

Optical Waveguides and Light Guides in Vat-Printed Photopolymers: Refractive-Index Contrast, Propagation Loss, Scattering, Coupling and Qualification

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Statement of Significance

A transparent vat-printed polymer is not automatically an optical waveguide. Guided-light performance emerges from the complete optical structure: refractive-index contrast, wavelength, core and cladding geometry, surface and interface roughness, absorption, scattering, bends, branches, coupling interfaces and environmental state. Vat photopolymerisation now spans accessible stereolithography and DLP light guides through sub-micrometre two-photon-polymerised photonic interconnects, but reported transmission, propagation loss and device performance are often not directly comparable. This review separates bulk optical material properties from waveguide-level performance and proposes a qualification architecture for printed light-guiding structures.

Keywords: vat photopolymerisation; optical waveguide; light guide; refractive index; core-cladding; total internal reflection; propagation loss; insertion loss; coupling; scattering; surface roughness; stereolithography; DLP; two-photon polymerisation; photonics; qualification

Abstract

Vat photopolymerisation can generate three-dimensional polymer optical paths whose geometry is difficult to obtain by conventional planar photonics. Recent work demonstrates DLP-printed elevated waveguides, DLP-printed photoluminescent waveguides and splitters, stereolithography-printed methacrylate waveguides whose optical output changes after solvent uptake, complex SLA waveguides for three-dimensional light redistribution, and two-photon-polymerised waveguides with sub-micrometre features and engineered core-cladding structures. These demonstrations also expose the qualification problem. Bulk refractive index and total transmittance do not determine propagation loss; surface stair-stepping, sidewall roughness, internal inhomogeneity, conversion state, bends, branches, interfaces and coupling can dominate. Propagation loss must be separated from insertion or coupling loss, and a waveguide tested at one wavelength or environmental state cannot be assumed equivalent at another. This review defines a state-based evidence chain from cured optical material to finished waveguide and integrated device, proposes minimum reporting requirements, and positions bulk-plastic standards such as ISO 13468-1:2019 and ASTM D1003-21 as supporting material-characterisation tools rather than substitutes for waveguide loss measurements. The 3Dresyns refractive-index material platform is included only as manufacturer implementation context; no waveguide loss, modal behaviour or device performance is inferred from nominal resin refractive index.

1. Scope and evidence boundary

ER-55 addresses passive light guiding in vat-photopolymerised polymer structures. It includes monolithic air-clad light guides, core-cladding waveguides, branched light-distribution structures and high-resolution waveguides fabricated by two-photon polymerisation where the optical path is formed from a photopolymerised network. Active photoluminescent waveguides are included only where they clarify the distinction between guided emitted light and passive transmission.

Chekkaramkodi et al. provide a broad review of VPP-fabricated photonic devices [1]; ER-55 differs by asking what evidence is required before a printed structure may carry a waveguide-performance claim.

The review is deliberately separated from ER-01, which controls optical-property reporting and cross-study comparability; ER-22, which controls ophthalmic-device qualification; ER-29, which controls material photophysics for two-photon polymerisation; ER-43, which controls multimaterial interfaces more generally; ER-44, which controls photoabsorbing fillers, optical attenuation and cure-depth response; ER-56, which controls the emissive state, including excitation/emission spectra, quantum yield, lifetime and afterglow; and ER-72, which controls environmental ageing. ER-55 uses refractive index, surface finish, conversion and environmental state only insofar as they determine waveguide-level guiding, loss or coupling.

The 3Dresyns Optical Selection System and refractive-index product families are manufacturer-defined material-selection resources. They are not independent evidence that a particular printed geometry is single-mode, low-loss, dispersion-controlled or suitable for a photonic device. Those outcomes require direct optical characterisation of the finished waveguide.

2. A waveguide is a material-geometry-interface system

In the simplest dielectric picture, light confinement requires an optical path whose effective refractive index exceeds that of the surrounding region sufficiently to support the intended guided mode. In printed polymers this may be achieved by a solid polymer surrounded by air, by a higher-index core within a lower-index cladding, or by a locally modified refractive-index region inside a nominally single material. The nominal bulk refractive index is therefore only one term in the device definition.

The same resin can produce very different optical outcomes depending on cross-section, wavelength, orientation, layer height, sidewall roughness, cure state and surface finishing. Conversely, similar optical transmission through a short straight coupon does not establish equivalent behaviour in long, curved, branched or tightly confined structures. Waveguide qualification must preserve the geometry and optical path actually used.

Table 1. Optical quantities that must not be conflated

Quantity	Engineering meaning	Principal non-equivalence
Bulk refractive index, n	Material optical response at a declared wavelength, temperature and cure state.	Does not by itself establish guided modes, numerical aperture or propagation loss.
Total transmittance	Fraction of incident luminous/radiant flux transmitted through a defined bulk specimen.	Includes a different geometry from guided propagation and may conceal scattering directionality.
Haze / wide-angle scattering	Bulk or surface-related scattering metric for a planar specimen under a named method.	Not a direct propagation-loss measurement in a waveguide.
Propagation loss	Distributed optical attenuation per unit guide length after separating fixed coupling/interface losses.	Not equivalent to insertion loss measured through one device.
Insertion loss	Total loss between defined input/output	Can contain coupling, facet, connector, branch

Quantity	Engineering meaning	Principal non-equivalence
	reference planes.	and propagation contributions.
Coupling loss	Loss associated with transfer between source/fibre/device and waveguide mode.	Does not quantify attenuation along the guide.
Bend / branch loss	Geometry-specific radiation, mismatch or scattering loss at curvature/junctions.	Cannot be inferred from straight-guide propagation loss.
Modal behaviour	Number, distribution and polarisation of supported modes at a wavelength.	Cannot be inferred solely from macroscopic transparency.

3. Evidence from vat-photopolymerised waveguides

Swargiary et al. fabricated a single-step DLP-printed integrated optical structure in transparent photosensitive resin and used an elevated tower-shaped waveguide to increase confinement. The study explicitly linked slicing-generated surface roughness and polymer–vapour interaction to optical response [2]. This is important because it demonstrates that a printable transparent resin and the printed surface are inseparable in the realised device.

Frascella et al. used DLP to fabricate photoluminescent polymer waveguides and splitters in which a copolymerised dye generated and guided luminescence [3]. This is an active-emission architecture rather than a passive low-loss transmission benchmark, so its success should not be translated into a generic propagation-loss claim. It nevertheless demonstrates how formulation chemistry can provide optical function without abandoning photopolymer printability.

ER-56 controls the emissive state - excitation/emission spectra, quantum yield, lifetime and afterglow; ER-55 retains only the guided-transmission endpoint.

Sharma, Bora and Mohammed printed methacrylate waveguides by stereolithography and showed that solvent absorption altered transmitted optical power [4]. The reported response was linked to polymer–solvent interaction and swelling, illustrating that the surrounding fluid can modify the effective optical boundary and therefore the measured waveguide output. Environmental state must consequently be part of any application-specific qualification.

Ansert et al. used commercial stereolithographic printing to create branched and multilayer polymer waveguides for spatial redistribution of light. Their 2026 study found strong effects of surface finishing and geometry: shorter paths, smoother surfaces and controlled branching/curvature improved light preservation [5]. The work is particularly useful for macroscopic VPP light guides because it separates architectural loss mechanisms from material transparency alone.

4. High-resolution and core-cladding waveguides

Two-photon polymerisation extends the same engineering problem into micron and sub-micron cross-sections. Gao et al. demonstrated three-dimensional polymer waveguides, Bragg gratings and resonators made by two-photon polymerisation, including air-bridge waveguides and coupling interfaces [6]. The result confirms that additive fabrication can produce integrated photonic building blocks, but it also highlights the importance of interface design and coupling rather than treating the printed polymer as an isolated optical material.

Gill and Marom fabricated single-mode air-cladded waveguides supported by a nano-fin and attributed measured propagation loss principally to surface roughness and high refractive-index contrast with air [7]. The study shows why extreme index contrast is not an unconditional advantage: it improves confinement but also increases sensitivity to interface quality and geometric perturbations.

Hazem et al. demonstrated a different route: multiple two-photon-polymerisation passes and local exposure control were used to create a core-cladding index contrast insideOrmocomp. Raman spectroscopy linked polymerisation state to the refractive-index modification, while smoothing of the core-cladding interface accompanied lower propagation loss [8]. This establishes a direct conversion-index-roughness-loss chain and is especially relevant to VPP materials engineering.

Table 2. Representative VPP waveguide evidence and the claim it supports

Study / process	Demonstrated evidence	Safe interpretation
Swargiary et al. 2020 · DLP	Single-step elevated polymer waveguide; optical response affected by printed surface and vapour interaction.	DLP can form integrated guiding structures; geometry/surface/environment remain device variables.
Frascella et al. 2018 · DLP	Photoluminescent printed waveguides and splitters with covalently incorporated dye.	Functional emitted-light guiding is possible; not a passive propagation-loss benchmark.
Sharma et al. 2021 · SLA	Methacrylate waveguide optical output changed with solvent absorption/swelling.	Environmental sorption can change waveguide response and must be qualified.
Ansert et al. 2026 · SLA	Complex branched/multilayer light guides; surface finishing and geometry altered transmission.	Macroscopic light-guide efficiency is strongly geometry- and finish-dependent.
Gao et al. 2020 · TPP	3D waveguides, gratings, resonators and engineered coupling interfaces.	High-resolution additive photonic devices are feasible; coupling and path geometry matter.
Gill & Marom 2021 · TPP	Single-mode air-clad nano-fin waveguides; measured polarisation-dependent loss.	Air-clad confinement is sensitive to roughness and high-contrast boundaries.
Hazem et al. 2025 · TPP	Local index control by multipass exposure; Raman/conversion mapping; low-loss core-clad guide.	Polymerisation state can be engineered as an optical-index variable within one printed material.

5. Refractive-index contrast: necessary but not sufficient

For a conventional step-index guide, the core-cladding index difference sets the confinement potential together with wavelength and cross-section. In macroscopic SLA/DLP light guides, air may function as the lower-index surrounding medium. In integrated photonics, a printed cladding or a locally modified index can reduce sensitivity to handling and surface contamination. A reported index difference should therefore always be paired with wavelength, material state and geometry.

A larger index contrast can enable tighter confinement, but it can also increase sensitivity to sidewall roughness because more optical power interacts with a high-contrast boundary. The appropriate design is consequently an optimisation, not “the highest RI available”. Core and cladding also need dimensional, chemical and ageing compatibility; a nominal index pair that delaminates, swells differently or drifts during post-cure is not a stable waveguide platform.

6. Surface and volume scattering

Layer lines, voxel boundaries, support marks, incomplete resin removal, polishing scratches, pores and phase-separated inclusions can all scatter guided light. The relative importance depends on wavelength and modal field distribution. For macroscopic SLA structures, Ansert et al. directly identified post-print surface finishing as a major transmission lever [5]. For micro-waveguides, Gill and Marom and Hazem et al. connect interface roughness to propagation loss [7,8].

Bulk haze and total luminous transmittance remain useful supporting descriptors, but they do not identify where loss occurs inside a waveguide. ISO 13468-1:2019 addresses total luminous transmittance of planar transparent, substantially colourless plastics and explicitly has a limited specimen/application scope [S1]. ASTM D1003-21 addresses haze and luminous transmittance of planar transparent plastics [S2]. Neither standard measures waveguide propagation loss, coupling efficiency, mode structure or bend loss.

7. Absorption, wavelength and photochemical state

Optical loss is wavelength-dependent. Residual photoinitiator, photoproducts, dyes, pigments, stabilisers and the cured polymer itself may absorb differently across UV, visible and near-infrared wavelengths. A resin described as clear to the eye can therefore be unsuitable for a specific photonic wavelength. Conversely, a dye deliberately introduced for photoluminescent guiding changes the optical function and invalidates simple comparisons with passive clear guides.

ER-44 controls absorber-driven attenuation and cure-depth response; ER-55 uses it only where wavelength-dependent absorption changes guided-light loss.

Post-cure can change conversion, density, residual chromophores and refractive index. Excessive exposure may also increase yellowing or stress in some systems. Accordingly, the optical state must be recorded after the complete printing, washing, drying, post-cure and surface-finishing sequence—not only in the uncured resin or a nominal material datasheet.

8. Coupling and reference planes

A short printed guide can appear lossy because the source is poorly coupled, while a high-propagation-loss guide can appear acceptable if the tested length is too short. Qualification should therefore separate fixed interface losses from length-dependent propagation. Cut-back or multi-length strategies are valuable where geometry permits; otherwise the method must explicitly state how source coupling, end-facet reflection and detector collection are handled.

For fibre-coupled systems, core size, numerical aperture, facet angle, alignment tolerance and index mismatch control coupling. For free-space or LED-coupled light guides, the relevant optical etendue and launch geometry are different. A universal insertion-loss number without source, detector and reference-plane definition is not portable between systems.

Loosen et al. describe a full production chain for printed polymer optical waveguides and the process steps that must be controlled across it [9].

Table 3. Minimum waveguide measurement architecture

Control	Minimum disclosure	Why required
Optical wavelength / spectrum	Source centre wavelength, bandwidth and power stability.	RI, absorption, scattering and modal behaviour are wavelength-dependent.
Geometry	Core/cladding dimensions, length, bends, branches, orientation and layer height.	Loss and confinement are geometry-specific.
Material state	Resin identity, print process, exposure, wash/dry/post-cure, ageing/conditioning.	Conversion and environment can change RI and loss.
Surface / interfaces	As-printed vs polished/coated; roughness method where relevant; facet preparation.	Surface scattering and coupling may dominate.
Launch / collection	Source/fibre/optic, alignment method, NA, detector aperture and reference plane.	Needed to interpret coupling and insertion loss.
Loss method	Direct insertion, cut-back, multi-length	Propagation loss must not be silently conflated

Control	Minimum disclosure	Why required
	regression, resonant or other named method.	with fixed losses.
Replicates / uncertainty	Number of guides, repeat alignments, uncertainty and failure exclusions.	Printing and optical alignment can be major variance sources.
Environmental state	Temperature, humidity and contacting fluid where relevant.	Sorption and thermo-optic effects can alter guiding.

9. Bends, branches and three-dimensional routing

The distinctive advantage of additive manufacturing is not simply the ability to replace a straight planar waveguide. It is the ability to route light through three dimensions, create monolithic branches, connect non-coplanar components and distribute illumination inside volumes. These geometries create loss mechanisms absent from a straight coupon: curvature can radiate power, abrupt branches create mode mismatch, and junction surfaces introduce additional scattering.

The 2026 SLA work of Ansert et al. provides direct evidence that branch angle, curvature, length and diameter affect preserved optical power in macroscale printed polymer guides [5]. At smaller scales, TPP enables compact curves and free-space interconnects but imposes tighter tolerances and stronger roughness sensitivity. Performance claims therefore need geometry-specific data rather than transfer from a straight reference guide.

10. Environmental and service-state effects

Sharma et al. show directly that solvent absorption can modify the optical output of a printed methacrylate waveguide [4]. This is not merely a sensing curiosity: it demonstrates that sorption changes the optical boundary condition and may change dimensions or local refractive index. Water, cleaning solvent, humidity and other service fluids should therefore be treated as possible optical-state variables.

Thermal expansion, thermo-optic response, post-cure ageing and photochemical yellowing can likewise alter guiding or coupling. ER-72 controls the broader environmental-ageing evidence; ER-55 requires only the subset needed to demonstrate retained optical function. “Stable waveguide” should mean that the defined optical endpoint is retested after the intended conditioning, not that the resin has a general stability descriptor.

11. Core-cladding and multimaterial architectures

A core and cladding may be fabricated from different photopolymers, from one material with exposure-induced local index modification, or from a printed core interacting with air or an external medium. Each route has different qualification needs. Multimaterial core-cladding systems require interface integrity and compatible shrinkage; exposure-written index structures require evidence that the index contrast persists after post-cure and ageing; air-clad guides require surface robustness and contamination control.

Hazem et al. provide a particularly strong single-material example because Raman spectroscopy, polymerisation state, refractive-index modification, interface roughness and propagation loss were examined together [8]. This avoids treating index as a free input independent of the cured network. It also reinforces the need to preserve conversion state in any comparison of RI-tuned printed materials.

12. Qualification levels

Table 4. Proposed evidence levels for vat-printed waveguides

Level	Evidence required	Permitted conclusion
L0 · Material screen	Bulk RI at wavelength + spectral	Candidate optical material only.

Level	Evidence required	Permitted conclusion
	transmission/haze + cure-state record.	
L1 · Straight-guide demonstration	Defined guide geometry + launch/collection + transmitted signal.	Light guiding demonstrated in that geometry.
L2 · Loss characterisation	Length-resolved or otherwise validated propagation-loss method + coupling controls + uncertainty.	Propagation-loss claim at the tested wavelength/state.
L3 · Geometry qualification	Bends/branches/interfaces tested in representative structures.	Architecture-specific optical performance.
L4 · Environmental retention	Optical endpoint repeated after defined humidity/fluid/temperature/UV/ageing exposure.	Condition-specific retained performance.
L5 · Integrated-device qualification	Final interfaces, packaging, source/detector, alignment tolerance and application test.	Device-level claim within the validated configuration.

13. 3Dresyns implementation boundary

The 3Dresyns refractive-index collection is structured for optical matching, optical prototyping, lens development, light-guide design and transparent functional parts. The controlled product corpus includes lower-index, medium-index and high-index routes and explicitly positions higher-index families for photonic and light-guiding structures [M1-M3]. WP-19 further describes a core-cladding selection concept in which a lower-RI material can serve as cladding and a higher-RI material as core [M4].

Those sources define a commercially available material-design space, not a waveguide-performance dataset. ER-55 therefore does not assign propagation loss, insertion loss, numerical aperture, modal count, coupling efficiency or environmental lifetime to any 3Dresyns grade unless those properties are measured on the finished waveguide. The correct implementation sequence is: select a wavelength-appropriate material pair or optical route, calibrate printing, manufacture the intended geometry, complete post-processing, then qualify the optical guide directly.

14. Minimum reporting checklist

- exact resin(s), batch/state where relevant, printer/process and build orientation;
- exposure and complete wash, dry, post-cure and surface-finishing history;
- refractive index with wavelength, temperature, method and specimen state;
- guide type: air-clad, core-clad, exposure-modified index, multimaterial or active-emission;
- core/cladding dimensions, total length, bend radii, branch angles and junction geometry;
- optical wavelength/spectrum, source, launch optics, numerical aperture and polarisation where relevant;
- detector/collection geometry and definition of optical reference planes;
- raw insertion/transmission result plus the method used to separate propagation from coupling/facet loss;
- surface/interface roughness or a justified surrogate when scattering is a relevant failure mode;
- replicate guides, repeated alignments, uncertainty and treatment of failed prints;
- environmental conditioning including fluid contact, humidity and temperature where relevant;
- after-ageing retest if durability, stability or service-life language is used.

15. Failure-mode and discrimination matrix

Table 5. Common optical observations and discriminating evidence

Observation	Competing explanations	Discriminating evidence
Low output power	Bulk absorption; surface scattering; poor	Multi-length or cut-back test; coupling

Observation	Competing explanations	Discriminating evidence
	launch; facet loss; bend/branch radiation.	reference; spectral transmission; surface inspection; straight control.
Large sample-to-sample variation	Print dimensional variation; roughness; cure-state drift; alignment sensitivity.	Dimensional/roughness map; repeated alignment; matched process records; replicate statistics.
Good bulk transparency but poor guide	Surface/sidewall scattering; weak confinement; geometric radiation.	Bulk coupon plus waveguide-specific loss and near-field/mode assessment.
Loss rises after solvent/humidity exposure	Sorption-induced RI/dimension change; swelling; interface damage; surface contamination.	Mass/dimension recovery; RI/optical retest after controlled dry/wet cycles.
High loss at bends only	Bend radius too small; modal redistribution; geometric roughness at curve.	Straight-guide baseline and controlled radius series.
Core-clad guide drifts after post-cure	Differential conversion/shrinkage or index evolution.	RI and dimension before/after post-cure; interface inspection; repeat loss measurement.
Apparent improvement after polishing	Reduced surface scattering or improved facet coupling.	Separate sidewall finish from end-facet preparation; repeat length-dependent loss test.

16. Research and standardisation priorities

- round-robin VPP waveguide specimens with common geometry and wavelength across SLA/DLP systems;
- methods that separate surface, volume and coupling loss in printed transparent polymers;
- conversion-resolved refractive-index measurements tied directly to propagation loss;
- core-cladding VPP studies outside the TPP scale, including multimaterial SLA/DLP systems;
- wavelength-resolved loss and dispersion data rather than visible clarity alone;
- quantitative effects of stair-stepping, layer height and build orientation on guided-light loss;
- controlled post-processing studies separating washing, polishing, coating and post-cure contributions;
- hydrothermal, solvent, UV and thermal ageing with repeat optical-guide characterisation;
- branch/bend design datasets linking printed geometry to excess loss and spatial light distribution;
- a minimum-reporting consensus for propagation loss, insertion loss, coupling and environmental state in additively manufactured polymer waveguides.

17. Conclusions

Vat photopolymerisation offers an unusual continuum of polymer light-guiding architectures, from millimetre-scale SLA/DLP light distributors to sub-micrometre two-photon-polymerised photonic interconnects. Across that scale range, the same central rule holds: a transparent resin or a target refractive index is not a waveguide performance claim. The realised guide is a material–geometry–surface–interface system.

The independent literature demonstrates that DLP and SLA can create integrated guides, splitters and complex three-dimensional light-distribution structures; that solvent uptake can change optical output; and that two-photon polymerisation can engineer both free-standing and core-cladding waveguides. It also demonstrates that surface roughness, coupling, geometry and polymerisation state materially affect loss. These factors must therefore be reported and controlled rather than hidden inside a single transmission number.

A defensible printed-waveguide claim should contain: material and cure state + wavelength + refractive-index architecture + exact geometry + surface/interface state + launch/collection definition + waveguide-specific loss method + uncertainty + service-state retention where relevant. Bulk transmittance and haze are useful supporting measurements, but the finished waveguide must be qualified as a waveguide.

Limitations

This review is a literature-based engineering synthesis and reports no new optical experiments. The evidence base spans materially different VPP scales, including DLP/SLA and two-photon-polymerisation systems; numerical loss values are therefore not pooled or ranked across studies. Several studies are device demonstrations rather than interlaboratory qualification studies. Bulk-plastic optical standards are cited only within their stated planar-specimen scopes and are not presented as waveguide propagation-loss standards.

Author contributions

Juan Seguro: conceptualisation, literature synthesis, engineering framework, writing and critical review.

Competing interests

The author is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. Manufacturer documentation is included only as implementation context and is separated from independent scientific evidence.

Data availability

No new experimental dataset was generated for this review. Scientific statements derive from the cited literature and standards; manufacturer examples derive from controlled 3Dresyns documentation.

Company information

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Standards - supporting bulk optical characterisation

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