

Improved Disorder Resilience in Small-Footprint Photonic Cavities with Periodicity Breaking

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The ongoing race to miniaturize photonic integrated circuits demands optical cavities not only exhibiting high quality-factors (Q), but that are also compact and robust. However, in conventional photonic crystal (PhC) designs, achieving high-Q typically requires large structures with extended periodicity, which increases sensitivity to fabrication-induced disorder as it multiplies imperfections, hampering reproducibility. 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. Multiple replicas of each design are fabricated, and near-field optical characterization, confirming both the Q enhancement and a marked improvement in spectral reproducibility, is performed. The reduced variability across nominally identical devices highlights the potential of engineered aperiodicity as a robust and scalable design strategy for high Q nanophotonic cavities, suitable for dense on-chip integration, paving the way for robust integration in active photonic platforms.

Their ability to support highly localized optical modes with high Q and low modal volumes (V)^[6] has made them ideal in research fields such as cavity quantum electrodynamics,^[7,8] integration of light sources,^[9,10] nonlinear optics,^[11–12] and optomechanics.^[13,14] Among them, cavities made from point-like defects within two-dimensional PhC slabs,^[15–20] particularly the widely adopted L3 design,^[4] provide a compact platform to engineer strong light–matter interactions while remaining compatible with planar fabrication techniques.

The quality factor of such PhC cavities is governed by radiation losses either in the plane or outside the slab hosting them. The former are straightforwardly suppressed by increasing the number of PhC unit cells surrounding the defect, while the reduction of the latter results from careful choice of the size and position of holes surrounding the defect. Consequently, most efforts have been devoted to the optimization of large footprint cavities: achieving ultra-high

Q-factors in PhC cavities typically requires extended PhC mirrors surrounding the defect region, often resulting in total cavity footprints exceeding $10 \times 10 \mu\text{m}^2$ ^[21,22] This increased footprint not only limits the achievable integration density in photonic circuits but also amplifies the sensitivity of the system to fabrication-induced imperfections, particularly in the mirror region where scattering losses accumulate. Indeed, as the number of PhC periods increases, so does the likelihood of disorder in hole positions,

1. Introduction

The optimization and control of the quality-factor (Q) of optical resonances are central challenges across nanophotonics,^[1–4] as resonant field build-up enhances light–matter interaction, spectral selectivity, and device efficiency. Photonic crystals (PhC) cavities represent one of the most powerful tools available for confining and manipulating light at the nanoscale.^[4,5]

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radii, or etching profiles, introducing scattering, and detuning of nominal resonances,^[23] as well as compromising device confinement performance. This is one of the many reasons encouraging the miniaturization imperative in integrated photonic platforms, demanding compact, highQ designs.

Within this framework, the interplay between footprint size, fabrication complexity, and optical performance demands innovative approaches beyond conventional few-parameter design. For example, correlated disorder-based materials^[24–28] have emerged as a compelling middle ground between the high spectral density of Anderson-localized modes present in random photonic systems and the high Q resonances in PhC cavities.^[2,29,30] Such exotic patterns have already demonstrated enhanced tolerance to fabrication-induced disorder thanks to their inherent spatial uniformity and robustness to local imperfections.^[29,30] More recently, related concepts have been explored in disorder-assisted PhC, where controlled structural correlations were shown to coexist with topological light confinement, extending the role of disorder from a limitation to a functional design parameter.^[31] These previous findings suggest that engineered geometrical disorder in single scatterer arrangements might be the key to unlock unprecedented performances in terms of resilience to fabrication-induced disorder.

In our recent work,^[32] we employed a gradient-based optimization framework based on non-Hermitian perturbation theory for quasinormal modes (QNMs).^[1,33–36] Interestingly, we demonstrated that L3 cavities with minimal PhC surroundings (just a few rows of holes) can be engineered to exhibit Q-factors on par with their large-footprint counterparts.^[3,32] Beyond the absolute Q-factor, the reduced footprint could offer decisive advantages for practical applications: higher integration density and simplified coupling to on-chip emitters or waveguides. Surprisingly, the minimization of in-plane losses, predominant in the case of a small footprint, produced irregular hole configurations considerably departing from the initial periodicity, resembling disordered systems, yet sustained highQ modes with minimal modal distortion with respect to the original L3 mode. These findings have suggested a possible convergence between the irregular configurations of holes in such optimized cavities and the well-known property of robustness to fabrication-induced disorder typical of correlated disorder photonic platforms.^[29] Validating this concept is the principal aim of this work, whose novelty does not lie in the optimization algorithm itself, which was introduced and discussed in detail in our previous study,^[32] but rather in its experimental validation and physical implications. We fabricated and characterized small-footprint L3 cavities with nominal geometries corresponding to those found at various stages of the automated optimization process.^[32] Their optical performance is evaluated using scanning near-field optical microscopy (SNOM).^[23,28–30,37,38] Our measurements confirm not only the anticipated Q-factor enhancements but also a significant increase in robustness to fabrication-induced disorder, compared to unoptimized designs. Our results illustrate that engineered disorder is not merely a compromise between order and randomness, but a design paradigm. By directly optimizing optical performance at the level of individual modes, we open new avenues for the realization of compact, robust, and highQ photonic cavities.

2. Results and Discussion

As explained in the Experimental Section, the design strategy is based on the results presented in ref. [32], obtained by applying the optimization method to the fundamental mode of a standard L3 PhC cavity with spatial extension of six lattice periods (R6 footprint). The finite element method (FEM) spatial distribution of the near-field electric field intensity of the unperturbed mode (acquired at 10 nm distance from the slab surface) is reported in **Figure 1a**. As shown in **Figure 1b**, the optimization process produces a gradual displacement of holes from their original positions (purple) to a configuration that maximizes Q (orange). Notably, small footprint cavities like R6 are dominated by in-plane losses; the holes therefore tend to re-arrange in the high-loss directions of the L3. Still, the final hole distribution is seemingly disordered, and yet precisely engineered. FEM simulations predict that this geometric evolution after 350 iterations results in a one-order-of-magnitude enhancement of the Q-factor (top panel of **Figure 1c**). The optimization induces the wavelength of the resonance to blueshift of ≈ 100 nm from the unperturbed to the final configuration, as reported in the bottom graph of **Figure 1c**. As explained in Experimental Section, we fabricated and investigated optically active small-footprint L3 cavities at three distinct stages along the optimization path, as shown in **Figure 1**: the unperturbed design (R6, $Q \approx 1500$), an intermediate configuration (R6-I, $Q \approx 5000$), and a final configuration (R6-II) with optimized $Q \approx 10^4$. Notably, the simulated 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 ($a = 330$ nm) and filling fraction is 6300, well below the value reached for R6-II. Moreover, despite the dramatic change in the design, the employed optimization method does not induce a significant modification of the L3 mode spatial distribution,^[32] as confirmed by the FEM near-field electric field intensity map of R6-II, reported in **Figure 1d**. Note that this holds also for the complete optimization process, which would include more than 15 000 iterations resulting in a $Q \approx 10^5$, as previously shown in ref. [32]; here, real samples were fabricated with design obtained with a number of iterations (350), leading to a nominal Q detectable with the spectral resolution limit of our experimental setup. **Figure 1e** reports the Scanning Electron Microscope (SEM) images of three examples of fabricated structures R6, R6-I and R6-II, where it is possible to observe the progressively aperiodic distribution of holes in the final configuration. Consistently, **Figure 2a** displays the SNOM-measured Photoluminescence (PL) spectra for each cavity type (R6, R6-I, R6-II), fabricated with a lattice constant of $a = 330$ nm, showing excellent agreement with the predicted spectral shift (**Figure 1c**, bottom panel). The overlaid PL spectrum of the quantum dots (QDs) (light blue) provides a reference for tuning the cavity modes into resonance with the emitter ensemble. We performed SNOM measurements on the samples, acquiring PL hyperspectral maps where a spectrum is acquired in every spatial position of the tip during the scan (see Experimental Section for details of the experimental setup). Each PL spectrum in the SNOM maps was then fitted using a Lorentzian function to extract the cavity mode peak. This procedure enables us to reconstruct spatial maps of the resonance wavelength shifts induced by the SNOM tip, providing detailed

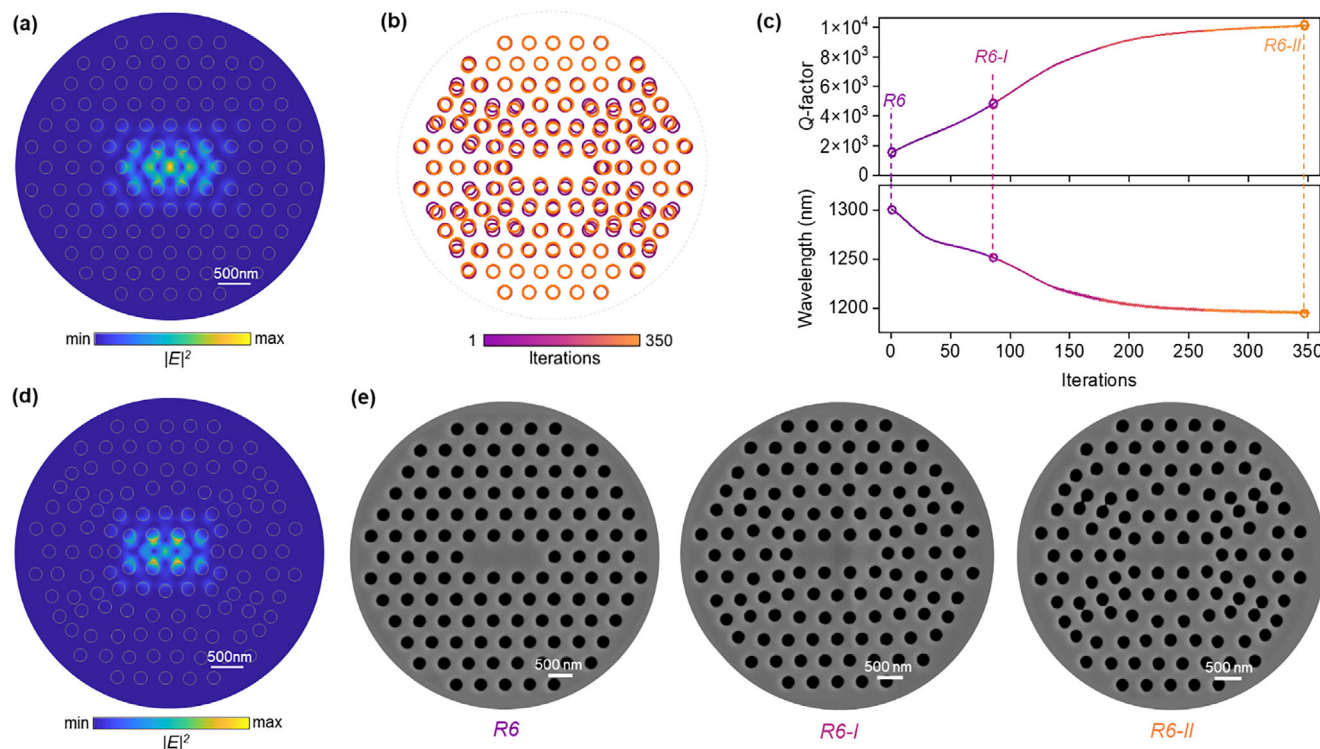


Figure 1. a) FEM near-field electric field intensity maps for the fundamental mode of the original L3 cavity (R6). The map is acquired at a 10 nm distance from the slab surface. b) Evolution of hole positions during the optimization process. Each circle represents a hole; color encodes the iteration stage from the unperturbed reference cavity (R6, purple) to the fully optimized configuration (R6-II, orange). c) Simulated Q-factor (upper panel) and resonant wavelength (lower panel) as a function of optimization iteration for an L3 with lattice constant $a = 330$ nm and hole radius $= 0.79 a$. Labels mark the three representative designs analyzed in this work: R6 (unoptimized), R6-I (intermediate), and R6-II (optimized). d) FEM near-field electric field intensity map for the fundamental mode of the optimized L3 cavity (R6-II). e) SEM images of fabricated L3 cavities corresponding to the three designs. All cavities share the same six-row PhC footprint but display increasingly disordered geometries due to the optimization.

insight into the local density of optical states (LDOS) distribution for each cavity mode.^[40] We report the spectral shift map of the R6-II cavity in Figure 2b, which showcases, thanks to the SNOM sub-diffraction resolution, the good agreement between measurements and simulations, and that the optical mode spatial distribution remains well-confined and spatially centered despite the increasing periodicity breaking. We experimentally validate the theoretical increasing trend in the Q factor of the realized small-footprint cavities by extracting the experimental values of the Q from the SNOM measurements. Figure 2 summarizes the simulated (Figure 2c, full squares) and experimental results (Figure 2d, full circles) for R6 ($a = 350$ nm), R6-I ($a = 370$ nm) and R6-II ($a = 390$ nm) cavities. Different lattice constants are considered for the R6, R6-I and R6-II configurations in order to align the corresponding cavity modes within the same spectral region. While the experimental Q-factors are consistently smaller than the FEM simulations, as an increase in the Q up to 3570 is observed, the trend is well reproduced. The values reported in Figure 2d are obtained by averaging the Q-factors extracted from PL spectra measured in all tip positions across each SNOM map. Since the near-field probe introduces a position- and local field strength-dependent perturbation^[18,41] that can locally increase radiative and absorptive losses, spatial averaging helps smooth out spatial variations and reduces the impact of tip-induced losses and provides a conservative and more reliable

estimate of the intrinsic cavity Q-factor by mitigating tip-induced effects.

Using this approach, we obtain average experimental values of $Q \approx 1055$ (R6), $Q \approx 2660$ (R6-I), and $Q \approx 3570$ (R6-II), compared to simulated values of $Q \approx 1550$, 4840, and 10 890, respectively. Such theoretical Q-factors of the R6 and R6-I cavities remain well below the instrumental resolution limit, whereas the optimized R6-II cavities approach this limit. For resonances around $\lambda \approx 1200$ nm (like for R6-II at $a = 390$ nm), the spectral resolution of the SNOM setup ($\Delta\lambda \approx 0.11$ nm) corresponds to a minimum detectable peak width of 0.22 nm, which limits the measurable Q-factor to a maximum of approximately $Q \approx 5450$. As a result, the experimentally extracted Q of the R6-II cavity (3570) represents a lower bound, limited by both the instrumental resolution and near-field perturbations. This estimation is in fact limited by the spatial averaging over the SNOM map, since locally higher Q values are observed for the optimized R6-II cavities (up to the spectral resolution limit, i.e., $Q = 5450$ in the considered spectral range). In addition to the tip perturbation on the Q-factor, two other physical phenomena can explain why the reported values are smaller than the maximum Q detectable with our experimental setup (≈ 6000): the first reason lies in the deviation from the nominal design, i.e., the fabrication-induced disorder. The second one is the additional channel of loss introduced by the QDs due to absorption and

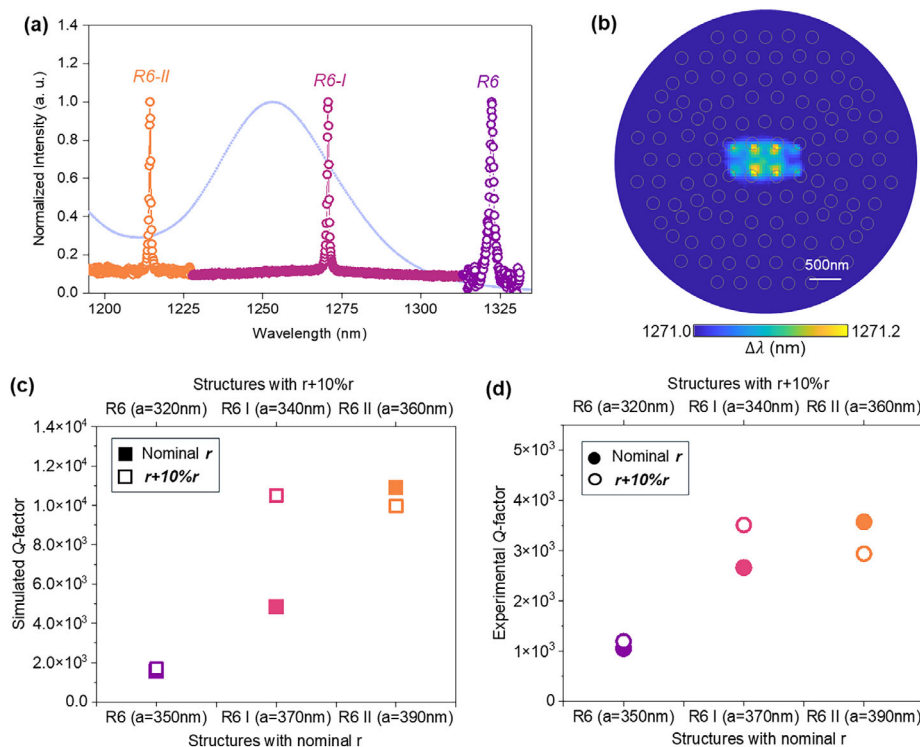


Figure 2. a) Normalized SNOM PL spectra for R6, R6-I, and R6-II cavities with $a = 330$ nm, confirming the predicted blueshift and spectral tuning through the optimization process. The overlaid light-blue shaded line represents the PL emission spectrum of the InAs QDs, used to assess spectral overlap. b) SNOM spectral shift map of the optimized (R6-II) L3 cavity ($a = 330$ nm), with overlapped design. c) FEM values of Q for nominal values of hole radius ($r = 0.83a$ for R6, $0.88a$ for R6-I, and $0.93a$ for R6-II) (full squares) and with hole radii increased by 10% (empty squares). d) Experimental values of Q for R6, R6 I, and R6 II obtained as a spatial average of SNOM reconstructed Q-maps for nominal values of hole radius ($r = 0.83a$ for R6, $0.88a$ for R6-I and $0.93a$ for R6-II) (full circles) and with hole radii increased by 10% (empty circles).

re-emission processes, and the presence of mid-band traps that arise from the QD growth.^[42] However, given the different independent channels of losses, it is impossible to draw conclusions relative to the dominant player that worsens the experimental Q factor. Nevertheless, significantly higher Q-factors are expected for otherwise identical cavities characterized via far-field measurements and/or in passive structures without embedded QDs.

In order to investigate the role of the filling fraction in the optical performances of the unperturbed and optimized cavities, the same analysis was conducted on cavities fabricated with a 10% increase in the radius of the holes, with lattice constants for R6 ($a = 320$ nm), R6-I ($a = 340$ nm) and R6-II ($a = 360$ nm). Interestingly, what arises from both experimental and theoretical values (empty squares and circles in Figure 2c,d) is that a change in the filling fraction leads to an important deviation from the expected trend; the maximum Q is obtained from R6-I, while that of R6-II is slightly quenched but still maintain a higher value than its unperturbed counterpart R6. This is likely due to the fact that the optimization process, starting with a different filling fraction (i.e., values of hole radius), would have led to different final distributions of the holes' positions.

Beyond the confirmed Q performance, the critical question of spectral reproducibility, often hampered by fabrication-induced disorder, remains. A rigorous analysis can be carried out in terms of spectral stability, which represents a crucial assessment to

highlight the applicative impact of the proposed cavities. In the context of cavity–emitter coupling, the key performance metric is the spectral overlap between the cavity resonance and the emitter ensemble. Defects and irregularities, which are typical consequences of the electron-beam lithography and etching processes, are known to induce significant variations in the optical response of photonic crystal cavities. Figure 3a shows two SEM images of representative R6 and R6-II cavities (top and bottom), with detailed zooms highlighting the presence of fabrication imperfections such as deviations in hole shape and roughness at the nanoscale. From the zoom inset of the R6 II, where green circles are overlapped, indicating the nominal design, it is clearly visible how some holes, supposed to be separated, merged in the fabricated structure. In conventional designs, such imperfections often result in spectral shifts of tens of nm across nominally identical replicas, limiting the practical reproducibility of photonic devices. The left (right) graph of Figure 3b reports the PL SNOM spectra relative to eight nominally identical replicas of R6 (R6-II) with $a = 320$ nm ($a = 350$ nm). While the fundamental mode of the unperturbed design different replica is spread in a spectral range of 25 nm, the optimized cavities show resonances which are only 7 nm spectrally apart. This observation can suggest an enhanced robustness to fabrication imperfections in optimized cavities, and an analog result is obtained for cavities with different filling fractions (hole radii $r' = 1.1r$), as shown in Figure S1 (Supporting Information).

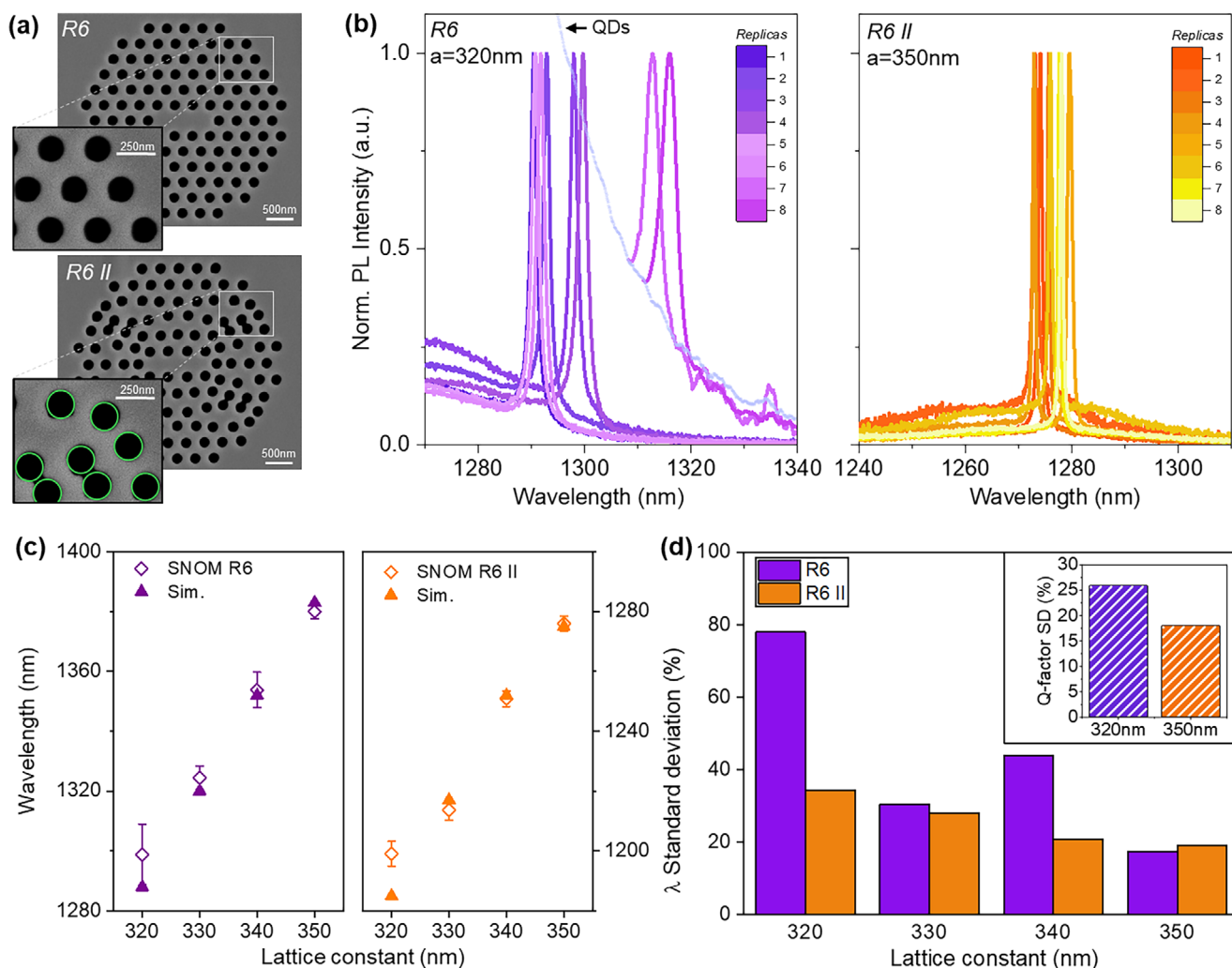


Figure 3. a) SEM images of the R6 (up) and R6-II (bottom) cavities with $a = 320$ nm. The insets are detailed zooms showing the fabrication-induced imperfections. Green circles indicate the nominal design of the R6-II cavity. b) Normalized SNOM PL spectra acquired at the location of maximum emission of eight nominally identical replicas of R6 with $a = 320$ nm (left) and R6-II with $a = 350$ nm (right) and nominal radii. In the left graph, the QD PL emission (light blue) is overlapped to the spectra. c) Diamonds: average wavelength of the cavity resonance obtained after measuring eight nominally identical replicas of each cavity type, each examined for four values of the lattice constant (R6, purple, and R6-II, orange); the error bars indicate the SD. Purple (orange) triangles: simulated values of the resonances for the R6 (R6-II) cavity at each lattice constant. d) Percentual SD of the resonance wavelength for each cavity type, quantifying improved spectral stability and fabrication tolerance in the optimized geometries. The inset shows the percentual SD of the average quality factors for eight replicas of R6 with $a = 320$ nm and of R6-II with $a = 350$ nm; these two lattice constants were chosen because they provide the only configurations in which the modes are located in the same spectral region (i.e., on the tail of the QDs emission as shown in Figure S2, Supporting Information) and therefore share a similar signal to noise ratio and a similar loss contribution introduced by the QDs.

Since the R6 and R6-II spectra of Figure 3b were acquired on cavities with different lattice constants, we address this aspect more rigorously with a systematic statistical approach; we measured eight nominally identical replicas for each design (R6 and R6-II with diff) and extracted the resonance wavelength by performing a Lorentzian fit on the PL peak from each SNOM spectrum. Since the fabrication-induced disorder is strongly dependent on the required nanometric details of a design, we repeated this analysis for four different values of the lattice constant ($a = 320, 330, 340$, and 350 nm) to investigate the role of the hole dimension (linked to the lattice constant through the filling fraction) in the reproducibility of the optical resonances. The average resonance wavelength for each set (composed of eight

nominally identical replicas) is shown in Figure 3c as purple and orange open diamonds for the R6 and R6-II structures, respectively, with error bars representing the standard deviation (SD) of the measurements. Simulated values are indicated by the triangles in the corresponding color, showing good agreement with experimental averages and a consistent redshift as the lattice constant increases. From these graphs, it is evident that the error bars, reflecting the variation of resonance wavelengths among replicas, are smaller for the optimized R6-II cavities compared to the unperturbed R6, indicating improved spectral stability. Additionally, in both cavity types, the SD decreases with increasing lattice constant, suggesting that larger pores are less susceptible to fabrication-induced disorder, leading to reduced deviations

from the nominal resonance wavelength. Nevertheless, at every lattice constant, the optimized R6-II structures consistently exhibit smaller absolute SD, confirming their superior robustness to disorder. The evaluation of the percentual error of each set of measurements, reported in Figure 3d, further strengthens this deduction; the histogram displays the relative SD (as a percentage of the average wavelength) for each lattice constant and cavity type. For small lattice constants, for which the fabrication errors are more dominant, the R6-II cavities (orange) exhibit lower relative fluctuations than the R6 (purple), and most of all, they follow a monotonic decrease, in sharp contrast to the irregular behavior of the unoptimized R6 sSD. Moreover, for applications requiring precise wavelength targeting, optimized cavities offer an additional advantage, particularly when comparing designs with the same resonant wavelength, such as R6 with $a = 320$ nm and R6-II with $a = 350$ nm. Not only does the broken periodicity enhance resilience to fabrication-induced disorder, as demonstrated by our results, but the optimization process also systematically leads to larger lattice constants (for a given wavelength). This inherently reduces the likelihood of critical lithographic imperfections, further improving reproducibility in fabricated structures. For practical Purcell-enhanced emission, maintaining spectral alignment across nominally identical cavities is a critical indicator of robustness, but the Q-factor is also a crucial parameter; we complete our analysis by focusing on the set of eight replicas of R6 ($a = 320$ nm) and R6-II ($a = 350$ nm). These two configurations, among all the ones available in our dataset, are the only one that can be compared in terms of extracted Q-factors: this is because their cavity modes fall within the same spectral region – on the tail of the QD emission spectrum (see Figure S2a, Supporting Information) – and therefore share comparable signal-to-noise ratios in the PL measurements and a similar loss contribution introduced by the QDs. The inset of Figure 3d shows reports percentualSD of the quality factors (estimated through the spatial average of the SNOM maps as explained above) for the two realizations datasets: this comparison shows that the R6-II design exhibits smaller Q-factor fluctuations, confirming enhanced reproducibility and robustness against fabrication-induced disorder. The comparative analysis for the percentual SD of the quality factors, also of R6II at 320 nm and R6 at 350 nm, is shown in Figure S2b (Supporting Information).

The observed enhancement in spectral reproducibility and tolerance to fabrication imperfections can be physically interpreted as a direct consequence of the correlated aperiodicity introduced by the optimization process. Our optimization procedure based on the QNM gradients directly minimizes radiative losses (imaginary part of the eigenfrequency). To do this, it modifies hole positions coherently, following the field pattern. As a result, holes in regions of strong out-of-plane radiation move in directions that destructively interfere with leakage, and neighboring holes move in a correlated, aperiodic fashion that smooths local field-phase discontinuities normally responsible for scattering. Unlike random disorder, which induces uncorrelated scattering and large fluctuations in the local optical potential, the gradient-based optimization generates spatially correlated displacements of the air holes that redistribute radiation losses in a controlled manner. This smooths out local variations in how the structure confines light, effectively creating a more uniform optical environment for the cavity mode. The resulting smoother refractive-index land-

scape is therefore intrinsically less sensitive to fabrication noise. This behavior parallels the suppression of density fluctuations observed in hyperuniform disordered photonic materials,^[24–30] where correlated disorder yields robust confinement. This interpretation is further supported by a pair correlation function analysis (Figure S3, Supporting Information),^[43] which reveals for the optimized cavities broadened short-range peaks and finite correlations at inter-hole separations that are forbidden in the periodic lattice, indicating the emergence of short-range positional disorder in the optimized structures.

3. Conclusion

In this work, we have demonstrated that engineered disorder, introduced through a gradient-based Q-factor optimization framework based on non-Hermitian perturbation theory,^[32] enables the realization of relatively highQ, small-footprint photonic crystal cavities with enhanced robustness to fabrication-induced disorder. While the optimization framework employed here has been previously introduced, this work provides its first systematic experimental validation in small-footprint PhC cavities and demonstrates its effectiveness in enhancing robustness against fabrication-induced disorder. By fabricating and characterizing L3 cavities at different stages of optimization – R6 (unoptimized), R6-I (intermediate), and R6-II (optimized) – we systematically validated the theoretical predictions through near-field optical measurements and statistical analysis across multiple replicas. Despite the aperiodic appearance of the optimized designs, the fundamental optical mode remains spatially confined and structurally stable. The superior Q-factor achieved within a footprint four times smaller than that of the standard L3 cavity's extension required to reach an equal (or even lower) Q highlights compactness as a genuine technological advantage, enabling denser, more robust, and easily scalable photonic integration. We further demonstrated that the optimized R6-II cavities exhibit not only higher Q-factors but also reduced fluctuations in resonance wavelength, confirming improved spectral reproducibility, making these engineered-disorder cavities more suitable for scalable photonic integration where spectral alignment with quantum emitters is critical. In addition, our statistical analysis suggests the existence of a threshold in lattice constant, beyond which lithographic imperfections become less prominent, suggesting that larger feature sizes can inherently reduce the impact of fabrication variability. The trend found in decreasing fluctuations in resonance wavelength persists across different lattice constants, indicating the effectiveness of optimization in mitigating the impact of fabrication variability, particularly for smaller-feature designs. The statistical analysis is based on eight nominally identical replicas for each design and lattice constant: the robustness demonstrated here should therefore be interpreted as a significant improvement in device-to-device reproducibility within the experimentally accessible ensemble. Nevertheless, altogether, our findings point in the direction of highlighting engineered disorder as a powerful and general design principle in nanophotonics, with important implications for the design of robust nanophotonic components. Unlike purely periodic or random systems, photonic cavities with engineered aperiodicity combine the strengths of compactness, high performance, and reproducibility. This paradigm opens the door to the scalable inte-

gration of high-quality nanophotonic components in active photonic platforms, with potential applications ranging from low-threshold nano-lasers to cavity quantum electrodynamics and nonlinear photonics.

4. Experimental Section

Design: The design method uses the theoretical framework of QNMs^[1,33] and relies on first-order non-Hermitian perturbation theory to efficiently compute the gradients of Q relative to arbitrary material boundary displacements.^[32] Given its first-order nature, the method requires only the calculation of the complex eigenfrequency and complex field profile of the QNM of interest. For reduced complexity, gradient-based automated optimization solely for rigid shifts in the position of all holes in the structure (keeping the hole radius constant), as fully explained in ref. [32] were employed. Calculations are done by employing a commercialFEMcomplex eigensolver (COMSOL Multiphysics^[39]). The designs are obtained by applying the optimization method to the fundamental mode of a standard L3 PhC cavity, defined over a spatial domain extending six lattice periods ($6a$) around the defect, referred to as R6. For a lattice constant $a = 330$ nm, this corresponds to a total footprint of $\approx 4 \times 4 \mu\text{m}^2$. This domain size represents the minimal configuration required to achieve acceptable modal confinement in a standard L3 cavity, yielding a baseline Q-factor of ≈ 1500 .^[32] The full details of the computational implementation, including hardware specifications, simulation settings, and convergence tests, are provided in Supporting Information of ref. [32]. Here, we refer to the studied structures as: R6 (the unperturbed L3), R6-I (intermediate configuration), and R6-II (optimized configuration). The three designs correspond to increasing Q-factors.

Sample Fabrication. The fabricated structures are based on GaAs heterostructures incorporating a dense layer of InAs QDs emitting at 1300 nm, which are grown by molecular beam epitaxy and embedded at the center of a 220 nm-thick GaAs membrane that spans the entire sample.^[16] The PhC designs are defined through a process combining electron-beam lithography, reactive-ion etching, and the selective removal of a 3 μm -thick AlGaAs sacrificial layer to release the membrane. To ensure optimal spectral overlap with the quantum dot emission band, we rescaled each cavity design at multiple lattice constants while maintaining a constant filling fraction (lattice constants (290–370) nm for the R6, (300–380) nm for the R6I, and (320–400) nm) for the R6-II in steps of 10 nm); for statistical analysis and reproducibility, eight nominally identical replicas were produced for each configuration.

Optical Characterization: PL measurements are performed at room temperature using a SNOM apparatus operating in the near-infrared with subwavelength spatial resolution. The system is configured in illumination/collection mode: excitation is provided by a 785 nm diode laser coupled into a chemically etched optical fiber, and the emitted PL signal is collected through the same near-field probe at each tip position with spectral resolution of 0.11 nm.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

correlated disorder, engineered disorder, near-field optical microscopy, photonic crystal cavities

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