

Microresonators and Frequency-Selective Optical Components Made by Photopolymerisation: Quality Factor, Surface and Drift

Engineering qualification of printed optical cavities from geometry and material loss to environmental stability

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Abstract

Photopolymerisation can directly fabricate three-dimensional optical microresonators and other frequency-selective structures, including whispering-gallery microcavities and microrings. Their performance is unusually sensitive to the interaction of material absorption, surface roughness, geometric error and environmental drift. High quality factor is therefore not a simple printing-resolution metric. Two-photon-polymerised hybrid microcavities have demonstrated quality factors above 10^5 , while subsequent work has explored asymmetric cavities, multiphoton-written microrings and polymer resonators for sensing. These results show that direct writing can produce functional resonators but also that Q , free spectral range and resonance wavelength are coupled to the exact fabrication and measurement state. This review separates intrinsic material loss, scattering, radiation loss and coupling loss; treats surface and geometry as optical boundary conditions; and defines drift, hysteresis and ageing as part of qualification. A minimum evidence framework is proposed around spectral measurement, coupling method, surface/dimensional metrology, thermal and humidity response, and repeat testing over time.

Keywords: microresonator; whispering-gallery mode; two-photon polymerisation; photopolymer; quality factor; surface roughness; resonance drift; optical cavity

1. Significance and scope

Optical resonators amplify small material and geometric changes because light circulates repeatedly near a boundary or around a cavity. This makes them powerful sensors and frequency-selective elements, but it also makes fabrication defects and environmental drift visible. ER-428 focuses on polymerised resonators whose function depends on resonance position, linewidth and Q . It does not equate geometric print resolution with optical resonator quality. Photonic packaging, interconnect alignment and chip-to-chip coupling are owned by ER-427; they are outside scope here except where external coupling changes the measured loaded Q .

2. High Q is a loss-budget result

Liu and co-workers directly wrote whispering-gallery microcavities by two-photon polymerisation of a zirconium/silicon hybrid sol-gel and reported Q up to 1.48×10^5 with surface roughness below 12 nm [1]. The same study identified material absorption as the limiting mechanism for the highest- Q devices. This establishes a central qualification principle: once geometry is sufficiently good, the material itself can become the dominant loss channel.

Measured Q combines multiple contributions. Material absorption, surface scattering, radiation leakage and coupling loading all broaden the resonance. A reported loaded Q cannot be compared directly with an intrinsic Q unless the coupling regime and extraction method are known. Device qualification should therefore state whether Q is loaded, intrinsic or inferred, and should preserve the full resonance spectrum needed to support that extraction.

3. Surface quality is an optical boundary condition

Whispering-gallery modes concentrate optical energy near the resonator perimeter, so nanoscale roughness can scatter light out of the circulating mode. Surface quality should be measured at the optical boundary rather than inferred from printer voxel size. Development residue, staircase artefacts, support removal and local overexposure can all produce boundary perturbations not captured by nominal resolution.

Tomazio and co-workers demonstrated femtosecond-laser fabrication of high- Q WGM microresonators by two-photon polymerisation [2], while Liu et al. later fabricated asymmetric polymer microcavities with Q around 10^5 [3]. These studies show that different resonator geometries can retain high Q , but they do not eliminate the need to measure the realised perimeter, thickness and coupling gap for each process.

4. Geometry sets resonance while material state sets both resonance and loss

Resonance wavelength and free spectral range depend on optical path length, which combines physical geometry with refractive index. Polymerisation conversion, post-cure, temperature and moisture can change refractive index and dimension together. A measured resonance shift therefore cannot be attributed to geometry or chemistry without additional evidence.

Multiphoton-absorption polymerisation has also been used to fabricate microring resonators [4]. Ring and WGM geometries illustrate the same metrological requirement: measured dimensions and process-matched refractive-index data should be used in the model, while deviations between model and spectrum should be treated as an error budget rather than absorbed into an arbitrary fitted index.

5. Frequency selectivity makes drift a functional failure mode

A resonator can remain transparent and mechanically intact while its resonance shifts beyond an allowed spectral window. Thermal expansion, thermo-optic response, humidity uptake and polymer relaxation can all cause drift. For sensing applications some of this sensitivity is intentional; for filters, references or stable cavities it is error. Qualification must therefore define which environmental sensitivity is the measurand and which is unwanted drift.

Qualification axis	Required evidence	Failure if omitted
Resonance spectrum	Wavelength/frequency sweep, linewidth, Q definition and coupling condition	A single peak or fitted Q can conceal loading and extraction assumptions
Optical boundary	Perimeter/surface roughness, coupling gap and as-built geometry	Printer voxel size can be mistaken for the resonator boundary quality
Material state	Resin/hybrid identity, conversion/post-cure, refractive index and absorption at test wavelength	Resonance or loss can be attributed to geometry when the material changed
Environmental drift	Temperature/humidity/time history with repeated resonance measurements	A mechanically intact cavity may leave its spectral specification
Repeatability	Device-to-device distribution of resonance, Q and coupling	A best device may not represent process capability

Table 1. Domain-specific qualification matrix for printed photopolymer microresonators.

6. Device-level verification

The primary evidence is the optical spectrum acquired under a defined coupling geometry. The source linewidth, wavelength calibration, detector response and sweep conditions should be compatible with the linewidth being measured. When a taper, bus waveguide or free-space coupler is used, its alignment and loading should be recorded because coupling changes can alter both depth and apparent linewidth.

6.1 Loaded and intrinsic Q must be separated

In a coupled resonator, the measured linewidth depends on internal cavity loss and external coupling. Critical, under- and over-coupled states can have different transmission signatures. A qualification report should provide the coupling configuration and the method used to infer intrinsic loss. Otherwise a change in gap or alignment can be mistaken for material or resonator degradation.

6.2 Free spectral range is a geometry-index consistency check

The spacing between resonances provides an independent check on optical path length. Comparing measured free spectral range with a model built from measured geometry and refractive index can reveal whether a resonance shift is plausibly due to dimensions, material index or mode assignment. This is particularly useful when absolute resonance position alone is underdetermined.

6.3 Surface roughness should be measured at relevant spatial scales

A single arithmetic roughness value may not predict scattering if the dominant spatial frequencies differ. Microscopy or profilometry should capture the perimeter and top/bottom surfaces that overlap the optical field. If post-processing smooths the surface, it should be treated as a controlled manufacturing step and its effect on dimensions and refractive index should be checked.

6.4 Thermal response combines thermo-optic and expansion terms

Resonance shifts with temperature because both refractive index and cavity dimensions change. These contributions can have opposite signs. A device-level temperature coefficient is therefore more useful for qualification than either coefficient alone, while separate material data remain valuable for modelling and transfer.

6.5 Sensor sensitivity is not the same as stability

Polymer resonators are attractive sensors because their resonances respond to refractive index, temperature, humidity or analyte binding. The 2025 review by Mazuryk and co-workers surveys polymer WGM resonators and highlights the breadth of sensing implementations [5]. For an engineering component, however, the same sensitivity becomes drift unless the environment is the intended input. Stability requirements should be written around the intended measurand and reference strategy.

6.6 Ageing should be tracked spectrally

Post-cure evolution, physical ageing, moisture uptake and contamination can change Q and resonance over time. Storage stability should therefore include repeated spectra on the same device with controlled re-alignment or an integrated coupling geometry. A one-time end-of-life measurement cannot distinguish monotonic ageing from reversible environmental response.

6.7 Process capability requires a distribution of cavities

High-Q demonstrations often focus on the best device. Manufacturing qualification requires the distribution of resonance position, Q and coupling across a defined population and build location. Outliers should be correlated with geometry or surface inspection where possible. This converts a record device into a process capability statement.

6.8 Mode assignment should be verified rather than assumed

Dense resonator spectra can contain several radial, azimuthal or polar mode families, and perturbations can cause avoided crossings or mode splitting. Assigning a measured peak only from its nominal wavelength can therefore misidentify the optical state. Geometry-based modelling, free-spectral-range trends, polarisation response and controlled coupling scans provide complementary evidence for mode assignment before Q or drift is compared across devices.

6.9 Measurement uncertainty should accompany small drift claims

When environmental drift is comparable to linewidth or to the wavelength-reference uncertainty, a reported shift needs an uncertainty budget. Laser calibration, scan nonlinearity, thermal stabilisation, fitting model, coupling-induced line-shape changes and re-alignment can all contribute. Repeated reference measurements and a stable control cavity help separate instrument drift from a genuine change in the printed resonator.

7. Minimum qualification framework

A minimum report should include material identity and optical constants; writing wavelength and exposure strategy; development and post-cure; resonator geometry and dimensional metrology; surface inspection; coupling geometry; spectral calibration; loaded/intrinsic Q definition; free spectral range; temperature/humidity at measurement; and repeatability across devices and over time.

The qualification state is resonator-material-coupling-environment. Changing the coupling gap, post-cure, cladding, wavelength band or environmental condition can invalidate a previously measured Q even if the CAD resonator is unchanged.

8. Engineering conclusions

Photopolymer microresonators can reach high optical quality, but Q is the end result of a loss budget rather than a direct measure of print resolution. Surface roughness, material absorption, geometry, coupling and environmental drift must be measured as a coupled system. The strongest qualification combines full spectra, as-built geometry, optical-material data and environmental repeat testing so that resonance shifts and linewidth changes can be assigned to a defensible mechanism.

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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.