Purcell-Enhanced Emission from Individual SiV$^-$ Center in Nanodiamonds Coupled to a Si$_3$N$_4$-Based, Photonic Crystal Cavity

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Hybrid quantum photonics combines classical photonics with quantum emitters in a post-processing step. It facilitates to link ideal quantum light sources to optimized photonic platforms.

INTRODUCTION

Diamond is among the leading material platforms for spin-based photonic quantum technologies $^{1,2}$. The negatively-charged silicon-vacancy center (SiV$^-$ center) became one of the most promising color center in diamond due to strong zero phonon line (ZPL) emission, narrow inhomogeneous distribution and negligible spectral diffusion $^{3,4}$ enabling two-photon interference from distinct SiV$^-$ centers without the need of frequency tuning $^{3}$. In combination with all-diamond nanophotonics the SiV$^-$ center recently showed intriguing progress realising an elementary quantum network node including the generation of Bell-states between the SiV$^-$ center spin and an incident photon as well as between the SiV$^-$ center spin and a nearby nuclear spin with 100 ms long coherence time $^{6}$, universal control over the cavity-coupled two-qubit register and heralded single photon storage in a long-lived spin memory $^{7}$. These fascinating achievements build on many years of research effort to develop the fabrication techniques for all-diamond photonic devices including plasma etching of single-crystal thin diamond films $^{8,9}$, angled plasma etching to fabricate suspended triangular nanobeam waveguides in single-crystal bulk diamond $^{10}$, isotropic etching $^{11}$ or ion beam writing $^{12}$. Furthermore, femtosecond laser writing methods have recently been investigated enabling the fabrication of three-dimensional architectures $^{13,14}$ and laser writing of coherent color centers $^{15}$.

However, traditional fabrication methods for photonic devices based on standard materials such as GaP, Si or Si$_3$N$_4$ still outperform diamond-based photonics in terms of optical quality, such as photon loss, design flexibility, standardization of the fabrication process, demands on high-quality substrates, high-throughput production or scalability to large-scale designs. It is therefore desirable to also utilize classical photonics for quantum applications.

Hybrid approaches pick up that challenge by combining quantum emitters with the most suitable photonics platforms. The post-processing step is an extraordinary challenge and can, for example, be realized by evanescent coupling. An idealized procedure utilizes preselected quantum emitters in a nanometersized host matrix to position the quantum light source with high accuracy in the interaction zone of the photonic device. Hybrid attempts based on color centers in diamond and high-refractive index photonics devices have been demonstrated in the past years $^{16-19}$ with challenges arising from weak evanescent coupling or high-background fluorescence. Reasonably large coupling was achieved between an ensemble of NV$^-$ center in nanodiamonds (NDs) and the mode of a high-$Q$, free-standing photonic crystal cavity (PCC) in Si$_3$N$_4$ where, at the same time, the background flu-
nescence was suppressed by $\sim -20\,\text{dB}$ in a crossed-waveguide pump-probe design [20]. Replacing the NV$^-$ center with the SiV$^-$ center could take advantage of the superior optical properties on the condition that above mentioned optical properties of the SiV$^-$ center also persist in small nanodiamonds. This, by itself non-trivial challenge, was solved in recent years demonstrating bulk-like optical and coherence properties of SiV$^-$ center in nanodiamonds [21] [22] with the additional development of high-precision nanomanipulation tools [11] [23]. The progress now lead to the ability to perform a post-processing procedure where all degrees of freedom of the coupling term to the SiV$^-$ center in NDs can be optimized [22].

In this work we post-process a high-$Q$ photonic crystal cavity (PCC) based on Si$_3$N$_4$ which was optimized for quantum photonics applications with SiV$^-$ centers in NDs. After a few optimization cycles on the evanescent coupling term we achieve a coherent coupling of the zero-phonon line (ZPL) to the mode of the PCC with a $\beta$-factor of 0.44 and a Purcell factor of 0.79 averaged over an ensemble of SiV$^-$ centers. After cooling the sample to liquid Helium temperatures we resolve the fine-structure of individual SiV$^-$ centers and achieve a Purcell enhancement of more than 4 for individual optical transitions. The highly efficient coupling of individual atomic transitions to photonic circuits lays the foundation for quantum applications such as quantum networks [24] or on-chip Boson sampling [25] based on hybrid quantum photonics.

RESULTS

Photonic Crystal Cavity

Our platform consists of a free-standing, crossed-waveguide PCC in Si$_3$N$_4$ featuring low-loss transmission and high-mode confinement together with a minimized cross-talk between pump and probe waveguide ($\sim -20\,\text{dB}$). On-chip, off-resonant excitation and emission is spatially separated. While the pump waveguide is optimized for 532 nm, the probe waveguide is optimized for 740 nm, which matches the ZPL of the SiV$^-$ center. Both waveguides are connected to grating couplers, which allow for out-of-plane excitation and readout. The on-chip excitation of the SiV$^-$ centers is achieved by evanescent coupling to the pump waveguide. The probe waveguide hosts a 1D photonic crystal cavity with its modes superimposed to the pump volume. Each cavity mirror consist of $N = 53$ holes with a period of $a = 265\,\text{nm}$. This periodic variation of permittivity forms a band gap in the visible range. A distance $cav = 232\,\text{nm}$ between these two mirrors is inserted, which results in spectrally separated states inside the photonic band gap optimized by FDTD simulations. The nanophotonic circuit is post-processed with an SiV$^-$ ensemble inside the crossing area of pump and probe beam (interaction zone), which is sketched in Fig. 1(a).

Post-Processing

The post-processing step for placing the ND within the interaction zone of the PCC follows the procedure described in Reference [20] [23]. A water dispersion of NDs with incorporated SiV$^-$ color centers is coated on the surface of the PCC chip. Suitable SiV$^-$ center are preselected using a custom-build confocal microscope. Superimposing the confocal scan with an AFM image enables the precise localization of the SiV$^-$ center host crystal. After the preselected ND is found, the AFM cantilever tip is used to push the ND in the interaction zone of the PCC. Several steps of the positioning procedure are shown in Fig. 1(b). The ND is pushed along a total distance of over 40 µm. The manipulation path is schematically drawn in the SEM image of the photonic device in Fig. 1(c). The positioned ND is off-resonantly excited through port 1 and its emission into the cavity-waveguide can be read out at port 3 and 4. The small inset shows an AFM image of the positioned ND in the interaction zone. A cross-talk measurement of the empty PCC probes the resonance modes. Therefore, a 532 nm laser with 0.6 mW is coupled into port 1 and the cavity signal is collected at port 3. The signal, arising from Si$_3$N$_4$ background fluorescence, is shown in Fig 3(a) (green), where the highest resonance at 721 nm shows a quality factor of $Q = 2260$ and the resonance near 737.4 nm has a $Q$-factor of $Q = 1000$.

Simulation of LDOS

The design of the freestanding PCC is numerically optimized via 3D FDTD simulations [26]. The PCC consists of two modulated Bragg mirrors with inserted cavity region in between. The periodicity of the holes $(a = 265\,\text{nm})$ is determined to match the bandgap region of the PCC to the investigated wavelength of the SiV$^-$ ZPL. To achieve high $Q$-factors optimization on the cavity length and hole diameter was performed [20] [27].

For a maximum enhancement of the emitted light, the source need to be placed in the antinode of the electric field distribution of the resonance mode [28]. Thus, the position of the SiV$^-$ embedded in a ND is carried out via 3D FDTD simulations [26] in two steps. For the simulation a cube-shaped (200 nm) ND is placed on the cavity region.

The first optimization step is the enhancement of the Local Density of States (LDOS) dependent on the emitter position (see Fig. 2(a)). The LDOS is proportional to the overlap integral between the electric field distribution of the resonance mode and the emitter [29]. According
FIG. 1. Nanopositioning of ND within cavity mode. a) The periodic change \( a \) of the material on both sides of the probe waveguide lead to a photonic band gap, while the cavity is formed by the distance \( \text{cav} \). The positioned ND can be evanescently excited through the pump waveguide. b) AFM images during nanopositioning of \( \text{SiV}^- \) ensemble into PCC. The distance of the initial position was approximately 40 \( \mu \text{m} \) to the final position on top of the cavity. c) SEM image of the PCC. The device has four grating couplers - two for coupling of green light (port 1 and 2) to off-resonantly excite the emitter in the interaction zone - and two grating couplers (port 3 and 4) for collecting the emission of the cavity system. The inset shows an AFM image of the ND ensemble placed in the interaction zone.

to the axes in Fig. 1 a) the dipole position, embedded in a ND placed on the cavity, is centered along \( y \)- and \( z \)-direction and varied along the longitudinal \( x \)-direction, since this component shows the strongest contribution to the convolution. For each position of the dipole, the normalized LDOS enhancement is calculated. Therefore, the enhancement of the LDOS through the cavity is divided by the LDOS enhancement for a waveguide without cavity. The highest enhancement (see Fig. 2 a)) for odd modes is achieved for a dipole shift of \( \sim (0.4-0.45) a \) from the symmetry plane of the center of the cavity, matching an antinode of the electric field distribution. For a reduction in simulation time, the number of segments in each Bragg-mirror was reduced to \( N = 18 \), which is qualitatively identical to \( N = 53 \).

The second part of the 3D FDTD simulations targeted the position optimization of the ND embedded emitter along the \( z \)-axis. Therefore, we quantify the coupling of the emitter to the cavity with the \( \beta \)-factor \([20]\), which gives the ratio of coupled spontaneous emission \( \Gamma_{\text{cav}} \) and the total amount of spontaneously emitted photons to free space and in the cavity \( \Gamma_{\text{free}} + \Gamma_{\text{cav}} \):

\[
\beta = \frac{\Gamma_{\text{cav}}}{\Gamma_{\text{free}} + \Gamma_{\text{cav}}} \quad (1)
\]

The \( \beta_{\lambda} \)-factor (spectrally resolved \( \beta \)-factor \([20]\)), correlating with LDOS enhancement, of the emission into the researched 5th-order resonance mode was examined. To consider the experimental degradation of the PCC due to the presence of the ND in the simulation, the number of segments in each Bragg-mirror was reduced from \( N = 53 \) to 27 (matching the \( Q \)-factor examined experimentally). The center of the ND was shifted according to the position in the AFM image in Fig. 1 c). The \( x \)-position of the dipole inside the ND is set to its optimal according to Fig. 2 a), while the \( z \)-distance from the surface of the cavity is altered. The resulting coupling efficiencies for different \( z \)-positions are shown in Fig. 2 b).

The maximum \( \beta_{\lambda} \) value of 78 \% is reached for the source being located 75 nm above the surface of the cavity.

FDTD simulations are carried out to compute the Purcell enhancement \([28]\) for the \( V \)-th-order resonance mode of the cross-bar PCCs with \( N = 27 \) and \( N = 53 \) holes, each with a 200 nm cube-shaped ND crystal on the cavity region as described above. The resulting Purcell-factors read \( F_p = 20 \) and \( F_p = 29 \), respectively for a spectrally and polarization matched resonance mode and an emitter located at the antinode of the electric field.

Purcell-Enhanced Photon Emission

After the ND is positioned on top of the interaction zone, the sample is placed inside a flow-cryostat and cooled to approximately 150 K. The emitter-cavity system is excited via port 1 with 130 \( \mu \text{W} \) of green laser while the emission is collected through port 3 (shown in Fig. 3 a) in orange). In blue, the free space emission of the \( \text{SiV}^- \) center is shown, where the ensemble is evanescently excited through port 1 and the emission is collected at the center position of the ND. Both collection procedures are shown in the small insets in Fig. 3 a).

The presence of the ND in the interaction zone changes the effective refractive index of the cavity. This leads to a red shift of the desired cavity resonance. Together with a change in temperature the shift is approximately 0.4 nm. The altered mode at \( \sim 737.9 \) nm of the PCC is fed by the ZPL of the \( \text{SiV}^- \) ensemble. The other resonances are slightly enhanced due to phonon side band coupling and scattered background fluorescence. The \( Q \)-factor of the desired resonance decreased from \( Q_{\text{cav}} = 1000 \) for the empty cavity to \( Q_{\text{coupled}} = 480 \) for the coupled system caused by scattering losses and degradation of the PCC.
resonance and leads to an average Purcell-enhancement nearly every second photon being emitted into the cavity (according to a NA=0.55 objective). This corresponds to $\eta_{\text{avg}} = 0.14$ where $\eta$ is the collection efficiency of the free space emission (according to a NA=0.55 objective). This corresponds to nearly every second photon being emitted into the cavity resonance and leads to an average Purcell-enhancement of 0.79 for all emitters inside the SiV$^-$ ensemble. The tuning mechanisms for modifying the ensemble coupling utilized so far, are position of the ND and temperature. In Fig. 3 b) the $\beta$-factors after optimizing the position of the ND and after temperature tuning are shown. The position and orientation of the ND in the interaction zone can be controlled by AFM-based nanomanipulation [22], which yields to a better dipole alignment of the ND to the cavity axis. Position 1 and position 2 in Fig. 3(b) correspond to a coupling averaged over the whole ensemble of 0.14 and 0.31, respectively. At position 2 we cooled the sample from 295 K to $\sim$ 150 K. This further increased the average ensemble $\beta$-factor to 0.44 (as shown in Fig. 3 a) and given in equation (1)).

Additional reduction of the temperature to $\sim$4 K reveals the fine structure splitting of the SiV$^-$ centers in the ensemble. Thus, instead of the average ensemble coupling the $\beta$-factors of individual transitions of single SiV$^-$ centers can be determined, as depicted in Fig. 4. Again, the free space emission (blue) needs to be compared to the joint emitter cavity signal (insets Fig. 4 a)). Freezing and unfreezing processes, together with temperature tuning further shifted the central frequency of the resonance mode to approximately 740.3 nm (depicted in gray Fig. 4 top). This implies a detuning from the average ensemble ZPL resonance at $\sim$ 738 nm leading to decreased average coupling. The detuning enables the coupling of individual, however more strained, SiV$^-$ centers (Fig. 4 top), apparent when zooming into the red square (Fig. 4 bottom). A splitting of (244 $\pm$ 10) GHz between the doublet of (A,B) and (C,D) is observed, while the splitting between C and D is (37 $\pm$ 10) GHz. These four lines arise from one SiV$^-$ center with an excited state splitting of 252 GHz and a ground state splitting of 46.3 GHz influenced by the strain inside the ND [4]. For the SiV$^-$ center transition A and D have the same dipole orientation as well as transition B and C [31]. Fig. 4 confirms that transition B and C show a better coupling to the cavity mode than transition A and D originating from dipole alignment of the emitter to the cavity axis. Similar dipole orientation of the transitions reach higher (B and C) and lower (A and D) coupling efficiencies to the cavity mode. From these values according to equation (1), we estimate the $\beta$-factor for all four transitions. The highest coupling was achieved for transition B, which is $\beta_B = 0.81$. This value translates to a Purcell enhancement of $F_{P,B} \approx 4$.

$4/5$ of the total spontaneous emission are channeled into the photonic circuit.
FIG. 3. Optimized emitter-cavity coupling. a) The cross-talk spectrum of the cavity (green) before the ND was placed, shows a resonance at 737.4 nm. In blue the free space emission of the SiV\(^-\) ensemble for \(\approx 150\) K. The free space emission was collected in the center, while excited over port 1, as it can be seen in the small inset. The spectrum of the coupled cavity emission in orange shows a clear magnification of the emission rate for the resonance at 737.9 nm (excited over port 1 and collected from port 3). A \(\beta\)-factor of 0.44 corresponding to a Purcell of 0.79 was calculated from the Lorentzian fits on the free space and the cavity-emitter emission spectra. b) Coupling evolution for different tuning mechanism like positioning of the ND inside the interaction zone and temperature tuning. The highest ensemble coupling was achieved for Position 2 and 150 K.

OUTLOOK

In our work we demonstrate the efficient coupling of individual optical transitions of SiV\(^-\) centers to a Si\(_3\)N\(_4\)-based cross-bar PCC with a Purcell enhancement of more than 4, where the enhanced signal was read out via a probe waveguide (with a PCC) by excitation via a crossed waveguide on chip. Much higher Purcell enhancement is prohibited by residual scattering from the ND reducing the overall Q-factor of the PCC. Furthermore, the achievable evanescent coupling strength is ultimately limited by the distance of the SiV\(^-\) center to the field maximum of the PCC. In future experiments we envision Purcell factors beyond 100 for single SiV\(^-\) center in nanodiamonds with diameter of a few ten nanometers. To emphasize the influence of the ND emitter host on the Purcell enhancement factor simulations without the scattering crystal were computed leading to \(F_p = 68\) \((N = 27)\) and \(F_p = 541\) \((N = 53)\), respectively for matched polarization of the emitter-cavity systems. The investigated hybrid quantum photonics platform brings cavity-mediated entanglement generation \([32, 33]\), efficient Bell-State measurements \([35, 36]\) and robust gates of distant emitters \([37]\) into reach. Quantum state transfer in an on-chip, integrated platform opens the door for long-distance quantum communication and linear optics quantum computing \([38]\). Quantum photonics based on SiV\(^-\) center in diamond, where the electronic spin is coupled to the environment whereas the nuclear spin is well-isolated, enable further applications relying on the electronic spin as broker unit with a connected, long-lived quantum memory. Applications range from photonic memories \([39]\) and quantum repeaters \([40]\) to error correction \([41]\) or enhanced quantum sensing \([42]\).

METHODS

Fabrication of Nanodiamonds

SiV\(^-\) containing diamond nanoparticles were obtained by HPHT treatment of the metal catalysts-free growth system based on a homogeneous mixture of naphthalene (C\(_{10}\)H\(_8\)), fluorographite (CF\(_1\)\(_1\)\(_1\)), and tetrakis(trimethylsilyl)silane (C\(_{12}\)H\(_{36}\)Si\(_5\)) which was used as the Si doping component. (Introduction of fluorine-containing compounds into the growth system was intended to reduce the content of NV centers in NDs-SiV\(^-\)). HPHT treatment of the initial homogeneous mixtures was carried out in a high-pressure apparatus of "Toroid" type. The experimental procedure consists of loading the high-pressure apparatus to 8.0 GPa, heating the samples up to 1450 \(^\circ\)C and short (3 s) isothermal exposures at these temperatures.

Fabrication of the Photonic Chip

Free-standing PCC devices on chip were realized on Silicon nitride-on-insulator wafers consisting of 200 nm stoichiometric Si\(_3\)N\(_4\) on top of a 2 \(\mu\)m thick SiO\(_2\) layer on top of Si. Fabrication of the nanophotonic circuits involved several steps of electron-beam lithography (e-beam) followed by reactive ion etching. The nanophotonic circuits were defined on top of the Si\(_3\)N\(_4\) layer using negative tone photoresist ma-N 2403 in the first lithography step and after were 75 % dry-etched into the silicon nitride layer using an CHF\(_3\)/O\(_2\) plasma. To realize freestanding PCC underneath SiO\(_2\) should be removed, which was achieved by opening a window around the photonic crystal region in the second step of lithography by means of exposing positive photoresist PMMA in this area. In the following step, the remaining 25 % of silicon nitride in the window
area was etched, while the waveguide inside of the window was protected with an ma-N 2403 photoresist; the waveguides outside the windows were protected by unexposed PMMA photoresist. After that, both photoresists were removed by O$_2$ plasma. In the last fabrication step SiO$_2$ layer in the windows was removed by wet etching, namely by immersing the chip in hydrofluoric acid (HF).

**Optical Methods**

The optical readout was established by a self build confocal microscope setup with an NA=0.55 objective (50x magnification). For scanning the sample, a galvo mirror system was used. With the help of a second laser path and a 4f-lens system, the laser can be set on a fixed position, while the readout is collected from a different position. The readout can be directed on a spectrometer and an avalanche photo diode.

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[1] Atatre, M., Englund, D., Vamivakas, N., Lee, S.-Y. & Wrachtrup, J. Material platforms for spin-based photonic quantum technologies. Nat Rev Mater 3, 38–51 (2018).
[2] Awschalom, D. D., Hanson, R., Wrachtrup, J. & Zhou, B. B. Quantum technologies with optically interfaced solid-state spins. Nature Photon 12, 516–527 (2018).
[3] Becker, J. N. & Becher, C. Coherence Properties and Quantum Control of Silicon Vacancy Color Centers in Diamond (Phys. Status Solidi A 11/2017). physica status solidi (a) 214, 1770170 (2017).
[4] Rogers, L. J. et al. Single Si-V$^-$ centers in low-strain nanodiamonds with bulklike spectral properties and nanomanipulation capabilities. Phys. Rev. Applied 11, 024073 (2019).
[5] Sipahigil, A. et al. Indistinguishable Photons from Separated Silicon-Vacancy Centers in Diamond. Phys. Rev. Lett. 113, 113602 (2014).
[6] Nguyen, C. T. et al. An integrated nanophotonic quantum register based on silicon-vacancy spins in diamond. Preprint at https://arxiv.org/abs/1907.13200 (2019).

[7] Nguyen, C. T. et al. Quantum network nodes based on diamond qubits with an efficient nanophotonic interface. Preprint at https://arxiv.org/abs/1907.13199 (2019).

[8] Faraon, A., Barclay, P. E., Santori, C., Fu, K.-M. C. & Beausoleil, R. G. Resonant enhancement of the zero-phonon emission from a colour centre in a diamond cavity. Nature Photonics 5, 301–305 (2011).

[9] Hausmann, B. J. M. et al. Integrated Diamond Networks for Quantum Nanophotonics. Nano Lett. 12, 1578–1582 (2012).

[10] Burek, M. J. et al. High quality-factor optical nanocavities in bulk single-crystal diamond. Nature Communications 5, 5718 (2014).

[11] Khanalilloo, B. et al. Single-Crystal Diamond Nanobeam Waveguide Optomechanics. Phys. Rev. X 5, 041051 (2015).

[12] Lagomarsino, S. et al. Evidence of Light Guiding in Ion-Implanted Diamond. Phys. Rev. Lett. 105, 233903 (2010).

[13] Sotillo, B. et al. Diamond photonics platform enabled by femtosecond laser writing. Scientific Reports 6, 35566 (2016).

[14] Courvoisier, A., Booth, M. J. & Salter, P. S. Inscription of 3d waveguides in diamond using an ultrafast laser. Appl. Phys. Lett. 109, 031109 (2016).

[15] Chen, Y.-C. et al. Laser writing of coherent colour centres in diamond. Nature Photonics 11, 77–80 (2017).

[16] Fu, K.-M. C. et al. Coupling of nitrogen-vacancy centers in diamond to a GaP waveguide. Appl. Phys. Lett. 93, 234107 (2008).

[17] Englund, D. et al. Deterministic Coupling of a Single Nitrogen Vacancy Center to a Photonic Crystal Cavity. Nano Lett. 10, 3922–3926 (2010).

[18] Barclay, P. E., Fu, K.-M. C., Santori, C., Faraon, A. & Beausoleil, R. G. Hybrid Nanocavity Resonant Enhancement of Color Center Emission in Diamond. Phys. Rev. X 1, 011007 (2011).

[19] Wolters, J. et al. Enhancement of the zero phonon line emission from a single nitrogen vacancy center in a nanodiamond via coupling to a photonic crystal cavity. Appl. Phys. Lett. 97, 141108 (2010).

[20] Fehler, K. G., Ovvyan, A. P., Gruhler, N., Pernice, W. H. P. & Kubanek, A. Efficient Coupling of an Ensemble of Nitrogen Vacancy Center to the Mode of a High-Q, Si3N4 Photonic Crystal Cavity. ACS Nano 13, 6891–6898 (2019).

[21] Jantzen, U. et al. Nanodiamonds carrying silicon-vacancy quantum emitters with almost lifetime-limited linewidths. New J. Phys. 18, 073036 (2016).

[22] Huler, S. et al. Preparing single SiV− center in nanodiamonds for external, optical coupling with access to all degrees of freedom. Preprint at https://arxiv.org/abs/1908.01591 (2019).

[23] Schell, A. W. et al. A Scanning Probe-Based Pick-and-Place Procedure for Assembly of Integrated Quantum Optical Hybrid Devices. Review of Scientific Instruments 82, 073709 (2011).

[24] Wehner, S., Ellekous, D. & Hanson, R. Quantum internet: A vision for the road ahead. Science 362, 6412 (2018).

[25] Spring, J. B., Metcalf, B. J., Humphreys, P. C., Kolthammer, W. S., Jin, X. M., Barbieri, M., Datta, A., Thomas-Peter N., Langford N. K., Kundys D., Gates J.C., Smith B. J., Smith P. G. R. & Walmsley, I. A. Boson Sampling on a Photonic Chip. Science 339, 798–801 (2013).

[26] Oskooi, A.F., Roundy, D., Ibanescu, M., Bermel, P., Joannopoulos, J.D. & Johnson, S.G. MEEP: A Flexible Free-Software Package for Electromagnetic Simulations by the FDTD Method. Comput. Phys. Commun. 181, 687–702 (2010).

[27] Akahane, Y., Asano, T., Song, B.S. & Noda, S. High-Q Photonic Nanocavity in a Two-Dimensional Photonic Crystal. Nature 425, 944-947 (2003).

[28] Purcell, E.M., Torrey, H.C & Pound, R.V. Resonance Absorption by Nuclear Magnetic Moments in a Solid. Phys. Rev 69, 37–38 (1946).

[29] Taflove, A. Oskooi, A. (Ed.), Johnson, S. (Ed.) Advances in FDTD Computational Electrodynamics: Photonics and Nanotechnology. (Artech House: Norwood, MA, 2013).

[30] Zhang, J. L. et al. Strongly Cavity-Enhanced Spon-
taneous Emission from Silicon-Vacancy Centers in Di-

[31] Rogers, L. J. et al. All-Optical Initialization, Read-
out, and Coherent Preparation of Single Silicon-Vacancy Spins in Diamond. Phys. Rev. Lett. 113, 263602 (2014).

[32] Imamouli, A. et al. Quantum Information Processing Using Quantum Dot Spins and Tivy QED. Phys. Rev. Lett. 83, 4204–4207 (1999).

[33] Kastoryano, M. J., Reiter, F. & Serssen, A. S. D. Dissipative Preparation of Entanglement in Optical Cavities. Phys. Rev. Lett. 106, 090502 (2011).

[34] Zheng, S.-B. & Guo, G.-C. Efficient Scheme for Two-Atom Entanglement and Quantum Information Processing in Cavity QED. Phys. Rev. Lett. 85, 2392–2395 (2000).

[35] Wals, E. & Vuckovic, J. Dipole Induced Transparency in Drop-Filter Cavity-Waveguide Systems. Phys. Rev. Lett. 96, 153601 (2006).

[36] Borregaard, J., Kmr, P., Kessler, E. M., Lukin, M. D. & Serssen, A. S. Long-distance entanglement distribution using individual atoms in optical cavities. Phys. Rev. A 92, 012307 (2015).

[37] Cirac, J. I., Zoller, P., Kimble, H. J. & Mabuchi, H. Quantum State Transfer and Entanglement Distribution among Distant Nodes in a Quantum Network. Phys. Rev. Lett. 78, 3221–3224 (1997).

[38] Kok, P. et al. Publisher’s Note: Linear optical quantum computing with photonic qubits [Rev. Mod. Phys. 79, 135 (2007)]. Rev. Mod. Phys. 79, 797–797 (2007).

[39] de Riedmatten, H. & Afzelius, M. Quantum Light Storage in Solid State Atomic Ensembles. In Predojevi, A. & Mitchell, M. W. (eds.) Engineering the Atom-Photon Interaction: Controlling Fundamental Processes with Photons, Atoms and Solids, Nano-Optics and Nanophotonics, 241–273 (Springer International Publishing, Cham, 2015).

[40] Munro, W. J., Azuma, K., Tamaki, K. & Nemoto, K. Inside Quantum Repeaters. IEEE Journal of Selected Topics in Quantum Electronics 21, 78–90 (2015).

[41] Terhal, B. M. Quantum error correction for quantum memories. Rev. Mod. Phys. 87, 307–346 (2015).

[42] Dejen, C., Reinhard, F. & Cappellaro, P. Quantum sensing. Rev. Mod. Phys. 89, 035002 (2017).