Optimal Photonic Crystal Cavities for Coupling Nanoemitters to Photonic Integrated Circuits

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Photonic integrated circuits that are manufactured with mature semiconductor technology hold great promise for realizing scalable quantum technology. Efficient interfaces between quantum emitters and nanophotonic devices are crucial building blocks for such implementations on silicon chips. These interfaces can be realized as nanobeam optical cavities with high quality factors and wavelength-scale mode volumes, thus providing enhanced coupling between nano-scale quantum emitters and nanophotonic circuits. Realizing such resonant structures is particularly challenging for the visible wavelength range, where many of the currently considered quantum emitters operate, and if compatibility with modern semiconductor nanofabrication processes is desired. Here, it is shown that photonic crystal nanobeam cavities for the visible spectrum can be designed and fabricated directly on-substrate with high quality factors and small mode volumes. Designs are compared based on deterministic and mode-matching methods and the latter is found advantageous for on-substrate realizations. The results pave the way for integrating quantum emitters with nanophotonic circuits for applications in quantum technology.

1. Introduction

Integrated quantum optics has a broad range of applications in quantum technologies,[1,2] including quantum information processing,[3] and sensing.[4] One of the key building blocks for the realization of quantum technologies are nonclassical light sources based on single photon emitters (SPEs). In the last decade, integrated quantum photonics has emerged as a tool to improve the performance of SPEs by altering their emission characteristics through integration with nanophotonic devices. The use of optical resonators is especially useful for improving the photon emission rate of SPEs via the Purcell effect.[5–8] This requires optical structures that support high-quality (Q)-factor resonator modes with small, i.e., wavelength-scale, mode volumes ($V_m$) tailored to the emission wavelength of a SPE. Photonic crystal (PhC) cavities have shown to be the superior resonator choice for integrated optics as they provide high $Q/V_m$ ratios[9,10] and therewith enable efficient light–matter interfaces. PhC cavities can be implemented as 2D slab geometries or 1D nanobeams,[11,12] where the latter has a smaller device footprint while achieving similar Q-factors, thus favoring densely integrated photonic circuitry.

While several types of SPEs are considered for applications in quantum optics,[13] e.g., quantum dots[14,15] or carbon nanotubes,[16,17] nitrogen vacancy (NV)-centers in diamond are particularly promising candidates because they are photostable and feature long spin-coherence times.[18] In integrated optics a great interest in coupling NV-centers to PhC cavities ensued[8,19–23] in order to make their attractive photophysical properties available in nanophotonic networks. Corresponding nanophotonic devices need to be fabricated from material systems, which are transparent in the visible wavelength range, in particular at 532 and 637 nm where NV-centers can be excited and emit fluorescence, respectively. Here, we use silicon nitride (SiN) because of its excellent compatibility with nanofabrication processes developed for high-quality photonic integrated circuits. While the devices considered in our work are optimized for NV-centers in nanodiamonds, similar coupling strategies apply for other quantum emitters, e.g., colloidal quantum dots or single-molecules, in nanoscale host material volumes that can be positioned in close proximity of a SiN nanobeam cavity.

Most of the SiN resonator designs reported in the literature consider free-standing PhC nanobeams[23–25] i.e., the substrate below the nanobeam is removed. Free-standing nanobeam cavities benefit from high refractive index contrast between the waveguide and a uniform environment (air) for achieving high Q-factors. However, such devices have limited compatibility with semiconductor industry processes, which will be desirable for future large-scale fabrication of integrated quantum technology. In an effort to avoid free-standing geometries but nevertheless
provide uniform environments around a PhC cavity such devices have been encapsulated with poly(methyl methacrylate) (PMMA) resulting in Q-factors of up to $10^5$ in simulations and several thousands in fabricated devices for 764 nm wavelength.

Here, we show how SiN-PhC nanobeam cavities with high $Q/V_{\text{in}}$ ratios can be realized directly on a silicon dioxide ($\text{SiO}_2$) substrate to provide efficient interfaces to single quantum emitters in the visible wavelength range. Our designs do not require additional processing steps that have limited compatibility with established thin-film technology for large-scale photonic circuit integration. A further advantage of our on-substrate designs is their improved thermalization with the substrate, which strongly benefits low-temperature implementations of waveguide-integrated quantum emitters that typically suffer from low specific heat capacity of suspended structures.

We find optimal performance for on-substrate PhC cavities by performing comparative studies of deterministic and mode-matching designs both in numerical simulation and experimental realization. The deterministic design approaches are based on band structure simulations\cite{10,28} while the mode-matching approach consists of brute-force parameter optimization\cite{23,29}.

We explicitly take fabrication constraints into account and consider that differences in hole size and distance (mode-matching design) as well as changes in waveguide width (deterministic designs) in the taper section have the strongest influence on device performance. We show that for a fixed number of holes, the mode-matching design requires a smaller taper section than the deterministic designs to obtain comparable Q-factors, which is advantageous in device fabrication. Based on the simulation results, we fabricate integrated PhC devices optimized for 637 nm wavelength, i.e., the zero phonon line of the NV$^-$ center in diamond, and measure resonances with Q-factors exceeding $10^5$.

2. Cavity Design

We consider design approaches for PhC cavities where mirror sections consisting of $N_{\text{mir}}$ periodic holes, as shown in Figure 1, create a photonic band gap around the resonant frequency $\omega_{\text{res}}$. These mirror sections have to be optimized in terms of the mirror strength $\gamma$ to achieve high Q-factors.

In the deterministic design approaches, originally developed in ref. [10,28], the confined mode in the band gap is created by quadratic tapering of the waveguide width $w$. In Figure 1a, the central waveguide width is decreased resulting in the dielectric mode moving into the bandgap ($e$-mode design). In Figure 1b instead, the central waveguide width is increased such that the air-mode moves into the bandgap (air-mode design). These approaches minimize the out-of-plane scattering by creating an attenuation profile of Gaussian-shape for the defect mode along the taper section.

Figure 1c shows the mode-matching design approach. In this case, the hole radii $r$ and hole distances $a$ are tapered down linearly from the mirror sections to the defect center, created by the defect length $l_d$. This maximizes the overlap integral of the modes within two neighboring segments by gradual variation of the band structure, thus resulting in minimal loss. Note that in the deterministic design no defect length $l_d$ is required; instead the mode is concentrated around the interface between the two taper sections.

3. Mirror and Band Structure Analysis

In a first optimization step, we employ the frequency-eigensolver MPB\cite{30} to calculate the transverse electric (TE) band structure for mirror sections that are defined by the unit cell shown in Figure 2a, with hole distance $a$, hole radius $r$, and waveguide width $w$. We fix the thickness of the SiN waveguide at $t = 200$ nm to match fabrication constraints. We then maximize the mirror strength $\gamma$ by varying $a, r$, and $w$, taking into account that the target frequency $\omega_{\text{res}}$ (Figure 2, black line) should lie in the center of the bandgap. The resulting parameters for the on-substrate design are $a = 205$ nm, $r = 60$ nm, and $w = 461$ nm. (The unit cell used for the mode-matching approach has slightly deviating mirror parameters: $a = 205$ nm, $r = 56$ nm, and $w = 492$ nm, resulting in a slightly lower $\gamma$). We compare this on-substrate PhC with a similar optimized free-standing PhC where parameter...
optimization yields $a = 250 \text{ nm}$, $r = 70 \text{ nm}$, and $w = 300 \text{ nm}$, similar to previous results.[23] The respective band structure calculations for the free standing (blue) and on-substrate designs (red) are shown in Figure 2a.

Optimal designs for free-standing and on-substrate nanobeams differ most significantly in their hole size and waveguide width. A smaller hole size for optimal on-substrate geometries as compared to free-standing designs is reasonable because the effective refractive index inside the unit cell is higher. Similarly, larger waveguide width for optimal on-substrate geometries as compared to free-standing designs are expected because a larger amount of material (SiN) is needed to confine the mode inside the waveguide rather than in the underlying substrate (SiO$_2$). We note that the resulting bandgap is located rather close to the respective light cone. A further increase of the waveguide width would separate the band frequencies further from the light cone, but also result in decreased mirror strength $\gamma$ due to a smaller size of the bandgap.

We find that the bandgap of the on-substrate design is significantly smaller than that of the free-standing design. This indicates that out-of-plane scattering into the substrate leads to reduced Q-factor and hints at the expected adverse effect of a substrate on the Q-factor.

After optimizing the unit cell of the mirror segments, we determine the number of mirror holes, for which the PhC losses are limited by out-of-plane scattering. An increasing number of mirror holes, $N_{\text{mir}}$, results in reduced transmission through the waveguide, thus impacting the signal to noise ($S/N$) ratio in a measurement. Figure 2b shows the relation between $N_{\text{mir}}$ and the Q-factor for mode-matching designs with $N_{\text{tap}} = 10$, both for free-standing (cf. ref. [23]) and on-substrate PhC nanobeams. While for the free-standing case a saturation of the Q-factor is reached already for $N_{\text{mir}} > 17$, in the on-substrate case Q is only saturated for $N_{\text{mir}} > 30$. This difference is expected as a consequence of the lower mirror strength $\gamma$ in the on-substrate case.

4. Optimization Results from Simulation

In a second step we optimize the taper section of the PhC cavities and analyze their Q-factors. Here we use the optimal mirror sections calculated in the previous section as a starting point for performing 3D-finite difference time domain (FDTD) simulations with the MEEP software package.[30]

For our simulations we fix the total number of holes to $N_{\text{tot}} = 35$ for all three designs and vary the number of taper hole $N_{\text{tap}}$. This choice allows for comparing different designs and ensures sufficient transmission in experimental measurements (see below). We further perform simulations for a fixed number of mirror holes, $N_{\text{mir}} = 35$, to analyze the influence of transmission losses.

In the deterministic designs quadratic tapering of the waveguide width creates a defect mode. We first tune the defect mode frequency to approximately $\omega_{\text{res}}$ for $N_{\text{tap}} = 35$ through variation of the central waveguide width $w_n$ (see Figure 1). An advantage of the deterministic designs is that results of the band structure calculations can be exploited for estimating the central waveguide width $w_n$ by comparing the variations of the $\varepsilon$-mode and air-mode frequencies at the edge of the first Brillouin zone when varying the waveguide width.[30] However, these values need to be verified by 3D-FDTD simulations because the exact deviation between the mode frequencies of the central segment and the resulting defect mode frequencies depends on the number of taper holes, $N_{\text{tap}}$. We find the central waveguide width $w_n = 625$ nm for the air-mode design and $w_n = 338$ nm for the $\varepsilon$-mode design. Based on these values, we then calculate the Q-factor of the defect mode under variation of $N_{\text{tap}}$. 

Figure 2. TE-Band structure analysis. a) $\varepsilon$- and air-modes (dotted lines) for periodic free standing (blue) and on-substrate (red) PhC nanobeam waveguides in the first Brillouin zone. The shaded regions represent the light cones for air and SiO$_2$ substrate and are only relevant for the respective designs. The targeted resonance frequency is shown as a black line. The bottom of the figure shows the schematic unit cells along the parameters for optimized mirror strength. b) Variation of Q-factor with $N_{\text{mir}}$ for $N_{\text{tap}} = 10$ for a mode-matching design. Analyzed for free-standing (blue) and on-substrate (red) devices. The Q-factors are normalized by the respective saturated values $Q_{\text{sat}}$. 

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Both designs approach the target wavelength of \( \lambda_{\text{res}} \) as function of \( N_{\text{tap}} \), with optimal values between \( 5 \) to \( 15 \) for the \( \varepsilon \)-mode design and \( 35 \) for the \( \mu \)-mode design. In the case where the number of mirror holes, \( N_{\text{mir}} \), is large enough to saturate the Q-factor, \( Q \), with \( N_{\text{mir}} = 35 \), the \( \varepsilon \)-mode design has an \( \varepsilon \)-mode wavelength of \( \lambda_{\text{res}} \) decreases with \( N_{\text{tap}} \) while it increases in the case of the \( \mu \)-mode design. This behavior is expected as the defect constitutes a perturbation of the optimized mirror segment (see Figure 2a), which supports an \( \varepsilon \)-mode with wavelengths \( \lambda_{\text{res}} \), and an \( \mu \)-mode with wavelengths \( \lambda_{\text{res}} \). Both designs approach the target wavelength of \( \lambda = 637 \text{ nm} \) at \( N_{\text{mir}} = 35 \).

By increasing the overall number of holes, we find that for \( N_{\text{tap}} > 20 \) both cavities are not completely scattering-limited anymore. In the case where the number of mirror holes, \( N_{\text{mir}} \), is large enough to saturate the Q-factor, i.e., we switch off the transmission losses, we find Q-factors of \( 3.8 \times 10^4 \) for the \( \varepsilon \)-mode design and \( 2.0 \times 10^4 \) for the \( \mu \)-mode design at the highest simulated taper hole number of \( N_{\text{tap}} = 35 \), as shown in Figure 3a,b, respectively.

We further extract the mode volumes from our calculations. With increasing \( N_{\text{tap}} \), the mode volume for the \( \varepsilon \)-mode design rises linearly from \( V_{m} = 1.29 \left( \frac{\varepsilon_{\mu}}{\varepsilon_{\text{air}}} \right)^3 \) at \( N_{\text{tap}} = 5 \) to \( V_{m} = 2.30 \left( \frac{\varepsilon_{\mu}}{\varepsilon_{\text{air}}} \right)^3 \) at \( N_{\text{tap}} = 35 \), while for the \( \mu \)-mode design we find an increase from \( V_{m} = 2.45 \left( \frac{\varepsilon_{\mu}}{\varepsilon_{\text{air}}} \right)^3 \) at \( N_{\text{tap}} = 5 \) to \( V_{m} = 5.98 \left( \frac{\varepsilon_{\mu}}{\varepsilon_{\text{air}}} \right)^3 \) at \( N_{\text{tap}} = 35 \). The significantly higher mode volumes of the \( \mu \)-mode design as compared to the \( \varepsilon \)-mode design are also visible in the mode profiles shown in Figure 3g,h.

When considering the coupling of an NV-center in a nanodiamond to the waveguide, it is noteworthy that the \( \mu \)-mode design might be favorable, because its field maximum is located inside the air-hole regions, where nanodiamonds could be placed. In contrast, in the \( \varepsilon \)-mode design, the field maximum is concentrated inside the dielectric medium such that emitters need to be placed inside the evanescent field surrounding the structure.

We now compare these deterministic designs to the mode-matching design where we are tapering hole distances and diameters as well as tuning the defect length \( l_{d} \). The resulting Q-factors are shown in Figure 3c, the resonance wavelengths in Figure 3f, and an exemplary mode profile in Figure 3i. In this design, the defect length is used to tune the cavity frequency. Accordingly, the Q-factor depends strongly on the defect length \( l_{d} \), which needs to be adjusted for each \( N_{\text{tap}} \), with optimal values between \( l_{d} = 80 \) to \( 90 \text{ nm} \) (We discuss the optimization of \( l_{d} \) in more detail in Supporting Information, see Figure S1, Supporting Information).

The optimization of the Q-factors in the mode-matching design relies on varying the size of the central segments \( a_{c} \) and the radii of the central holes \( r_{c} \), which are both changed linearly with respect to \( a_{c} \) and \( r_{c} \) of the mirror section (see Figure 1). For the mode-matching design, the taper optimization is computationally very expensive, because prior parameter estimation from the design approach is not possible (except for an approximation of the defect length \( l_{d} \) to match the target frequency). The parameters \( a_{c} \) and \( r_{c} \) have to be iteratively optimized in terms of both the Q-factor and wavelength \( \lambda_{\text{res}} \) by executing 3D-FDTD simulations of the entire cavity structure. Using this brute force approach, we find optimal design parameters for the taper section as \( a_{c} = 175 \text{ nm} \) and \( r_{c} = 46 \text{ nm} \). A resulting mode profile is shown in Figure 3i.

Based on this parameter set, we calculate the Q-factor as a function of the number of taper holes \( N_{\text{tap}} \) as shown in Figure 3c. Note that the x-axis in this case only shows maximal values of up to \( N_{\text{tap}} = 18 \) (as compared to \( N_{\text{tap}} = 35 \) for the deterministic designs) and that the Q-factors depicted here are always the result of cavities with an optimal defect length \( l_{d} \) (see Supporting Information). We find that the Q-factor reaches a maximal value of \( Q = 6.8 \times 10^4 \) at \( N_{\text{tap}} = 15 \), where the mode volume...
$V_m = 1.41 \left( \frac{\lambda}{n_{SiN}} \right)^3$. If $N_{tap}$ is increased further, the Q-factor decreases because transmission losses become dominant. This is seen from comparison with saturated Q-factors for large numbers of $N_{mir}$ (green curve) reaching $Q = 1.75 \times 10^5$ with a corresponding $V_m = 1.48 \left( \frac{\lambda}{n_{SiN}} \right)^3$ at $N_{tap} = 18$.

From our simulations, we find that the Q-factors for the deterministic air-mode design and the mode-matching design reach comparable values, however, the latter requiring a much smaller number of taper holes ($N_{tap} = 15$ for the mode-matching design vs $N_{tap} = 35$ for the air-mode design). The mode-matching design is further favorable for realizing small mode volumes, i.e., less than one quarter of the mode volume for the air-mode design. The mode volume the $\epsilon$-mode design on the other hand is comparable to that of the mode-matching design, but features much lower Q-factors. Overall, we conclude that the mode-matching design shows favorable performance for realizing efficient interfaces to quantum emitters, such as the NV-centers considered here, because it achieves maximal $Q/V_m$ ratios for a low number of taper holes.

We further find that Q-factors $> 10^6$ are achievable with free-standing SiN PhC designs for even smaller taper sections ($N_{tap} > 7$), while maintaining a sub-wavelength $V_m$ (not shown). In such free-standing designs, loss channels into the substrate are strongly suppressed and significantly higher $Q/V_m$ ratios are achievable (in simulation). However, in experiments targeting the visible wavelength range, it turns out to be difficult to take advantage of the theoretical performance of free-standing designs, which are not compatible with current semiconductor industry processes for realizing large-scale photonic integrated circuit implementations.

5. Experimental Results

In order to experimentally test the simulated PhC-cavity designs and the conclusions drawn from the simulated performance characteristics, we fabricate PhC nanobeam cavities with deterministic dielectric-mode and air-mode designs as well as mode-matching designs. The cavities are integrated with nanophotonic waveguides that allow for performing transmission measurements from which we extract the Q-factors and resonance wavelengths.

The PhC nanobeam cavity devices are fabricated from 200 nm SiN thin films on insulator using electron beam lithography (EBPG) and reactive ion etching (see Supporting Information for details). Each nanobeam cavity is fabricated directly on the SiO$_2$ substrate and connected via nanophotonic waveguides to optical grating couplers that provide interfaces to optical fibers. We optimize our nanofabrication recipes to accurately produce the design values of each PhC nanobeam cavity as variations in waveguide width and hole radius can lead to significant shifts of the resonance wavelength and reduced Q-factors.

We assess the fabrication tolerances of the devices in scanning electron microscopy (SEM), revealing overall low side-wall roughness and high circularity of the holes, as shown in Figure 4a–c. We are able to match the simulated mode-matching and air-mode design values for waveguide width and hole radius in fabricated devices to within $\approx 10$ and 3 nm, respectively. For the dielectric-mode design, we find similar tolerances for the waveguide width, but the hole radii in the narrow center region are increased by $\approx 6$ nm. This labels the dielectric-design somewhat more challenging in fabrication as compared to the air-mode and mode-matching designs.
We find that fabricated devices with large numbers of holes suffer from low optical transmission, and hence, only considered device designs with \( N_{\text{tot}} \leq 35 \) holes. This choice allows for simultaneously obtaining high S/N transmission measurement signatures and high Q-factors, in accordance with above FDTD simulations. We restrict our experimental studies to device designs with parameter sets for which we expect the highest Q-factors from Figure 3, because each fabricated design requires fine-tuning of the defect length \( l_d \), hole distance \( a \), hole radius \( r \), and waveguide width \( w \), in order to achieve resonances at the desired target wavelength (i.e., 637 nm). Consequently, we consider mode-matching geometries with \( N_{\text{tap}} \leq 15 \) taper holes and deterministic design with \( N_{\text{tap}} = 20–35 \) taper holes.

We assess the Q-factors and resonance wavelengths of fabricated PhC cavity devices in transmission measurements shown schematically in Figure 4d. The PhC nanobeam cavity is located at the center of the nanophotonic circuit and connects to 500 nm wide, 200 nm thick waveguides that allow for supplying white light from a polarized supercontinuum laser source (450–900 nm) via optical grating couplers aligned to input 2 of a single-mode fiber array (see Figure 4d). Light that is transmitted through the PhC nanobeam cavity is guided via a waveguide of similar dimensions to a grating coupler aligned with the output fiber in the array that connects to a spectrometer. The grating couplers are optimized for TE optical modes at the desired target wavelength and support a \(-3\) dB bandwidth of \( \approx 20 \) nm as shown by the blue curve in Figure 4e. This measurement configuration enables measurements of the entire bandgap when considering the 80 nm band over which the transmission from a grating coupler exceeds the noise floor of the spectrometer.

In anticipation of integrating fluorescent nanoemitters with the PhC cavities the devices shown in Figure 4d feature additional optical access optimized for guiding 532 nm light from inputs 1 and 3 to the center of the nanobeam under perpendicular incidence. In the future, these input ports will allow for optical excitation of NV-centers in diamonds positioned within (the vicinity of) the mode volume of the cavity but do not influence the cavity performance in the designs considered here. Modern foundry services may also enable innovative emitter-waveguide coupling strategies by exploiting advanced multi-layer thin-film processes.\[32]\]

Transmission measurements from fiber-input 2 to the output-fiber (Figure 4d) show characteristic spectra similar to the one presented in Figure 4e for a PhC cavity with mode-matching design and \( N_{\text{tot}} = 21 \) holes. For optimized designs, we observe the edges of the photonic bandgap at 603 nm and 665 nm as well as a resonance peak at the desired target wavelength of 637 nm. Within the bandgap transmission is suppressed by \(-30\) dB with respect to the transmission on resonance. We further observe artifacts in the spectrum (here at 617–627 nm), which we attribute to transverse magnetic (TM) modes that are guided in our 200 nm thick waveguides and lie outside the design bandwidth of our grating couplers.

For deterministic PhC cavity designs with \( N_{\text{tot}} = 35 \) holes, we observe resonances with Q-factors of several thousands for all considered numbers of taper holes as shown in Figure 5a,b. The Q-factors extracted from measured devices generally fall below those found in FDTD simulations but confirm the conclusion that air-mode designs yield higher Q-factors as compared to dielectric-mode designs, as also seen in Figure 3a,b. The resonance wavelength for both dielectric- and air-mode designs, shown in Figure 5d,e, respectively, approaches the desired target wavelength in qualitatively similar fashion as expected from FDTD simulations (see Figure 3d,e).

For mode-matching designs, we observe that the highest Q-factors (up to \( Q = 4500 \)) are realized for taper sections with three to seven holes, as visible in Figure 5c for devices with \( N_{\text{tot}} = 35 \). We measure resonance wavelengths in a 20 nm band around the target wavelength of 637 nm for fixed defect lengths, as shown in Figure 5f. Devices with \( N_{\text{tap}} > 10 \) are not shown in Figure 5f because the bandwidth of our grating couplers limits transmission of cavity resonances in this wavelength range, as evident from Figure 4e. This circumstance is owed to the relatively strong shift of the resonance frequency with the number of taper holes for fixed defect lengths as compared to deterministic designs, which was also observed in the simulation.

![Figure 5. Measurements of the three PhC cavity geometries. a–c) Q-factors and d–f) resonance wavelengths \( \lambda \) for different numbers of taper holes \( N_{\text{tap}} \) and a total number of \( N_{\text{tot}} = 35 \) holes for the e-mode, air-mode, and mode-matching designs, respectively.](https://www.advancedsciencenews.com)
data of Figure 3. In designs with six taper holes and 28 mirror holes, we extract Q-factors of \( Q = 4187 \pm 11 \) from a Lorentzian fit to the data at the desired target wavelength, as shown in the inset of Figure 4e. We note that the simulated Q-factor is larger than the measured Q-factor, which has additional loss contributions, e.g., scattering due to fabrication imperfection and absorption in the substrate.

We conclude that material and fabrication imperfections (e.g., the resolution of our EBPG system) prevent the experimental realization of mode-matching designs with higher Q-factors for larger numbers of taper holes, resulting in maximal measured Q-values for \( N_{\text{tap}} < 7 \). Nevertheless, the mode-matching designs achieve the highest overall Q-factors for the lowest number of taper holes among all design types, which is consistent with our expectation from 3D-FDTD simulation results (see Figure 3). Fabrication imperfections are most severe for the dielectric-mode design, which also yielded the lowest Q-factors after parameter optimization. We find reasonable qualitative agreement when comparing dielectric-mode, air-mode, and mode-matching designs in 3D-FDTD simulations and measurements of devices fabricated in electron beam lithography and reactive ion etching. Our results imply that PhC cavities with mode-matching designs are advantageous for realizing efficient interfaces between optical waveguides and nanoscale emitters, because they achieve high Q-factors already for a small number of taper holes, which are the most challenging constituent of PhC cavities in terms of nanofabrication tolerances.

6. Conclusions and Outlook

In summary, we have optimized SiN nanobeam PhC cavities on SiO\(_2\) substrates in the visible wavelength range for the coupling of nanoscale emitters to photonic integrated circuits. As an exemplary use-case, we consider NV-centers in diamond as quantum emitters and optimize PhC cavity designs for a target wavelength of 637 nm, corresponding to the zero-phonon line of NV\(^-\) defects. As feature sizes in resonant nanophotonic structures scale with (fractions of) the wavelength, our use-case realizes particularly challenging nanofabrication requirements as compared to many other solid-state quantum sources emitting at longer wavelengths. We take these nanofabrication requirements into account throughout the simulation of suitable designs and show that it is possible to realize high-Q PhC cavities in SiN nanobeams despite the small refractive index contrast with the SiO\(_2\) substrate. A comparison of three on-substrate cavity designs (dielectric-mode, air-mode, and mode-matching) in 3D-FDTD simulations yields the highest \( Q/V_{\text{n}} \) ratios for mode-matching designs that show Q-factors > 10\(^5\) while maintaining wavelength-scale mode volumes.

We test the feasibility of realizing efficient light-matter interfaces at visible wavelengths (here 637 nm) as on-substrate nanobeam PhC cavities in CMOS-compatible processes by fabricating such devices in state-of-the-art lithography on SiN thinfilms. Through careful parameter tuning, we are able to realize PhC cavity devices with resonance wavelengths of 637 nm for all three geometries (dielectric-mode, air-mode, and mode-matching). We find that mode-matching designs with smaller taper sections, consisting of only three to seven holes, show superior performance, i.e., Q-factors, over deterministic designs with significantly larger taper sections of up to 30 holes. These findings are in qualitative agreement with 3D-FDTD simulations while showing lower overall Q-factors, which we attribute to fabrication and material imperfections. Such imperfections are easier mitigated for mode-matching geometries, which feature a larger design parameter space as compared to deterministic geometries.

We envision further optimization of PhC cavity interfaces through modified geometries that compensate correlations between waveguide width and hole diameters, by considering elliptical hole shapes and by resorting to ridge or strip-loaded waveguide geometries.\(^2\) Future experimental realizations should also suppress the TM modes observed in our transmission spectra, as these provide additional loss channels. This could for example be achieved by reducing the waveguide height, which would however also result in a smaller effective refractive index contrast between nanobeam and substrate and thus yield smaller band gaps. The integration of nanoscale emitters with nanobeam PhC cavities will further require methods for compensating the effects of scattering centers in the vicinity of the cavity mode volume.

We conclude that even moderate Purcell-enhancement, as expected for integrating nanoemitters with the PhC cavity geometries considered here, will notably enhance the coupling efficiency to waveguides. Nanophotonic circuits further offer great versatility in configuring the optical inputs and outputs to light-matter interfaces like the PhC nanobeam cavities presented here (see Figure 4d). Such integrated solutions are attractive for simultaneously interfacing photonic networks with large numbers of emitters in a scalable fashion by exploiting small device footprints and highly reproducible fabrication routines. Our results thus pave the way for supplying single-photons from a large number of nanoscale emitters into quantum photonic circuits as desired for integrated quantum technologies.

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.

Keywords

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