Monolithic Silicon-Based Nanobeam Cavities for Integrated Nonlinear and Quantum Photonics

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Photonic resonators that allow an electromagnetic field to be confined in an ultrasmall volume with a long decay time are crucial to a number of applications requiring enhanced nonlinear effects. For applications to integrated photonic devices on chip, compactness and optimized in-plane transmission become relevant figures of merit as well. Here we optimize an encapsulated Si/SiO₂ photonic-crystal nanobeam cavity at telecom wavelengths by means of a global optimization procedure, where only the first few holes surrounding the cavity are varied to decrease its radiative losses. This strategy allows us to theoretically achieve intrinsic quality factors close to 10 million, sub-diffraction-limited mode volumes, and in-plane transmission above 65%, in a structure with a very small footprint of about 8 μm². We address and quantitatively assess the dependence of the main figures of merit on the nanobeam length and on fabrication disorder. Finally, we study a system of two optimized and laterally coupled nanobeam cavities with the goal of demonstrating an unconventional photon blockade at room temperature in a monolithic passive device. We estimate the single-photon nonlinearity of this device and discuss the relevant figures of merit, which lead to sub-Poissonian photon statistics of the transmitted signal. Our results hold promise for prospective experiments in low-power nonlinear and quantum photonics.

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I. INTRODUCTION

The search for ultrahigh-Q/V photonic-crystal (PC) cavities has attracted considerable attention in the field of nanophotonics during the last two decades [1]. The diffraction-limited confinement enabled by PC cavities (with mode volumes V of the order of a cubic wavelength in the medium) and the possibility of achieving high quality factors Q have led to several remarkable demonstrations in the context of enhanced light-matter interaction [2–11] and optical nonlinearities [12–19]. One-dimensional PC nanobeam cavities, in particular, have been widely used, as they have a significantly smaller footprint than their two-dimensional PC counterparts [20]. Cavity designs for achieving quality factors of the fundamental mode in the range 10⁸–10⁹ and mode volumes of the order of (λ/n)³ have been proposed for freestanding nanobeam cavities [21,22]. The efforts toward increasing Q/V for nanobeam cavities have been mainly focused on silicon photonics at telecom wavelengths [23–30], allowing integration with optoelectronic devices on a single CMOS chip [31].

As far as working performance is concerned, nanobeam systems in freestanding membranes (air bridges) may be affected by mechanical instabilities and environmental changes, thus making integration challenging. This problem has been solved by means of SiO₂ encapsulation [32], with the added benefit that it naturally improves the thermal resistance, as SiO₂ provides a better heat sink than air [33], and it mitigates loss channels related to the etching of air holes and the introduction of leaky surface states into the silicon [34]. However, due to the reduction of the contrast between the refractive indices in the system (nSiO₂ = 1.44 in the telecom range), high Q factors are more difficult to achieve, even theoretically, as index-guided confinement becomes less effective. Nevertheless, optimization of the Q factors of Si/SiO₂ nanobeam cavities has been achieved through a smooth variation of the cavity edges, such that the confined electromagnetic mode follows a Gaussian envelope function [35,36]. This technique, commonly referred to as gentle confinement, effectively reduces the leaky components of the cavity mode out of the plane, and it has been exploited to obtain theoretical Q factors of up to 10⁷ for encapsulated nanobeams [37]. While gentle confinement has been shown to be very effective for increasing the Q factor of nanobeam cavities, the main drawback arises from the large number of
holes affected by the optimization, resulting in very long structures that may be highly sensitive to disorder effects [20, 37].

In this paper, we follow a different route to achieve simultaneous optimization of either the $Q$ factor or the transmission of such monolithic nanobeam cavities, in which only the first few holes surrounding the defect region are varied to decrease radiative losses. This technique has been extremely successful for two-dimensional PC cavities, where outstanding figures of merit have been realized [38–42]. Specifically, we use a global optimization strategy combined with first-principles numerical simulations in order to maximize the cavity quality factor $Q_c$ at telecom wavelengths, in a space defined by the optimization parameters of the nanobeam. The optimized cavity design has a quality factor close to 8 million, a diffraction-limited volume, a transmission exceeding 50%, and a very small footprint. Additionally, we study the effect of disorder on $Q_c$ and find that an average quality factor of about one million is still achievable when we consider state-of-the-art tolerances in sample-fabrication techniques. The cavity designs presented in this paper are of particular interest for applications in classical and quantum silicon photonics on integrated chips, where the enhancement of linear and nonlinear interactions plays a fundamental role in the device functionality. To this end, we finally give a realistic estimate of the ratio of the single-photon nonlinearity to the loss rate, and quantitatively assess an integrated device based on two coupled nanobeam cavities with the aim of achieving sub-Poissonian photon statistics using the physical mechanism known as unconventional photon blockade (UPB) [43]. The latter effect, whose optimal parameters are determined by the single-cavity figures of merit and photon hopping in a two-coupled-cavity configuration [43,44], has been recently measured in active devices at cryogenic temperatures, and it typically requires a weaker effective nonlinearity compared with the conventional photon blockade [45]. Here, passive silicon-based devices with coupled nanobeam cavities would allow one to realize the UPB paradigm at room temperature in a monolithically integrated photonic chip, thus showing the great potential of these systems for quantum photonics experiments on an all-silicon platform.

The paper is organized as follows. In Sec. II, we present the optimization of the nanobeam cavity and compute the main figures of merit of the optimal design. In Sec. III, we study the dependence of the total quality factor $Q$ and the in-plane transmission on the number of holes on each side of the cavity. The effects of disorder are studied in Sec. IV, and we estimate the single-photon nonlinear coupling and discuss its potential applications in quantum photonic devices in Sec. V. Finally, the main conclusions of the paper are presented in Sec. VI.

II. OPTIMIZATION OF NANOBEAM-CAVITY DESIGN

We show in Fig. 1(a) a schematic representation of the nanobeam structure optimized in the present work. The cavity is created by increasing the distance between two adjacent holes by introducing a lattice offset $\Delta x_c$. A total number of holes $N$ is considered on each side of the cavity, and the first five are allowed to vary (in position and size) to optimize the quality factor $Q_c$ of the fundamental cavity mode. Since we preserve the mirror symmetry with respect to the center of the nanobeam, only the $x$ coordinate and the radius $r$ of holes $i$ (for $1 \leq i \leq 5$) are changed, i.e., $x'_i = x_i + dx_i$ and $r'_i = r_i + dr_i$, where a positive (negative) $dx$ means outward (inward) displacement. We adopt the structural parameters originally reported in Ref. [26] for an asymmetric silicon-on-insulator (SOI) nanobeam-cavity structure, i.e., lattice parameter $a = 350$ nm, hole radii $r = 98$ nm, thickness $d = 260$ nm, and width $w = 500$ nm, leading to a resonant mode at telecom wavelengths. These parameters are shown in Fig. 1(b), where the silicon structure is assumed to be completely encapsulated in SiO$_2$, unlike what was done in Ref. [26]. However, our starting cavity design is taken from the same publication and is given by the set $(dx_1, dx_2, dx_3, dr_1, dr_2, dr_3, \Delta x_c) = (110, 60, 25, -33, -18, -13, 7.5)$ nm, which yields a three-dimensional finite-difference time-domain (3D-FDTD) [46] quality factor $Q_c = 3.1 \times 10^4$ at $f = 193$ THz for the fundamental mode. In Fig. 1(c), we show the projected structure of the TE-like bands of the nanobeam, computed with the MIT photonic-band package MPB [47], where the yellow region indicates the photonic band gap and the cavity frequency is represented by the horizontal black dashed line. The corresponding intensity profile of the cavity mode, which displays a node at the center of the structure, is shown in Figs. 1(d) and 1(e) for $z = 0$ and $y = 0$, respectively.

The basic design above represents our starting point for carrying out the optimization procedure by making small modifications to $\Delta x_c$ and the holes surrounding the cavity. Specifically, we consider the five holes closest to the nanobeam center, which are the most relevant for the confinement of cavity modes, as clearly seen in Figs. 1(d) and 1(e). This choice sets the overall dimension of the parameter space to 11. We use a particle swarm algorithm to carry out the global optimization, with $Q_c$ as the objective function, and use first-principles FDTD simulations [46] to evaluate $Q_c$. We find an optimal cavity quality factor of $7.8 \times 10^6$ at a resonance frequency of $f = 194.6$ THz, corresponding to an improvement of two orders of magnitude with respect to the nonoptimized design. This quality factor is achieved with a structure as short as $N = 20$ (see Fig. 2), and it is one order of magnitude larger than those obtained by applying the gentle-confinement strategy with the same sample length in freestanding nanobeams.
FIG. 1. (a) Schematic representation of a nanobeam cavity with a total of \(N\) holes on each side, and a lattice offset \(\Delta x_c\). The red holes are allowed to vary (in size and position), and \(\Delta x_c\) is also allowed to vary while preserving the mirror symmetry with respect to the center of the cavity. (b) Parameters of the nanobeam unit cell. (c) Structure of the TE-like bands of (b) in the projected Brillouin zone, where the dashed horizontal line represents the nonoptimized cavity mode with \(f = 193\) THz and \(Q_c = 3.1 \times 10^4\). The band-gap and light-cone regions are highlighted in yellow and gray, respectively. (d) Electric-field-intensity profile \(|E|^2\) of the cavity mode at \(z = 0\). (e) As (d), for \(y = 0\).

[20]. The main figures of merit of our optimized cavity are shown in Table I, where the linear mode volume is defined as

\[
V_l = \frac{\int \epsilon(r)|E(r)|^2 \, dr}{\max \{\epsilon(r)|E(r)|^2\}},
\]

and the nonlinear mode volume as [48]

\[
V_{nl} = \frac{\left[\int \epsilon(r)|E(r)|^2 \, dr\right]^2}{\int \epsilon^2(r)|E(r)|^4 \, dr},
\]

In Eqs. (1) and (2), \(\epsilon(r)\) is the dielectric function of the system, and the integration is carried out over the whole computational-cell volume. The very small mode volumes reported in Table I for our optimal design of an encapsulated nanobeam cavity lead to enhancement factors of \(Q_c/V_l\) and \(Q_c^2/V_{nl}^2\) in the ranges of \(10^7(n_{Si}/\lambda)^3\) and \(10^{13}(n_{Si}/\lambda)^6\), respectively, highlighting the potential of such a photonic structure for linear and nonlinear applications in ultracompact devices. In addition, these values exceed those previously obtained through gentle confinement with \(N = 40\), i.e., with a structure twice as long overall [37]. In order to verify the robustness of our results with respect to the number of varying holes, we also add the next three holes to the parameter space (increasing its dimension to 17) and carry out an independent optimization, which shows no significant...
improvement in the cavity figures of merit (see the results in Appendix A). The structural parameters obtained for the optimized designs after using the particle swarm algorithm are reported in Appendix B for completeness, for both the five- and the eight-hole variation. Finally, to visualize the effect of the optimization, we report in Appendix C also the Fourier transforms of the components $E_y$ of the cavity mode for both the five- and the eight-hole case, highlighting the suppression of the radiative contributions inside the light cone, which is the origin of the $Q_c$ enhancement [35,49].

III. TRANSMISSION

The in-plane transmission of the nanobeam cavity can be estimated using the temporal coupled-mode theory presented in Ref. [50], where the cavity, with its intrinsic $Q_c$, is assumed to be weakly coupled to a ridge waveguide, which is quantified by an effective $Q_w$ that represents the finite lifetime of the cavity-waveguide coupling. Thus, the total $Q$ factor of the waveguide-cavity coupled system can be written as

$$\frac{1}{Q} = \frac{1}{Q_c} + \frac{1}{Q_w},$$

and the transmission at the cavity resonance takes the simple form

$$T = \frac{Q^2}{Q_w^2}.$$  

The behavior of $Q$ and $T$ as a function of the total number of holes, $N$, is shown in Fig. 2 for the optimized cavity. Evidently, the total quality factor of the system displays an exponential increase with $N$ before eventually saturating at the value $Q_c$ (i.e., the value for $N > 20$), corresponding to the limit where the cavity and the waveguide are no longer coupled, i.e., with infinite $Q_w$ and zero transmission. In contrast, with a decreasing number of holes, $T$ increases and approaches 1 for the smallest sample studied ($N = 8$) at the expense of the total $Q$ factor. Optimizing the transmission implies compromising between high $Q$ and high $T$ in order for one to be able to efficiently inject and extract light into and from the system, while keeping losses low. We find the optimal transmission to be at $N = 15$, where $Q \sim 1.5$ million with a transmission above 60%. Note that in the case of a gentle-confinement geometry in a freestanding nanobeam cavity [20], a minimum of $N = 15$ should be considered, which leads to $T$ values above 90%, but $Q$ factors below $10^5$. The present approach allows us to keep outstanding figures of merit with encapsulated and very compact structures.

IV. DISORDER EFFECTS

When one is dealing with realistic samples, disorder is always present, originating from unavoidable imperfections introduced at the fabrication stage. This effect is commonly modeled by assuming noncorrelated Gaussian fluctuations in either the positions, i.e., $(x, y) \rightarrow (x + \delta x, y + \delta y)$, or the sizes, i.e., $r \rightarrow r + \delta r$, of all the holes in the whole photonic structure, where the standard deviation of the corresponding Gaussian probability distribution, $\sigma$, is taken as the disorder parameter [51–54]. We carry out such an analysis for our nanobeam-cavity designs by computing 100 independent disorder realizations for each $\sigma$ value, to obtain the average quality factor of the cavity modes, $\langle Q_c\rangle$.

The results are shown in Fig. 3, where we plot $\langle Q_c\rangle$ as a function of $\sigma/a$ for the optimized cavity. Two independent cases are considered, one in which either the positions or the sizes of all the holes are varied at the same time (red curve), and another in which only their sizes fluctuate (blue curve). Most often, the latter case is believed to be the dominant source of fabrication imperfections due to the etching process. We specifically compute $\langle Q_c\rangle$ for $\sigma = \ldots$
cavities may be key to a number of applications requiring enhanced on-chip nonlinearities, such as all-optical switching and optical routing, which could eventually find applications in, e.g., photonic-based neuromorphic computing. Beyond applications in classical nonlinear optics, we also envision interesting perspectives in quantum photonics, in particular in the generation of nonclassical states of radiation such as entangled photon pairs by spontaneous four-wave mixing. In the following, we focus on the on-chip generation of sub-Poissonian photon statistics by exploiting the intrinsic nonlinearity of the material.

First, we give an estimate of the single-photon nonlinearity in the nanobeam cavity, i.e., the interaction energy between two photons simultaneously present in the resonator, induced by a given nonlinear process. This is the key quantity to consider for low-power nonlinear-optics applications, and for more recent proposals for quantum photonics experiments in passive materials (i.e., not exploiting intrinsic absorption resonances of the medium). For silicon, it is relevant to calculate this contribution when it is induced by a third-order nonlinear susceptibility of the material, quantified by the elements of the tensor $\chi^{(3)}$.

For the case of a passive nonlinear resonator, the nonlinear energy shift for a resonant mode at frequency $f_0$ is given by the relation [27,44]

$$U_{\text{nl}} = \frac{3(hf_0)^2}{4\varepsilon_0} \int \chi^{(3)}(\mathbf{r})|\mathbf{E}(\mathbf{r})|^4 d\mathbf{r}$$

$$\approx \frac{3(hf_0)^2}{4\varepsilon_0 V_{\text{nl}}^2} \bar{\chi}^{(3)}$$

where the approximate expression is given in terms of the nonlinear mode volume for third-order nonlinear processes [Eq. (2)], and $\bar{\chi}^{(3)}$ represents a weighted value of the nonlinear susceptibility that takes into account its spatial dependence. To give quantitative estimates, we assume constant values for the real part of the nonlinear susceptibility and relative dielectric permittivity equal to those that are known for silicon at telecom wavelengths [60], i.e., $\chi^{(3)} = 0.25 \times 10^{-18} \text{ m}^2/\text{V}^2$ and $\varepsilon_r = 12.09$, respectively, and neglect nonlinear contributions from the silica. For our optimized cavity, we numerically calculate the integral in Eq. (5), obtaining the value $U_{\text{nl}} \approx 1.6 \times 10^{-4} \mu\text{eV}$. From results in Fig. 2, and taking into account that $Q_d \approx 2.5 \times 10^6$ for a size disorder of $\sigma/a = 0.002$ ($\sigma \sim 0.7 \text{ nm}$ for our current design), we can realistically achieve $Q \approx 10^6$ ($1/Q \rightarrow 1/Q + 1/Q_d$) at telecom energies (0.8 eV) with a sample length of $N = 15$. This gives a theoretical ratio between the nonlinearity and the intrinsic cavity loss rate in the order of $U_{\text{nl}}/hf_0 \sim 2 \times 10^{-4}$. While such a value makes it very challenging to directly probe single-photon nonlinearities with these devices [27], it is a very promising estimate for quantum photonics experiments relying on, e.g., quantum interference effects [29,43].

\[\text{FIG. 3. Cavity quality factor } \langle Q_c \rangle \text{ averaged over 100 disorder realizations as a function of the disorder parameter for the optimized cavity with five varying holes. The red curve corresponds to disorder in both the positions and sizes of the holes, while the blue curve corresponds to disorder in the hole sizes only.}\]
Here, we propose a fully integrated monolithic device that allows sub-Poissonian photon statistics to be generated at the output, by exploiting only the $\chi^{(3)}$ response of crystalline silicon and thus working at virtually room temperature. In order to characterize the single-photon nonlinear behavior of the device, we calculate the second-order correlation function at zero time delay, which is a measurable quantity that allows one to assess the sub-Poissonian photon statistics. As a first step, we calculate the characteristic parameters of a coupled-nanobeam-cavity device that are relevant to the quantum master-equation model, starting from the optimized parameters of a single-nanobeam cavity (loss rate, transmission, nonlinearity) obtained above. In particular, we define the tunnel-coupling rate, $J$, and the loss rates of the normal modes here. The parameter $J$ is obtained from 3D-FDTD simulations of the whole coupled-cavity device as a function of the cavity-to-cavity distance $d$ and deduced from the calculated normal-mode splitting between the symmetric and antisymmetric modes (in particular, we take $J$ to be half of the normal-mode splitting as a reasonable estimate).

The resulting exponential scaling of $J$ versus $d$ is represented in Fig. 4(a). Notice that we numerically calculate the normal-mode splitting up to $d = 750$ nm, and then extrapolate the following points since the algorithm is not able to resolve the smallest values. In Fig. 4(b), we also show the symmetric ($\gamma_S$) and antisymmetric ($\gamma_A$) normal-mode loss rates. To make the final estimate of the correlation functions as realistic as possible, we correct the values of the intrinsic loss rate obtained from the FDTD simulations with a disorder contribution, assumed to be equal for the two resonators. These values are reported in Fig. 4(b) as a function of the distance between the two nanobeam cavities, and compared with the value for an

![Graphs and images](Figures)
TABLE II. Summary of linear and nonlinear figures of merit for a nanobeam cavity with eight varying holes. The ratio \( Q_c/V_i \) is relevant to linear phenomena, while \( Q_c/V_{nl} \) is mostly employed for nonlinear applications.

<table>
<thead>
<tr>
<th>f (THz)</th>
<th>( Q_c )</th>
<th>( V_i (\lambda/\eta_{Si})^3 )</th>
<th>( V_{nl} (\lambda/\eta_{Si})^3 )</th>
<th>( Q_c/V_i (\eta_{Si}/\lambda)^3 )</th>
<th>( Q_c/V_{nl} (\eta_{Si}/\lambda)^6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>194.6</td>
<td>8.1 \times 10^6</td>
<td>0.38</td>
<td>1.92</td>
<td>2.13 \times 10^7</td>
<td>1.78 \times 10^{13}</td>
</tr>
</tbody>
</table>

isolated cavity (also corrected for a disorder contribution). The two normal-modes loss rates converge to the isolated-cavity value at distances \( d \) larger than approximately 1 \( \mu \)m, as expected. These parameters are employed to calculate the zero-delay second-order correlation at the output of the schematic device represented in Fig. 4(b): two coupled encapsulated-nanobeam cavities, 1 and 2, are coherently pumped only through the access ridge waveguide that directly feeds cavity 1, and output radiation is collected only through the channel directly outgoing from the same resonator. The full quantum master-equation modeling of this device has already been reported in Ref. [44], to which we refer for details. Here we employ the same model, with input parameters given by the \( U_{nl} \) value calculated in the previous paragraph for the nonlinear coupling in each resonator, and with the \( d \)-dependent values of \( J, \gamma_S \), and \( \gamma_J \) given in Figs. 4(a) and 4(b). The isolated-cavity resonance, \( f_0 \), is given by the optimized design of Sec. II, and the pump rate of cavity 1 is fixed at \( F = 10\gamma_S \).

Finally, we calculate the steady-state second-order correlation function collected from cavity 1, \( g_2^{(2)}(0) \), as described in Ref. [44]. The results are shown by a color-scale plot in Fig. 4(d) as a function of both \( d \) and \( \Delta = h(f_{\text{pump}} - f_0) \), where \( f_{\text{pump}} \) is the driving pump frequency. We notice that two regions can be identified in which the output photon stream is antibunched, i.e., it satisfies \( g_1^{(2)}(0) < 1 \), one corresponding to \( d \sim 100 \text{ nm} \) [with \( g_1^{(2)}(0) \sim 0.005 \)] and another around \( d \sim 900 \text{ nm} \) [with \( g_1^{(2)}(0) \sim 0.16 \)]. It is interesting to notice that for \( d \sim 100 \text{ nm} \), disorder would act on the coupled-mode resonances to cause a relative standard deviation in the tunnel-coupling rate of \( \delta J/J \sim 0.025 \), while for \( d \sim 900 \text{ nm} \) the corresponding estimate would give \( \delta J/J \sim 13 \). These values can be inferred from a previous theoretical study performed on coupled L3 cavities, and represent a reasonable estimate also for the coupled-nanobeam cavities when we assume \( \sigma_a = 0.002 \) [53]. Evidently, then, the normal-mode splitting for large intercavity distances would be hard to resolve, due to disorder, while for \( d \sim 100 \text{ nm} \) the antibunching could be realistically measured in state-of-the-art devices. However, it should be noticed that at large \( J \) values, the normalized nonlinearity \( U_{nl}/\gamma_S \) would be quite small, and the resulting low output signal would need to be compensated with a larger pump rate [43]. In this respect, our optimized nanobeam-cavity design, which allows a large in-plane transmission, might be key to achieving the output signal necessary to measure the coincidence counts.

VI. CONCLUSIONS

We design an encapsulated Si/SiO\(_2\) photonic-crystal nanobeam cavity by means of a global optimization strategy, where only the holes closest to the cavity are varied to increase the quality factor of the system. Differently from the commonly adopted gentle-confinement mechanism, our approach results in a structure with a very small footprint of around 8 \( \mu \)m\(^2\), a total \( Q \) of several million, a small linear mode volume in the 0.4(\( \lambda/n \))\(^3\) range, and a transmission above 50\%, thus achieving very high figures of merit for such an ultracompact photonic device. We study the effects of intrinsic disorder on the quality factor of the nanobeam cavity and find that, when we consider typical tolerances achieved in modern sample-fabrication techniques, the quality factor remains in the range of one million, which still corresponds to an outstanding result given the short length of the structure. Our nanobeam designs are of special relevance for applications in integrated photonics, where extremely large factors \( Q_c/V_i \) and \( Q_c/V_{nl} \) are required for enhanced optical nonlinearities. To corroborate our findings, we estimate a realistic single-photon-to-loss-rate ratio of approximately 2 \( \times \) 10\(^{-4}\) for our best compact devices, where the role of disorder and fabrication imperfections is also taken into account. The latter value is among the highest values reported in the literature for such a figure of merit, and will motivate realizing these devices in quantum photonic experiments on

TABLE III. Optimal design parameters for cavities with five and eight varying holes, as found by the global optimization.

<table>
<thead>
<tr>
<th>Hole 1</th>
<th>Hole 2</th>
<th>Hole 3</th>
<th>Hole 4</th>
<th>Hole 5</th>
<th>Hole 6</th>
<th>Hole 7</th>
<th>Hole 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>( dx ) (nm)</td>
<td>36.3</td>
<td>6.5</td>
<td>4.2</td>
<td>7.8</td>
<td>11.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( dr ) (nm)</td>
<td>-44.7</td>
<td>-30.6</td>
<td>-12.5</td>
<td>5.2</td>
<td>11.8</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Optimization with eight varying holes, \( \Delta x_c = 29.7 \text{ nm} \)

<table>
<thead>
<tr>
<th>Hole 1</th>
<th>Hole 2</th>
<th>Hole 3</th>
<th>Hole 4</th>
<th>Hole 5</th>
<th>Hole 6</th>
<th>Hole 7</th>
<th>Hole 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>( dx ) (nm)</td>
<td>36.2</td>
<td>6.7</td>
<td>4.2</td>
<td>7.8</td>
<td>11.1</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>( dr ) (nm)</td>
<td>-44.6</td>
<td>-30.5</td>
<td>-12.5</td>
<td>5.1</td>
<td>11.8</td>
<td>0.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>
chip. As an example of possible applications in quantum photonics, we propose a coupled-cavity-based device that generates sub-Poissonian photon statistics on chip.

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APPENDIX A: CAVITY WITH EIGHT VARYING HOLES

We report in Table II the optimal figures of merit for a nanobeam cavity with eight optimized holes, for completeness. Notice that no significant improvement is obtained with respect to the five-hole case.

APPENDIX B: OPTIMIZED CAVITY PARAMETERS

Here we report the structural parameters obtained from our particle swarm algorithm for the optimal designs corresponding to both five and eight modified holes. The parameters of the modified holes are reported in Table III for both designs.

APPENDIX C: FOURIER TRANSFORM OF NEAR-FIELD COMPONENTS

To visualize the effect of optimization, we plot in Figs. 5(a) and 5(b) the far-field projection of the cavity mode along the \( k_x \) direction at \( k_y = 0 \) for the five- and eight-hole cases, respectively. The vertical blue dashed curves correspond to the points where the cavity frequency crosses the light line, while the black dashed curves show the corresponding far-field projections for the nonoptimized cavity. The far field is obtained from the Fourier transform of the near field computed in an \( xy \) plane localized 70 nm above the nanobeam surface, and, because of the even symmetry of \( E_y \) with respect to the \( y \) coordinate, it is dominated by the near-field component \( E_y \) when \( k_y = 0 \) (see Ref. [61]). Figure 5 shows the suppression of the radiative contributions to the far field inside the light cone of the structure for the optimal cavity designs, which results in the enhancement of \( Q_c \) [35,49].

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