

Compact High-Q Photonic Crystal Cavities with Improved Robustness to Disorder

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Abstract— Compact photonic crystal cavities enable dense integration but typically require large footprints to achieve high Q-factors, increasing sensitivity to fabrication disorder. We present high-Q, small-footprint cavities optimized through a non-Hermitian perturbation theory framework, where periodicity breaking enhances resilience to fabrication-induced disorder as demonstrated by the near-field scanning optical microscopy experiment.

Keywords— photonic-crystals, optical nanocavities, near-field scanning optical microscopy, non-Hermitian photonics.

I. INTRODUCTION

Periodic nanostructures are widely used in photonics to engineer light–matter interaction [1–4]; however, their optical response is often strongly affected by fabrication imperfections, motivating increasing interest in design strategies that enhance robustness and reproducibility in real nanofabricated systems. Among those, photonic crystal (PhC) slab cavities [1] enabling strong light confinement within ultra small volumes, are widely used in integrated photonics and quantum optical platforms. Achieving high quality (Q) factors in these systems typically requires extended periodic mirrors surrounding the cavity defect, leading to large device footprints and enhanced sensitivity to fabrication induced disorder. Nanofabrication imperfections such as hole size variations, sidewall roughness, and positional errors introduce scattering losses and resonance detuning, limiting device reproducibility. This issue is particularly critical for applications requiring spectral alignment across multiple devices.

In this work, PhC slab cavities as small as $4 \times 4 \mu\text{m}^2$, achieving relatively high Q comparable to conventional large L3 cavities, despite occupying only a fraction of their footprint, are numerically and experimentally demonstrated. These structures are obtained through an optimization process that introduces an aperiodic, yet highly controlled, pattern of holes surrounding the cavity [4,5].

II. METHODS

The investigated structures are based on L3 PhC slab cavities defined within a footprint of approximately $4 \times 4 \mu\text{m}^2$ (corresponding to 6 lattice periods). Starting from the unoptimized periodic design (R6), a gradient-based optimization framework based on non-Hermitian perturbation theory for quasnormal modes [4,6] is employed to maximize the cavity Q-factor of the fundamental L3 mode (Fig. 1a) by

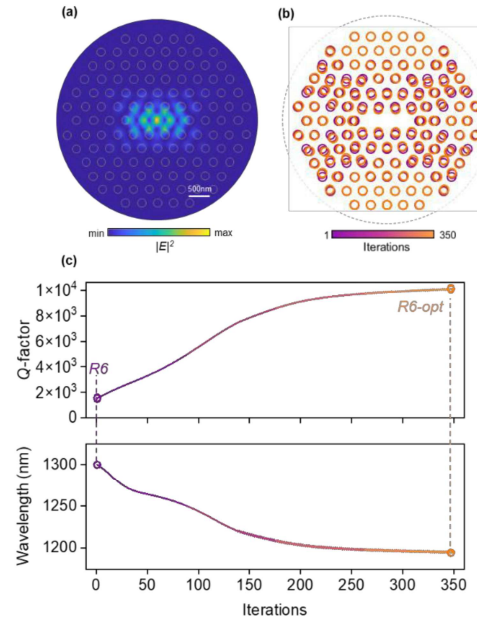


Fig. 1 (a) Simulated near-field electric field intensity maps for the fundamental mode of the original L3 cavity (R6). (b) Evolution of hole positions during the optimization process from the unperturbed reference cavity (R6, purple) to the fully optimized configuration (R6-opt, orange). (c) Simulated Q-factor (top panel) and resonant wavelength (bottom panel) as a function of optimization iteration for an L3 with lattice constant $a=330\text{nm}$ and holes radius $= 0.79a$.

iteratively displacing the air holes surrounding the defect region. The optimization introduces in the final optimized design (labelled as R6-opt) correlated hole displacements that progressively break the original lattice periodicity while preserving the overall cavity symmetry [5]. Fig. 1(b) illustrates the displacement pattern of the air holes introduced during the optimization, while Fig. 1(c) summarizes the evolution of the cavity Q-factor (top panel) and resonant wavelength (bottom panel) along the optimization trajectory from R6 to R6-opt. The fabricated samples are based on GaAs heterostructures incorporating a dense layer of InAs quantum dots (QDs) emitting at 1300 nm. Optical characterization is achieved at room temperature using scanning near-field optical microscopy (SNOM).

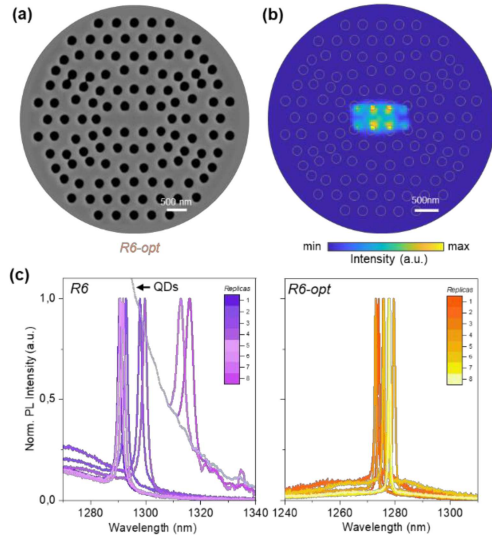


Fig. 2 (a) SEM image of the fabricated optimized R6-II cavity. (b) SNOM map of the optimized fundamental mode in the R6-II cavity. (c) Normalized SNOM PL spectra acquired at the location of maximum emission of eight nominally identical replica of R6 with $a=320\text{nm}$ (left) and R6 II with $a=350\text{nm}$ (right) and nominal radii. In the left graph the QD PL emission (light blue) is overlapped to the spectra.

III. RESULTS AND DISCUSSION

In Fig. 2a we report the Scanning Electron Microscopy (SEM) image of the fabricated L3 cavity with optimized design (R6-opt), characterized by a final Q of $\sim 10^4$, that is comparable to the Q of a standard L3 cavity with 12 lattice periods (therefore extending up to $8 \times 8 \mu\text{m}^2$ for the same lattice constant). A rigorous experimental characterization performed on R6-opt cavities with different lattice constants confirm that Q-factors follow the trend predicted by simulations, with a systematic increase from the unoptimized R6 design to the fully optimized design [4,5]. Moreover, the SNOM map acquired on the R6-opt cavity, shown in Fig. 1 (b), further demonstrates that the cavity mode remains well confined and spatially stable despite the periodicity breaking.

Beyond quality factor optimization, spectral reproducibility represents a critical and often overlooked limitation, largely arising from fabrication-induced disorder. Quantifying spectral stability provides a stringent metric to evaluate the applicability of the proposed cavities. In particular, for cavity-emitter coupling, performance is governed by the spectral alignment between the cavity mode and the emitter ensemble. Imperfections inherent to electron-beam lithography and etching processes are known to induce substantial device-to-device variations in photonic crystal cavity resonances. Here, we approach this issue by systematically investigating the spectral stability of optimized small-footprint cavities through a statistical analysis performed on multiple nominally identical replicas, directly linking engineered periodicity breaking to enhanced robustness against fabrication-induced disorder. Figure 2 (c) compares the SNOM photoluminescence (PL) spectra measured on multiple nominally identical replicas, revealing a significantly reduced spread of resonance wavelengths for the optimized cavities (right panel) with respect to the standard L3 R6 (left panel). This behavior indicates a reduced sensitivity to fabrication-induced imperfections, attributed to the correlated nature of the periodicity breaking introduced by the optimization [5].

IV. CONCLUSION

We have demonstrated that controlled periodicity breaking enables compact photonic crystal slab cavities combining high Q-factors with enhanced robustness to fabrication-induced disorder. By applying mode-driven optimization to small-footprint L3 cavities, we achieve improved optical performance together with significantly enhanced spectral reproducibility. In contrast to strictly periodic or fully disordered designs, PhC cavities based on engineered aperiodicity simultaneously achieve compact footprints, high optical performance, and improved reproducibility, making them suitable for dense on-chip integration.

REFERENCES

- [1] Y. Akahane, T. Asano, B. S. Song, S. Noda, "High-Q photonic nanocavity in a two-dimensional photonic crystal," *Nature*, vol. 425, pp. 6961, 2003.
- [2] M. Modaresialam, N. Granchi, M. Stehlik, C. Petite, S. Delegeanu, A. Gourdin, M. Bouabdellaoui, F. Intonti, B. Kerzabi, D. Grosso, L. Gallais, and M. Abbarchi, "Nano-imprint lithography of broad-band and wide-angle antireflective structures for high-power lasers," *Optics Express*, vol. 32, pp. 12967-12981, 2024.
- [3] L. Fagiani, N. Granchi, A. Zilli, C. Barri, F. Rusconi, M. Montanari, E. Mafakheri, M. Celebrano, M. Bouabdellaoui, M. Abbarchi, F. Intonti, A. Khurshed, P. Biagioni, M. Finazzi, M. A. Vincenti, M. Bollani, "Linear and nonlinear optical properties of dewetted SiGe islands," *Optical Materials: X*, vol. 13, pp. 100116, 2022.
- [4] N. Granchi, F. Intonti, M. Florescu, P. D. García, M. Gurioli, and G. Arregui, "Q-Factor Optimization of Modes in Ordered and Disordered Photonic Systems Using Non-Hermitian Perturbation Theor," *ACS Photonics*, vol. 10 (8), pp. 2808-2815, 2023.
- [5] N. Granchi, C. Gonzini, M. Lodde, G. Calusi, René P. J. Van Veldhovem, A. Fiore, G. Arregui and F. Intonti, "Improved Disorder Resilience in Small-Footprint Photonic Cavities with Periodicity Breaking," *Advanced Optical Materials*, doi.org/10.1002/adom.202502531, 2026.
- [6] P. Lalanne, W. Yan, K. Vynck, C. Sauvan, J. P. Hugonin, "Light Interaction with Photonic and Plasmonic Resonances," *Laser & Photonics Review*, vol. 12, pp.17000113, 2018.