Title: Origin of Microsphere Surface Roughness Linked to Capillary Wave Fluctuations

ABHISHEK SURESHKUMAR[1], GEORGES PERIN[1], HELENE OLLIVIER[1], YANNICK DUMEIGE[1], JULIEN LAPEYRE[2], ROZENN BERNARD[2], KELIG TERRIEN[3], ADIL HABOUCHA[3], BERTRAND DUDOUX[3], STEPHANE TREBAOL[1*]

[1]ENSSAT, UMR 6082-CNRS-Institut FOTON, Université de Rennes, 6 rue de Kerampont, 22300 Lannion, France
[2]INSA Rennes, UMR 6082-CNRS-Institut FOTON, Université de Rennes, F-35000 Rennes, France
[3]Photonics Bretagne, 4 Rue Louis de Broglie, 22300 Lannion, France

**stephane.trebaol@univ-rennes.fr*

Abstract for Technical Review (200-300 words)

Whispering-gallery-mode (WGM) microsphere resonators are widely utilised in advanced photonic systems; however, achieving high-quality factors (Q) at visible wavelengths remains challenging. Microspheres operating near 420 nm report Q-factors that are three to four orders of magnitude lower than those observed at infrared wavelengths. This reduction is primarily due to increased scattering losses at shorter wavelengths. Although surface roughness has long been recognised as the main source of these losses, its physical origin has remained unclear and is often attributed to unavoidable fabrication imperfections.

In this study, we experimentally demonstrate that frozen capillary waves generated during fabrication are the primary cause of surface roughness in WGM spherical resonators. The roughness caused by capillary waves at a liquid spherical interface is described by $\sigma^2 = k_B T/(\gamma(L - 1)(L + 2))$, where σ is the root mean square (RMS) roughness, k_B is Boltzmann's constant, T is the softening temperature, γ is the surface tension, and L is the spherical harmonic of capillary wave. In this model, thermal fluctuations determine the amplitude of surface perturbations, while surface tension acts as a restoring force. As the microsphere cools and solidifies, these thermally generated surface waves become permanently frozen into the glass surface, shaping the final roughness profile.

To validate this model, we characterised silica microsphere surfaces using atomic force microscopy (AFM) and statistical variogram analysis. The variogram displayed a linear dependence on a semi-logarithmic scale, from which we extracted an RMS roughness of 0.15 nm. Using this measured roughness, we estimated a silica surface tension of approximately 0.2 N/m at a softening temperature of 1500 K, in excellent agreement with previously reported values. Together, the variogram analysis and surface tension estimate provide strong evidence that the observed surface morphology results from frozen capillary waves rather than accidental fabrication imperfections.

By identifying and quantifying the capillary-wave contribution to surface morphology, this work establishes a physical basis for scattering losses in visible-wavelength microsphere resonators and suggests ways to reduce them. This insight allows the development of improved fabrication protocols to achieve ultra-high-Q performance in the visible and ultraviolet spectral regions.

Summary for Program Display (50-150 words)

Whispering-gallery-mode (WGM) microsphere resonators are key components in photonic systems, but achieving high quality factors (Q) at visible wavelengths remains challenging due to increased scattering losses. Microspheres operating near 420 nm typically exhibit Q-factors several orders of magnitude lower than those at infrared wavelengths, with surface roughness identified as the main loss mechanism. In this work, we demonstrate that this roughness comes from frozen capillary waves formed during the microsphere fabrication process. The capillary-wave model predicts the RMS roughness based on thermal fluctuations and surface tension in the molten state. To validate this, we performed atomic force microscopy (AFM) and variogram analysis, obtaining an RMS roughness of 0.15 nm. From this, we inferred a silica surface tension of ~0.2 N/m at 1500 K, consistent with the literature. These findings confirm capillary-wave freezing as the primary source of roughness and suggest pathways for achieving ultra-high-Q performance in the visible regime.

Keywords

Whispering-gallery-mode resonators, surface roughness, capillary waves, atomic force microscopy