

# Simulation of NV centers coupled to silicon nitride photonic crystal nanobeam cavities

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## Abstract

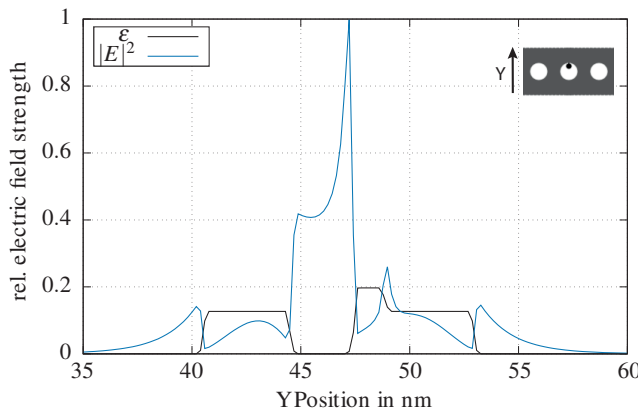
We report on the design of PhC nanobeam cavities for the possible integration of NV-centers in diamond on a nanophotonic chip. In particular, we use 3D-FDTD simulations to optimise the cavity Q-factor and analyse the coupling strength between the NV-center and the cavity, dependent on the position and orientation of the emitter.

The efficient integration of single-quantum emitters with photonic circuits is a major challenge for the development of quantum technologies. A scalable implementation of single-photon emitters (SPEs) on a chip requires a low-loss interface and strong light-matter interactions while maintaining a high coupling strength to the SPE. If a SPE is placed in a cavity, the spontaneous emission rate can be enhanced based on the Purcell effect. This enhancement factor can be described as:

$$F_p = \frac{3Q}{4\pi^2 V_m} \frac{(2\kappa)^2}{4(\omega - \omega_{\text{cav}})^2 + (2\kappa)^2} \frac{|\vec{\mu} \cdot \vec{E}(\vec{r}_0)|^2}{|\vec{\mu}|^2 |\vec{E}_{\text{max}}|^2}, \quad (1)$$

where  $\omega_{\text{cav}}$ ,  $\kappa$ ,  $Q$  and  $V_m$  are the frequency, FWHM, quality factor and mode volume of the defect mode respectively;  $\omega$  is the frequency of the dipole transition and  $\vec{\mu}$  is the dipole transition moment. The electric field at the SPEs position is given by  $\vec{E}(\vec{r}_0)$  and the maximum electric field by  $\vec{E}_{\text{max}}$ . Assuming zero detuning ( $\omega_{\text{cav}} \approx \omega$ ) and alignment of the transition dipole moment along the electric field ( $\vec{\mu} \parallel \vec{E}$ ), the crucial parameters for a strong enhancement are a high  $Q$ -factor, low mode volume and high relative electric field strength at the SPE. Here, we present results for geometry optimisations based on 3D-FDTD simulations of photonic crystal nanobeam cavities embedded with a  $\text{Si}_3\text{N}_4$  waveguide. While a low, wavelength scale mode volume can be easily achieved by design, we optimise the structure in terms of a high  $Q$ -factor of the localised cavity mode. In the next step, we include a NV-center inside a nanodiamond, modelled by a dipole, which is positioned in close proximity to the defect center of this optimised device and analyse it's coupling strength to the confined light mode. We study how the  $Q$ -factor changes in dependence of the position and polarisation of the NV-center. We determine the sensitivity of coupling conditions to emitter position and orientation.

We show that it is possible to create a coupled system that maintains a high  $Q$ -factor of the resonant mode, while achieving a moderate coupling strength with the SPE, within a realistic parameter range. Our results indicate that it is sufficient to place the SPE close to the cavity for an efficient coupling, thus allowing for the usage of such devices in photonic integrated circuits.



**Fig.1:** Electric field strength profile of the resonant mode, if a nanodiamond modelled by a diamond sphere with  $r = 25$  nm is introduced at the border of the central air hole of the optimised design (Fig.1: Top right). The perturbation of the dielectric structure results in an asymmetrical mode profile. The maxima of the electric field strength lie within the air-diamond interface at  $y \approx 47$  nm. Thus if the SPE is positioned at the border of the nanodiamond, it lies within these maxima. The  $Q$ -factor decreases from  $3.6 \cdot 10^6$  to  $1.7 \cdot 10^5$  compared to the unperturbed structure.