

Microwave Dielectric Resonators and RF Components in Printed Photopolymers: Permittivity, Loss and Thermal Stability

Material-process-frequency qualification for resonators, filters, antennas and metallised RF structures

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Abstract

Vat photopolymerisation can produce geometrically complex radiofrequency and microwave structures, but the electromagnetic response is governed by the cured material state rather than by printer resolution alone. This review connects complex permittivity, dielectric loss, dimensional accuracy, metallisation and thermal drift to the behaviour of printed resonators, filters, antennas and hybrid RF structures. Published studies demonstrate that ceramic-filled photocurable resins can shift permittivity, that stereolithography can be used to implement microwave circuits, and that ceramic stereolithography can realise high-Q dielectric resonators with geometries that are difficult to machine conventionally. These demonstrations are not interchangeable: polymer-rich composites, sintered ceramic bodies and metallised polymer structures occupy different loss, stability and processing regimes. The central qualification problem is therefore to measure the dielectric spectrum of the actual cured state, propagate its uncertainty together with dimensional tolerances into device simulations, and verify the completed device over frequency and temperature. A minimum evidence framework is proposed that treats resin batch, cure/post-cure, filler dispersion, moisture, surface finish, metallisation and thermal history as part of the RF material identity.

Keywords: microwave; radiofrequency; photopolymer; stereolithography; dielectric resonator; permittivity; loss tangent; thermal stability; additive manufacturing

1. Significance and scope

Microwave and RF components convert small errors in dielectric properties and geometry into measurable shifts in resonance, impedance, phase and insertion loss. Vat photopolymerisation is attractive because it can generate complex three-dimensional dielectric and metallisation-support geometries, but this freedom does not remove the need for frequency-specific materials data. ER-426 owns the link between printed photopolymer state, dielectric metrology and completed RF component performance. It does not treat high-frequency behaviour as a generic extension of low-frequency capacitance data. The frequency boundary is explicit: terahertz components, THz dielectric dispersion and THz metrology are treated separately in ER-425 and are not claimed here.

2. Permittivity and loss are frequency- and state-dependent

Malas and co-workers formulated TiO₂- and calcium-copper-titanate-filled photocurable resins and measured their dielectric response at 2.5 GHz, 5 GHz and 12–18 GHz [1]. The work shows both the opportunity and the qualification burden: filler addition can raise the real part of permittivity, while viscosity, dispersion and printing behaviour change at the same time. A single supplier value for relative permittivity is therefore insufficient for a component whose operating band, cure state or filler loading differs from the measurement condition.

The engineering measurand is complex permittivity, with the real component governing stored electric energy and the imaginary component or loss tangent contributing to dissipation. Both should be measured over the relevant band on specimens that reproduce print orientation, cleaning and post-cure. If anisotropy is plausible, specimen orientation must be part of the test matrix. Moisture and temperature can modify both dimensions and dielectric response and should not be relegated to a separate mechanical ageing report.

3. Resonators expose the coupled material-geometry error budget

A dielectric resonator is especially sensitive to the product of geometry and dielectric state. Robins and co-workers used ceramic stereolithography to fabricate higher-order-mode alumina resonators and reported an unloaded quality factor around 2172 for the demonstrated TE₁₁₂ architecture, approximately 44% higher than the comparison geometry in that study [2]. The result demonstrates what additive geometry can achieve, but it is a ceramic SLA result after ceramic processing, not evidence that an as-cured polymer composite will inherit the same Q.

The distinction is essential. In polymer-rich photopolymer composites, dielectric loss and thermal expansion may dominate. In debound and sintered ceramic SLA, shrinkage, density and phase state dominate. In metallised photopolymer structures, conductor roughness, plating continuity and contact interfaces add another loss path. Qualification should therefore identify the architecture class before comparing numerical performance across papers.

4. Microwave circuits add interfaces and metallisation

Torregrosa-Penalva and co-workers demonstrated stereolithographic routes for microwave circuits and emphasised dielectric characterisation as part of implementation [3]. Hybrid additive approaches can also use selectively metallisable SLA polymers to place

conductors on complex three-dimensional supports [4]. In these systems the electromagnetic boundary is determined not only by the bulk polymer but by conductor thickness, conductivity, roughness, adhesion and edge definition.

A metallised polymer component should consequently be inspected as an interface system. DC continuity does not establish low RF conductor loss, and a visually continuous coating does not establish uniform current distribution at microwave frequencies. Surface preparation, plating sequence and conductor thickness should be recorded together with S-parameters and, where relevant, extracted conductor or resonator loss.

5. Thermal stability is an electromagnetic property

RF components may remain mechanically intact while drifting out of specification. Temperature changes permittivity, loss and physical dimensions; polymers can also relax after post-cure or absorb moisture. Resonant frequency, impedance and phase can therefore shift without cracking or gross deformation. Thermal qualification should measure the device response itself during or after controlled conditioning, not only tensile or glass-transition properties of a companion coupon.

The useful thermal metric depends on function. Resonators require frequency and Q drift; filters require centre frequency, bandwidth and insertion loss; antennas require matching and radiation characteristics; transmission structures require phase and attenuation. The temperature coefficient of a constituent material is informative only when it is propagated through the actual device architecture.

Qualification axis	Required evidence	Failure if omitted
Dielectric spectrum	Complex permittivity and loss over the operating band on process-matched coupons	A low-frequency or supplier value can misplace resonance and impedance
Geometry and interfaces	As-built dimensions, surface state, metallisation thickness/continuity and interface description	CAD dimensions or DC continuity can be mistaken for RF boundary conditions
Thermal/environmental state	Temperature and humidity history with repeat dielectric or device measurements	Electromagnetic drift may occur without visible mechanical failure
Device verification	S-parameters plus resonant, radiating or phase metrics appropriate to the component	Coupon data alone do not qualify the realised RF function
Transfer control	Resin/filler batch, print orientation, cure/post-cure and finishing route	Data from one material-process state may be reused outside its validated window

Table 1. Domain-specific qualification matrix for microwave and RF photopolymer components.

6. Device-level verification

The completed component is the final qualification object. A resonator should be measured for resonant frequency, unloaded or loaded Q as appropriate and coupling; a filter for S11, S21, centre frequency and bandwidth; an antenna for matching and radiation metrics; a waveguide or transmission line for propagation and transition losses. Calibration and de-embedding should be described because fixture and connector errors can be comparable to the printed-device contribution.

6.1 Effective permittivity should not be confused with constituent permittivity

Architected cells, porosity and ceramic-air mixtures can generate effective dielectric properties that differ from the intrinsic solid phase. Recent ceramic-SLA dielectric resonator work deliberately uses architecture to grade or anisotropically tailor effective permittivity [5]. Such control is valuable, but the resulting effective medium belongs to a specified geometry and frequency regime. It should be validated by measurement rather than treated as a transferable material constant.

6.2 High-Q claims require a loss budget

Measured Q combines dielectric, conductor, radiation and coupling losses. When a printed resonator is compared with a machined reference, changes in geometry, density, surface finish and coupling must be separated as far as the experiment permits. Otherwise a Q improvement can be incorrectly assigned to the material or printing route. Reporting the measurement fixture, coupling regime and extraction method is therefore part of the evidence.

6.3 Filled resins create a printability-permittivity trade-off

Increasing ceramic loading can raise permittivity but also raise viscosity, sedimentation risk and optical attenuation at the cure wavelength. Malas et al. explicitly observed printability dependence on the dispersed phase [1]. The filler concentration should therefore be reported on an unambiguous mass or volume basis, together with particle size, dispersion procedure and rheological state. Cure-depth or exposure response should be re-established after formulation changes.

6.4 Dimensional metrology belongs in the electromagnetic model

Resonant frequency and impedance can be highly sensitive to small dimensional shifts. The realised structure should be measured after cleaning and post-cure, and the measured dimensions or bounded tolerances should be propagated through simulation. This converts a nominal CAD model into a manufacturing model and allows the dominant uncertainty - material, geometry or interface - to be identified.

6.5 Thermal cycling should distinguish reversible drift from ageing

A component can show reversible temperature-dependent frequency shift, irreversible post-cure drift, moisture-related loss or progressive interface degradation. A useful protocol includes baseline stabilisation, controlled temperature/humidity exposure and repeated device measurements. The acceptance criterion should be expressed in RF units rather than only in dimensional or mechanical units.

6.6 The evidence boundary between polymer and ceramic SLA must remain explicit

Ceramic stereolithography demonstrates geometric freedom and high-performance resonator architectures, while polymer-composite VPP demonstrates tunable dielectric feedstocks. These routes share optical patterning but not final material state. Debinding and sintering replace the polymer matrix and create a different density, shrinkage and loss regime. ER-426 uses ceramic results to define device and geometry possibilities, not to infer the dielectric performance of cured photopolymers. Dielectric-resonator antenna arrays fabricated additively illustrate the importance of carrying the realised dielectric state into millimetre-wave array analysis [6], while architected perforated SLA substrates show that geometry can deliberately reduce effective loss or tailor angular response [7].

7. Minimum qualification framework

A minimum RF report should include material and batch identity; filler identity and loading where applicable; printing wavelength and orientation; cure and post-cure; dimensional and surface metrology; frequency-resolved complex permittivity or a justified device-extraction method; metallisation details where present; calibration/de-embedding; device S-parameters; and thermal/humidity conditioning when service stability matters.

The controlling state is material-process-frequency-temperature. Any change in formulation, post-cure, architecture, coating or operating band should trigger an explicit transfer assessment rather than silent reuse of prior dielectric numbers.

8. Engineering conclusions

Printed RF components should be qualified as coupled electromagnetic structures, not as geometries made from a nominally dielectric resin. Vat photopolymerisation can enable complex resonators, filters and metallised three-dimensional circuits, but permittivity, loss, geometry, interfaces and thermal state jointly determine performance. The strongest workflow links coupon dielectric data to measured as-built geometry and then verifies the completed component over its operating band and environmental window.

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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.