

Printed Micro-Optics in Photopolymers: Lens Form, Surface Error, Refractive State and Optical Qualification

From printed geometry to measured wavefront: state variables and qualification routes for polymer micro-optics

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Abstract

Printed micro-optics are unusually sensitive to the difference between nominal shape and realised optical state. This review treats a printed lens as a coupled geometry-material system: sag, centring, edge form, surface spatial-frequency content, refractive index, dispersion and environmental conditioning all contribute to focal and wavefront performance. Two-photon and vat-photopolymer routes are compared as manufacturing platforms rather than ranked by nominal resolution alone. The review separates metrology of form from metrology of refractive state, then links both to focal length, point-spread function, modulation transfer and scatter. Particular attention is given to process-induced shrinkage, voxel anisotropy and post-cure drift, because these can produce apparently correct dimensions while moving optical power. Qualification is framed around traceable surface and material measurements that predict functional error before system-level testing, with multilevel Fresnel microlenses providing an example of how fabrication fidelity and focusing efficiency must be assessed together.

Keywords: printed micro-optics; photopolymer; two-photon lithography; microlens; surface error; refractive index; wavefront; optical qualification

1. Significance and scope

Micro-optics compress an optical prescription into dimensions where micrometre-scale form error and nanometre-to-micrometre surface structure are no longer secondary manufacturing details. A qualification strategy must therefore identify which measured variables control optical power, aberration and scatter, and must distinguish those variables from printer settings. The central engineering problem is not whether a lens can be printed, but whether its finished form and refractive state remain within a functionally justified acceptance region after cleaning, post-cure and environmental exposure.

1.1 Corpus boundary

ER-331 owns qualification of printed refractive micro-optics as finished optical components. ER-332 owns subwavelength metasurfaces, ER-338 periodic photonic crystals, ER-339 resolved diffractive phase elements, and ER-427 photonic packaging/alignment. ER-331 may use those technologies as comparison points but does not absorb their device physics.

2. Geometry is not optical performance

A CAD-perfect lens can fail optically when polymerisation shrinkage, voxel anisotropy, slicing, support interaction, development and post-cure change the sag profile. Qualification therefore starts with measured surface form and not nominal geometry. Form error, local roughness and edge roll-off should be separated because they influence focal length, scatter and aberration differently [1,2,4] [6].

3. Refractive state must be treated as a material variable

The relevant refractive index is that of the finished, conditioned optic at the wavelength and temperature of use. Conversion, residual solvent, water uptake and post-cure can shift density and dispersion. Optical qualification should therefore pair dimensional metrology with refractive-index or wavefront measurements instead of assuming a catalogue index [1-3].

4. Manufacturing-route effects

Two-photon lithography offers sub-micrometre placement and freeform 3D geometry, whereas projection and layerwise vat processes trade resolution for throughput [1-3]. The engineering choice should be based on the spatial frequency of the required surface, acceptable staircase error, field size and the ability to measure the finished optic.

5. Optical qualification

A defensible qualification sequence combines surface profilometry or interferometry, refractive-state measurement, focal or modulation-transfer testing, stray-light or scatter assessment and environmental conditioning. A focal spot alone cannot distinguish surface-form error from index error or alignment bias [5].

6. Qualification architecture

Qualification should close a causal loop between measured form, optical material state and device response. Surface sag and centring establish the macroscopic optical boundary; roughness and mid-spatial-frequency error address scatter; refractive index and dispersion establish optical power; focal, wavefront or MTF measurements then test whether these inputs explain the realised function. When the model does not close, the unexplained residual is itself a manufacturing signal rather than a reason to tune acceptance limits retrospectively.

7. Minimum evidence for transfer

Transfer evidence must include the finished-optic state, not only the exposure recipe. A defensible transfer package records resin/material identity, fabrication modality, writing or projection strategy, development and post-cure history, surface-form metrology, index/dispersion conditions and at least one functionally relevant optical measurement. For freeform optics, spatially resolved form error is more informative than a single RMS number; for diffractive or multilevel elements, step fidelity and focusing efficiency should be retained together [5].

7.1 Evidence hierarchy and transfer

Evidence is strongest when an independent measurement predicts the direction of optical change. For example, a measured index shift should predict focal-length drift with the correct sign, while increased high-spatial-frequency roughness should increase scatter without necessarily moving paraxial focus. Reproducing only a focal spot is weaker evidence because different combinations of form and refractive error can give similar intensity images.

7.2 Research priorities

Priority work includes reference micro-optics with traceable sag and wavefront maps, interlaboratory comparison of polymer refractive-index measurements, and uncertainty budgets that propagate form and index error into optical acceptance. Long-term data are also needed on humidity, temperature and post-cure relaxation because polymer optics can drift after dimensional inspection has already passed.

Table 1. Minimum qualification matrix for printed photopolymer micro-optics.

Optical state	Minimum measurement	Qualification purpose
Geometry	surface sag, diameter, centring, edge form	establishes actual optical boundary
Surface	roughness and mid-spatial-frequency error	predicts scatter and wavefront degradation
Material state	refractive index and dispersion at use wavelength	separates geometry from optical-material effects
Function	focal length, wavefront or MTF	tests system-relevant performance
Stability	thermal/humidity conditioning and retest	tests drift after fabrication

8. Interpretation matrix

Interpretation should separate optical symptoms that are degenerate in a single test. Focal shift, broadened PSF, edge aberration and environmental drift each admit several mechanisms; the discriminating control is the measurement that isolates form, refractive state or scatter rather than another image of the same focal plane.

Table 2. Diagnostic interpretation matrix for printed micro-optics.

Observed optical response	Competing mechanism	Discriminating measurement
Focal length offset with good form	refractive index differs from design	measure index/dispersion and wavefront
Broad PSF with correct focal length	roughness or higher-order form error	surface PSD and interferometry
Edge aberration only	centering or edge roll-off	full-aperture form map
Optics drift after humidity exposure	sorption-induced index or geometry shift	mass/index/form before and after conditioning

9. Limitations and evidence gaps

The literature is rich in proof-of-concept lenses but sparse in common metrology and uncertainty reporting. Material formulations, development protocols and optical wavelengths differ substantially across studies, so numerical performance thresholds are not portable without matched state variables. This review does not prescribe a universal roughness, index or wavefront limit; those limits must be derived from the optical system requirement and the measurement capability available to enforce it.

10. Conclusions

Printed micro-optics should be released on the basis of measured optical state, not CAD fidelity alone. Form, surface spectrum and refractive index are independent contributors to performance and must be measured at conditions relevant to use. When those quantities are linked to wavefront, focal or MTF behaviour, process changes can be diagnosed rather than compensated blindly. The practical endpoint for ER-331 is a qualification chain in which geometry and material measurements explain optical performance with declared uncertainty.

References

1. Wang H, Zhang W, Ladika D, Yu H, Gailevičius D, Wang H, Pan C-F, Nair PNS, Ke Y, Mori T, Chan JYE, Ruan Q, Farsari M, Malinauskas M, Juodkazis S, Gu M, Yang JKW. Two-Photon Polymerization Lithography for Optics and Photonics: Fundamentals, Materials, Technologies, and Applications. *Advanced Functional Materials*. 2023;33(39):2214211. doi:10.1002/adfm.202214211.
2. Chekkaramkodi D, Jacob L, Shebeeb CM, Umer R, Butt H. Review of vat photopolymerization 3D printing of photonic devices. *Additive Manufacturing*. 2024;86:104189. doi:10.1016/j.addma.2024.104189.
3. O'Halloran S, Pandit A, Heise A, Kellett A. Two-Photon Polymerization: Fundamentals, Materials, and Chemical Modification Strategies. *Advanced Science*. 2023;10(7):e2204072. doi:10.1002/advs.202204072.
4. Zhou X, Hou Y, Lin J. A review on the processing accuracy of two-photon polymerization. *AIP Advances*. 2015;5(3):030701. doi:10.1063/1.4916886.
5. Wang Z, Chen L, Zang T, Naderi Bakhtiyari A, Qi D, Wu Y, Yu W, Zheng H. Enhancing optical integration: One-step fabrication of multilevel and bifocal Fresnel diffractive microlenses with high focusing efficiency via two-photon polymerization. *Journal of Manufacturing Processes*. 2025;149:198-206. doi:10.1016/j.jmapro.2025.05.071.
6. Gonzalez-Hernandez D, Varapnickas S, Bertoncini A, Liberale C, Malinauskas M. Micro-Optics 3D Printed via Multi-Photon Laser Lithography. *Advanced Optical Materials*. 2023;11(1):2201701. doi:10.1002/adom.202201701.

Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. No comparative product recommendation is made.

Data availability

No new experimental dataset was generated for this review.