

Diffractive Optical Elements Made by Photopolymerisation: Phase Control, Surface Quantisation and Efficiency

Engineering surface-relief and volumetric diffractive elements from phase height to order efficiency and stray light

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3Dresyns by Resyner Technologies S.L.

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Abstract

Diffractive optical elements made by photopolymerisation encode optical phase in surface relief or discretised height levels, making phase-depth fidelity, quantisation, roughness and material index central manufacturing variables. This review distinguishes a resolved diffractive optical element from both refractive micro-optics and subwavelength metasurfaces. Two-photon and vat-photopolymer reviews provide the process context, while direct fabrication of multilevel Fresnel diffractive microlenses illustrates the coupling between step fidelity and focusing efficiency. Qualification is organised around measured relief depth, lateral registration of phase zones, refractive index at the operating wavelength, diffraction efficiency and unwanted-order power. A nominally correct profile can still lose efficiency through index error or roughness, while an efficiency deficit can arise from phase-depth bias, quantisation or alignment. The proposed framework therefore requires a measured phase model rather than efficiency alone.

Keywords: diffractive optical element; photopolymer; phase quantisation; surface relief; diffraction efficiency; Fresnel lens; two-photon polymerisation

1. Significance and scope

A diffractive optical element converts a manufactured height or refractive-index pattern into phase delay. The relevant dimensional error is therefore not generic surface deviation but error in the phase function after the realised refractive index is considered. This makes vertical calibration, lateral zone placement and material dispersion jointly responsible for efficiency and wavefront quality.

1.1 Corpus boundary

ER-339 owns resolved diffractive optical elements based on surface-relief or phase quantisation. ER-331 owns refractive micro-optics, ER-332 subwavelength metasurfaces, ER-338 periodic photonic crystals, and ER-428 microresonators. ER-339 excludes structures whose function depends primarily on subwavelength meta-atom resonance.

2. Phase depth is the central fabrication state

A surface-relief DOE converts height into optical phase through refractive-index contrast. Height error, index error and wavelength therefore enter the same phase budget. Geometry and optical material state must be measured together [1-4] [5].

3. Quantisation trades manufacturability for efficiency

Binary and multilevel phase surfaces approximate a continuous phase function. Fewer levels simplify fabrication but generate stronger unwanted orders; more levels demand tighter height control and edge fidelity [3].

4. Pixel and edge effects matter

Finite lateral resolution, voxel shape, layer staircasing and polymer shrinkage alter duty cycle and transition sharpness. Small systematic errors can shift energy between diffraction orders without visibly changing the macroscopic part.

5. Qualification by order-resolved efficiency

A complete test measures intended-order efficiency, zero-order leakage, stray orders and wavelength/angle dependence. Focal intensity alone can hide substantial parasitic power.

6. Qualification architecture

Qualification should reconstruct the realised phase profile from measured surface height and refractive index, then compare it with the design phase. Zone placement, step height and edge fidelity are measured separately because they redistribute optical power differently. Diffraction efficiency, focal distribution or wavefront measurement then tests the functional consequence of the reconstructed phase error.

7. Minimum evidence for transfer

Transfer evidence includes the fabrication and post-cure state, profile metrology, operating wavelength, index/dispersion data, aperture definition and measurement of desired and unwanted diffraction orders. Multilevel Fresnel microlenses demonstrate why step count and fabricated relief must be connected explicitly to focusing efficiency rather than inferred from nominal design [3].

7.1 Evidence hierarchy and transfer

A phase-depth bias should shift power systematically among orders, whereas roughness or edge defects can increase diffuse scatter. Measuring only the main-order efficiency cannot separate those mechanisms. The evidence hierarchy therefore favours a measured relief-to-phase calculation combined with order-resolved optical data.

7.2 Research priorities

Priority work includes traceable vertical calibration for multilevel relief, aperture-wide phase metrology and uncertainty budgets that propagate index and height error into efficiency. Environmental studies should quantify whether moisture or thermal exposure changes both geometry and refractive state enough to invalidate an initially correct phase profile.

Table 1. Minimum qualification matrix for photopolymer diffractive optical elements.

Diffractive state	Minimum measurement	Qualification purpose
Phase geometry	relief height and lateral duty cycle	defines designed phase
Material	index at test wavelength	converts height to phase
Efficiency	power in intended order	tests useful function
Stray light	zero and unwanted orders	reveals quantisation/fabrication error
Bandwidth	efficiency versus wavelength/angle	tests application window

8. Interpretation matrix

Reduced main-order efficiency, increased zero order, asymmetric sidelobes and wavelength-dependent focus error are treated as distinct observations. The matrix pairs them with profile, registration, index and scatter measurements so that the corrective action addresses the actual phase error source.

Table 2. Diagnostic interpretation matrix for diffractive-efficiency loss.

Optical observation	Plausible phase error	Discriminating control
High zero order	insufficient phase depth or level bias	height/index measurement
Efficiency falls off-design wavelength	expected phase dispersion or material dispersion	spectral efficiency curve
Asymmetric orders	duty-cycle or alignment error	profile and beam alignment check
Good efficiency, poor image contrast	surface roughness or stray scatter	scatter and MTF measurement

9. Limitations and evidence gaps

DOE architectures range from binary gratings to many-level Fresnel and freeform phase plates. Efficiency depends strongly on design, wavelength and aperture, so values from one element cannot define universal acceptance for another. This review focuses on the measurement architecture needed to connect manufactured phase relief to optical output.

10. Conclusions

Photopolymer diffractive optics are qualified when the realised phase function, not just the surface shape, is known. Relief depth, lateral quantisation and refractive state should predict the distribution of optical power among desired and unwanted orders. ER-339 therefore turns profile metrology into a phase-based manufacturing decision and keeps subwavelength metasurface physics outside its scope.

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. 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.
4. 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.
5. Fan D, Smith CS, Unnithan RR, Kim S. 3D printed diffractive optical elements for rapid prototyping. *Micro and Nano Engineering*. 2024;24:100270. doi:10.1016/j.mne.2024.100270.

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.