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Cavity-Enhanced Photon Emission from a Single Germanium-Vacancy Center in a Diamond Membrane

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The nitrogen-vacancy center in diamond has been explored extensively as a light-matter interface for quantum information applications, however it is limited by low coherent photon emission and spectral instability. Here, we present a promising interface based on an alternate defect with superior optical properties (the germanium-vacancy) coupled to a finesse 11,000 fiber cavity, resulting in a 31±12-fold increase in the spectral density of emission. This work sets the stage for cryogenic experiments, where we predict a factor of 20±7 increase in the spontaneous emission rate.

Defect centers in diamond can exhibit long-lived spin states that are accessible via coherent optical transitions [1–3], providing a promising platform for quantum nonlinear optics [4] or quantum networks [5, 6]. There have been impressive steps towards creating such a network using the nitrogen-vacancy (NV) center in diamond, with several critical components demonstrated in the last decade [7–15]. Nevertheless, optically-mediated entanglement rates for NVs have been limited to tens of Hz [14] due to the low fraction (3%) of photons emitted into the coherent zero phonon line (ZPL), the difficulty of collecting these photons into a single optical mode, the long excited state lifetime (12 ns), and spectral diffusion of the emitter. This platform could be improved by coupling defects to an optical resonator, thereby increasing the ZPL emission rate into a well-defined mode. However, enhanced spectral diffusion near surfaces has thus far impeded attempts to realize stable NV centers in small-mode-volume optical cavities [15, 17].

An alternative approach explores group IV defect centers such as the silicon-vacancy (SiV) [18, 19] and germanium-vacancy (GeV) centers [20, 21]. While their spins interact strongly with phonons (necessitating experiments at low temperature [3] or in a high-strain regime [22]), their optical properties are superior. Owing to inversion symmetry, these particular defects have larger ZPL fractions (60–70%) and exhibit strongly reduced spectral diffusion compared to the NV center [23, 24]. Moreover, there is evidence that the GeV also has high quantum efficiency [21]. Integrating GeV centers into optical resonators is therefore a promising step toward generating highly efficient or even deterministic interactions between spins and photons [25].

Over the last decade, two primary approaches for coupling diamond defect centers to optical cavities have emerged: (1) diamond nanophotonics and (2) open-geometry microcavities. Emitters coupled to low-mode-volume nanophotonic resonators can exhibit high Purcell enhancement [15] and can even enter the high-cooperativity regime [26, 27]. Despite their inversion symmetry, SiVs in such structures still suffer from increased spectral diffusion and inhomogeneous broadening due to nearby diamond surfaces, lattice damage, and material strain [28]. This is further exacerbated for the GeV, since the heavier ion leads to increased implantation damage. Furthermore, the GeV ZPL occurs at a shorter wavelength (603 nm), making fabrication substantially more challenging as it requires smaller feature sizes and has increased sensitivity to surface roughness.

In contrast to nanofabricated devices, open Fabry-Pérot microcavities offer much narrower resonator linewidths as well as in-situ spectral and spatial tunability. Importantly, these systems can accommodate microns-thick diamond membranes in which even NV centers can exhibit minimal spectral diffusion and bulk-like optical properties [29]. So far it has proved challenging to fabricate membranes with sufficient surface quality as to achieve very high cavity finesse. This is particularly true when the energy of the optical mode is concentrated in the diamond (so-called “diamond-like” modes) since the electric field has an antinode at the air-diamond interface [30]. Indeed, the only demonstration of coupling between a single emitter in a diamond membrane and an open cavity used a finesse $\mathcal{F} = 5,260$ mode localized in

FIG. 1. A schematic of the cavity setup, where $L$ is the cavity length and $t_d = 862^{±13}_{±13}$ nm is the membrane thickness.
Our microcavities comprise a macroscopic flat mirror (substrate from Coastline Optics) and a microscopic spherical mirror deposited on the tip of a single-mode optical fiber (Thorlabs 630HP). The spherical dimple of the fiber mirror is machined using a laser ablation technique \[33\] and has an effective radius of curvature \( R = 43.1 \pm 0.6 \) \( \mu \)m \([34]\). Both the flat and fiber substrates are coated with dielectric Bragg stack mirrors (LASEROPTIK) with alternating high and low index layers of Ta\(_2\)O\(_5\) and SiO\(_2\), respectively. The flat mirror is low-index terminated such that the addition of the diamond membrane increases the mirror reflectivity; it also produces an electric field-antinode at the mirror-diamond interface. In contrast, the fiber mirror is high-index terminated (designed for use in air) and has an electric-field mode \( \text{of} \) (Fig. 1). Here, bright spots correspond to single GeVs and contours are drawn at 4,000 counts/s to qualitatively show emitter localization. We perform a detailed study of the well-isolated GeV center marked with an arrow (henceforth referred to as the studied emitter). We confirmed that this was a single defect \( \text{measured intensity autocorrelation of} \ g^2(0) = 0.25 \pm 0.16 \ [34] \) with a lifetime \( \tau = 6.0 \pm 0.1 \) ns.

The modest fluorescence count rates observed can be attributed to a combination of low transmission in the collection path, narrow spectral filtering, and much of the emission either exiting through the flat mirror \( \text{which is} \) designed for normal incidence \( \text{or} \) being confined to the membrane in the form of guided modes \([35]\). Counts are further reduced by the presence of an additional dark state, which may be a different charge state of the GeV center \([35]\). To quantify the impact of such a state, we probed the population dynamics of the studied emitter by measuring \( g^{(2)} \) as a function of excitation power and found that the dynamics were well-described by a three-level model including power-dependent shelving \([34]\). From this analysis, we predict a dark-state equilibrium population of \( 96 \pm 18\% \) at infinite pump power, corresponding to a bright-state photon emission rate of \( (6.7 \pm 0.9) \times 10^6 \) photons/s. Reassuringly, there has been some evidence that the dark-state population can be reduced via laser repumping/gating \([27, 35]\). Moreover, non-radiative decay paths may further limit photon counts, as varying estimates of quantum efficiency have been reported recently \([24, 35, 36]\). Finally, photon emission was further limited by our inability to saturate most emitters due to the low absorption cross-section at 532 nm \([37]\) and destructive interference of the pump laser within the diamond membrane.

We can replace the 100× objective with the fiber mirror to observe cavity-coupled GeV emission as a function of cavity length, where Fig. 2 shows such a measurement at the position of the studied GeV. There is a clear peak in photon counts where the cavity length is resonant with the thermally broadened ZPL; optical filtering results in a profile that deviates from the expected Lorentzian. We repeat this measurement at various x-y positions on the membrane and plot the difference between maximum and minimum counts in Fig. 2. Moreover, the lateral resolution is set by the 532 nm excitation spot size (\( \approx 1 \mu \)m) since the cavity waist diameter is much larger (\( \approx 3 \mu \)m). The contours obtained from the confocal measurement are overlaid for comparison, revealing...
FIG. 2. a) A confocal image of membrane fluorescence (600 − 605 nm) taken at \( P = 19 \) mW. The white contours indicate emitter localization and the studied GeV center is indicated with an arrow. b) Cavity-coupled emission as a function of cavity length at the position of the studied GeV center (\( \mathcal{F} = 11,200 \pm 170 \) at 603 nm). The non-Lorentzian shape is determined by the filters in the collection path. c) A map of cavity-coupled emission amplitude taken at \( P = 19 \) mW over the same area as in a). The confocal contours are overlaid and the studied defect is indicated. d) Broadband cavity transmission as a function of cavity length. The dashed lines correspond to numerical fitting of the fundamental and first order transverse modes of the \( m = 15 \) and 16 longitudinal modes.

FIG. 3. a) GeV center spectrum taken in the confocal configuration. The pure dephasing rate \( \gamma^*/(2\pi) = 5.22 \pm 0.05 \) THz is indicated. b) GeV center fluorescence as a function of cavity length. The colored region represents the integration window. c) Integrated spectrum taken in the cavity configuration. The light trace shows the raw data, and the dark trace has been averaged over 40 points.

Beyond spatial correlations between Figs. 2a and c, further evidence that we are probing a cavity-coupled GeV center can be obtained by comparing emitter spectra from both setups. Figure 3b shows a confocal spectrum for the studied emitter, which exhibits a strong ZPL emission around 603 nm with a FWHM linewidth of \( \gamma^*/(2\pi) = 5.22 \pm 0.05 \) THz [34]. A corresponding cavity measurement can be obtained by exciting the emitter while scanning the cavity length and acquiring a spectrum at each position (Fig. 3c). Integrating the emission along one mode using a 2 nm window about the resonance results in the light trace shown in Fig. 3c, where the noise can be attributed to mechanical instability of the cavity. To show the underlying spectral shape we also average the data using a 40 point window (dark trace). Both measurements were taken using a 605 ± 15 nm bandpass filter (Semrock), which did not limit the observed spectra. The peaks around 597 and 609 nm in Fig. 3c...
are due to mechanical disturbances causing the cavity to pass through the same resonance twice. The qualitative similarities between the confocal and cavity spectra further confirm that the collected emission is coming from a GeV center.

In principle, comparison of cavity-coupled and free-space GeV fluorescence rates allows us to quantify cavity funneling. However, we must carefully account for different excitation intensities arising from interference effects in the diamond membrane and cavity. We thus compare the saturating fluorescence counts at infinite pump power ($I(\infty)$) obtained by fitting saturation curves with the model $I(P) = I(\infty) \frac{P}{P + P_{\text{sat}}} + c_{\text{bg}}$, where $I$ is the observed count rate, $P$ is the excitation power, $P_{\text{sat}}$ is the saturation power, and $c_{\text{bg}}$ accounts for a linear background. In the confocal setup, we measure a saturation power of $P_{\text{sat}} = 3.9 \pm 0.3 \text{ mW}$ and extract a saturating fluorescence count rate of $I_{\text{free,meas}}(\infty) = 4.0 \times 400 \text{ counts/s}$. We note that this is lower than the count rates observed in Fig. 2a and we attribute this discrepancy to variation in optical alignment. There is consequently some additional error on the free-space emission rate which is not captured by our estimate of the collection efficiency for the confocal path ($\eta_{\text{free}} = (3.5 \pm 0.5) \times 10^{-3}$ counts/photon), which yields $I_{\text{free}} = I_{\text{free,meas}}/\eta_{\text{free}} = (1.2 \pm 0.3) \times 10^{6}$ photons/s, the total emission rate of the defect. Comparing this value to the maximum photon emission rate predicted at infinite pump power results in a quantum efficiency of $17\pm5\%$ for the studied GeV center, which falls within the range of reported values [24, 25, 30]. Furthermore, we collect photon emission between 600 - 605 nm, corresponding to a photon spectral density of $900 \pm 40$ photons/(s GHz) (see [34] for details).

We then study the saturation behavior of the emitter coupled to the $m = 15, 16, 17$ longitudinal modes of the cavity. For each excitation power, we measure fluorescence as a function of cavity length (Fig. 4b). The amplitudes of these resonances are estimated by fitting with Gaussians, and are plotted as a function of excitation power in Fig. 4b. As expected, the cavity-coupled fluorescence decreases with mode number as the cavity mode volume increases. Fitting the $m = 15$ data to the saturation model yields $P_{\text{sat}} = 3.1 \pm 0.5 \text{ mW}$ and $I_{\text{cav,meas}}(\infty) = 380 \pm 50 \text{ counts/s}$. We estimate a collection efficiency of $\eta_{\text{cav}} = (8.2 \pm 1.2) \times 10^{-2}$ counts/photon for the cavity setup, resulting in a corrected saturating fluorescence count rate of $I_{\text{cav}} = I_{\text{cav,meas}}/\eta_{\text{cav}} = 4.700 \pm 900$ photons/s. Moreover, we estimate a cavity linewidth of $\kappa/(2\pi) = 1.08 \pm 0.17 \text{ GHz}$, leading to a cavity-enhanced peak spectral density of $2.800 \pm 700$ photons/(s GHz), a factor of $31_{-12}^{+12}$ greater than what was obtained with the confocal measurements. The experimentally determined efficiency of emission into the $m = 15$ mode is then $\beta_{\text{exp}} = I_{\text{cav}}/I_{\text{free}} = 0.40^{+0.14}_{-0.19}\%$ (details in [34]).

For comparison, we simulate the expected $\beta$ value (Fig. 5) for an emitter resonantly coupled to the $m = 15$ cavity mode as a function of diamond thickness [34]. Here, the solid line shows the result for the target implantation depth (125 nm) and the shaded regions reveal the spread for one- or two-times the standard deviation in depth ($\sigma = 20 \text{ nm}$), resulting in $\beta$ between 0.08% and 2.0% at $t_d = 862 \text{ nm}$. The peaks in efficiency as a function of diamond thickness correspond to “diamond-like” modes, where the electric field in the diamond is maximized. We note that the observed $\beta_{\text{exp}} = 0.40^{+0.14}_{-0.19}\%$ lies at the lower range of expected values, which we tentatively attribute to non-ideal emitter location along the cavity axis due to implantation straggle.

Cooling such a high-quality membrane to cryogenic temperatures should result in a narrowing of the ZPL optical transitions, approaching the radiative limit of $\gamma/(2\pi) = 27 \text{ MHz}$ for a 6.0 ns excited-state lifetime. In this regime the cavity linewidth should far exceed that of the emitter, allowing for a Purcell enhancement of resonantly coupled optical transitions. The expected enhancement can be calculated using the extracted room-temperature system parameters as $F_p \approx \frac{\beta_{\text{exp}}}{\xi/\gamma}$, where $\xi = 0.6$ is the GeV Debye-Waller factor [35]. This would result in a ZPL enhancement of $F_p = 32_{-16}^{+12}$ (assuming unity quantum efficiency and full depopulation of the dark state).
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FIG. 5. Simulated $\beta$ for an emitter resonantly coupled to the $m = 15$ mode as a function of diamond thickness, with the experimentally derived value of $\beta_{\text{exp}} = 0.40_{-0.19}^{+0.14}\%$ plotted at the extracted membrane thickness $t_d = 862_{-1}^{+4}$ nm.


