

Xolography – Rapid volumetric 3D printing of optical elements

Martin Regehly¹, Yves Garmshausen², Torsten Döhler¹, Martin Herder²

¹ Technische Hochschule Wildau, Hochschulring 1, 15745 Wildau

² xolo GmbH, Volmerstraße 9B, 12489 Berlin

Corresponding author: martin.regehly@th-wildau.de

Xolography is a dual-color volumetric 3D printing technology enabling the continuous, layer-free fabrication of transparent optical components in minutes. Here, we present the characterization of xolographically printed elements using the acrylate-based xoloClear resin. We report refractive index dispersion ($V_d \approx 62$), nanometer-scale surface roughness ($S_a = 28$ nm), and an iterative pre-compensation scheme that improves shape precision, reducing front-surface shape deviation from 45.6 μm to 2.1 μm RMS.

1 Introduction

The additive manufacturing (AM) of optical components requires high structural precision, isotropic bulk properties, and optical-grade surface smoothness. Conventional layer-based techniques like Stereolithography (SLA) or Digital Light Processing (DLP) suffer from stair-casing artifacts and internal material interfaces, requiring extensive post-processing such as manual polishing or coating. Two-Photon Polymerization (2PP) provides sub-micrometer resolution but is limited by fabrication speed for micrometer-to-millimeter scale optics. [1]

Xolography overcomes these limitations as a continuous volumetric additive manufacturing (VAM) methodology. By intersecting a thin UV light sheet ($\lambda_1 = 375$ nm) with a projected visible light image ($\lambda_2 = 450$ -700 nm), dual-color photoinitiators (DCPI) are locally excited to initiate localized polymerization within a moving resin volume. This process omits layer recoating and build-plate attachment, producing homogeneous, interface-free optical elements directly out of the vat within minutes. [2]

2 Material and Methods

Material and Hardware: Printing experiments were conducted using the commercial urethane-methacrylate resin xoloClear ($\eta = 2.5$ Pa·s at 25°C), containing a spiropyran-based DCPI (DCPI 2001). Resin was filled into transparent 10×35×10 mm³ fluorescence cuvettes. Volumetric printing was executed on a xolo XUBE-2 printer. A dual-sided laser module generated an intersecting UV light sheet focused to a FWHM thickness of 50 μm . Orthogonal visible projections were focused onto the light sheet plane using a 4K DMD projection system.

Print Workflow and Post-Processing: STL models were sliced with a step size of 1 μm and fabricated at a print speed of $v_p = 2$ mm/min and UV dose $E_{UV} = 9$ mJ/mm². Following printing, parts were

extracted, washed in tripropyleneglycol monomethylether (TPM) for 20 min, rinsed in isopropyl alcohol (IPA) for 30 s, and immersed in IPA containing 2 wt% TPO-L (90 s). Parts were oven-dried at 70°C (5 min), post-cured under UV-LED irradiation (10 min), and thermally annealed at 110°C (15 min). Residual yellow coloration from reaction by-products was photo-bleached under a white-light LED array (6000 K, 130 mW/cm², 15 min).

Metrology: Refractive index (n) dispersion was determined across the visible spectrum (390 - 670 nm) using a minimum deviation spectrometer with a hollow glass prism setup. Surface topography and areal roughness were measured using White Light Interferometry (WLI) and 3D laser confocal microscopy (Keyence VK-X3000 / VK-X3050, 10X/20X objectives, $\lambda_c = 0.08$ mm). Shape fidelity was evaluated by aligning stitched 3D point-clouds against nominal CAD geometries.

3 Results and Discussion

Optical Dispersion and Refractive Index: The spectral dispersion of both unreacted liquid resin and cured polymer was fitted using the three-term Cauchy equation $n(\lambda) = A + B/\lambda^2 + C/\lambda^4$:

State	A	B	C	$n(587.6 \text{ nm})$	V_d
Liquid	1.4503	0.0130	-0.0003	1.4831	~ 23
Cured	1.5028	0.0023	0.0003	1.5126	~ 62

Tab. 1 Cauchy parameters, refractive indices, and Abbe numbers for liquid and cured xoloClear (Relative error = 0.14%).

Polymerization induces a refractive index increase of $\Delta n \approx 0.03$ at 587.6 nm (d -line) due to molecular densification. The crosslinking reaction triggers a strong shift in optical dispersion, driving the Abbe number from $V_d \approx 23$ in the liquid resin to $V_d \approx 62$ in the solid state. While the liquid feedstock resides in the highly dispersive flint-glass regime, the fully

cured xoloClear polymer transitions into the crown-glass region of the Abbe diagram (comparable to N-BK7 or PMMA). This combination of an elevated refractive index and low chromatic dispersion makes the cured matrix well-suited for multi-element imaging optics.

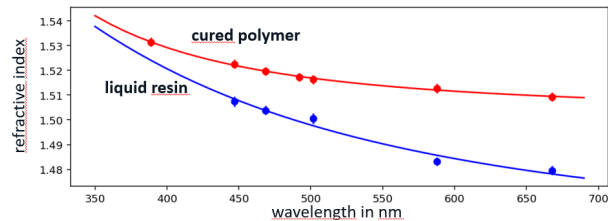


Fig. 1 Refractive index dispersion and Cauchy fit curves.

Optical Dispersion and Refractive Index: Surface quality was evaluated in the center of a printed plano-convex lens ($d = 7$ mm, $\text{ROC} = 30$ mm) using WLI after polynomial tilt and form subtraction.

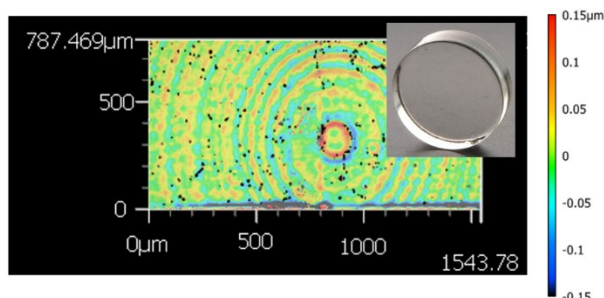


Fig. 2 Printed lens & Surface characterization using WLI.

The areal surface roughness of S_a (Mean Height) = 28 nm and S_q (RMS Height) = 53 nm demonstrates that xolography delivers optical-grade surface quality directly out of the vat without secondary polishing. Previously reported line-profile comparisons confirm that printed optics match the surface finish of commercial polished glass lenses ($R_a = 19\text{--}21$ nm). [1]

Shape characterization and digital pre-compensation: To evaluate geometric fidelity, a plano-convex lens (PCV) with a diameter of $d = 7$ mm and radius of curvature (ROC) of 30 mm was printed and characterized via 3D confocal profilometry ($16 \times 12 = 192$ stitched sub-images).

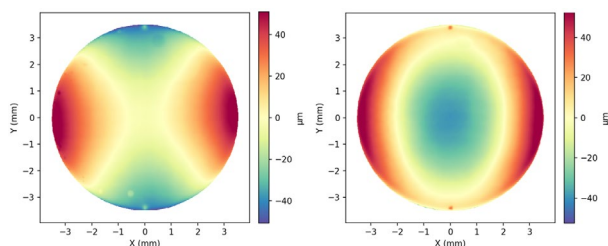


Fig. 3 Height deviation of the printed PCV lens (Generation 0) with respect to the ideal PCV lens. Left: flat back surface, right: curved front surface.

Initial uncompensated prints (see Fig. 3) exhibited a pronounced astigmatism shape deviation of the lens attributed to the opposing two light sheet setup. To eliminate these errors, an iterative compensation loop was implemented. Height-error maps extracted from laser confocal microscopy were fitted using Zernike polynomials and applied to the nominal geometry for generating a next generation input STL model.

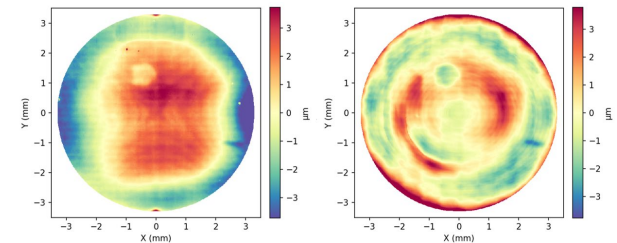


Fig. 4 Height deviation of the STL-corrected (Generation 3) printed PCV lens compared to the ideal PCV lens. Left: flat back surface, right: curved front surface

The compensation loop reduced front-surface RMS shape error by 22-fold (from 45.6 μm down to 2.1 μm) across the 7 mm aperture, demonstrating two micrometer geometric shape precision for the third-generation corrected lens. (Fig. 4) A residual astigmatism is still visible in back surface of the lens.

Lens surface	Original STL	Compensated (Gen-3)
Front (curved side)	45.6 μm RMS 96.1 μm PV99	2.1 μm RMS 7.9 μm PV99
Back (flat side)	22.8 μm RMS 98.4 μm PV99	2.0 μm RMS 8.5 μm PV99

Tab. 2 Shape precision comparison: Uncompensated vs. compensated printed PCV lens ($\text{ROC} = 30$ mm).

4 Conclusion

Xolography enables rapid, continuous volumetric 3D printing of optical elements. By combining xoloClear resin with digital pre-compensation workflows, we demonstrated low chromatic dispersion, optical surface smoothness directly out of the vat and 2 μm shape fidelity via closed-loop digital mesh correction. These results make xolography as a transformative platform for rapid prototyping and custom fabrication of complex, freeform optical components.

5 References

- [1] M. Herder, Y. Garmshausen, M. C. Tauber, Y. Arzhangnia, M. Reuter, "Direct 3D printing of optical elements with xolography", Proc. SPIE **13381**, Advanced Fabrication Technologies for Micro/Nano Optics and Photonics XVIII, 133810C (2025)
- [2] M. Regehly, Y. Garmshausen, M. Reuter, N. F. König, E. Israel, D. P. Kelly, C.-Y. Chou, K. Koch, B. Asfari, S. Hecht, "Xolography for linear volumetric 3D printing", Nature **588**, 620–624 (2020).