

Fast-Timing Scintillator Architectures Made with Photopolymers: Light Yield, Decay, Transport and Radiation Stability

From photocurable scintillator formulation to timing-relevant printed detector performance

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Abstract

Photocurable scintillators make it possible to fabricate radiation-sensitive structures with geometries that are difficult to obtain by machining or casting, but the timing performance of a printed detector cannot be inferred from fluorophore lifetime alone. Detected pulse shape and timing depend on energy transfer, scintillation decay, photon path-length distribution, bulk attenuation, scattering, surface state, detector coupling and electronic readout. This review separates these terms and examines evidence from fast-curing organic scintillators, perovskite-photopolymer composites and recent DLP-printed radiation-hard plastic scintillators. The published literature shows that rapid optical responses, pulse-shape discrimination and substantial relative light yield can coexist with photocurable processing, while also exposing ageing, leaching and radiation-induced transmission loss as independent qualification variables. An engineering framework is proposed that treats intrinsic emission kinetics, optical transport and radiation stability as separate but coupled gates. Minimum reporting includes formulation identity, print and post-cure conditions, specimen geometry, excitation or radiation field, spectral response, absolute or relative light yield, decay model, attenuation, surface/coupling state and dose-history-dependent remeasurement.

Keywords: scintillator; photopolymer; DLP; stereolithography; light yield; decay time; radiation hardness; optical transport; timing

1. Significance and scope

A fast scintillator must produce useful photons quickly and deliver enough of them to the photodetector with a sufficiently narrow distribution of arrival times. Photopolymer printing adds geometric freedom but also introduces layer interfaces, cure heterogeneity, residual absorber, surface stair-stepping and post-cure history. ER-423 therefore owns the chain from formulation through intrinsic scintillation and optical transport to timing-relevant detector response.

ER-423 owns scintillator-intrinsic optical response and the timing chain; ER-424 separately owns neutron-converter loading, capture efficiency, light collection and neutron/gamma discrimination in detector structures.

2. Photocurable formulation and light yield

Frandsen and co-workers developed light-cured organic scintillator formulations compatible with 405 nm curing and reported relative light yields up to 83% of EJ-276 together with neutron-gamma pulse-shape-discrimination capability [1]. That result shows that rapid curing and useful scintillation are compatible, but it also demonstrates why formulation metrics must be multi-objective: the same study examined optical clarity, hardness, cure speed, light yield, PSD and ageing.

A formulation that maximises fluor concentration can suffer self-absorption, crystallisation, phase separation or leaching. Relative light yield should therefore be measured on specimens with matched geometry and optical coupling, and the reference detector must be identified. Otherwise a “percent of reference” value cannot be compared across laboratories.

3. Decay time is not the complete timing budget

Giuri and co-workers reported an approximately nanosecond-scale effective decay for a stereolithographically printed perovskite-photopolymer scintillator [2]. This is a promising intrinsic timescale, but the measured event time also includes photon transport. In a large or optically lossy component, photons can experience different path lengths, reflections and scattering histories before reaching the sensor.

The timing budget should therefore distinguish material emission decay from transport broadening and photodetector/electronics jitter. Geometry changes that improve energy deposition or segmentation may lengthen some optical paths. Conversely, a highly absorbing or rough structure may suppress late photons at the cost of light yield. Optimisation requires both timing distribution and detected-photon statistics.

4. Radiation stability and optical damage

Radiation can alter both the polymer matrix and the scintillation system. Anand and co-workers compared DLP-printed scintillators after gamma irradiation and observed composition-dependent light-yield and transmission losses at high dose while the measured photoluminescence decay profile remained comparatively stable [3]. This separation is important: unchanged decay kinetics do not imply unchanged detector sensitivity when optical transmission has degraded.

Radiation qualification should therefore repeat transmission, light yield and decay measurements after defined accumulated dose and recovery time. Dose rate, atmosphere, temperature and the interval between irradiation and testing can influence the observed state and should be recorded.

5. Ageing, leaching and post-processing

Frandsen and co-workers also reported time-dependent light-yield changes and addressed leaching or haze in high-fluor formulations through post-treatment [1]. Such effects are not secondary to detector qualification. A washing step that removes mobile material may improve optical stability but also change composition, dimensions or surface state. Post-cure can increase conversion while changing refractive index and fluor environment.

The final detector should therefore be characterised only after the full manufacturing sequence is frozen. Intermediate material measurements are useful for diagnosis, but they cannot substitute for the processed object.

Qualification axis	Required evidence	Failure if omitted
Scintillator state	Matrix, fluor/wavelength-shifter identity and loading, cure/post-cure state, density and optical clarity	Timing results cannot be assigned to a reproducible scintillator formulation
Timing response	Instrument response function, excitation/radiation source, rise/decay descriptors and coincidence method	Intrinsic decay time can be mistaken for detector timing resolution
Optical transport	Geometry, surface finish, attenuation/scattering and sensor coupling measured with the timing specimen	Photon transport can dominate a nominally fast material response
Discrimination	PSD method, energy window, acquisition chain and figure of merit reported separately from timing metrics	Neutron/gamma discrimination and fast timing can be conflated
Radiation stability	Dose/fluence, spectrum and temperature defined with remeasurement of light output and timing	Initial light yield can be mistaken for stable detector performance

Table 1. Domain-specific qualification matrix for fast-timing scintillator architectures.

6. Device-level verification

6.1 The scintillation chain contains multiple rate-limiting steps

Fast timing cannot be assigned to the decay constant of a fluorophore alone. Energy must first be deposited in the matrix or high-Z phase, transferred to an emitting state, converted into photons, transported through the printed body and detected by a photosensor with its own transit-time spread. Any slow transfer component, reabsorption/re-emission cycle or long optical path can broaden the measured pulse even when the intrinsic emitter is fast. For that reason, material photoluminescence lifetime and detector coincidence timing should be treated as related but non-equivalent observables. The perovskite-filled stereolithography result of Giuri and co-workers, with an effective decay near the nanosecond scale, is an important materials demonstration, but the engineering gate for a timing detector remains the complete assembled timing response [2].

6.2 Fluor loading, cure depth and optical clarity form a three-way trade-off

Photocurable organic scintillators require enough primary and secondary fluor content to achieve efficient energy transfer and useful spectral matching, yet those same dopants can absorb the cure wavelength. Chandler and co-workers showed directly that fluorescent dopants alter the critical energy dose and penetration depth in vat-photopolymerised scintillator formulations [4]. This creates a coupled optimisation problem: increasing fluor loading can improve scintillation until self-absorption, phase separation or cure attenuation dominates. Cure-depth measurements therefore belong in scintillator formulation development, and optical clarity should be assessed at the dimensions of the intended detector rather than only in thin coupons.

6.3 Pulse-shape discrimination and fast timing are different objectives

Neutron/gamma pulse-shape discrimination exploits differences in the temporal distribution of scintillation light, while fast-timing applications generally seek the narrowest and earliest possible response. A formulation optimised for one objective is not automatically optimal for the other. Photocurable PVT-based scintillators have demonstrated strong PSD performance relative to commercial references while remaining 3D printable [5], but PSD figure of merit does not substitute for coincidence-time resolution, nor does a short mean decay time guarantee neutron/gamma separation. The reporting set should therefore name the detection task explicitly and use the task-specific figure of merit.

6.4 Geometry and optical transport can dominate the measured device response

Additive manufacturing enables segmented, curved or internally structured scintillators, but geometry changes the distribution of photon path lengths, reflection events and interfaces. Surface roughness and layer boundaries can increase scattering; reflective coatings or optical grease can change collection; and embedded voids can create long tails or spatial non-uniformity. A timing measurement should therefore report specimen geometry, surface finish, wrapping, coupling medium, photosensor area and readout position. When two formulations are compared, the optical boundary conditions should be held constant or included explicitly in the uncertainty budget.

6.5 Radiation-hardness qualification must track optical and kinetic changes separately

Recent DLP-printed scintillator work has shown that radiation exposure can reduce transmission and light yield without necessarily changing the measured photoluminescence decay profile [3]. This distinction is useful because it separates damage to light transport or excitation efficiency from changes in the emitting-state kinetics. Radiation-hardness testing should consequently track at least absorbed dose, dose rate, atmosphere, time after exposure, transmission, light yield, spectral shape and decay. A single post-irradiation light-output number cannot identify the damage mechanism and should not be used alone to extrapolate service lifetime.

6.6 Timing qualification should report the instrument response explicitly

When decay or coincidence times approach the nanosecond or sub-nanosecond regime, the measurement system becomes part of the result. Detector transit-time spread, digitizer bandwidth, trigger definition, fitting interval and deconvolution method can all shift the reported value. A material comparison should therefore include the reference scintillator, photosensor, optical coupling and acquisition chain, ideally measured in the same session. If an effective decay constant is obtained from a multi-exponential fit, the fit model and relative amplitudes should be reported because a small slow component can influence pile-up or timing tails without strongly changing the dominant fitted lifetime. Device qualification should use the timing metric required by the application rather than treating a photoluminescence lifetime as a complete detector specification.

6.7 Manufacturing repeatability needs batch and within-part statistics

Scintillator performance is unusually sensitive to small compositional gradients because fluor concentration, initiator residue and optical clarity all affect detected light. Additive manufacturing introduces additional spatial variables: layer exposure, recoating, oxygen history and post-cure penetration. A credible production qualification therefore needs more than one successful print. Replicate coupons from different positions in the build, multiple builds and measurements along the thickness of larger parts should be used to estimate repeatability. The relevant acceptance criterion may be the distribution of light yield, timing or PSD rather than the best value achieved. This statistical view is particularly important for arrays, where one under-performing region can dominate detector calibration or reconstruction error.

7. Minimum qualification framework

A timing-oriented qualification should report: resin and scintillator chemistry; cure wavelength and dose; layer thickness or writing conditions; post-cure; specimen dimensions; surface finish; photodetector type and optical coupling; radiation source and geometry; light-yield calibration; spectral emission; decay model and fit range; attenuation or transmission; and environmental/radiation ageing.

At least three outputs should remain separate: intrinsic or effective decay time, detected light yield and event-level timing resolution. Pulse-shape discrimination, when relevant, is a fourth metric and should include the energy interval and analysis definition.

8. Engineering conclusions

Photopolymer-based scintillators are credible candidates for fast-timing architectures when formulation and geometry are qualified together. The key error is to equate a short fluorescence or scintillation decay with a fast detector. Printed interfaces, attenuation, scattering, coupling and radiation-induced optical damage can dominate the delivered pulse. A robust qualification therefore couples intrinsic kinetics with optical transport, light yield, ageing and the final event-level timing metric.

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Competing interest

Juan Segurola is founder, CEO and CTO of 3Dresyns by Resynr Technologies S.L., which develops and commercialises photopolymer materials and related additive-manufacturing technologies. This review is an engineering analysis and does not constitute a product-performance claim or a device qualification.