Nanobeam photonic crystal cavities engineered for minimized quantum dot spectral broadening

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Abstract: Nanobeam photonic crystal cavities are engineered to provide large Purcell radiative rate enhancements for single quantum dot single-photon emitters while minimizing spectral broadening induced by etched sidewalls.

On-chip light sources capable of producing indistinguishable single-photons on-demand at rates exceeding 1 GHz are desirable for integrated photonic quantum technologies. Single III-V semiconductor quantum dots (QDs) are very promising on-chip sources that can produce close to ideal single-photon emission at high rates [1], and are amenable to integration within nanophotonic geometries that can efficiently funnel emitted photons into photonic circuits [2, 3]. In this context, integration of a QD within nanophotonic cavities may be employed to enhance the radiative rate of desired QD transitions via the Purcell effect. Such a feature can be effectively leveraged to achieve higher triggered single-photon emission rates and to improve photon indistinguishability [4]. Indeed, improvement of single-photon indistinguishability at time scales comparable to the QD transition lifetime, T_1, has been demonstrated [4]. At time scales $\gg T_1$, however, charge fluctuations from nearby etched surfaces have been shown to lead to significant QD spectral broadening [5], impacting indistinguishability.

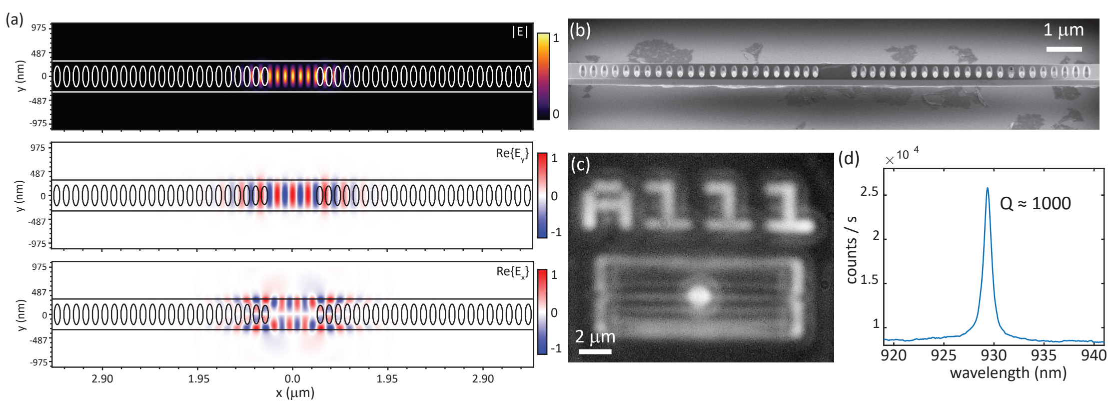

Fig. 1. (a) Electric field profile (magnitude and y and x components) for an optimized PhC cavity mode at $\lambda \approx 940$ nm, with $Q \approx 10^4$, resulting in a predicted Purcell factor $F_p \approx 400$. The nanobeam width is 620 nm, wider than the typical <400 nm value [3]. (b) Scanning electron micrograph of fabricated nanobeam PhC. (c) Micro-photoluminescence image of quantum dot ensemble emission coupled to a nanobeam cavity mode. Here, the 780 nm pump light is filtered by a 900 nm long-pass filter. (d) Quantum dot ensemble photoluminescence spectrum for a fabricated nanobeam pumped at high intensity, showing a resonance at ≈ 930 nm with $Q \approx 1000$.

To achieve substantial Purcell radiative enhancement factors, $F_p \propto Q/V$, small modal volumes V are necessary if high quality factors Q are either unachievable (e.g., due to fabrication imperfections) or undesirable (e.g. for spectrally broad operation [6]). The small V requirement, however, translates into cavity designs in which QDs must be placed at distances from etched sidewalls considerably smaller than the $\approx$ 300 nm limit, observed by Liu *et al.* in ref. [5], necessary to avoid detrimental effects that reduce the coherence of the emission. To overcome such limitation, here we develop nanobeam photonic crystal (PhC) cavities with potential to provide large Purcell factors to the emission of embedded QDs located at distances $>$ 300 nm away from any etched surfaces. Notably, such specification requires that the starting geometry for the PhC design be a *multimode* nanobeam waveguide that supports at least two modes of the same symmetry, in addition to a non-etched central confinement region. Both characteristics lead to complications in cavity design based on deterministic strategies [7]. In our work, a shape optimization approach based on search algorithms [8] is employed to design optical cavities that comply with the following geometric constraints: a $>$ 310 nm distance between a QD located in the center of the cavity and nearby sidewalls; a minimum hole size of 100 nm, for ease of fabrication, and a slab thickness of 190 nm. The PhC lattice constant and (elliptical) hole major and minor radii display a nearly Gaussian, parameterized spatial dependence along the nanobeam length. In addition, the edges of the holes closest to the QD are allowed to be anywhere between 310 nm and 560 nm away from the emitter. It is worth noting that the single QD positioning accuracy in the Fig. 1(a) cavity should be $\approx$ 150 nm and $\approx$ 300 nm in the $x-$ and $y-$ directions respectively, to maximize the Purcell factor. Such accuracy is well within reach of recently demonstrated methods, e.g. micro-photoluminescence imaging [5]. In the optimization routine, Purcell factors F_p were determined using 3D finite-difference time-domain simulations. In these, a y-oriented (see Fig. 1(a)) radiating electric dipole was placed in the center of the cavity, and the ratio $P_{\text{rad}}/P_{\text{hom.}} = F_p$ between the total steady-state power emitted in the cavity and in a homogeneous medium was calculated. To ensure a near-global maximum, the optimization was performed in two consecutive steps: a global search using an evolutionary algorithm; and a final local refinement through a derivative-free simplex algorithm. Three distinct cavities were produced in this manner. Figure 1(a) shows one of the obtained cavities, supporting a mode at $\lambda \approx 940$ nm with $F_p > 400$ with $Q \approx 10^4$, consistent with a mode volume $V \approx 1.91\,(\lambda/n)^3$.

The designed geometries were fabricated on an epitaxially grown wafer consisting of a 190 nm thick GaAs layer containing a high density ($> 10/\,\mu\text{m}^2$) of InAs QDs at the center, on top of a 1 μm $Al_{0.68}Ga_{0.32}As$ sacrifical layer. Electron-beam lithography and inductively-coupled plasma reactive-ion etching were used to transfer the nanobeam patterns to the QD-containing GaAs layer, after which the AlGaAs sacrificial layer was removed with hydrofluoric acid. A scanning electron micrograph of a fabricated device is shown in Fig. 1(b). Prior to fabrication the high-density QD ensemble was shown to produce photoluminescence emission over a wavelength range between $\approx$ 900 nm and $\approx$ 1050 nm.

Preliminary testing of fabricated devices was done by micro-photoluminescence (μPL) spectroscopy at 4 K. Figure 1(c) shows a μPL image of a cavity, pumped with 780 nm laser light (above the GaAs bandgap), evidencing coupling of light emitted by the QD ensemble to a spatially confined cavity mode. A spectrum taken at high pump intensity, shown in Fig. 1(d), displays a resonance at $\approx$ 930 nm with $Q \approx 1000$, relatively close to predicted in simulations. Deviations from the model are likely due to fabrication imperfections, and are currently being investigated. A series of spectra were also taken at low pump intensities, shown in Fig. 2. Here, the saturation of the $\approx$ 929 nm sharp line (labeled QD in the figure) with pump power, suggests coupling of a single QD to the cavity mode at $\approx$ 928 nm.

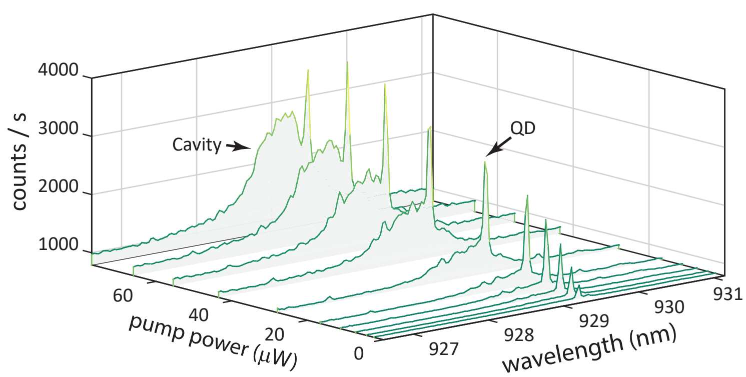

Fig. 2. Quantum dot photoluminescence spectra at varying pump powers obtained for a fabricated cavity. Saturation of the sharp QD line at a pump power of $\approx$ 50 μW evidences single dot coupling to the cavity mode.

In summary, we have engineered nanobeam photonic crystal cavities that minimize the influence of etched sidewalls upon quantum dot emission spectral width, while still allowing large Purcell factors to be achieved. We anticipate that single-photon sources based on single QDs embedded in such cavities may display improved single-photon indistinguishability at long time-scales. This work is ongoing, and updated results will be presented at the conference.

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