising additive manufacturing methods for optical components.^[1,2] The lithographic fabrication method has gathered significant attention due to its range in resolution and structure size, reaching from multiple millimeters^[3] down to nanometers,^[4,5] making it a powerful tool for fabrication of optics,^[2,6–8] quantum applications,^[9–11] fluidics,^[12,13] and micromechanics.^[14–16] The process is based on photoactive resins, structured via two-photon absorption, a nonlinear optical process wherein the concurrent absorption by a photosensitive molecule is triggered by near infrared, ultra-short pulsed and tightly focused laser light. Precise movement of this polymerized volume in the focus, called a voxel (volume pixel) in the photopolymer using galvo scanners allows polymerization of arbitrary 3D structures. The resin-based approach enables a range of different materials to be processed like optical polymers,^[1]

glasses,^[17–20] or ceramics.^[21] While offering the resolution and versatility in producing highly complex structured geometries, 2PP is currently a research-focused technology. Prototypes fabricated with 2PP often show multifunctional capabilities, but their practical application, especially in optical systems, is frequently limited due to challenges in the seamless integration of printed structures into functional setups. Often fabricated on carrier substrates such as glass,^[3,6,13] silicon,^[22] or optical fibers,^[7,23] prototypes require careful handling, particularly for micro-scale features. As optical elements made of polymers are highly sensitive to dust, dirt, or scratches, handling and manipulating such printed elements becomes highly complex. From an industrial production perspective, the process is constrained by its high cost and lengthy fabrication, making it less viable for large-scale manufacturing. Recently, the introduction of Two-Photon Polymerization Grayscale Lithography (2GL) has accelerated production by dynamically adjusting the laser power during the fabrication. This allows the fabrication of optically smooth surfaces with larger slicing distances in comparison to the typical 2PP

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fabrication, reducing printing times.^[6,24] However, with improvements in speed and surface finish, 2GL is still limited in production capacities. In this context, several fabrication methods have been reported for the production of polymer micro-lenses. Among the most common are Ultra-Precision Diamond Turning, Laser Direct Writing (LDW), and Nanoimprint Lithography (NIL). While Diamond Turning achieves surface roughness values below $R_a = 10$ nm and dimensional errors below $0.5 \mu\text{m}$,^[25] micro-structured surfaces or diffractive surface structures are limited to the sizes of the diamond tool radii. LDW in photore-sists enables flexible fabrication of diffractive optical elements. A few machines allow binary writing with feature sizes below $0.5 \mu\text{m}$, achieved through a radial-moving beam on a rotating substrate. With grayscale systems, surface roughness can be lowered down to $R_a = 20\text{--}40$ nm, yet the process is mostly limited to 2.5D.^[26,27] Electron Beam Lithography (EBL) achieves the highest structural resolution with feature sizes below 50 nm, yet fabrication often requires multiple days for a single master. The surface roughness varies due to staircasing effects comparable to stereolithography. In addition, proximity effects hinder the fabrication of diffractive structures, limiting the capabilities of EBL for micro-optics.^[28] Since all these processes are serial processes, their throughput remains inherently low. While these methods are essential for the precise fabrication of optical master structures, they are not suitable for high-volume production. Therefore, replicating optical master structures through parallel processes such as NIL or Injection Molding is the key to an ultra-precise, high-throughput manufacturing of advanced optical systems. NIL offers rapid replication and surface roughness below $R_a = 35$ nm,^[29,30] but is limited to shallow and planar structures, proving inefficient in the fabrication of refractive aspheres and structures exceeding structural depth.^[31] The production of multiple parts from a single prototype requires a stamp, which resembles the master structure in the highest possible accuracy. Therefore, repetitive techniques such as NIL often use polydimethylsiloxane (PDMS) stamps because they are cheap and easy to produce via casting,^[32] achieve high resolution and are well-suited in lab-based environments such as microfluidics^[33] or photonics engineering.^[34] While PDMS stamps provide high pattern accuracy, their lifetime is typically limited to only 10–50 replications due to their weak resistance against external influences such as mechanical and thermal stress or chemical exposure. Therefore, tool-based manufacturing processes like injection molding are fundamental for high-quality mass production, especially for micro-optical components such as free-form lenses, diffractive optical elements or micro-lens-arrays.^[35–37] One injection molding shot takes less than 30 s making it suitable to produce more than 1000 parts per day with a single cavity molding tool. As injection molding does not require photopolymerizable resins, a wide mixture of different materials can be injected, such as thermoplastic polymers,^[38–40] or glass.^[41–43] The most significant advantage of the injection molding process is its high scalability paired with extreme robustness of the tools. Although the initial costs are relatively high, a precisely manufactured injection molding tool enables the production of an extensive number of polymer optics^[36] with consistent precision in a short time period, highlighting the process efficiency and productivity. To maintain the goal of mass-producible high precision polymer components, micro- and nanostructures are usually embedded directly into

functional parts such as lenses and thus are directly carved into the molding tool. Since injection molding is a process that involves high pressures and temperatures, the durability of the tool relies on the materials used and therefore often consists of aluminum, hardened steel or additional coatings, further increasing the surface hardness. The direct integration of optical structures in these surfaces and their accuracy is mostly limited to classic subtractive tooling approaches such as milling and turning. Tooling with a focused ion beam has been shown as a promising technique to fabricate small diffractive lenses but is not suitable for lens arrays or bigger structures, since the process is heavily cost- and time-intensive and requires uncommon tool materials like titanium.^[44] To overcome these limitations, indirect integration methods such as electroplating have emerged as powerful alternatives. Electroplating is a precise technique to create high-precision tool inserts for injection molding.^[45] In the process, nickel is transferred onto a micro-structured surface via a Galvano process to create a precise mold, referred to as shim, resembling the surface structure in nickel. The subsequent integration of the shim into an injection molding tool enables imprinting of the negative structure into a polymer component, making it a suitable technique to integrate microstructure-based optical functions into polymer surfaces.^[40,46] In general, nickel offers multiple advantages, including high robustness, stiffness, and a thermal expansion coefficient that is close to tooling steel, which makes a nearly seamless integration into injection molding tools possible. While different metal alloys like copper can also be plated, they are not suitable for the high pressure and temperatures of the molding process. Recent developments also demonstrated tool-fabrication via casting of amorphous metals as an alternative to nickel-shims which delivered promising results for tooling in future applications.^[47]

To validate the unique production value and versatility of the proposed approach, we demonstrate the fabrication of an aspherical, diffractive micro-lens array, initially produced as a high-resolution prototype using 2GL and subsequently replicated as a scalable polymer component. We demonstrate the optical properties of both, the master structure and the replica to demonstrate the immense potential of the process chain, enabling next-generation optical devices and advanced sensor systems.

2. Results and Discussion

In this section, the complete fabrication workflow of the aspherical micro-lens array is presented. We start from optical design and 2GL 3D printing through electroplating-based mold production and injection molding and conclude with optical performance validation. **Figure 1** provides a process overview of the steps included in the production process.

2.1. Optical Design, 3D printing, and Topography of Master Structures

The master sample consists of multiple lens arrays composed of three design types that have different focal lengths, diameters, and surface properties as well as the two logos, visible on the right of **Figure 2**. All lenses have been designed using the

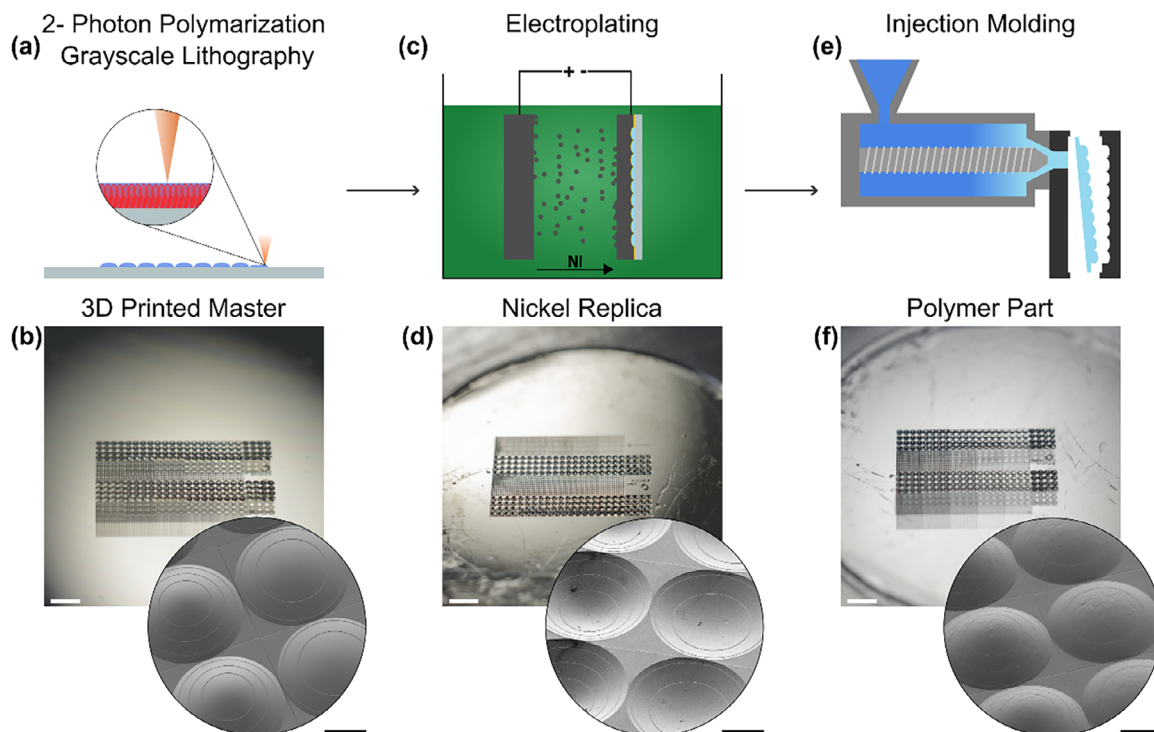


Figure 1. Fabrication workflow and manufactured micro-optical elements at each stage of the workflow. Schematic of the process in three steps. a) Two-photon polymerization grayscale lithography to produce a 3D printed master structure containing aspherical, diffractive micro-lenses on a glass substrate. c) Electroplating of the surface structures, coated via physical vapor deposition. e) Injection molding with the nickel mold for high-fidelity replication of the surface. Associated photographs and SEM micrographs of the results for b) 3D printing, d) Electroplating, f) Injection molding. White scale bars represent 1 mm, black scale bars represent 100 μm .

raytracing software Ansys Zemax OpticStudio 20.1. The optical designs in the top two rows of the master were adjusted for the refractive index of the used injection molding material cyclic olefin copolymers (COC TOPAS 5013L-10, TOPAS Advanced Polymers GmbH), while the bottom two rows were adjusted for the refractive index of the resist used in fabrication of the 3D printed master, Nanoscribe IP-S^[48] (Nanoscribe GmbH & Co. KG, Germany). COC was chosen as molding material due to the low process viscosity and high structure replication abilities as measured by Rytka.^[49]

The lens arrays include multiple conic lenses with diameters of 100 and 300 μm , designed for the wavelength of 633 nm. The two shortest focal length designs of each type are presented in Figure 3a,b. The surface of the conic is given by the formula

$$z(r) = \frac{r^2/\text{ROC}}{1 + \sqrt{1 - (1+k)r^2/\text{ROC}^2}} \quad (1)$$

where z is the height, r the radius, ROC the radius of curvature and k the conic constant. For a fixed diameter and focal length, ROC and k are optimized in the design software. The focal lengths of the smaller 100 μm lenses are fixed at 100, 200, 300, 400, and 500 μm , as well as 200, 400, 600, 800, and 1000 μm for the larger 300 μm diameter lenses. As the refractive index of the photopolymer Nanoscribe IP-S for the 3D printed master and the polymer COC TOPAS 5013L-10 for the replicated

lenses differ slightly, we design two pairs of lenses for each design, one for the 3D printed master and one for the replicated lenses. All lenses exhibit diffraction-limited focal spots. In addition to the monochromatically designed conic lenses, four hybrid achromatic lens designs have been designed for the two wavelengths 500 and 700 nm, a diameter of 300 μm , and focal lengths of 200 and 400 μm , the first of which can be seen in Figure 3c. These hybrid lenses^[50] consist of an aspheric base topography, which has a diffractive lens structure on top. The topography is given as

$$z(r) = \frac{r^2/\text{ROC}}{1 + \sqrt{1 - (1+k)r^2/\text{ROC}^2}} + \sum_{m=2}^M a_{2m} r^{2m} + \frac{\lambda}{2\pi n} \text{mod} \left(\sum_{k=0}^K b_{2k} \left[\frac{r}{r_{\text{norm}}} \right]^{2k}, 2\pi \right) \quad (2)$$

Here, the first part describes the underlying conic lens topography as already given above. The first sum with parameters a_{2m} defines the aspheric part up to order M , and b_{2k} gives the diffractive polynomial terms up to order K . Furthermore, r_{lens} , n_{lens} , and λ are defined as the lens radius, the refractive index of the lens, and the wavelength of the diffractive lens. In our study, we optimize the lens surfaces up to the terms a_{16} and b_{16} , corresponding to an aspherical order of $M = 8$ and a diffractive order of

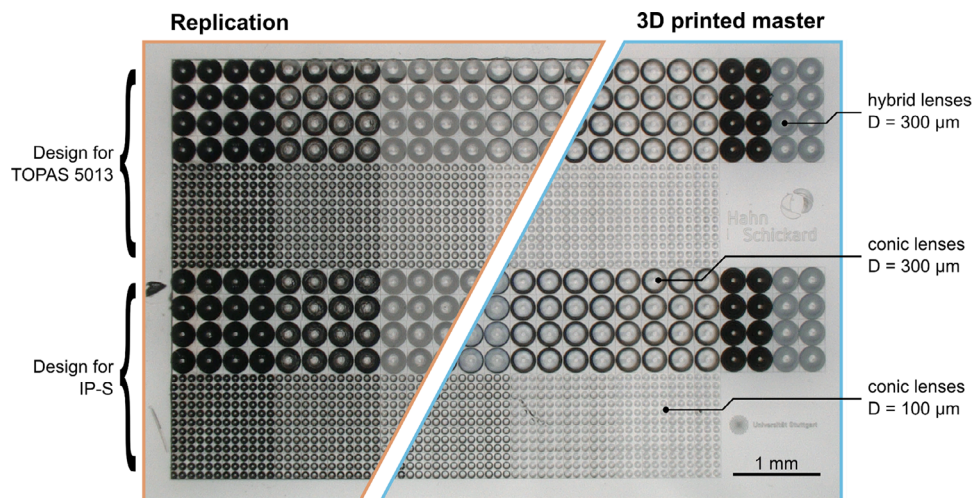


Figure 2. Top-view microscope image of the lens array comparing the master and replication. The left side shows the replicated structure, the right side the 3D printed master (imaged with Keyence VHX6000). In total 1632 lenses are displayed. The top two rows show conic and hybrid lenses designed for TOPAS 5013L-10 as well as the Hahn–Schickard Logo. The bottom two rows display the same lenses, designed for Nanoscribe IP-S and the logo of the University of Stuttgart. 1440 refractive conic lenses ($D = 100\ \mu\text{m}$), 160 refractive conic lenses ($D = 300\ \mu\text{m}$), and 32 hybrid achromatic aspheric-diffractive lenses ($D = 300\ \mu\text{m}$) were printed within 13 h.

$K = 8$. The hybrid lenses have diffraction-limited spots for the entire spectral range between the design wavelengths of 500–700 nm. In total, the 3D printed master consists of 1632 lenses and the two logos, placed over an area of 4.8 mm by 7.2 mm. The heights range from 4.65 μm for the 100 μm diameter, 500 μm focal length refractive lens design for COC TOPAS 5013L-10, to 73.56 μm for the 300 μm diameter, 200 μm focal length hybrid achromatic lens design for Nanoscribe IP-S. These two lenses also illustrate the range of numerical apertures (NAs) of the array, ranging from 0.10 to 0.60, respectively. For the same NA lens, the designs from Nanoscribe IP-S are slightly higher than those for COC TOPAS 5013L-10 due to their smaller refractive index. All lens design parameters are given in Tables S1 and S3 (Supporting Information).

The designs are fabricated by 2GL using a commercially available 3D printer (Quantum X, Nanoscribe GmbH & Co. KG). A femtosecond pulsed laser centered at a wavelength of 780 nm with a repetition rate of 80 MHz is focused through a 25x magnification objective with a NA of 0.8 (Zeiss LCI Plan-Neofluar 25x/0.8 Imm Korr DIC) and into the clear and liquid photoresist Nanoscribe IP-S (Nanoscribe GmbH & Co. KG), which has been dropped onto a square glass substrate (25 mm sidelength and 0.7 mm thickness). Due to the high intensity in the focus, two photons are absorbed simultaneously, resulting in the polymerization of an ellipsoid-shaped portion of the photoresist, called a voxel. The laser is scanned in the xy-plane using a pair of Galvo mirrors with a speed of 200 mm s^{-1} , and each scanned line is separated by a hatching distance of 200 nm. After finishing the first layer, the substrate moves down by the slicing distance of 1 μm using a piezo-electric stage and continues to print the next layer. Typically, this relatively large slicing distance would result in a rough surface with steps on the order of the slicing distance and is usually circumvented by reducing the slicing distance and increasing print time. 2GL overcomes this issue by adjusting the laser power dynamically between 8 and 50 mW with an acousto-optical modulator that adjusts the power depend-

ing on the designed surface. 2GL keeps the printing time minimal and provides highly smooth surfaces with root-mean square surface roughness values S_q down to single-digit nanometers.^[24] Larger structures than the field of view of the microscope objective are created by stitching multiple printing fields together. Fabrication of the circa 35 mm^2 large master sample takes ≈ 13 h. An overview photograph and SEM micrograph of the 3D printed master is presented in Figure 1b, while a top-view microscope image is depicted in Figure 2.

We measured and analyzed the topography of the 3D printed master using confocal microscopy ($\mu\text{surf expert}$, Nanofocus AG). The measured topography of the highest NA lenses of each of the three lens design types are depicted in Figure 3a,c as they are the thickest lenses for each design type and have the steepest edges, resulting in the most challenging topographies for each fabrication step. The center column in Figure 3 displays the topography, measured with a confocal microscope with a 0.95 NA, 50x magnification objective. The only visible steps are the desired diffractive structures of the hybrid lens in Figure 3k, which show up as concentric rings. The right column of Figure 3 illustrates profiles of the measured topography in x- and y-direction as marked in the corresponding topography plot in the center. Here, we also show the designed profile and the deviations from the design, where a defocus term was subtracted as the lens concentrates all optical power in the top surface. The deviations of the 100 μm conic lens presented in Figure 3f are below 0.4 μm peak-to-valley (PtV) for both profiles. The conic lenses with a diameter of 300 μm depicted in Figure 3b have maximum deviations below 1 μm PtV for each profile. This discrepancy in comparison to the smaller conic lens in Figure 3a scales well with the size of the lens. The deviations of the hybrid lens shown in Figure 3c are roughly on the same scale as the ones of the larger conic lens. They have four distinct jumps in the deviations at the position of the diffractive rings and can be explained by slight radial shrinking of the structure during polymerization. Moreover, we analyzed the surface roughness of the sample by extracting several 100 μm by 100 μm

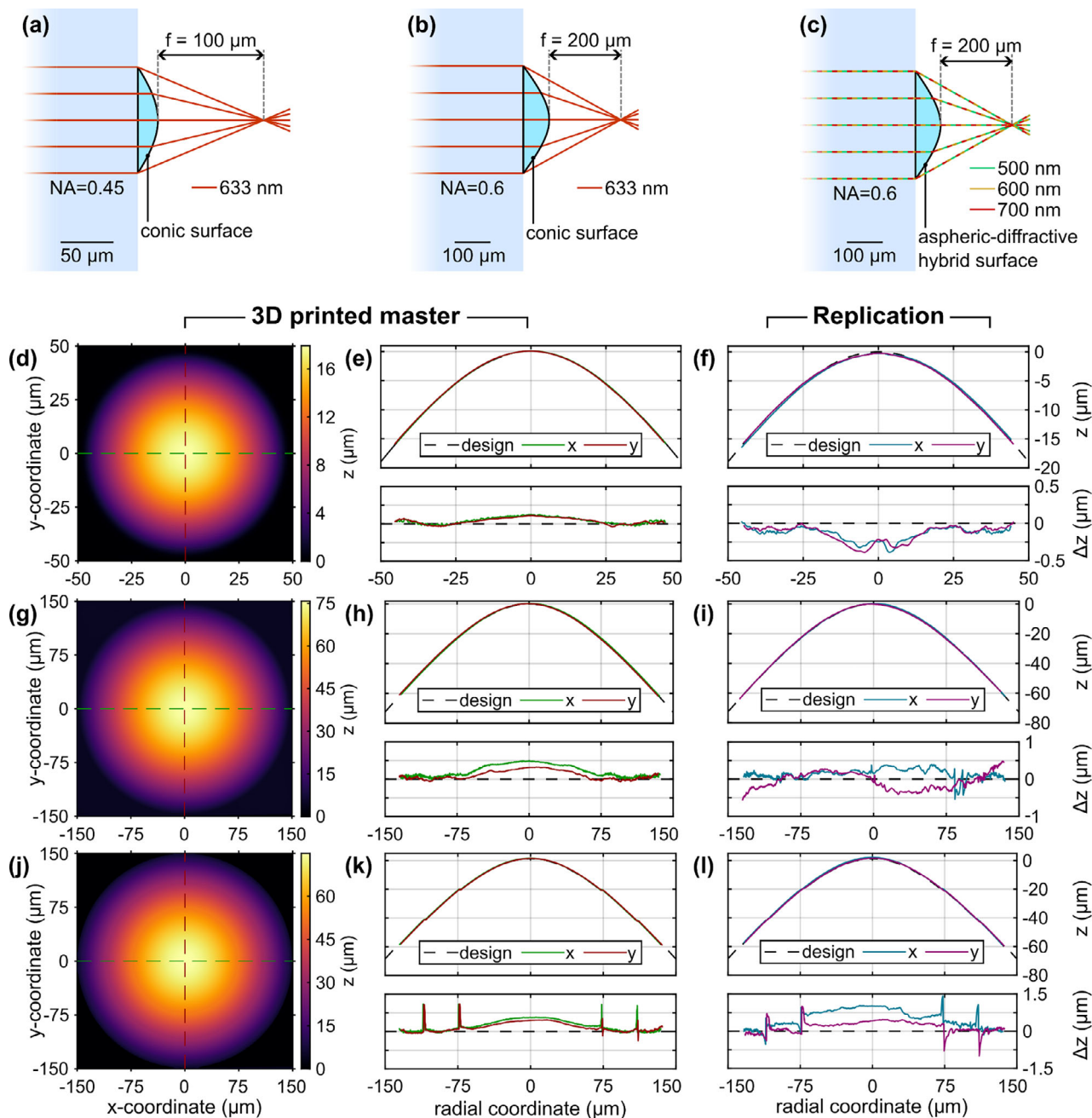


Figure 3. Ray-optical design, topography, profiles, and profile deviations of the 3D printed master and replicated lenses. a) Conic lens with a diameter of 100 μm and a focal length of 100 μm. b) Conic lens with a diameter and focal length of 300 and 200 μm, respectively. Both conic lenses are designed for the wavelength 633 nm. c) Hybrid achromatic lens consisting of an aspheric base topography with a diffractive surface on top. The hybrid lens is designed for the wavelength range of 500–700 nm with a diameter and focal length of 300 and 200 μm respectively. Panels (d–f) show the 2D topography and profile plus profile deviations of the 3D printed master and replicated conic lens shown in (a). In panels (g–i), we give the 2D topography, profile, and profile deviations of the 3D printed master and replicated hybrid lens schematized in (c). The profiles and profile deviations are displayed as cuts in x- and y-direction and compared to the design. The z- and Δz-scales are the same for each lens type of the 3D-printed master and replication.

fields of the confocal measured topographies. We subsequently Fourier short-pass filtered the topography with a filter areal linear Gaussian at the spatial cut-off frequency of $2.5 \mu\text{m}^{-1}$. We determined the root mean square (rms) surface roughness (Sq) of the 3D printed master samples to be at 4–17 nm (ISO 25178-1).

2.2. Replication of Optical Structures

As presented in Figure 1 the replication of the 3D printed aspherical micro-lenses involves a multi-step process that transforms a printed prototype into a scalable polymer optic. One major step is

the replication of the optical structures in a metallic mold insert via nickel electroplating.

To enable the plating process, a conductive seed layer of 3 nm chrome and 10 nm gold was deposited via physical vapor deposition (PLS 500, Pfeiffer Vacuum GmbH) on the 3D-printed surface. Electroplating was then performed in a small-scale plating unit (Walter Lemmen GmbH) using a nickel salt electrolyte. With a constant current density of 0.17 A dm^{-2} over a period of 120 h $\approx 5 \text{ mm}$ of nickel was deposited on the surface. This prolonged deposition time ensured a uniform and defect-free nickel layer suitable for use as a mold insert in the injection molding process. After deposition the 3D-printed master was mechanically separated from the nickel shim and residual resist was removed through various cleaning steps. Electric discharge machining was used to prepare the mold insert for the injection molding tool.

The final replication step, as shown in Figure 1e was conducted via injection molding. The nickel shim was integrated into a custom mold insert and mounted on an Arburg 370A machine (ARBURG GmbH & Co. KG). Cyclic olefin copolymer (COC, TOPAS 5013L-10) was used as molding material in the following step. Molding parameters are included in the Supporting Information. Due to a refractive index of $n_d = 1.533$ and a high optical transparency, the material was well-suited for precision molding of optical components. Smaller surface defects were seen in the SEM but only had minor influences on the optical performance as shown in the following results. The observed defects are likely occurring from adhesion phenomena between COC and nickel, as reported in previous studies.^[49]

We measured and analyzed the topography of the injection molding parts via confocal microscopy. As shown in Figure 3, the resulting geometries exhibit sub-micron deviations relative to the printed samples. The analyzed replicated samples have S_q rms surface roughness values between 6 and 20 nm, showing only a small increase in comparison to the 3D printed master and highlighting the effectiveness of the galvanically assisted replication and accuracy of injection molding for sub-micron features.

2.3. Optical Performance Testing

Analyzing surface topography is only one step in optics evaluation, with the main one being optical performance testing. We measure, analyze, and discuss both the beam profiles and imaging quality of both the 3D printed master as well as the replicated lenses depicted in Figure 1b,f, respectively.

To measure the beam profiles, we utilize a setup previously introduced in ref. [24]. The samples are illuminated by a collimated and wavelength-tunable laser source (NKT SuperK Extreme and NKT SuperK Select+, NKT Photonics A/S) which is then directed onto the lenses. The light is subsequently focused by the manufactured optics and imaged by a basic microscopy setup consisting of a 60x magnification, 0.7 NA microscope objective (CFI S Plan Fluor 60x ELWD MRH08630, Nikon), a 1.5x magnification tube lens, and a camera (GC2450C, Allied Vision). In order to measure the 3D intensity distribution around the focal plane, the lenses are axially moved around the focus by $\pm 50 \mu\text{m}$ in steps of $0.1 \mu\text{m}$ by a piezoelectric stage (P-736 PI nano Z, Physik Instrumente (PI) SE & Co. KG). In Figure 4, we plot the intensity in

the focal plane on the left and the axial intensity in the yz -plane for the three lens designs with highest NA. We directly compare the beam profiles of the 3D printed master and the replicated lenses. To quantify deviations, we fit a Gaussian function to the intensity along the x -, y -, and z -axis through the point of highest intensity. From these fits we can extract the full width at half maximum (FWHM) values, giving us the opportunity for a quantitative performance comparison. All FWHM values of the measured 3D printed master and the measured replicated lenses as well as the design are plotted in Figure S1 (Supporting Information). The beam profiles for three lenses of the 3D printed master, designed for the photopolymer Nanoscribe IP-S are shown in Figure 4a,c,e, those of the replicated master, designed for COC TOPAS 5013L-10 in Figure 4b,d,f. For the 3D printed refractive master lens with a diameter and focal length of $100 \mu\text{m}$, depicted in Figure 4a, we measure a symmetric focal spot, where even the first diffraction ring of the Airy disk is visible in the xy -focal plane. The FWHM values in the focal plane are $1.28 \mu\text{m}$ in x - and $1.28 \mu\text{m}$ in y -direction, and $7.97 \mu\text{m}$ along the optical axis. The beam profile for the same lens design of the replicated sample is depicted in Figure 4b and exhibits the same symmetrical focus spot, with FWHM of 1.26 , 1.25 , and $8.17 \mu\text{m}$ in x -, y -, and z -direction. The difference of the fitted values is small enough to be attributed to measuring inaccuracies in the setup and manual alignment of the two samples. The 0.6 NA lenses also show great focusing performance, as graphed in Figure 4c,e, and the expected tighter intensity distribution in comparison to the 0.45 NA design plotted in Figure 4a. The more concentrated intensity distribution is also quantitatively given in the fitted FWHM values. The beam profiles of the 3D printed master lens with a diameter and focal length of 300 and $200 \mu\text{m}$ is presented in Figure 4c and has a FWHM of 0.98 , 0.99 , and $5.34 \mu\text{m}$ in x -, y -, and z -direction. The beam profile of the replicated lens of the same design is presented in Figure 4d and shows slightly larger FWHM values with 1.19 , 1.56 , and $5.51 \mu\text{m}$ in x -, y -, and z -direction. There are, however, some aberrations left in the system most likely resulting from the larger PtV surface topography discrepancies to the design. The most visible aberration in the beam profiles shown for both the 3D printed master lens in Figure 4c and the replicated lens in Figure 4d is coma, which could be corrected by tilting the sample. The performance of the refractive-diffractive hybrid achromatic lens is displayed in Figure 4e for the 3D printed master and in Figure 4f for the replicated sample. Differences in performance of the 3D printed master and the replicated lenses illustrate the same trend as the purely refractive lens in Figure 4c,d. At the shorter end of the design spectrum of 500 nm , the 3D printed master lens has FWHM values of 0.81 , 0.86 , and $3.98 \mu\text{m}$ in x -, y -, and z -direction. The replicated lens has slightly larger values with 1.09 , 1.24 , and $3.86 \mu\text{m}$ in x -, y -, and z -direction. As expected theoretically, the FWHM values in x - and y -direction follow a linear trend with the wavelength. The measured focal length shift with wavelength, expressed by the longitudinal chromatic aberration (LCA) is $\pm 276 \text{ nm}$ for the 3D printed master lens and $\pm 209 \text{ nm}$ for the replicated lens. These LCA values are both smaller than the designed diffraction-limited range of $2.6 \mu\text{m}$ for the 3D printed master and $2.5 \mu\text{m}$ for the replicated lens, determined by Ansys Zemax OpticStudio, illustrating ideal achromatic behavior, which is important for imaging applications. All FWHM values of both the 3D printed master and the replicated

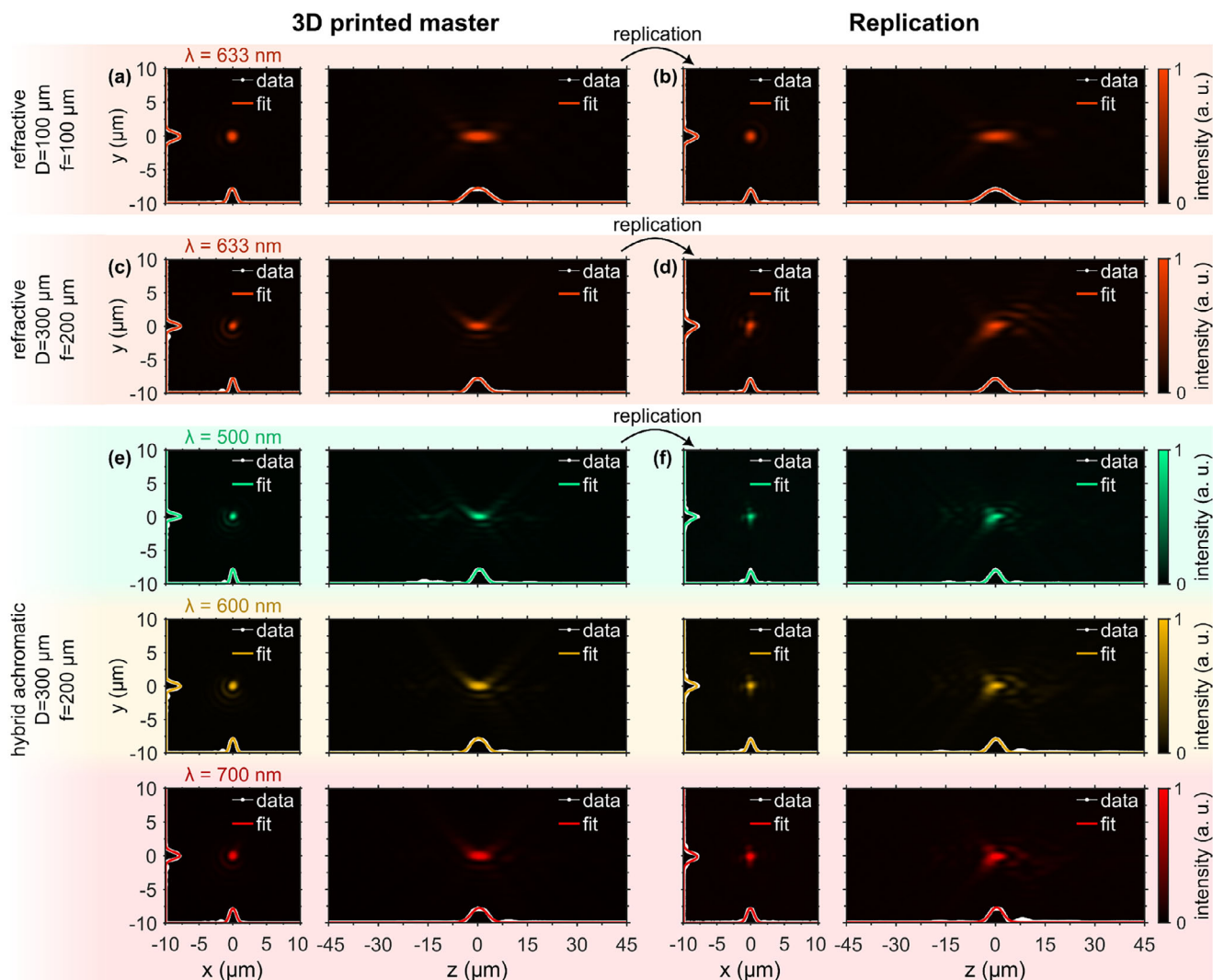


Figure 4. Beam profile comparison of the 3D printed (left) and replicated lenses (right). Both the xy-intensity in the focal plane and the intensity along the optical axis, with a cut along the yz-plane are shown. All plots show intensity profiles across the x-, y-, and z-direction which are all fitted with a Gaussian profile. The fitted FWHM-values are graphed and compared to the design in Figure S1 (Supporting Information). The panels in (a,b) show the beam profile of the refractive lens with both a diameter and focal length of 100 μm at a wavelength of 633 nm. (c,d) depict the intensity distributions of the refractive lens with a diameter of 300 μm , focal length of 200 μm also at 633 nm. Panels (e,f) show the intensity distributions of the hybrid refractive-diffractive achromatic lens with a diameter of 300 μm and focal length of 200 μm at the wavelengths 500 nm in green, 600 nm in yellow, and 700 nm in red.

lenses are plotted in Figure S1 (Supporting Information), giving a direct comparison. In general, the replicated lenses show only slight deviations in focusing performance from the 3D printed master, highlighting the potential of galvanically assisted injection molding replication for mass producible freeform optical solutions. Optical performance deviations of the manufactured lenses from the design can be explained with the topographical errors from the design, slight misalignment such as tilts in the optical setup, and during printing and replication. Further corrections in the optical quality could be made using an iterative optimization algorithm for the surface deviations,^[24,51] resulting in profile deviations below 100 nm PtV.

We additionally analyzed the imaging quality with a USAF 1951 resolution test chart, which are depicted in Figure 5. Here,

we examine both the 3D printed master and the replicated lenses, two refractive lens designs with diameters and focal lengths of 100 and 200 μm , as well as 300 and 400 μm , respectively. The imaging quality of the hybrid lens design with a diameter and focal length of 300 and 400 μm is also shown in Figure 5. The setup was previously highlighted in refs. [24,52] and utilized with minor adjustments. A collimated white light LED (MCWHL1 and SM1U25-A, Thorlabs) strikes a diffuser (DG10-1500-A, Thorlabs), ensuring a homogeneous illumination, is focused by a 20x magnification microscope objective (M Plan Apo 20x, NA = 0.42, Mitutoyo) through the USAF 1951 resolution test chart (USAF HI-RES Target 2IN SQ NEG, Edmund Optics) onto the lens array. The beam diameter can be adjusted with an iris placed in the back focal plane of the objective. Images of the test charts

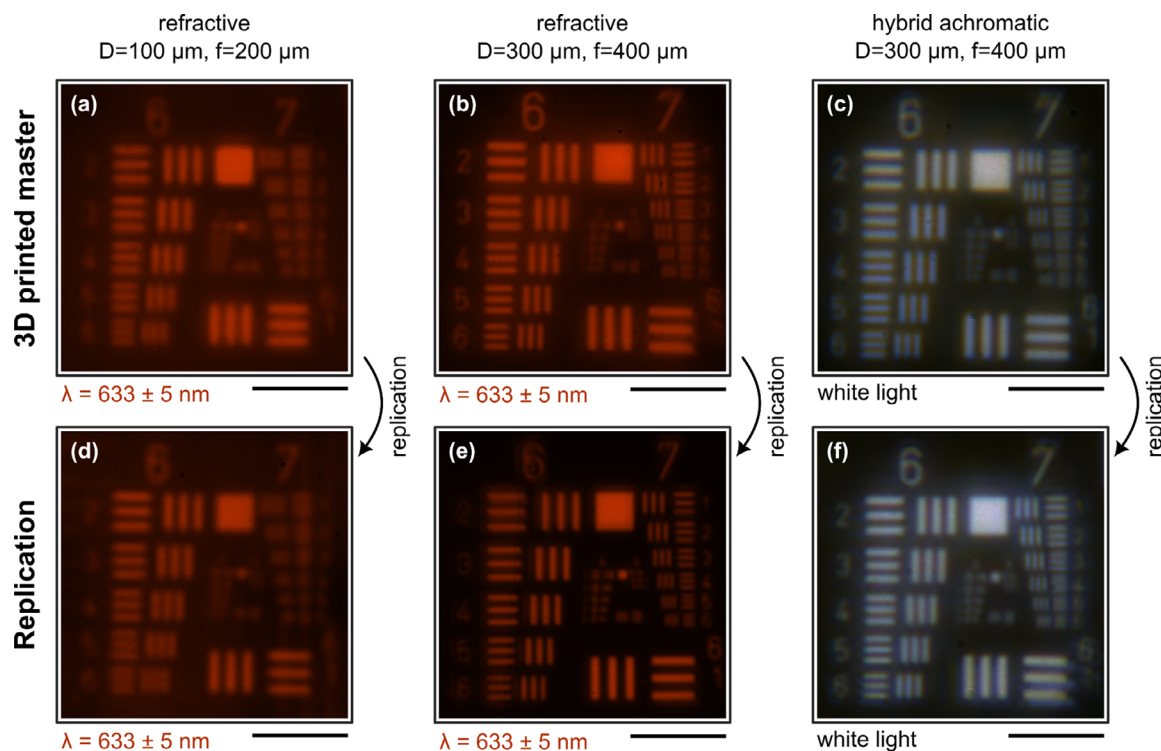


Figure 5. Imaging quality comparison of the 3D printed master and replication with an USAF 1951 test chart. The scale bars have a length of 50 μm and correspond to the physical size of the test chart. Panels (a) through (c) show imaging tests with the 3D printed lenses, (d–f) depict imaging tests with the replicated lenses having the same lens designs. The images (a,d) are taken with the 100 and 200 μm focal length refractive lens, (b) and (e) with the 300 and 400 μm focal length refractive lens. (c,f) Hybrid achromatic imaging with white light using the 300 μm diameter, 400 μm focal length lens.

formed by the lenses are imaged by a microscopy setup consisting of a 50x magnification microscope objective (M Plan Apo 50x, NA = 0.55, Mitutoyo), a tube lens, and a camera (UI-3180CP-C-HQ R2.1, IDS). For the imaging tests of the purely refractive lenses, a bandpass filter centered at 633 nm with a FWHM of 10 nm (FL05632.8-10, Thorlabs) is placed in between the LED light source and the diffusor. The imaging tests of the refractive lenses have been imaged in the monochromatic mono8 format and recolored with color of light with a wavelength of 633 nm. The hybrid lens imaging tests were conducted in the RGB8 format. In Figure 5, we compare the imaging performance of the 3D printed master and replicated lenses, again using three different lenses. The performance of the refractive lens with a diameter of 100 μm and focal length of 200 μm is displayed in Figure 5a for the 3D printed master lens and in Figure 5d for the replicated lens. The imaging performance of both lenses is comparable, with clear lines of the USAF 1951 test chart until about group 6, element 4 (90.5 lp mm^{-1}). No noticeable field curvature or distortion is apparent for the 3D printed master and the replicated lens. Imaging with the larger 300 μm diameter, 400 μm focal length refractive lens is demonstrated in Figure 5b,e, for the 3D printed master and the replicated lens, respectively. This lens, with a slightly larger 0.35 NA in comparison to the smaller 100 μm diameter lens, illustrates higher contrast for both the 3D printed master and replicated lens, where element 3 of group 7 (161.3 lp mm^{-1}) can still be distinguished. Again, no major field curvature or distortion are visible. White-light imaging with the hybrid achromatic lens with diameter and focal lengths of

300 μm and 400 μm , respectively, is depicted in Figure 5c for the 3D printed master and in Figure 5f for the replicated lens. The imaging contrast is comparable to the larger refractive lens presented in Figure 5b,e. Both lenses provide high-quality achromatic imaging with only slight transverse chromatic aberrations, visible for example as the slight off-white coloring in the upper part of the 3D printed master lens. All lenses show performant high-contrast imaging in the visible with no apparent field curvature or distortion. Differences in performance of the 3D printed master and the replicated lenses are minute, emphasizing the powerful technique of replication. Imaging performance could be enhanced using doublet designs that can be replicated by our presented method if 3D printed in a two-sided design such as presented by M. Schmid et al.^[53]

3. Conclusion and Outlook

We demonstrated a functional process chain to replicate 2GL printed optical structures via small-scale electroplating and injection molding. The process enables the production of small aspheric optics with high NA, low surface roughness $\approx 10 \text{ nm S}_q$ rms, and integrated surface features such as achromatic diffractive correction. We have validated the process with an injection molding machine, but the small-scale electroplating makes it also suitable for lab-based “table top” processes like NIL or molds for PDMS casting. The resulting nickel molds are highly durable and allow production of multiple thousands of parts with a single mold with precision in the range of the printed master structures.

We have measured the optical quality of both, master and molded lenses, and conclude that molded replicas reproduce the performance of the grayscale structures not only in the optical quality but also in the surface roughness.

This process chain enables both prototyping and large-batch manufacturing of high-NA micro-optics, from refractive micro-lenses to hybrid refractive–diffractive achromats, with cycle times under a minute per lens array. Future work may address system-level integration of said micro-optics in larger assemblies and photonic components. Applications could also include further materials research, enabling unique combinations such as glass-based micro-optics for injection molding.^[42,43,54,55] The extreme resolution of the mastering process, paired with a high-accuracy replication, allows for the integration of anti-reflective microstructures in the master and therefore in the mold. The integration of functional elements such as optical alignment structures, anti-reflective structures,^[30] or meta-optical structures needs to be further investigated in future research. Optimizing the injection molding process will lead to smaller cycle times and higher surface quality, enabling a large-scale production process for otherwise almost impossible optic designs. Different sources have shown direct printing of multi-element optical systems.^[7,22,24] Replication of such systems through injection molding will require additional manufacturing steps. One approach can be the replication of individual lenses and the subsequent combination of these to form a compound optical system. A major application example for such replication processes could be found in the manufacturing of endoscopic devices or smartphone lenses, where barrels are commonly used to stack individual lenses after fabrication. These approaches often require active alignment, which could be avoided if lens stacks were directly produced in a single step. A manufacturing route capable of replicating complex lens assemblies as demonstrated through 3D printing would represent a significant breakthrough for optics manufacturing.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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additive manufacturing, grayscale lithography, injection molding, micro-optics, replication, two-photon polymerization

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- [1] H. Wang, W. Zhang, D. Ladika, H. Yu, D. Gailevicius, H. Wang, C.-F. Pan, P. N. S. Nair, Y. Ke, T. Mori, J. Y. E. Chan, Q. Ruan, M. Farsari, M. Malinauskas, S. Juodkazis, M. Gu, J. K. W. Yang, *Adv. Funct. Mater.* **2023**, 33, 2214211.
- [2] D. Gonzalez-Hernandez, S. Varapnickas, A. Bertoncini, C. Liberale, M. Malinauskas, *Adv. Opt. Mater.* **2023**, 11, 2201701.
- [3] S. Ristok, S. Thiele, A. Toulouse, A. M. Herkommer, H. Giessen, *Opt. Mater. Express* **2020**, 10, 2370.
- [4] G. Seniutinas, A. Weber, C. Padeste, I. Sakellari, M. Farsari, C. David, *Microelectron. Eng.* **2018**, 191, 25.
- [5] L. Zheng, K. Kurselis, A. El-Tamer, U. Hinze, C. Reinhardt, L. Overmeyer, B. Chichkov, *Nanoscale Res. Lett.* **2019**, 14, 134.
- [6] T. Aderneuer, O. Fernández, R. Ferrini, *Opt. Express* **2021**, 29, 39511.
- [7] T. Gissibl, S. Thiele, A. Herkommer, H. Giessen, *Nat. Photonics* **2016**, 10, 554.
- [8] B. H. Cumpston, S. P. Ananthavel, S. Barlow, D. L. Dyer, J. E. Ehrlich, L. L. Erskine, A. A. Heikal, S. M. Kuebler, I.-Y. S. Lee, D. McCord-Maughon, J. Qin, H. Röckel, M. Rumi, X.-L. Wu, S. R. Marder, J. W. Perry, *Nature* **1999**, 398, 51.
- [9] M. Colautti, P. Lombardi, M. Trapuzzano, F. S. Piccioli, S. Pazzagli, B. Tiribilli, S. Nocentini, F. S. Cataliotti, D. S. Wiersma, C. Toninelli, *Adv. Quantum Technol.* **2020**, 3, 2000004.
- [10] L. Bremer, K. Weber, S. Fischbach, S. Thiele, M. Schmidt, A. Kaganskiy, S. Rodt, A. Herkommer, M. Sartison, S. L. Portalupi, P. Michler, H. Giessen, S. Reitzenstein, *APL Photonics* **2020**, 5, 106101.
- [11] A. Landowski, J. Gutsche, S. Guckenbiehl, M. Schönborg, G. von Freymann, A. Widera, *APL Photonics* **2020**, 5, 016101.
- [12] M. Luitz, B. M. Kirpat Konak, A. Sherbaz, R. Prediger, N. Nekoonam, B. Di Ventura, F. Kotz-Helmer, B. E. Rapp, *Adv. Mater. Technol.* **2023**, 8, 2300667.
- [13] G. van der Velden, D. Fan, U. Staufer, *Micro Nano Eng.* **2020**, 7, 100054.
- [14] I. S. Ladner, M. A. Cullinan, S. K. Saha, *RSC Adv.* **2019**, 9, 28808.
- [15] Y. Lin, J. Xu, *Adv. Opt. Mater.* **2018**, 6, 1701359.
- [16] M. Carlotti, V. Mattoli, *Small* **2019**, 15, 1902687.
- [17] F. Kotz, A. S. Quick, P. Risch, T. Martin, T. Hoose, M. Thiel, D. Helmer, B. E. Rapp, *Adv. Mater.* **2021**, 33, 2006341.
- [18] X. Wen, B. Zhang, W. Wang, F. Ye, S. Yue, H. Guo, G. Gao, Y. Zhao, Q. Fang, C. Nguyen, X. Zhang, J. Bao, J. T. Robinson, P. M. Ajayan, J. Lou, *Nat. Mater.* **2021**, 20, 1506.
- [19] P.-H. Huang, M. Laakso, P. Edinger, O. Hartwig, G. S. Duesberg, L.-L. Lai, J. Mayer, J. Nyman, C. Errando-Herranz, G. Stemme, K. B. Gylfason, F. Niklaus, *Nat. Commun.* **2023**, 14, 3305.
- [20] J. Bauer, C. Crook, T. Baldacchini, *Science* **2023**, 380, 960.
- [21] J. C. Sängner, B. R. Pauw, H. Sturm, J. Günster, *Open Ceramics* **2020**, 4, 100040.
- [22] S. Thiele, K. Arzenbacher, T. Gissibl, H. Giessen, A. M. Herkommer, *Sci. Adv.* **2017**, 3, 1602655.

- [23] T. Gissibl, S. Thiele, A. Herkommer, H. Giessen, *Nat. Commun.* **2016**, 7, 11763.
- [24] L. Siegle, S. Ristok, H. Giessen, *Opt. Express* **2023**, 31, 4179.
- [25] M. Jagodzinski, S. Kühne, D. Oberschmidt, *J. Opt. Microsyst.* **2024**, 4, 023501.
- [26] M. Haefner, C. Pruss, W. Osten, *Appl. Opt.* **2011**, 50, 5983.
- [27] S. Wang, Z. Zhou, B. Li, C. Wang, Q. Liu, *Mater. Today Nano* **2021**, 16, 100142.
- [28] V. Grigaliunas, A. Lazauskas, D. Jucius, D. Virzonis, B. Abakeviciene, S. Smetona, S. Tamulevicius, *Microelectron. Eng.* **2016**, 164, 23.
- [29] M. Choi, J. Kim, S. Moon, K. Shin, S.-W. Nam, Y. Park, D. Kang, G. Jeon, K.-I. Lee, D. H. Yoon, Y. Jeong, C.-K. Lee, J. Rho, *Nat. Mater.* **2025**, 24, 535.
- [30] A. Jacobo-Martín, N. Jost, J. J. Hernández, C. Domínguez, G. Vallerotto, S. Askins, I. Antón, I. Rodríguez, *Opt. Express* **2021**, 29, 34135.
- [31] N. Kooy, K. Mohamed, L. T. Pin, O. S. Guan, *Nanoscale Res. Lett.* **2014**, 9, 320.
- [32] Y. Xia, J. Tien, D. Qin, G. M. Whitesides, *Langmuir* **1996**, 12, 4033.
- [33] K. Raj M, S. Chakraborty, *J. Appl. Polym. Sci.* **2020**, 137, 48958.
- [34] C. Park, W. Kim, Y. Kim, H. Sung, J. Park, H. Song, J. Kim, D. K. Oh, H. Kang, N. Jeon, J. Rho, H. Lee, *Adv. Opt. Mater.* **2024**, 12, 2301562.
- [35] Y. Hu, C. Xue, *Sci. Rep.* **2025**, 15, 15451.
- [36] C. Peixoto, P. T. Valentim, P. C. Sousa, D. Dias, C. Araújo, D. Pereira, C. F. Machado, A. J. Pontes, H. Santos, S. Cruz, *Precis. Eng.* **2022**, 76, 29.
- [37] H. Zhang, H. Liu, N. Zhang, *Micromachines* **2022**, 13, 1530.
- [38] V. Kalima, J. Pietarinen, S. Siitonen, J. Immonen, M. Suvanto, M. Kuittinen, K. Mönkkönen, T. T. Pakkanen, *Opt. Mater.* **2007**, 30, 285.
- [39] A.-K. Holthausen, O. Riemer, J. Schmütz, A. Meier, *J. Manuf. Processes* **2017**, 26, 290.
- [40] S. Wagner, K. Treptow, S. Weser, M. Drexler, S. Sahakalkan, W. Eberhardt, T. Guenther, C. Pruss, A. Herkommer, A. Zimmermann, *Micromachines* **2023**, 14, 1223.
- [41] S. Guo, M. A. Ali, M. A. Mohamed, X. Han, X. Liu, J. Qiu, *Mater. Chem. Front.* **2024**, 8, 1400.
- [42] M. A. Mohamed, M. A. Ali, G. Shaorun, X. Liu, J. Qiu, *Adv. Opt. Mater.* **2024**, 12, 2400323.
- [43] M. Mader, O. Schlatter, B. Heck, A. Warmbold, A. Dorn, H. Zappe, P. Risch, D. Helmer, F. Kotz, B. E. Rapp, *Science* **2021**, 372, 182.
- [44] S. Ristok, M. Roeder, S. Thiele, M. Hentschel, T. Guenther, A. Zimmermann, A. M. Herkommer, H. Giessen, *Opt. Lett.* **2020**, 45, 1184.
- [45] W. Ehrfeld, *Micro System Technologies* 90, Springer, Berlin **1990**, 521–528.
- [46] M. Roeder, T. Guenther, A. Zimmermann, *Micromachines* **2019**, 10, 233.
- [47] S. Kluck, R. Prediger, L. Hambitzer, N. Nekoonam, F. Dreher, M. Luitz, M. Lunzer, M. Worgull, M. Schneider, B. E. Rapp, F. Kotz-Helmer, *Adv. Sci.* **2024**, 11, 2405320.
- [48] M. Schmid, D. Ludescher, H. Giessen, *Opt. Mater. Express* **2019**, 9, 4564.
- [49] C. Rytka, Replication of functional polymeric micro- and nanostructures, <https://doi.org/10.17877/DE290R-17239>, (accessed: July 2025).
- [50] M. Schmid, F. Sterl, S. Thiele, A. Herkommer, H. Giessen, *Opt. Lett.* **2021**, 46, 2485.
- [51] J. Weinacker, S. Kalt, P. Kiefer, P. Rietz, M. Wegener, *Adv. Funct. Mater.* **2024**, 34, 2309356.
- [52] L. Siegle, D. Xie, C. A. Richards, P. V. Braun, H. Giessen, *Opt. Express* **2024**, 32, 35678.
- [53] M. Schmid, S. Thiele, A. Herkommer, H. Giessen, *Opt. Lett.* **2023**, 48, 131.
- [54] M. A. Mohamed, M. A. Ali, S. Guo, X. Liu, S. Sun, J. Qiu, *Adv. Opt. Mater.* **2025**, 13, 2403434.
- [55] M. A. Mohamed, M. A. Ali, G. Shaorun, X. Liu, J. Qiu, *Adv. Opt. Mater.* **2024**, 12, 2400576.