

TOPOLOGY OPTIMIZATION OF QUANTUM OPTO-MECHANICAL SYSTEMS

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Abstract

Quantum opto-mechanical resonators are nanoscale oscillators capable of responding to ultra-weak perturbations, making them exceptionally sensitive measurement devices and promising components for emerging quantum technologies such as quantum memories (Yang, 2026). As these technologies mature, the next generation of opto-mechanical systems must simultaneously achieve strong opto-mechanical coupling, ultra-high mechanical quality factors, wide phononic band gaps for vibrational isolation, and high manufacturing yield—requirements that are difficult to meet using conventional design approaches.

A central mechanism enabling ultra-high quality factors is dissipation dilution, in which the effective mechanical dissipation is reduced by storing most of the elastic energy in nearly lossless tensile stress rather than in lossy bending deformation (Fedorov, 2019). This allows resonators to reach quality factors far exceeding those predicted by intrinsic material losses. Complementarily, phononic crystals exhibit frequency band gaps where mechanical waves cannot propagate due to periodic geometric or material variations, enabling strong suppression of vibrational leakage and radiative loss channels (Sigalas and Economou, 1992). Together, dissipation dilution and phononic band-gap engineering form the foundation of high-Q, low-loss opto-mechanical devices. This work introduces a density-based topology optimization framework for designing prestressed opto-mechanical resonators in which dissipation dilution is enhanced through engineered geometric nonuniformities. The resonator incorporates an array of nanopillars forming a phononic crystal, enabling tailored dispersion properties while maintaining strong opto-mechanical coupling. Robust optimization techniques are integrated to improve manufacturing yield and enhance numerical stability throughout the design process.

A key challenge in optimizing highly prestressed membranes is the onset of numerical instabilities associated with wrinkling, where compressive principal stresses lead to buckling modes. To ensure stable optimization, we introduce a dedicated wrinkling constraint that suppresses inadmissible compressive stress states. Non-physical compressive stresses stemming from the non-smooth

representation of the boundary between material and void domains, are solved by a regularization of the principal stresses.

By jointly optimizing the prestress distribution through the resonator topology and tuning the phononic crystal via nanopillar placement, we demonstrate substantial improvements in mechanical quality factor, significant suppression of radiative loss channels, and the emergence of wide, tunable phononic band gaps. These results highlight the potential of topology-optimized resonator–phononic-crystal architectures as a pathway toward next-generation quantum opto-mechanical technologies

References

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