

Electromagnetic Shielding Qualification of Vat-Printed Conductive Composites: Shielding Effectiveness, Frequency, Thickness and Anisotropy

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Statement of Significance

Electrical conductivity and electromagnetic interference (EMI) shielding effectiveness are related but non-equivalent material responses. A vat-photopolymerised composite can show a measurable DC conductive network without providing useful attenuation at the frequency, thickness and field configuration relevant to an enclosure; conversely, shielding can depend strongly on architecture, orientation and loss mechanisms that are invisible to a single resistivity number. This review therefore treats EMI shielding as a frequency-resolved qualification problem. The evidence chain is defined as conductive-network formation → specimen state → test geometry → scattering parameters → total shielding effectiveness → reflection/absorption interpretation → orientation and thickness → durability → device-level validation. The central proposition is that no shielding claim should be inferred from filler identity, nominal loading, conductivity or sheet resistance alone.

Keywords: electromagnetic interference; EMI shielding; shielding effectiveness; vat photopolymerisation; conductive photopolymer; stereolithography; DLP; silver nanowire; carbon nanotube; graphene; anisotropy; S-parameters; ASTM D4935; additive manufacturing

Abstract

Electrically functional photopolymers are increasingly used to create geometrically complex components for electronics, sensing and radio-frequency research, but electromagnetic shielding is often inferred too early from conductivity measurements. This Engineering Review separates the formation of a conductive network from the evidence required for an EMI-shielding claim. Shielding effectiveness is treated as a frequency-, thickness-, geometry- and orientation-dependent response measured through transmission/reflection methods rather than as an intrinsic extension of DC conductivity. ASTM D4935-18(2026) is positioned as a planar far-field method over its stated frequency range, while higher-frequency waveguide and coaxial measurements require explicit fixture and sample descriptions [1,2]. Published additive-manufacturing studies demonstrate that infill architecture, conductive-filler orientation, cellular geometry and printing direction can materially change shielding behaviour even when feedstock chemistry is unchanged [3-6]. VPP-specific literature adds a second constraint: silver nanowires, carbon nanomaterials and conductive polymers can create electrically functional photopolymers, but dispersion, optical attenuation, cure depth, viscosity, post-cure and drying can alter the realised network [7-11]. The review proposes a minimum qualification framework covering S-parameters, total shielding effectiveness, reflection and absorption terms, specimen thickness, density, orientation, conditioning and enclosure-level verification. Current 3Dresyns conductive materials are included only as commercial implementation examples; their electrical positioning does not constitute an EMI-shielding result without frequency-resolved measurement. The objective is to provide a defensible route from printable conductivity to validated shielding performance.

1. Introduction

Electromagnetic shielding is a system function. The engineering question is not simply whether a printed material conducts electricity, but how much incident electromagnetic power is transmitted through a defined specimen or device over a defined frequency range. This distinction matters in additive manufacturing because the same material can be printed with different thicknesses, infill patterns, wall structures, build orientations and conductive-network anisotropy. These geometric degrees of freedom can change both electrical transport and electromagnetic attenuation [3-6].

The distinction is even more important in vat photopolymerisation (VPP). Conductive fillers and intrinsically conducting species interact with the photochemical process itself. They can absorb or scatter the exposure wavelength, increase viscosity, agglomerate or sediment, reduce cure depth, modify conversion and create through-thickness gradients. Post-curing, thermal treatment, solvent removal and hydration can then change the final electrical state [7-11]. A conductivity value measured on one surface or in one direction therefore cannot be assumed to describe the electromagnetic response of the final printed object.

This review is restricted to shielding qualification: how conductivity, frequency, thickness, orientation, architecture and measurement method interact, and what evidence is required before a VPP material can be described as an EMI shield.

2. What shielding effectiveness measures

For a planar specimen under a defined fixture, a vector network analyser commonly provides the complex reflection and transmission scattering parameters S_{11} and S_{21} . Their magnitudes are used to estimate reflected and transmitted power fractions. Total shielding effectiveness, SE_T , expresses attenuation of transmitted power in decibels. In the simplest power-ratio form, $SE_T = -10 \log_{10}(T)$, where T is the transmitted power fraction. Reflection and effective absorption terms may then be derived from the same scattering data, but the decomposition depends on definitions and assumptions and should be reported together with the equations used [2,3].

The practical consequence is that shielding effectiveness is not a scalar property independent of the experiment. It is measured under a frequency band, incidence condition, specimen geometry and fixture. ASTM D4935-18(2026) defines a planar, normal-incidence, far-field procedure and states a nominal range of 30 MHz to 1.5 GHz for the described holder. The standard also emphasises mismatch, dynamic range and ancillary-equipment accuracy as contributors to uncertainty [1]. Results produced in X-band waveguides, custom coaxial fixtures or free-space systems therefore cannot be pooled with ASTM D4935 measurements without acknowledging the different field and sample conditions.

Statement	Minimum evidence	What does not establish it
“Electrically conductive”	Defined resistivity/conductivity or sheet-resistance method, specimen state, direction and conditioning.	Filler identity or nominal concentration alone.
“EMI shielding”	Frequency-resolved transmission measurement and SE_T for a defined thickness, geometry and method.	DC conductivity or sheet resistance alone.
“Absorption-dominant”	S-parameter-based analysis with stated equations and valid separation of reflection/absorption terms.	Low reflection visually inferred from colour or surface appearance.
“Broadband shielding”	Continuous or sufficiently dense measurements across the claimed band with fixture validity over that band.	One or two spot frequencies.
“Lightweight high shielding”	SE reported together with thickness, density/areal density and the exact normalisation used.	A dB value from a thicker/heavier specimen without mass basis.
“Isotropic shielding”	Measurements at multiple material/build orientations or tensor-aware electrical/EM characterisation.	One build orientation or one surface measurement.
“Durable shielding”	Repeat SE after defined thermal, humidity, flexural, abrasion or chemical conditioning.	Fresh-specimen conductivity.

Table 1. Evidence required for common EMI-shielding statements.

3. Conductivity is not shielding effectiveness

Electrical conductivity influences impedance mismatch, current dissipation and the ability of a composite to interact with an incident field, but it is only one input. Classical conductive-polymer measurements already showed that shielding depends on sample and frequency conditions rather than conductivity alone [2]. Modern additive-manufacturing studies make the same point more directly: printing pattern and infill can change resistivity and shielding simultaneously, while oriented microstructures can tune shielding in different directions [3,4].

Near a percolation threshold, small changes in filler connectivity can produce large changes in DC transport. That does not imply a proportional change in SE_T at all frequencies. Dielectric loss, magnetic loss where present, interfacial polarisation, multiple internal reflections, surface impedance, specimen thickness and structural resonances can alter the RF/microwave response. For this reason, a material-selection workflow should use conductivity as a screening variable and shielding measurement as the qualification endpoint.

The distinction also protects against misleading “maximum conductivity” logic. A highly conductive skin may produce strong reflection, which can be desirable for an enclosure but undesirable for applications seeking absorption-dominant attenuation or reduced secondary electromagnetic pollution. Conversely, a moderately conductive, lossy or architected composite can attenuate through multiple mechanisms [12]. The desired balance depends on the device.

4. Measurement architecture and uncertainty

The measurement method must match the claim. ASTM D4935-18(2026) is useful for comparative planar material screening under its specified far-field normal-incidence geometry. The method is not a generic replacement for waveguide testing at several gigahertz, near-field coupling, cable/connector shielding or enclosure testing [1]. At higher frequencies, rectangular-waveguide or coaxial fixtures are common; the specimen must conform to the fixture, and calibration planes, air gaps, flange pressure and sample machining can dominate error for thin or rigid materials.

A defensible report should state the network analyser, fixture type, calibration method, frequency span and resolution, specimen lateral dimensions and thickness, number of replicates, build orientation, surface preparation and conditioning. The raw or processed S11 and S21 data should be retained. If SE_R and SE_A are reported, the equations and any multiple-reflection assumptions should be supplied. If values approach the dynamic-range limit of the apparatus, the result should be reported as a bound rather than as an exact dB number.

Route	Useful domain	Required disclosure	Principal limit
ASTM D4935-type coaxial holder [1]	Planar far-field material comparison, nominally 30 MHz–1.5 GHz for the specified holder.	Holder/specimen geometry, calibration, frequency points, thickness, uncertainty.	Not an enclosure test and not automatically valid outside the method range.
Waveguide S-parameter test	Microwave bands defined by the waveguide size.	Waveguide band, sample fit, calibration/reference plane, thickness, S11/S21.	Band-limited; edge gaps and machining strongly affect result.
Custom flanged coaxial fixture	Broad material screening when fixture is validated; used in AM studies [3].	Fixture geometry, validation/reference, field assumptions and dynamic range.	Cross-study comparability depends on fixture equivalence.
Free-space horns	Large or architected panels at microwave/mmWave frequencies.	Antenna distance, beam size, incidence, time gating, reference, panel size.	Edge diffraction and finite-aperture effects.
Enclosure/device test	Final functional verification including seams/openings.	Enclosure geometry, apertures, grounding, source/receiver placement and frequency.	Cannot be reduced to an intrinsic material SE number.

Table 2. Measurement routes and principal interpretation limits.

5. Conductive-network formation in VPP

5.1 Carbon and conducting-polymer routes

DLP studies using polyaniline and graphene demonstrate the basic VPP trade-off: conductive fillers can form a measurable network after photocuring, but dispersion, agglomeration and optical interaction determine how much filler can be incorporated while preserving printability [7,8]. Han and Cho produced PANI-nanofibre/graphene polyacrylate composites and quantified surface resistance and conductivity after DLP printing [7]. Jang and Cho later examined PANI/graphene-filled ABS-like resins and again showed coupled electrical, mechanical and rheological effects [8]. These are electrical-function studies, not direct EMI-shielding demonstrations, which is precisely why conductivity should be kept separate from SE qualification.

Mitkus, Scharnofske and Sinapius showed that even 0.1 wt.% of poorly dispersed MWCNT, graphene nanoplatelet or carbon-black additions could materially reduce photopolymer cure depth, while the electrical/dielectric response depended on filler and dispersion route [9]. A VPP shielding formulation therefore cannot be optimised only for percolation: it must retain an exposure window that prints the intended thickness and geometry reproducibly.

5.2 Silver and silver-nanowire routes

Silver nanowires offer high-aspect-ratio conductive pathways at lower geometric occupation than spherical metal particles. Glier et al. developed conductive silver-nanowire photopolymer composites and demonstrated functional electrical behaviour after photopolymer processing [10]. Tan et al. later reported a freeze-dried silver-nanowire resin for VPP printing of stretchable conductive nanocomposites [11]. These studies support the feasibility of VPP-compatible silver networks but do not create a universal shielding value: nanowire dispersion, contact resistance, orientation, cured thickness and post-treatment remain specimen-specific.

6. Thickness, frequency and architecture

A shielding result must always travel with thickness. Increasing thickness changes the propagation path and can increase attenuation even when bulk conductivity is unchanged. The relationship is frequency dependent because skin depth, dielectric response and wavelength also change. Reporting “SE = X dB” without thickness and frequency removes the information needed to reproduce or compare the result.

Additive manufacturing adds architecture as another design variable. Truman et al. showed that different infill patterns and infill densities changed both resistivity and EMI SE in conductive printed polymers [3]. Shi et al. demonstrated that cellular geometry in graphene/CNT/PLA composites could retain or modify X-band shielding while reducing material use [5], and related CNT/PLA architectures show comparably geometry-dependent attenuation [15]. Guan et al. went further by deliberately coupling microplatelet orientation and macroscopic geometry, showing that directionally designed structures can tune EMI SE [4]. These studies are not VPP studies, but they establish a transferable qualification principle: a printed shield is a material–architecture system.

7. Build anisotropy and directionality

VPP is often assumed to be more homogeneous than extrusion because each layer is photochemically generated from a liquid bath. That does not guarantee electromagnetic isotropy. Filler sedimentation, shear during recoating, cure-front migration, surface segregation, layer-wise conversion gradients and directional post-processing can produce through-thickness differences. Conductive pathways may also be interrupted at weakly connected layer interfaces even when bulk mechanical anisotropy is modest.

The minimum anisotropy check is to measure conductivity and shielding in orientations that interrogate in-plane and through-thickness transport where the geometry permits. If an enclosure wall is printed vertically in service but coupons are tested only parallel to the build platform, the result may not represent the device. Directional EMI studies in other AM processes show that orientation can materially alter attenuation, so a VPP shielding paper should demonstrate isotropy rather than assume it [3,4,6,13,14].

8. From coupon to enclosure

A planar coupon qualifies a material state under a measurement fixture. An enclosure introduces seams, fasteners, apertures, ventilation holes, cable penetrations, conductive joints and grounding paths. Leakage through a gap can dominate even when the wall material has high coupon SE. Conversely, a lower-SE material may perform adequately if the enclosure architecture suppresses leakage in the relevant band.

The qualification sequence should therefore proceed from material coupon to printed panel to representative assembly. Dimensional fidelity matters because wave-scale openings and wall-thickness variation can alter shielding. For conductive VPP composites, interface bonding between separately printed sections or between printed polymer and metallic inserts should be electrically characterised as well as mechanically inspected. The final claim should be no broader than the tested configuration.

9. Durability and state dependence

Conductive networks in polymer composites can evolve after printing. Thermal ageing can change polymer shrinkage and particle contact; humidity can alter ionic or PEDOT:PSS-type conduction; solvents can extract mobile species; flexing can disrupt or reconnect nanowire and nanotube pathways; abrasion can remove a conductive surface-rich layer. Post-curing may improve conversion while changing network spacing. A single fresh-coupon SE measurement therefore cannot support a durable-shielding claim.

A service-relevant protocol should repeat both electrical and shielding measurements after predefined conditioning. The stress history should be chosen for the use case: thermal cycles for electronics enclosures, humidity for exposed devices, bend cycles for flexible parts, cleaning/chemical exposure for laboratory hardware, and UV/thermal ageing where outdoor or high-temperature use is expected. The same frequency band and fixture should be used before and after conditioning so that change is attributable to the specimen rather than the method.

3Dresyns implementation examples

The products below illustrate how commercial conductive photopolymers can enter the proposed qualification workflow. They are not cited as independent scientific evidence of EMI shielding and no shielding-effectiveness value is assigned unless it is measured under a defined frequency, thickness and fixture. Current controlled 3Dresyns documentation identifies the electrical material class and intended manufacturing route; device-level EMI suitability remains an application-specific validation task.

Product	Documented implementation role	Relevant shielding question	Validation boundary
3Dresyn AgNSEK1 [M1]	Non-soluble electrically conductive silver-based VPP resin; current TDS documentation is controlled in the 2026 technical-document set.	Can a continuous silver-rich printed network provide repeatable SE across the target band and thickness?	Electrical product positioning does not establish SE _T , absorption/reflection balance or enclosure performance.
3D-ADD EKC [M2]	Silver-nanowire additive for designing conductive photopolymers; it is not presented as a ready-to-print VPP resin.	How do nanowire connectivity, optical transparency, dosage, matrix compatibility and post-cure affect frequency-resolved shielding?	Additive positioning, transparency and conductivity do not establish broadband shielding or printed-part performance.

Product	Documented implementation role	Relevant shielding question	Validation boundary
3Dresyn GrapNSE K1-MWCNT Bio [M3]	Non-soluble MWCNT-based electrically conductive photopolymer platform.	How do CNT dispersion, build orientation and cure state affect anisotropic conductivity and SE?	CNT-based conductivity is a screening attribute; shielding requires direct RF/microwave measurement.

Table 3. 3Dresyns implementation examples and their validation boundary.

These examples are most useful when treated as controlled starting materials in a qualification matrix. A minimum programme would print matched-thickness coupons in multiple orientations, record electrical resistivity in the corresponding directions, measure S11/S21 across the target band, repeat after conditioning and then validate a representative enclosure or component. Product selection alone should never be presented as completion of that chain.

10. Minimum reporting framework

Category	Minimum information	Reason
Material state	Resin/product ID or full research composition; filler class; dispersion route; storage/age; batch.	Conductive networks are formulation- and history-dependent.
Printing	Printer/process, wavelength, layer thickness, exposure, orientation, support strategy, part thickness.	VPP parameters affect conversion, geometry and filler distribution.
Post-processing	Wash medium/time, drying, post-cure dose/time, thermal treatment, surface finishing.	Electrical state can change after printing.
Electrical screening	Resistivity/conductivity or sheet resistance; electrode geometry; direction; temperature/humidity.	Separates DC network formation from EMI qualification.
EM measurement	Fixture/method, calibration, frequency range/resolution, S11/S21, specimen dimensions, replicate count.	Makes SE reproducible and comparable.
Shielding outputs	SE_T and, if used, SE_R/SE_A with equations; thickness; density/areal density; uncertainty.	Prevents decontextualised dB claims.
Anisotropy	Build orientation and measurement directions; at least two relevant orientations where feasible.	Printed conductive networks may be directional.
Durability	Conditioning protocol and repeated electrical/SE measurements.	Fresh performance is not durable performance.
Device validation	Representative panel/enclosure, seams/apertures/grounding and use-relevant frequency band.	Coupon SE is not enclosure SE.

Table 4. Minimum reporting framework for an EMI-shielding VPP study.

11. Research gaps

The principal gap is direct VPP EMI-shielding evidence. The field contains a growing set of VPP conductive photopolymers, but comparatively few studies take the next step to frequency-resolved SE with thickness, orientation and durability controls. This creates an opportunity for research that connects photopolymer cure physics to RF performance rather than simply reporting higher conductivity.

A second gap is anisotropy mapping. Build-direction effects are well documented in extrusion-based shielding studies, while VPP filler orientation and through-thickness network continuity remain undercharacterised. A third gap is transparent shielding, where silver-nanowire or conductive-polymer systems must balance optical transmittance against sheet resistance and SE. A fourth gap is multimaterial integration: conductive walls, dielectric windows, embedded contacts and metallic inserts require interface-level electromagnetic characterisation.

Finally, reporting needs to converge. Density-normalised or thickness-normalised shielding metrics can be useful for lightweight comparison, but they should not replace the absolute SE, thickness and density from which they were derived. The most valuable future studies will provide raw S-parameters, uncertainty, matched geometric controls and application-relevant conditioning so that material design and enclosure design can be connected quantitatively.

12. Conclusions

- Electrical conductivity is a screening variable for EMI-shielding materials, not an EMI-shielding result.
- A defensible shielding claim requires frequency-resolved transmission/reflection measurement for a defined specimen thickness, geometry, orientation and fixture.
- ASTM D4935-18(2026) provides a useful planar far-field method within its stated scope; microwave waveguide, free-space and enclosure tests answer different questions.
- VPP conductive formulations couple network formation to dispersion, viscosity, optical attenuation, cure depth, conversion and post-processing, so printability and electrical function must be co-qualified.
- Additive-manufacturing evidence shows that infill, cellular geometry and conductive-filler orientation can materially alter EMI SE independently of nominal composition.
- Build anisotropy should be measured rather than assumed absent in vat-printed conductive composites.
- Durable shielding requires repeated measurement after application-relevant conditioning, and device-level shielding requires validation of seams, apertures, interfaces and grounding.
- 3Dresyns conductive materials and additives provide implementation platforms for this qualification framework, but their electrical positioning does not by itself establish SE_T, SE_R, SE_A or enclosure-level performance.

Limitations

This review is an engineering synthesis rather than a preregistered systematic review or meta-analysis. EMI studies use different frequency bands, fixtures, specimen geometries, thicknesses and conductive architectures, so shielding values are not pooled across non-equivalent measurement conditions.

Author contributions

J.S.: conceptualisation, methodology, literature synthesis, engineering interpretation, writing, review and editing.

Competing interests

The author is affiliated with 3Dresyns by Resyner Technologies S.L. Commercial 3Dresyns products are discussed only as implementation examples and are not used as independent evidence of EMI-shielding effectiveness.

Data availability

No new experimental EMI-shielding dataset is reported in this Engineering Review. The manuscript is based on published standards, peer-reviewed literature and controlled 3Dresyns product documentation. Product-specific shielding claims require separate frequency-resolved measurements on defined printed and post-processed specimens.

Company information

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