

Terahertz Components Made from Photopolymers: Dielectric Dispersion, Absorption, Geometry and Metrology

Material-property qualification and dimensional control for printed THz quasi-optics and wave structures

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Abstract

Vat photopolymerisation offers the geometric resolution needed for many terahertz quasi-optical components, but common photocurable polymers can exhibit substantial frequency-dependent absorption. The design problem is therefore inseparable from materials metrology. This review connects complex permittivity, refractive index, absorption coefficient and loss tangent to printed geometry, surface quality and measurement method. Published THz time-domain spectroscopy of commercial photopolymers demonstrates wide material-to-material variation, while recent stereolithography studies show that non-polar fillers such as PTFE can reduce absorption without abandoning high-resolution photopolymer processing. The review distinguishes bulk dielectric loss from geometry-induced scattering and reflection, and emphasises that nominal CAD dimensions are insufficient when feature size approaches the wavelength or when shrinkage alters phase delay. A qualification framework is proposed around frequency-resolved material properties, anisotropy, cure/post-cure state, dimensional metrology, surface condition and device-level S-parameter or optical measurements. The engineering objective is not to identify a universally “THz-transparent resin,” but to establish a traceable material-process-frequency window for each component.

Keywords: terahertz; photopolymer; stereolithography; dielectric loss; absorption coefficient; refractive index; THz-TDS; quasi-optics; additive manufacturing

1. Significance and scope

At terahertz frequencies, polymer selection and component geometry are strongly coupled. The same high-resolution photopolymer process that can fabricate fine lenses, lattices or wave structures may use a resin with appreciable THz absorption. ER-425 therefore treats dielectric characterisation as part of manufacturing qualification rather than a datasheet property imported after the component has been designed.

2. Frequency-resolved dielectric properties are mandatory

Duangrit and co-workers characterised multiple photocurable polymers from 0.2 to 1.4 THz using THz time-domain spectroscopy and reported substantial variation in dielectric constant and loss tangent among materials [1]. The implication is fundamental: a single low-frequency permittivity value, an optical refractive index or a supplier’s generic “low loss” descriptor cannot define THz performance.

The relevant quantities are complex and frequency dependent. Depending on the device, refractive index, dielectric constant, loss tangent and absorption coefficient may all be required. The specimen preparation, thickness and extraction model should be reported because uncertainty in thickness directly propagates into the recovered optical constants.

3. Photopolymer absorption can dominate

A recent process-and-material review emphasised that many printable polymers absorb strongly in the THz region and identified material loss as a major constraint on high-resolution additive manufacture of quasi-optics [2]. Phillips and co-workers subsequently demonstrated stereolithography-compatible PTFE-filled photopolymer composites with reduced absorption relative to the neat resin, including a reported reduction near 1 THz at the highest tested PTFE loading [3].

This is a useful design route but introduces the usual composite trade-offs: filler dispersion, cure attenuation, viscosity, surface quality and effective-medium behavior. A lower bulk absorption coefficient is beneficial only if the resulting print still meets dimensional and surface requirements.

4. Geometry, shrinkage and surface state

THz wavelengths are large compared with visible-light optical wavelengths, but many functional features in lenses, diffractive elements, lattices and waveguides are still a significant fraction of the operating wavelength. Polymerisation shrinkage, pixel or layer quantisation and post-cure distortion can therefore shift phase response or resonant frequency.

Surface roughness and staircase structure add scattering and can perturb boundary conditions. The as-printed geometry should be measured rather than inferred from CAD. When the component relies on periodic cells or graded phase, local feature dimensions and pitch require explicit metrology. Bulk dielectric data and geometry measurements should then be used together in simulation or error analysis.

5. Lattices and effective properties

Purlu and Elmabruk examined how lattice geometry changes the effective THz dielectric response of 3D-printed photopolymers [4]. This illustrates a second route to property control: effective medium can be changed by geometry as well as chemistry. Such designs require a clear distinction between the intrinsic dielectric properties of the solid polymer and the effective properties of the printed architecture.

A lattice that gives a desired effective permittivity may also introduce anisotropy, fabrication tolerances and scattering. Measurements should therefore include sample orientation and polarisation when these effects can matter.

Qualification axis	Required evidence	Failure if omitted
Dielectric spectrum	Complex permittivity or refractive index/loss versus frequency, sample thickness and extraction model	A single nominal dielectric constant cannot support broadband THz design
Material-process state	Resin/composite batch, conversion/post-cure, filler loading, moisture and print orientation	Dielectric data may not represent the state used in the final component
Geometry and surface	As-built dimensions, shrinkage/warpage and roughness relative to wavelength and local field scale	CAD geometry can be mistaken for electromagnetic geometry
Device response	Transmission/insertion loss plus focal, modal, resonant or phase response over the operating band	Coupon properties may not predict the assembled component
Environmental drift	Temperature/humidity history with repeat dielectric or device measurements	Frequency shift or loss drift may occur without visible mechanical failure

Table 1. Domain-specific qualification matrix for terahertz photopolymer components.

6. Device-level verification

Material coupons are necessary but insufficient. A lens should be checked for focal behavior and transmission; a waveguide or resonator should be checked for insertion loss, mode or resonance position; a filter should be checked for its full spectral response. Furlan and co-workers demonstrated 3D-printed diffractive THz lenses as an early example of geometry-specific verification [5].

The device test should use the same frequency range as the material characterisation and should record alignment, polarisation, reference path and environmental conditions. Agreement with simulation is meaningful only when the simulation uses measured material properties and measured or tolerance-bounded geometry.

6.1 Complex permittivity extraction is an inverse measurement problem

THz time-domain spectroscopy does not measure permittivity directly. It measures a transmitted or reflected electric field from which phase and amplitude differences are used to recover refractive index, absorption and complex permittivity. Sample thickness, parallelism, time-window selection, multiple reflections and the chosen inversion model can therefore bias the result. Thickness uncertainty becomes particularly important when a small dimensional error produces a phase error comparable to the material effect being estimated. A qualification report should state the extraction method, specimen thickness measurement and frequency-dependent uncertainty rather than presenting a smooth dielectric curve without a metrological chain.

6.2 Cure and post-cure state belong in the dielectric material identity

Photopolymer dielectric properties can change with conversion, residual monomer, post-cure and absorbed moisture. These variables alter density and molecular mobility and can modify both the real and imaginary parts of the dielectric response. For THz design, the specimen used to determine dielectric properties should therefore follow the same print orientation, cleaning and post-cure route as the functional component. If the component will operate over a temperature or humidity range, environmental conditioning should be incorporated into the dielectric characterisation rather than treated as a purely mechanical ageing test.

6.3 Ceramic and low-loss fillers improve one property while stressing the print process

Filled photopolymers can raise permittivity or reduce absorption, but the filler also changes viscosity, sedimentation behavior, scattering at the cure wavelength and shrinkage. High-permittivity TiO₂- and CCT-filled resins have been demonstrated for vat photopolymerisation aimed at microwave and THz applications [6], while more recent PTFE-filled systems target lower THz absorption [3]. These are opposite dielectric design directions, yet both require the same process controls: particle-size distribution, dispersion state, loading basis, cure-depth response and dimensional verification. Effective-medium predictions should be treated as models to be validated against the cured printed composite, not as substitutes for measurement.

6.4 Resonant and phase devices amplify small material or geometric errors

A lens or broad transmission window can tolerate a different error budget from a high-Q resonator or narrowband filter. Resonant frequency depends on both geometry and dielectric properties; phase elements integrate small local thickness errors into wavefront error. The 3D-printed horn-lens work reported at 220 GHz illustrates how dielectric-property modification and geometry act together at device level [7]. For resonant or phase-selective components, sensitivity analysis should therefore perturb measured permittivity and measured dimensions simultaneously. This converts the design model into a manufacturing tolerance model and makes it possible to decide whether material control or geometric control dominates the final uncertainty.

6.5 A digital thread should connect coupon data to the final device

The most transferable workflow records resin batch, filler batch where relevant, print orientation, exposure settings, post-cure, coupon dielectric data, final-part dimensions and device response under one identifier. When a material or process parameter changes, the previously measured dielectric dataset should not be silently reused. This is particularly important for photopolymers because apparently minor changes in post-cure dose or filler dispersion can move both attenuation and dimension. The useful deliverable is therefore not a single permittivity number but a bounded material-process-frequency dataset linked to the actual manufacturing state.

6.6 Surface roughness should be compared with the electromagnetic scale, not only with printer resolution

A dimensional roughness value becomes electromagnetically important relative to wavelength, local field concentration and incidence angle. The same printed surface may be negligible for a low-frequency lens yet materially increase scattering or loss in a higher-frequency resonant structure. Roughness should therefore be measured over spatial bandwidths relevant to the component rather than summarised by a single printer nominal resolution. Staircase orientation, support-removal marks and resin residue can produce directional roughness that is not captured by an isotropic average. When surface finishing is applied, dielectric properties should be rechecked if the treatment adds coatings, infiltrants or thermal history.

6.7 Thermal and environmental drift can move a device even when the resin remains mechanically intact

THz components can fail functionally through small changes in refractive index or dimension long before visible mechanical damage occurs. Temperature changes alter dielectric response and dimensions; absorbed water can increase loss; and long-term polymer relaxation can shift resonant geometry. Qualification for narrowband or phase-sensitive devices should therefore include environmental sensitivity of the electromagnetic response itself, not only a post-ageing visual inspection. Repeated S-parameter, focal or spectral measurements during temperature and humidity cycling can identify reversible drift separately from permanent ageing. If the intended application requires calibration stability, the allowable drift should be expressed in device units such as resonance shift, insertion loss or focal displacement.

7. Minimum qualification framework

A minimum THz report should include resin/composite identity; cure and post-cure; print orientation; sample thickness and dimensional metrology; THz-TDS or other dielectric method; frequency-resolved n , permittivity, loss tangent or absorption as appropriate; uncertainty; and device-level response. For composites, filler identity, size, loading, dispersion procedure and effective-medium assumption should be recorded.

The controlling qualification object is the material-process-frequency state. Changing post-cure, filler loading, print orientation or operating band can invalidate the previously measured dielectric constants.

8. Engineering conclusions

Photopolymer THz components should be designed from measured dielectric spectra, not from generic resin labels. High-resolution vat photopolymerisation is valuable because it enables complex quasi-optics, but its materials can be lossy. Chemistry, filler strategy and geometry can each tune the response, while shrinkage and surface state can move the realised device away from the model. Traceable frequency-resolved metrology on both coupons and final components is therefore the central qualification requirement.

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Competing interest

Juan Segurola is founder, CEO and CTO of 3Dresyns by Resyner 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.