

Radiofrequency Antennas and Transmission Structures on Printed Photopolymers: Dielectric Loss, Metallisation and Geometry

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Abstract

Printed photopolymers can function as dielectric substrates, lenses, resonators, radomes, waveguide bodies and metallised radiofrequency structures, but RF performance is never a property of geometry alone. Relative permittivity and dielectric loss depend on frequency, cure state, filler state, temperature and moisture; metallisation adds conductivity, roughness, thickness and adhesion variables; dimensional error changes phase, impedance and resonance. This review defines a state-resolved qualification architecture for printed photopolymer RF structures. It separates dielectric characterization from conductor characterization and both from device-level S-parameters and radiation performance. It treats frequency, orientation, post-cure, surface preparation, plating sequence, skin-depth adequacy, connector/feed geometry and dimensional metrology as non-compensatory controls. The resulting framework prevents agreement at one resonance or gain value from masking a wrong dielectric model, lossy metallisation or geometry drift.

Keywords: radiofrequency; antennas; transmission lines; photopolymers; dielectric loss; relative permittivity; metallisation; surface roughness; S-parameters; additive manufacturing

1. Significance and scope

Vat photopolymerisation has been used to fabricate high-permittivity resin composites, dielectric lenses, dielectric resonator antennas, metallised reflector antennas, waveguide filters and horn antennas [1-5]. Those demonstrations establish manufacturing feasibility, not transferable RF constants. The engineering object is the complete material-process-geometry-conductor-frequency state. A resin value measured at one frequency or cure state cannot be inserted uncritically into another antenna design, and a visually continuous metal layer does not establish RF-equivalent conductivity.

1.1 Corpus boundary

Published incumbents retain neighbouring ownership. ER-07 owns electrically functional photopolymer resins; ER-16 owns electromagnetic-interference shielding materials; ER-21 owns dielectric/piezoelectric functional composites; ER-55 owns optical waveguides; ER-157 owns electrically and thermally functional particulate materials; ER-158 owns dielectric and ferroelectric functional materials; ER-261 owns printed conductors and resistive elements; and ER-263 owns dielectric breakdown and insulation ageing. ER-269 owns RF transmission and radiation structures in which microwave/mm-wave dielectric state, metallisation and dimensional geometry jointly determine impedance, loss, phase and radiation. ER-268 remains optical photosensor integration and ER-270 thermal-storage structures. Forward roadmap identifiers provide planning boundaries only.

2. Complex permittivity must be measured at the operating band

RF design requires the complex permittivity, not a low-frequency dielectric constant. ASTM D2520-21 explicitly covers relative complex permittivity and dissipation factor of nonmagnetic solid dielectrics at microwave frequencies and notes its relevance to transmission lines, antennas, radomes, resonators and phase shifters [6]. Malas, Isakov, Couling and Gibbons demonstrated that ceramic loading can raise the dielectric response of a VPP resin composite intended for microwave/THz devices, while the same filler state also changes morphology and processing [1]. Qualification therefore records frequency, specimen geometry, orientation, cure/post-cure, conditioning, filler fraction and measurement method together with uncertainty.

3. Geometry and dielectric state are coupled variables

A printed lens, resonator or substrate converts geometric dimensions and dielectric properties into electrical length. Kim, Kim, Won, Yu and Yoon showed that SLA resin geometry can be deliberately structured to alter effective permittivity in a 5.8 GHz lens [2]. Araujo and co-workers used ceramic stereolithography and subwavelength structures to engineer isotropic and anisotropic dielectric regions in a dual-band resonator [3]. These studies support geometry-enabled dielectric engineering, but they also show why CAD dimensions cannot be qualified independently of the realized material state.

4. Metallisation is an RF process, not a cosmetic coating

When the printed polymer is used as a conductive RF boundary, surface preparation, seed layer, plating chemistry, thickness, continuity and roughness become electrical variables. Guo and co-workers combined SLA with electroless nickel, copper electroplating and chromium protection for a Ka-band reflector [4]. Bachiller and co-workers used VPP polymer bodies followed by electroless and galvanic copper metallisation for high-frequency filters and horn antennas and explicitly treated sandblasting erosion and plating thickness as dimensional deviations [5]. The conductor must therefore be qualified after the complete finishing sequence.

5. Skin depth, conductivity and roughness set conductor loss

At microwave and millimetre-wave frequencies, current is confined near the conductor surface. A metallised polymer can therefore approach bulk-metal RF performance only when the conductive layer is sufficiently thick relative to skin depth and when conductivity, roughness, seams and local thinning are controlled. DC sheet resistance is useful but not a complete substitute for RF surface resistance. Corners, recesses and internal channels require evidence that plating coverage is continuous where current density is high.

6. Feeds, interfaces and assembly can dominate the measured response

Connector launch, solder or conductive adhesive, ground continuity, slot geometry, air gaps and fixture pressure can shift impedance or create loss unrelated to the printed dielectric. Device qualification should preserve the actual feed and assembly. A resonance shift can reflect permittivity error, geometry error, feed parasitics or metallisation thickness; the cause should be discriminated rather than corrected by retuning alone.

7. Frequency scaling magnifies manufacturing error

As wavelength decreases, fixed dimensional errors become a larger phase fraction and surface roughness becomes more consequential. A process acceptable at 1-6 GHz cannot be presumed acceptable at Ka-band or 100 GHz. Qualification should express critical dimensions relative to wavelength or guided wavelength and should propagate measured dimensional tolerances through the electromagnetic model. Feature compensation is valid only when its sign and magnitude are stable across build position and orientation.

8. Environmental state belongs in RF qualification

Photopolymers can change dimensions and dielectric properties with temperature, moisture uptake and physical ageing. The RF state should therefore declare temperature and conditioning, particularly for narrow-band resonators, high-Q filters and lenses. Environmental testing should repeat both material-level dielectric measurements and device-level S-parameters or radiation measurements when the intended service envelope makes drift consequential.

9. Non-compensatory qualification matrix

Gate	Required evidence	Blocking failure
G1 Dielectric state	Complex permittivity/loss measured at relevant frequency and condition	Datasheet or low-frequency value substituted for operating-band measurement
G2 Geometry	Critical dimensions and orientation measured after post-processing	CAD geometry used without realized-part metrology
G3 Metallisation	Coverage, thickness, conductivity and roughness characterized	Visual continuity used as proof of RF conductor quality
G4 Interfaces	Feed, connector, ground and assembly state frozen	Fixture/feed parasitics allowed to drift
G5 RF response	S-parameters and, where applicable, radiation metrics measured over band	Single resonance or gain point used as complete qualification
G6 Environment	Temperature/moisture ageing challenge matched to use	Room-state result generalized to service

10. Minimum reporting set

Report resin/formulation identity, filler state, printer, orientation, layer thickness, exposure and post-cure; dielectric test method, frequency, specimen geometry, conditioning, relative permittivity and loss tangent; metallisation chemistry, surface preparation, layer thickness, conductivity/resistance and roughness; critical RF dimensions and metrology; feed/connector architecture; simulated material model; measured S-parameters; and, for antennas, gain, efficiency, polarization and radiation pattern over the declared band. Acceptance limits should be linked to the intended device function rather than a generic resin specification.

11. Knowledge boundary

The cited evidence establishes that printed dielectric and metallised structures can be fabricated and measured across microwave and millimetre-wave use cases. It does not establish transferable permittivity or loss values across resin chemistries, cure states, frequencies, temperatures or moisture states; it does not establish that a DC conductivity or visually continuous coating predicts RF surface resistance; and it does not establish universal dimensional tolerances, gain, efficiency or bandwidth for printed antennas and transmission structures. Device-specific qualification therefore remains necessary at the intended operating band, geometry, conductor state and environmental condition.

12. Conclusions

Printed photopolymer RF structures are coupled electromagnetic-manufacturing systems. Complex permittivity, conductor surface state and geometry must all be measured in the relevant frequency and environmental state. Device-level agreement with simulation is strongest evidence when it closes the loop back to measured material properties and realized dimensions, not when one parameter is tuned until a resonance aligns. Qualification is therefore hierarchical: material, metallisation, geometry, interface and complete-device measurements each retain their own gate.

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