

Tunable cavity coupling of a single Sn- V^- center in nanodiamond across the bad-emitter and bad-cavity regimes

S. Sachero¹,^{*} R. Berghaus¹, F. Feuchtmayr¹, N. Lettner¹, P. Maier¹, E. Nieto Hernandez²,
S. Ditalia Tchernij², and A. Kubanek^{1,3,*}

¹*Institute for Quantum Optics, Ulm University, 89081 Ulm, Germany*

²*Physics Department, University of Torino, via P. Giuria 1, 10125 Torino, Italy*

³*Center for Integrated Quantum Science and Technology (IQST), Ulm University, Albert-Einstein-Allee 11, 89081 Ulm, Germany*



(Received 14 July 2025; revised 1 October 2025; accepted 3 November 2025; published 20 November 2025)

Efficient coupling between quantum emitters and optical cavities is essential for scalable quantum photonic technologies. Group-IV vacancy centers in diamond, particularly the negatively charged tin-vacancy center, have emerged as promising candidates due to their spectral stability, high Debye-Waller factor, and large orbital splitting in ground states. Here, we demonstrate controlled coupling of a single negatively charged tin-vacancy center hosted in a nanodiamond to a fully tunable Fabry-Pérot microcavity. At cryogenic temperatures, we access the weak-coupling regime and observe a transition from the bad-emitter regime to the bad-cavity regime as the optical transition of the color center narrows. At 4 K, a Purcell factor exceeding 1.7 is measured, confirming cavity-enhanced emission. The obtained results demonstrate the potential of Sn- V^- centers in nanodiamonds as a coherent single-photon source for quantum networks.

DOI: [10.1103/8yqs-wtp2](https://doi.org/10.1103/8yqs-wtp2)

I. INTRODUCTION

Coupling a quantum emitter to a single mode of light is fundamental for various quantum technologies, such as quantum repeaters and quantum networks [1–3]. A key requirement for the successful implementation of these applications is the generation of coherent single photons [4,5], which must be emitted in a well-defined optical mode. The efficiency of coherent-photon emission primarily depends on the intrinsic properties of the emitter. In this context, group-IV vacancy (G4V) centers in diamond have emerged as promising candidates [6–8]. The aforementioned centers exhibit a high Debye-Waller factor, with over 60% of their emission residing within the zero-phonon line (ZPL) [9–12]. Furthermore, their D_{3d} symmetry renders them robust against electric-field fluctuations [13–15], ensuring stable and coherent emission. Among these centers, the negatively charged tin-vacancy (Sn- V^-) center stands out due to its high quantum efficiency [16–18] and large ground-state (GS) orbital splitting (around 850 GHz) [19], which significantly suppresses

phonon-mediated decoherence at moderate cryogenic temperatures.

To further enhance photon emission into the ZPL, color centers can be integrated into optical microcavities. Depending on the atomic polarization decay rate (γ), cavity-field decay rate (κ), and atom-cavity coupling rate (g), different regimes of cavity quantum electrodynamics can be accessed. From the strong-coupling regime ($g \gg \kappa, \gamma$) [20], where coherent energy exchange dominates [21,22], to the weak-coupling regime, where loss processes (γ or/and κ) dominate the atom-cavity coupling rate [23,24].

In the weak-coupling regime, two distinct subregimes can be identified depending on the relative magnitudes of γ and κ : the bad-emitter regime ($\kappa \ll \gamma$) [25], where the emitter's rapid dephasing rate dominates the emitter-cavity interaction, and the bad-cavity regime ($\kappa \gg \gamma$) [26], where the cavity decay rate is the fastest decay channel. In the bad-emitter regime, the cavity funnels the emission into a narrower cavity mode [27,28], thereby yielding a frequency-tunable bright and narrow single-photon source [25,29]. Further narrowing of the emitter linewidth, achievable, for example, through cryogenic cooling in solid-state defects, can bring the system into a transitioning regime where $\gamma < \kappa$ [26], which in this paper we refer to as the bad-cavity regime. In this regime, the cavity modifies the spontaneous emission rate, leading to enhanced emission via the Purcell effect [30–32].

*Contact author: alexander.kubanek@uni-ulm.de

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

The coupling efficiency is limited by competing loss channels. In particular, unwanted scattering or absorption processes, commonly denoted as κ' , contribute to additional losses that degrade the overall system efficiency. These losses compete with the desired cavity-field decay rate κ , effectively reducing the fraction of photons emitted into the target optical mode. As a result, only a fraction of the emitted photons is channeled into the well-defined cavity mode. Therefore, minimizing κ' is critical for optimizing the performance of cavity-enhanced single-photon sources.

Open-access Fabry-Pérot (FP) microcavities are particularly well suited to such applications due to their high spectral resolution, narrow optical linewidths [33], and *in situ* tunability [24]. Recent work has demonstrated the integration of G4V centers into diamond membranes, enabling coherent optical control and cavity coupling [34–37]; however, the fabrication of high-quality, ultra-thin diamond membranes remains technically challenging. Surface roughness and interface imperfections can significantly degrade the quality of the coupled system. A scalable and practical alternative is to host color centers in nanodiamonds (NDs) [28,38–40]. NDs offer several advantages: size-selective fabrication minimizes scattering losses, precharacterization of individual emitters, and allows deterministic integration into the cavity, eliminating the need for lateral cavity scanning.

Here, we demonstrate controlled coupling of a single Sn- V^- center hosted in an ND by coupling its ZPL to a fully tunable FP microcavity. The proven single-photon nature of the Sn- V^- center under off-resonant excitation allows the direct detection of coherent photons from the ZPL, which are expected to preserve optical coherence. The narrowing of the single Sn- V^- optical transitions at cryogenic temperatures allows the operation of the ND-cavity system in the weak-coupling regime [23]. Further cooling to 4 K leads to an additional reduction of the linewidth transitioning the operation of the system from the bad-emitter regime (100 K) to the bad-cavity regime. In the latter, we observe a reduction in the excited-state lifetime corresponding to a Purcell factor above 1.7, confirming cavity-enhanced emission.

II. ASSEMBLY OF THE HYBRID ND-CAVITY SYSTEM

A. Experimental platform

Our platform is a fully tunable hemispherical FP microcavity formed by a CO₂-laser-ablated concave mirror and a macroscopic flat mirror. The measured radii of curvature (ROCs) of the spherical structure are $\text{ROC}_x \approx 25 \mu\text{m}$ and $\text{ROC}_y \approx 22 \mu\text{m}$, resulting in an ellipticity of 14%. The cavity consists of two symmetrically designed distributed Bragg reflector (DBR) mirrors. The coating presents a

first stopband centered at $\lambda = 620 \text{ nm}$ with a transmission $T = 650 \text{ ppm}$ corresponding to a coating-limited finesse of $F_{\text{ideal},618} = 4800$. The second stopband in the green wavelength range, with a transmission of 6400 ppm, has a coating-limited finesse value of 400.

The cavity is embedded in a titanium bucket [purple rectangle in Fig. 1(a)]. The flat cavity mirror is mounted on three nanopositioners (2xANPx101 and ANPz102, attocube systems AG), which enable precise tuning of the cavity length. A multimode fiber (MM), positioned below the cavity, collects the transmitted laser signal. A mode-matched achromatic lens couples the excitation laser into the cavity mode and collects, in reflection, the emitted fluorescence signal. To optimize coupling efficiency, the achromatic lens is mounted on three nanopositioners allowing x , y , and z tunability. The experimental setup, including the microcavity, optical filters, and excitation and detection fibers, is placed within a liquid-helium-bath cryostat (dashed rectangle).

B. Creation and positioning of the single Sn- V^- center

To create Sn- V^- centers in NDs, size-selected diamond particles with an average size of 180 nm [41] are implanted with a broad beam of $^{120}\text{Sn}^-$ ions at an energy of 60 keV and a fluence of $1 \times 10^{11} \text{ ions/cm}^2$ at the Torino 100 keV ion implanter (LIUTo) [42]. To promote the formation of color centers, the sample is annealed in high vacuum for 1 h at 1200 °C and in oxygen at 405 °C for 1 h [43].

The sample is characterized off-resonantly with a 532-nm laser at room temperature (RT) using a custom-built confocal microscope. Once a single emitter with favorable optical properties is identified, it is transferred to the approximate center of the hemispherical cavity structure using an atomic force microscope (AFM) [39,44]. An AFM scan of the spherical structure confirms the success of the transfer [Fig. 1(b)]. A higher-resolution (enlarged) AFM image reveals the shape and the size of the ND, approximately $150 \times 150 \times 80 \text{ nm}^3$. A room-temperature optical characterization of the same Sn- V^- center confirms that the transfer process preserves the emitter's optical properties. In Table I, we summarize the values of the ZPL, lifetime (τ_0), and saturation parameters (P_{sat} and I_{sat}) from the free-space characterization (see Appendix A).

The measured τ_0 value is $(21.7 \pm 0.3) \text{ ns}$, significantly larger than the value reported for bulk diamond [18, 45]. Nonetheless, significantly longer lifetimes have been recently reported for Sn- V^- centers in NDs [46,47]. A variation and a broader distribution of the excited-state lifetime is often observed in ND [47–50]. This can be attributed to multiple factors: local strain [45], variations in the local density of optical states (LDOS), which depend on particle size [47,48,51–53], and the emitter's position relative to the surface [54,55]. We therefore conclude that the longer

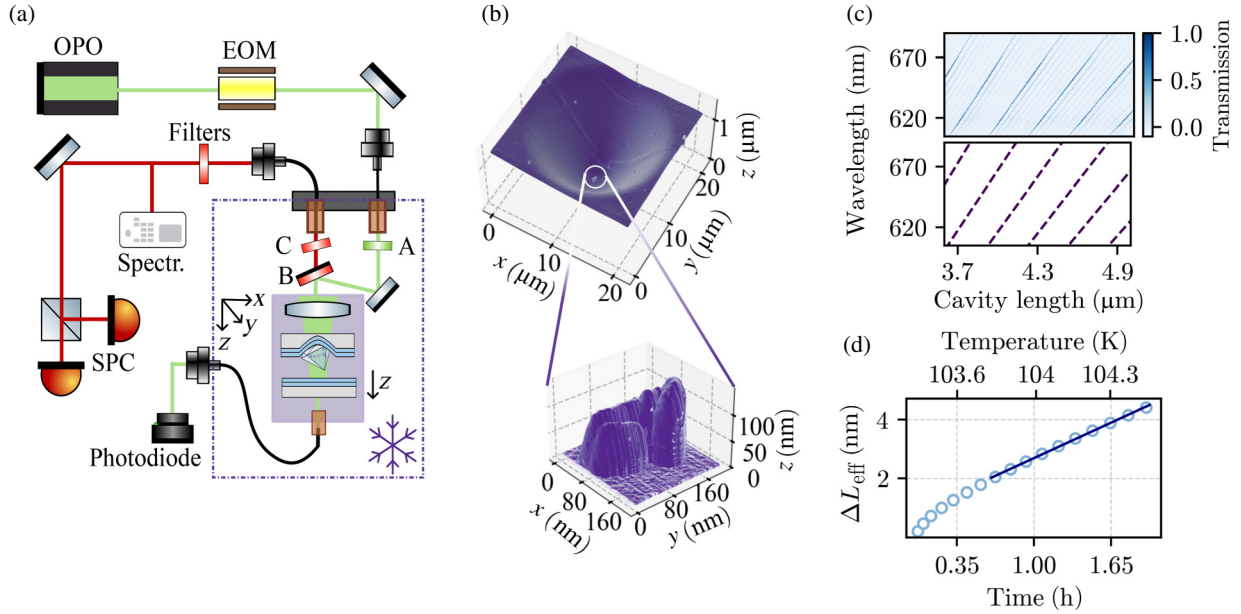


FIG. 1. Assembled hybrid ND-cavity system. (a) Schematic of the experimental setup. The single-mode excitation fiber guides the laser signal from the optical parametric oscillator (OPO) and electro-optic modulator (EOM) to the bath cryostat (purple-dashed box), which houses the microcavity, the achromatic lens (purple box), optical filters (A and C), the dichroic mirror (B), and the excitation and detection fibers. The detection fibers lead the signal to the spectrometer (Spectr.), the single-photon counters (SPC), and photodiode. (b) AFM scan of the spherical structure containing the ND. The measured ROCs are $\text{ROC}_x \approx 25 \mu\text{m}$ and $\text{ROC}_y \approx 22 \mu\text{m}$. The enlarged view shows a high-resolution AFM scan of the ND, whose size is approximately $150 \times 150 \times 80 \text{ nm}^3$. (c) Upper panel: cavity transmission spectra with the integrated ND probed by a white-light-emitting diode (WLED) source showing the wavelength-dependent position of the cavity resonances at different cavity lengths. Lower panel: theoretical distribution of the fundamental mode wavelengths for an empty cavity, calculated with Eq. (1). (d) Shift of the cavity length (ΔL_{eff}) due to the temperature rise measured over 2 h. The dots represent the estimated values of ΔL_{eff} , calculated from the free spectral range (FSR) determined using the WLED spectrum (see Appendix B). The blue line represents a linear fit with a slope of $\alpha = (5.1 \pm 0.03) \times 10^{-6} \text{ K}^{-1}$.

lifetime observed here arises from a combination of these factors.

C. Characterization of the hybrid ND-cavity system

After transferring the ND into the hemispherical structure, we proceed with the characterization of the resulting ND-cavity system. As a first step, we perform multiple cavity transmission scans. By evaluating the ratio of the

TABLE I. Free-space optical properties of the $\text{Sn-}V^-$ center at RT, under off-resonant excitation, after the transfer into the concave cavity mirror.

Parameter	Value	Unit
ZPL	620.1 ± 0.1	nm
FWHM	6.20 ± 0.03	nm
$g^2(0)$	0.25 ± 0.04	
Lifetime $g^2(t)$	24 ± 2	ns
Pulsed lifetime	21.7 ± 0.3	ns
P_{sat}	1.20 ± 0.08	mW
I_{sat}	185 ± 6	kC/s

free spectral range (FSR) to the full width at half maximum (FWHM) of the transmission resonances, we extract an average finesse value of $F_{\text{exp},618} = 4600 \pm 500$ at 618.7 nm. This value is in good agreement with the ideal finesse $F_{\text{ideal},618}$, indicating that the presence of the ND does not introduce scattering losses.

The cavity dispersion is characterized by transmission white-light-emitting diode (WLED) spectra as a function of the cavity length [upper panel in Fig. 1(c)]. The good agreement between the experimental data and the simulation of the fundamental-mode wavelengths (lower panel), based on the model for an empty cavity,

$$\nu_m = \frac{c}{2L} \left(m + \frac{\cos^{-1}(\sqrt{1 - L/\text{ROC}})}{\pi} \right), \quad (1)$$

confirms that including the ND at such short cavity lengths does not significantly distort the mode dispersion (see Appendix C).

Subsequently, the setup is indirectly cooled by a surrounding liquid-nitrogen chamber. At approximately 100

K, the system reaches thermal equilibrium, providing relative passive thermal stability for the cavity. To monitor stability, transmission WLED spectra are acquired continuously over a 2-h period [see Appendix B]. During this time, a drift in the effective cavity length (L_{eff}) of approximately 5 nm is observed. This drift is attributed to a gradual temperature increase throughout the measurement. To confirm this hypothesis, the drift in cavity length is fitted as a function of temperature using a linear model [Fig. 1(d)]. The resulting slope corresponds to a coefficient of thermal expansion (CTE) of $\alpha = (5.10 \pm 0.03) \times 10^{-6} \text{ K}^{-1}$. The good agreement of the estimated value with the reported CTE of titanium, $\alpha = 6.8 \times 10^{-6} \text{ K}^{-1}$ [56] supports our interpretation.

III. CAVITY COUPLING OF THE SINGLE Sn-V^- CENTER

Off-resonant measurements are performed by exciting and detecting through the fundamental modes of the cavity. To enable simultaneous excitation and detection of the ZPL emission, the resonance condition $L_{\text{eff}} = m \times (\lambda_m/2)$ must be satisfied for both the excitation wavelength (approximately 533.3 nm) and the detection wavelength (approximately 618.5 nm).

A simulation of the resonance condition, performed with the excitation wavelength fixed, reveals that for $L_{\text{eff}} \approx 3.7 \mu\text{m}$ the second-next resonance wavelength matches the ZPL of the Sn-V^- center [Fig. 2(a)]. This corresponds to

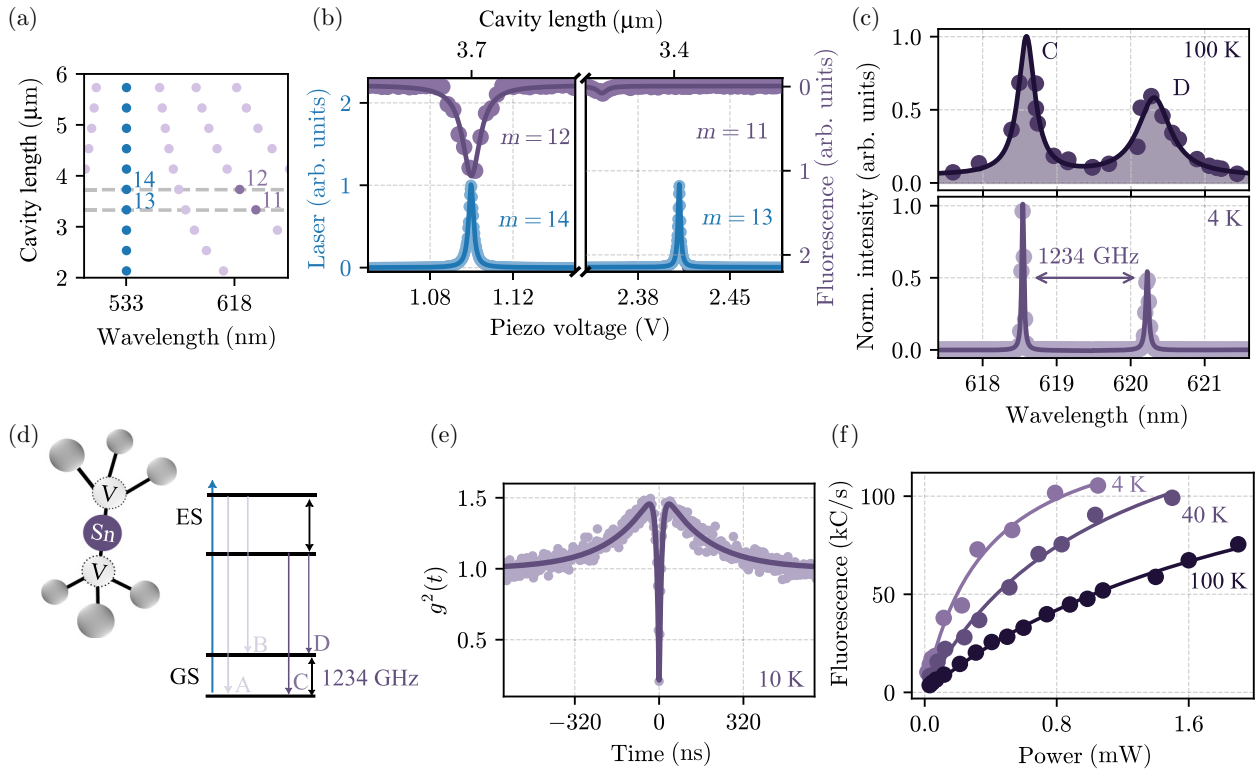


FIG. 2. Characterization of a single Sn-V^- center through the cavity mode at 10 and 100 K. (a) Simulated resonance condition for FP cavity for different cavity lengths assuming a fixed excitation wavelength of 533.3 nm. Laser resonances are shown as blue dots, and corresponding detection resonances are shown as purple dots. The effective cavity lengths used in plot (b) are indicated by the horizontal dashed lines (gray). (b) Cavity length scans over two cavity resonances at 4 K with a fixed laser wavelength 533.3 nm. The transmitted laser signal is shown in blue and the reflected cavity coupled fluorescence signal is shown in purple. A fluorescence signal is detected only when exciting through mode number $m_{\text{exc}} = 14$. When $m_{\text{exc}} = 13$, the emitter is coupling to a higher-order mode instead. (c) PL spectrum of the single Sn-V^- center, revealing the fine structure (at low temperature). The C and D transitions are fitted with a Lorentzian curve both at 100 and 4 K, resulting in ZPL positions of (618.5 ± 0.1) and (620.3 ± 0.1) nm, respectively. (d) Left: atomic structure of Sn-V^- centers in the diamond lattice. The tin atom (Sn) lies between two adjacent carbon atoms (V). Right: energy-level scheme of the measured Sn-V^- center, showing a ground-state splitting of 1234 GHz. The blue line represents the laser excitation. (e) Second-order autocorrelation measurement at 63 μW , showing antibunching with single-photon purity, without background correction: $g^2(0) = 0.21 \pm 0.03$. (f) Saturation curves at 10, 40, and 100 K. The data points represent the average photon counts acquired over a 30-s trace, while the solid line corresponds to the fitted function. The x axis reports the power values measured on the optical table, before coupling into the SM fiber.

excitation and detection through the mode numbers $m_{\text{exc}} = 14$ and $m_{\text{det}} = 12$. For mode numbers higher or lower than $m_{\text{exc}} = 14$, the ZPL is spectrally filtered out by the cavity and no significant counts are detected.

To verify the simulation, we experimentally tune the cavity length across two excitation resonances while simultaneously recording the laser transmission signal [blue curve, Fig. 2(b)] and the fluorescence signal in reflection (purple curve). Pronounced fluorescence is observed only when $m_{\text{exc}} = 14$ and $m_{\text{det}} = 12$, confirming cavity-emitter coupling at $L_{\text{eff}} \approx 3.7 \mu\text{m}$. A weak fluorescence signal is also detected for $m_{\text{det}} = 11$, suggesting partial coupling to a higher-order cavity mode.

The fluorescence resonance appears broadened compared to the laser transmission due to the lower piezo-scanning speed, which is necessary to increase sensitivity to the lower photon counts. The extended scan time increases sensitivity to mechanical and environmental drifts, leading to additional broadening.

Photoluminescence (PL) spectral probing at 100 K is shown in Fig. 2(c) (upper panel). The excitation laser, an optical parametric oscillator (OPO) (HÜBNER Photonics C-WAVE GTR), is tuned together with the cavity length. For each excitation wavelength, a PL spectrum is recorded (see Appendix D). By summing all spectra, two distinct optical transitions, labeled C and D, become visible. These transitions arise from the characteristic splitting of orbital levels due to spin-orbit interaction, which originates from the D_{3D} symmetry of the $\text{Sn-}V^-$ center in diamond [14]. This symmetry results from the tin atom occupying a split-vacancy configuration [left panel, Fig. 2(d)]. Spin-orbit coupling leads to the formation of four orbital levels: two from the GS splitting and two from the excited-state (ES) splitting [9]. The corresponding optically allowed transitions are labeled A, B, C, and D in Fig. 2(d) (right panel). At 4 K, only transitions C and D occur, and only at higher temperatures (> 70 K) do transitions A and B become visible [45]. In our experiment, due to the weak emission of transitions A and B, we can only observe transitions C and D, even at higher temperatures. At 100 K, these transitions are fitted with a Lorentzian, and the resulting wavelengths are (618.6 ± 0.1) and (620.3 ± 0.1) nm, respectively. The respective linewidths are (210 ± 20) and (410 ± 20) GHz.

The PL spectrum at 4 K reveals a narrowing of the optical transitions to the spectrometer resolution limit of 16 GHz. The emission wavelengths at this temperature are (618.54 ± 0.03) and (620.22 ± 0.03) nm, respectively. The resulting GS splitting is 1234 GHz [lower panel, Fig. 2(c)]. This value is significantly larger than the theoretically predicted 850 GHz [19], indicating substantial strain in the surrounding ND lattice. Such enlarged GS splittings are not unexpected and are commonly observed in nanodiamonds [43], where local strain fields often exceed those in bulk diamond [50,57]. This enhanced

TABLE II. Saturation power and intensity values, measured in the cavity, resulting from the fit $I = I_{\text{sat}} \times P / (P_{\text{sat,cav}} + P)$.

Temperature (K)	$P_{\text{sat,cav}}$ (mW)	I_{sat} (kC/s)
10	0.37 ± 0.06	150 ± 10
40	1.1 ± 0.2	180 ± 20
100	2.2 ± 0.2	162 ± 9

splitting can, in fact, be advantageous for high-fidelity microwave spin control [58,59].

Single-photon emission is confirmed by Hanbury Brown-Twiss measurements. The emitter is excited with the OPO at 533.25 nm, enabling detection on resonance at 618.54 nm. The collected fluorescence is split by a 50:50 beam splitter and directed to two single-photon counters (SPCs). To account for the prominent bunching observed in Fig. 2(e), the data points are fitted with a three-level model equation [49,60]. A minimum value of $g^2(0) = 0.21 \pm 0.03$, without any background correction, demonstrates the single-photon purity of the $\text{Sn-}V^-$ center. The single-emitter behavior under off-resonant excitation enables direct detection of ZPL photons.

An investigation of the saturation behavior of the emitter at 4, 40, and 100 K [Fig. 2(f)] reveals that as the temperature decreases, the saturation power also decreases (Table II).

This behavior is governed by the relationship $P_{\text{sat,cav}} \propto 1/\sigma$, where σ is the absorption cross section of the emitter [61]. At lower temperatures, the optical linewidth of the emitter narrows due to reduced phonon interactions and spectral diffusion, effectively increasing σ . The higher absorption cross section enables more efficient photon absorption, reducing the optical power necessary to reach saturation.

IV. CAVITY-ENHANCED INTERACTION OF THE $\text{Sn-}V^-$ CENTER IN THE WEAK-COUPLING REGIME

In the bad-cavity regime, the lifetime of the emitter is reduced due to the Purcell effect. The overall Purcell enhancement can be estimated as [62]

$$F_P = \frac{\tau_0}{\tau_p}, \quad (2)$$

where τ_p and τ_0 (Table IV) are the cavity-modified and free-space spontaneous emission lifetimes, respectively.

To estimate τ_p , we measure power-dependent second-order autocorrelation functions ($g^2(t)$) and fit the data with the three-level model equation [60]. Since the decay rate (γ_1) varies linearly with the excitation power, the resulting values are fitted with the model $\gamma_1 = m \times P + 1/\tau$ [63].

Lifetimes of (14 ± 1) and (19 ± 2) ns are extracted at zero excitation power at around 30 and 100 K, respectively

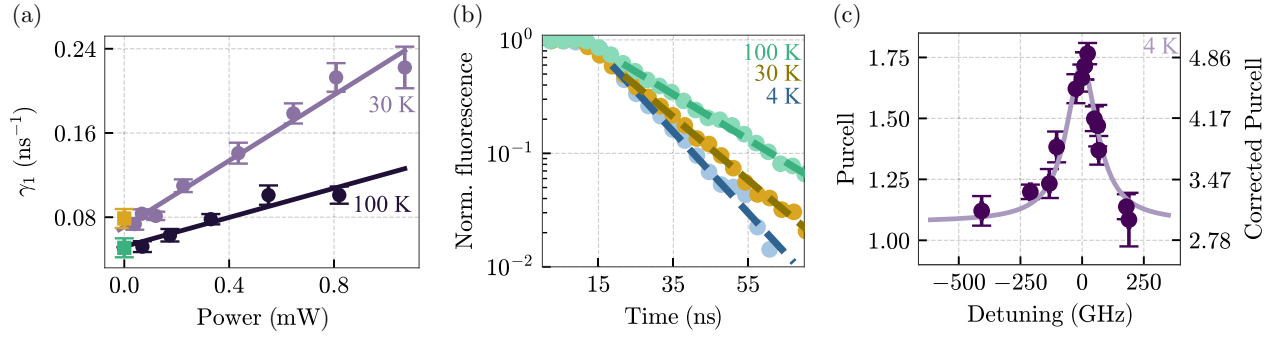


FIG. 3. Cavity-induced enhancement of the spontaneous decay rate across different temperatures. (a) Decay rate (γ_1), extracted from fitting $g^2(t)$ functions measured under varying excitation powers. The solid line represents the linear fit. The estimated lifetime values are (14 ± 1) ns at 30 K and (19 ± 2) ns at 100 K. The green and yellow squares are the lifetime values estimated from the pulse measurements. (b) Logarithmic scale of pulsed lifetime measurements at three different temperatures (4, 40, and 100 K). The dashed lines are the linear fits to extrapolate the lifetime values. The obtained lifetime values are (12.2 ± 0.3) ns at 4 K, (15.8 ± 0.3) ns at 40 K, and (21 ± 1) ns at 100 K. (c) Purcell factor, estimated as the ratio between the free-space and cavity-modulated lifetimes as a function of cavity detuning. The cavity length varies between fully off resonance and on resonance.

[Fig. 3(a)]. The measurements are performed with the cavity maintained on resonance with the emitter frequency by actively adjusting the cavity length to compensate for temperature-induced drifts. The resulting lifetime values are confirmed through pulsed lifetime measurements. The OPO laser, fixed at 533.25 nm, is pulsed off with an electro-optic modulator (EOM) while recording the time delay between the excitation pulse and the detected fluorescence photons. By fitting the data with an exponential decay, we obtain the following lifetime values: (12.2 ± 0.3) ns at 4 K, (15.8 ± 0.3) ns at 40 K, and (21 ± 1) ns at 100 K [Fig. 3(b)]. As shown in Fig. 3(a), the pulsed lifetime measurements (yellow and green square) intersect the linear extrapolation of the power-dependent γ_1 values at zero excitation power. The agreement confirms the reliability of the extracted lifetime values. The lifetime reduction indicates that the system operates in the weak-coupling regime.

At 100 K, the emitter linewidth ($\gamma = 210$ GHz) exceeds the cavity-field decay rate ($\kappa = 15$ GHz), placing the system in the bad-emitter regime ($\gamma > \kappa, g$) [25]. In this regime, only a fraction (κ/γ) of the spontaneous emission couples to the cavity mode [64]. As a result, spontaneous emission is funneled into the cavity mode without significantly modifying the emitter's radiative lifetime [29,65,66]. This explains the weak observed Purcell enhancement: the measured lifetime of (21 ± 1) ns is only marginally shorter than the free-space value (see Table I).

In contrast, at lower temperatures, the narrowing of the emitter optical transitions enables operation in the bad-cavity regime ($\gamma < \kappa$), where the cavity-field decay rate dominates. Under these conditions, we estimate a Purcell factor of $F_P = 1.78 \pm 0.04$. The definition of F_P [Eq. (2)] includes the emission into the incoherent phonon sideband and the free-space continuum [31]; however, since only the fraction of emission coupled into the C optical

transition is enhanced by the cavity, we correct F_P with a factor $\epsilon = 0.36$. The correction factor ϵ accounts for nonunity quantum efficiency (approximately 80% [16]), a limited Debye-Waller factor (around 56%, estimated from the free-space photoluminescence spectrum), and off-resonant branching ratio into the C transition (80% [36]). Accounting for all these effects, we estimate a corrected Purcell enhancement of $F_{P,ZPL} = 4.9$.

The Purcell factor (F_P) follows a Lorentzian dependence on cavity detuning [36,67,68]:

$$F_P = F_{\text{cav}} \left(\frac{\vec{E}(r)\vec{\mu}}{|\vec{E}_{\text{max}}||\vec{\mu}|} \right)^2 \frac{1}{1 + \left(2Q \left(\frac{\lambda}{\lambda_{\text{cav}}} - 1 \right) \right)^2} + F_{\text{FP}}. \quad (3)$$

The first term accounts for spatial and spectral mismatch between the emitter dipole $\vec{\mu}$ and the cavity field $\vec{E}$, while F_{FP} accounts for background modifications to the emission rate due to the cavity environment. For perfect alignment, the enhancement is given by $F_{\text{cav}} + F_{\text{FP}}$, where the theoretical Purcell factor F_{cav} is [62]

$$F_{\text{cav}} = \frac{3}{4\pi^2} \times \left(\frac{\lambda_c}{n} \right)^3 \times \frac{Q}{V_{\text{mode}}}. \quad (4)$$

For our FP cavity—operating at a wavelength of $\lambda_c = 618.5$ nm, an estimated quality factor of $Q_{\text{ideal}} = 56400$, and a mode volume of $V_{\text{mode}} = 21\lambda_c^3$ —we obtain $F_{\text{cav}} = 205$; however, since the ND is located on the spherical structure rather than at the field maximum of the cavity mode, it experiences weaker coupling.

To quantify the effect of this spatial mismatch, we use the ratio $\{\omega_0/[\omega(L)]\}^2$, which effectively describes the reduction of the optimal coupling due to the position

[69]. Incorporating this spatial misalignment, we obtain a corrected Purcell factor of $F_{\text{cav}} = 173$.

To understand the significant discrepancy between the theoretically predicted Purcell factor and the experimentally measured value, we perform a detailed analysis of the system's spectral properties by measuring the Purcell enhancement as a function of cavity-emitter detuning [Fig. 3(c)]. The detuning-dependent lifetime measurements allow us to extract the effective cavity-field decay rate and assess whether additional broadening mechanisms are degrading the cavity performance. Cavity detuning is achieved by tuning the excitation wavelength and adjusting the cavity length to maintain resonance conditions for $m_{\text{det}} = 12$ and $m_{\text{exc}} = 14$. For every cavity detuning, we perform pulsed lifetime measurements, with increasing acquisition time for larger detuning to account for minor fluorescence counts.

Fitting the detuning-dependent data yields an effective cavity-field decay rate of $\kappa_{\text{exp}} = (160 \pm 30)$ GHz, nearly an order of magnitude larger than the expected value of 15 GHz. This broadening arises from fast mechanical vibrations and thermal drift, which shift the cavity resonance during acquisition [70]. Despite manually compensating for slow drifts, rapid fluctuations reduce the effective quality factor to $Q_{\text{exp}} = (3100 \pm 600)$. Under these realistic conditions, the maximum achievable Purcell factor is limited to $F_{\text{vib}} = 10 \pm 2$. This value reflects the upper bound imposed by the degraded Q factor.

Comparing F_{vib} with the measured Purcell factor $F_p = 4.9$ [Eq. (2)] provides insight into the efficiency of coupling between the emitter and the cavity mode. We obtain an effective spatial alignment factor of approximately 49%. This value corresponds to the fraction of the C emitter dipole moment μ that is aligned with the cavity electric field (E), assuming perfect spatial overlap. Conversely, when we do not explicitly correct for the branching ratio, we find an alignment factor of about 38%. This lower value implicitly includes both the dipole misalignment and the reduction in effective coupling strength due to the branching ratio. Thus, improving the spatial alignment of the emitter within the cavity field, by moving or rotating the ND, could lead to a higher Purcell factor and further lifetime reduction.

V. CONCLUSION

We demonstrate the successful coupling of a single $\text{Sn-}V^-$ center in an ND to an FP cavity. The small size of the ND minimizes scattering losses [25,44,69]. As a result, the cavity maintains a finesse of 4600 ± 500 , comparable to that of a bare cavity. Furthermore, we show that the dispersion of the cavity modes remains unaffected by the presence of the ND and can be accurately predicted using the model for an empty cavity. The presence of a single

$\text{Sn-}V^-$ center in the ND, as confirmed by the observed minimum of the autocorrelation function $g^2(0) = 0.21 \pm 0.03$, enables the detection of coherent ZPL photons. This coherence is crucial for the generation and establishment of indistinguishable photons, a key requirement for scalable quantum networks and spin-photon interfaces [7,71,72]. By cooling the system to cryogenic temperatures, we operate it in the weak-coupling regime. Specifically, at 100 K, a linewidth of 210 GHz allows operation in the bad-emitter regime, where we observe single-photon emission into the cavity mode over a very broad spectral range, which can be exploited to realize a continuously tunable, narrow-band single-photon source [25,27–29]. Further cooling narrows optical transition C and shifts the system into the bad-cavity regime, where a clear lifetime reduction, corresponding to a Purcell factor of 1.78 ± 0.04 , is observed. This enhancement is crucial for realizing highly efficient photon sources, as it increases the probability of photon emission into the desired cavity mode, thereby improving the brightness and emission rate for quantum photonic applications. Probing the fine structure reveals an increased GS splitting of 1234 GHz, favorable for high-fidelity microwave spin control [58,59].

By detuning the cavity from fully on resonance to off resonance, we probe the emitter's lifetime under varying coupling conditions. These measurements reveal a coupling efficiency of approximately 49%, indicating that precise manipulation of the position of the ND using an AFM could further enhance the interaction between the cavity and the C optical transition [39,73]. Moreover, we observe that rapid mechanical vibrations of the cavity degrade its performance, limiting the maximum achievable Purcell factor by approximately an order of magnitude. Therefore, improving the mechanical stability of the cavity is crucial for further increasing both the Purcell enhancement and emitter-cavity coupling efficiency [74].

These results demonstrate that the integration of single $\text{Sn-}V^-$ centers in size-controlled NDs within tunable FP microcavities provides a practical route toward versatile and tunable quantum light-matter interfaces.

ACKNOWLEDGMENTS

This project was funded by the German Federal Ministry of Research, Technology and Space (BMRTS) under the project QR.N (16KIS2208). We acknowledge additional support from the LasIonDef project (GA no. 956387) (LASer fabrication and ION implantation of DEFects as quantum emitters), funded by the European Research Council under the Marie Skłodowska-Curie Innovative Training Networks program. Further funding was provided by the European Union's QuantERA Program through the SensExtreme project (499192368), which is gratefully acknowledged. The authors thank Professor Dr. Christine Kranz, Dr. Gregor Neusser, and the Focused Ion

Beam Center at Ulm University for their support with FIB milling. Jens Fuhrmann is acknowledged for the annealing of the samples, and Nadia Elia for her assistance during the measurements. We are grateful to Pureon AG for providing the nanodiamond powder, and to the service team at HÜBNER Photonics for their valuable support in optimizing the C-WAVE GTR widely tunable continuous-wave laser system.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: FREE-SPACE CHARACTERIZATION

We performed room-temperature (RT) characterization to identify a suitable single $\text{Sn-}V^-$ center for integration into the Fabry-Pérot (FP) microcavity. The selection was primarily guided by the emission stability of the center, with particular attention paid to the absence of blinking under higher off-resonant excitation powers (see Fig. 4). Ensuring stable emission is essential for reliable cavity coupling, as blinking would strongly limit the efficiency of photon collection.

The optical properties of the single $\text{Sn-}V^-$ center were characterized at RT, both before and after its transfer into the hemispherical structure of the cavity mirror. As no significant differences are observed between the two measurements, we report only the data obtained after the transfer.

The characterization is performed using a home-built confocal microscope. Figure 5 shows the confocal scan under continuous off-resonant excitation at 532 nm, where the ND appears as a bright spot approximately in the middle of the structure. After identifying the ND, we acquire the PL spectrum, shown in Fig. 6(a). The ZPL is clearly visible and is well fitted by a Lorentzian function, yielding

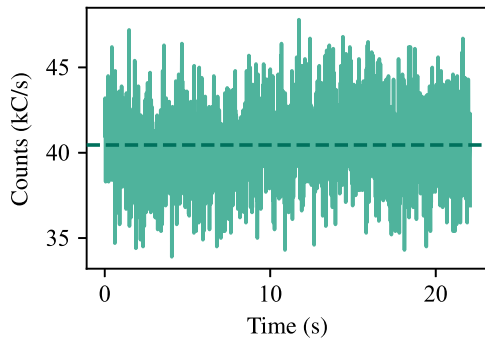


FIG. 4. Count trace of the integrated single $\text{Sn-}V^-$ center under 2-mW excitation power. The dashed dark green line shows the average number of recorded counts.

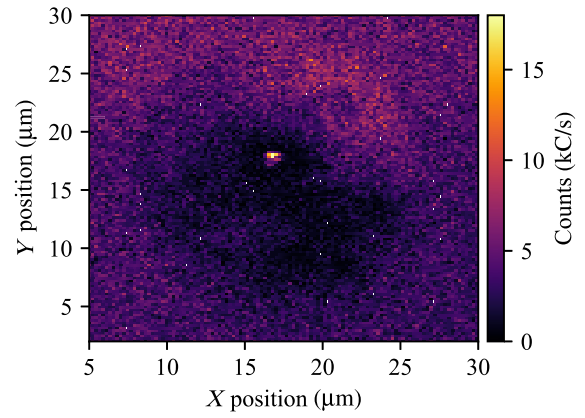


FIG. 5. Confocal microscope scan of the nanodiamond inside the hemispherical structure.

a center wavelength of (620.1 ± 0.1) nm and an FWHM of 6 nm. The measured ZPL position is in good agreement with the typical ZPL position reported for $\text{Sn-}V^-$ centers in bulk diamond [15,16,75]. Additionally, a weaker peak is observed at 660 nm, which is attributed to the phonon sideband, consistent with previous reports [16]. From the ratio of the integrated intensities of the ZPL and the phonon sideband, we estimate a Debye-Waller factor of approximately 56%, in agreement with previously reported values [16,45].

The quantum nature of the emitter is confirmed with Hanbury Brown-Twiss measurements. To account for the prominent antibunching observed in the inset of Fig. 6(a), the data points are fitted with a three-level model equation:

$$g^2(t) = 1 + c \times (\beta \times e^{-\gamma_1|t-t_0|} + (\beta - 1) \times e^{-\gamma_2|t-t_0|}), \quad (\text{A1})$$

where γ_1 and γ_2 are the decay rates of the excited state and shelving state, respectively. The other parameters are: t_0 , the temporal offset; c , which determines how pronounced the antibunching is; and β , which weights the two exponential factors. The observation of antibunching with a minimum value of $g^2(0) = 0.25 \pm 0.04$, without any background correction, demonstrates the quantum nature and single-photon purity of the $\text{Sn-}V^-$ center.

We further investigate the saturation behavior of the emitter [Fig. 6(b)]. Each data point corresponds to the time-averaged count rate over 30 s. The resulting value of saturation power (P_{sat}) and saturation intensity (I_{sat}) are $P_{\text{sat}} = (1.20 \pm 0.08)$ mW and $I_{\text{sat}} = (185 \pm 6)$ kC/s. The estimated saturation values are comparable with the values reported for $\text{Sn-}V^-$ centers in bulk diamond [16,18].

To estimate the spontaneous decay rate in free space at RT, we measure power-dependent second-order autocorrelation functions. The decay rate (γ_1) varies linearly with the excitation power [63,76], so the extracted values are fitted with the model $\gamma_1 = m \times P + 1/\tau$ [Fig. 6(c)].

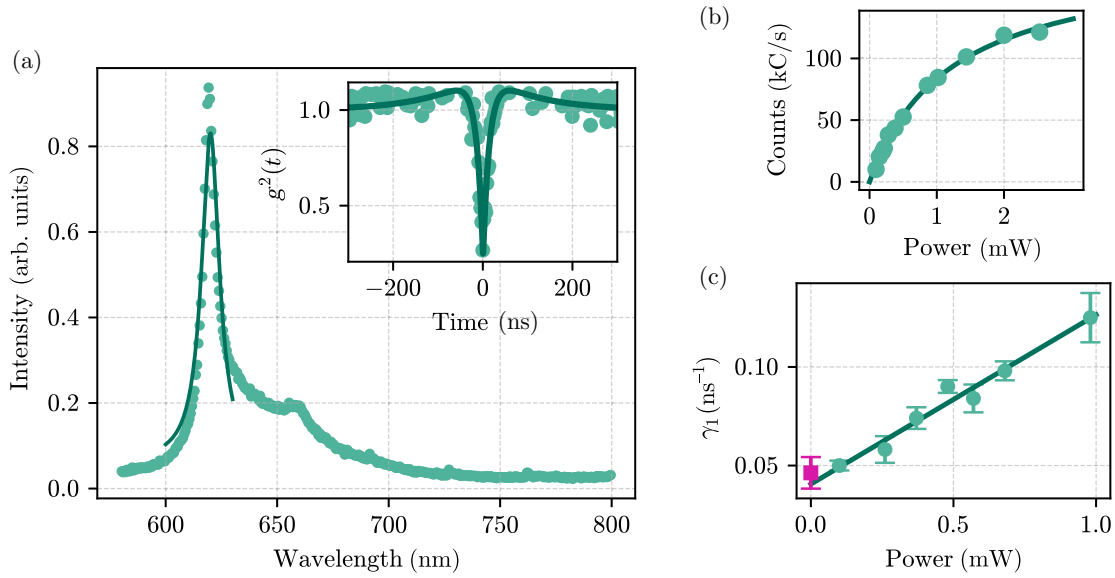


FIG. 6. Room-temperature characterization of the Sn- V^- center inside the hemispherical structure. (a) Off-resonant PL spectrum; the Lorentzian fit (solid line) results in a ZPL of (619.7 ± 0.2) nm and a FWHM of 6 nm. Inset: second-order autocorrelation function proving the quantum nature of the emitter, $g^2(0) = 0.25 \pm 0.04$. (b) Saturation curve; the data points are the average of the time trace recorded over 30 s. The theoretical fit leads to $I_{\text{sat}} = (185 \pm 6)$ kC/s and $P_{\text{sat}} = (1.20 \pm 0.08)$ mW. (c) Decay rate (γ_1), extracted from fitting the power-dependent $g^2(t)$ curves, as a function of the excitation power. The solid line represents the linear fit, leading to a lifetime of (24 ± 2) ns. The pink square is the lifetime estimated with the pulse measurements $\tau_{\text{pulsed}} = (21.7 \pm 0.3)$ ns.

From the fit, we determine a lifetime of $\tau_0 = (24 \pm 2)$ ns at zero excitation power. Since the shelving state decay rate (γ_2) varies linearly with the excitation power [63], we performed a linear fit, yielding a nonradiative decay lifetime of $\tau_2 = (250 \pm 40)$ ns at zero excitation power. To better understand this additional decay channel, we estimated its lifetime at 100 and 30 K. The resulting values are reported in Table III. Similar to what has been observed in bulk diamond, the lifetime of the nonradiative channel decreases with temperature [77]. Our measured values fall within the range measured for the Sn- V^- center in bulk diamond ($40 < \tau_2 < 220$) ns [18,36,45], suggesting that no additional ND-specific nonradiative decay channels are evident.

To validate the lifetime result, we perform pulsed lifetime measurements by exciting the Sn- V^- center with a pulsed 532-nm laser and recording the time delay between the excitation pulse and the detected fluorescence photon. The resulting exponential decay is fitted with a

single exponential function. The resulting lifetime value is $\tau_{\text{pulsed}} = (21.7 \pm 0.3)$ ns (pink square).

The predicted and previously observed lifetimes for Sn- V^- centers in bulk diamond range from 5 to 7 ns [16,18,19,78]. Recent studies on single Sn- V^- centers in NDs reveal a broader range of measured lifetime values ($4 < \tau_0 < 16$ ns) [46,47].

Several factors can influence the radiative decay rate, including the LDOS [52,53,55], damage induced during sample preparation [45], the presence of nonradiative decay channels [79], and the emitter's position relative to the surface [54].

The LDOS is sensitive to both the emitter's distance from the diamond surface and the ND size. Specifically, a higher LDOS provides more available photonic states for the color center to transition into, resulting in a shorter lifetime. Conversely, a lower LDOS can extend the lifetime [52,55]. This behavior has been observed for N- V^- centers, where a correlation between ND size and emitter lifetime was reported [53]. Similarly, for G4V centers in bulk diamond, emitters implanted at depths less than 20 nm exhibit shorter lifetimes [54]. Additionally, lattice damage induced during annealing or implantation processes can significantly affect the spontaneous emission lifetime [45].

In our case, it is plausible that the implantation process, particularly given the large size of the Sn atom, introduced substantial lattice damage that was not fully recovered by thermal annealing [45]. A second contributing factor

TABLE III. Nonradiative lifetime values estimated at zero excitation power.

Temperature (K)	τ_2 (ns)
30	135 ± 13
100	210 ± 20
297	250 ± 40

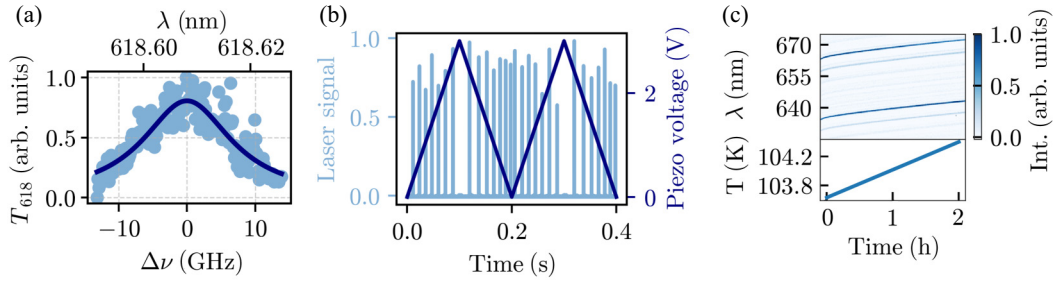


FIG. 7. Cavity characterization at 618.7 nm. (a) Transmitted laser scan over a cavity resonance. The Lorentzian fit yields a cavity-field decay rate of $\kappa = (15 \pm 1)$ GHz. (b) Voltage ramp over 100 ms (blue lines) while the transmitted laser signal is recorded with a photodiode. The resulting average finesse value is $F_{\text{exp},618} = 4600 \pm 500$. (c) Upper panel: 7200 transmitted WLED spectra acquired over 2 h. Lower panel: recorded temperature (K) during the spectra acquisition.

could be the deeper position of the $\text{Sn-}V^-$ center, consistent with the absence of blinking under off-resonant excitation. While the precise origin of this unusually long total lifetime remains uncertain due to unknown defect depth and lattice conditions, we attribute the effect to a combination of these factors.

APPENDIX B: CHARACTERIZATION OF THE EXPERIMENTAL PLATFORM

Figure 7(a) shows a cavity transmission measurement performed to determine the cavity-field decay rate. A resonant laser at 618.61 nm is scanned twice over the cavity resonance, while the transmitted laser is detected with an SPC. A Lorentzian fit to the transmission peak yields a cavity-field decay rate of (15 ± 1) GHz.

The finesse is determined by the cavity-scan length [Fig. 7(b)], where a voltage is applied to the z piezo while recording the transmitted laser intensity with a photodiode. The piezo voltage is swept from 0 to 3 V and back (dark blue trace), allowing multiple forward and backward piezo ramps to be analyzed to estimate an average finesse. Each resonance (light blue lines) is fitted with a Lorentzian. From the ratio of the FSR to the FWHM, we extract an average finesse of $F_{\text{exp},618} = 4600 \pm 500$ at 618.7 nm.

Figure 7(c) displays the transmission spectra of a WLED, recorded over a total duration of 2 h, showing individual spectra. To estimate the effective change in cavity length, ΔL_{eff} , we track the shift in wavelength position of the fundamental cavity mode over time. Specifically, the shift in resonance wavelength between the spectra acquired at $t = 0$ and $t = 2$ h is used to quantify the cavity length variation, $\Delta L_{\text{eff}} = (\lambda_{\text{res},2\text{h}} - \lambda_{\text{res},0})/2$. The corresponding values of ΔL_{eff} are presented in Fig. 1(d) of the main text.

APPENDIX C: CAVITY MODE DISPERSION

We further characterize the cavity mode dispersion to investigate the influence of the ND on the cavity field. Using a WLED, we record the wavelength-dependent cavity resonances as a function of the cavity length. The

transmitted light is collected through the transmission fiber and recorded with a spectrometer. A total of 300 consecutive spectra are acquired while scanning the cavity length from 5.0 to 3.7 μm . The data reveal the presence of the fundamental mode along with higher-order modes, as shown in Fig. 8. The dashed lines show the simulated data obtained with the model for an empty cavity, including the Gouy phase (1).

For the simulation, an ROC of 24 μm has been used, and the longitudinal mode index m varies from 11 to 17. The overlap of the simulated resonances and experimental data demonstrates that introducing the ND in the hemispherical structure does not alter the mode profile.

APPENDIX D: PL SPECTRUM PROBING AT 100 K

PL spectral probing at 100 K is performed by tuning both the wavelength of the excitation laser and the cavity length to enable detection of ZPL emission through $m_{\text{det}} = 12$ and green excitation through $m_{\text{exc}} = 14$.

In Fig. 9 (lower panel), we report all the recorded spectra as a function of the excitation wavelength. The

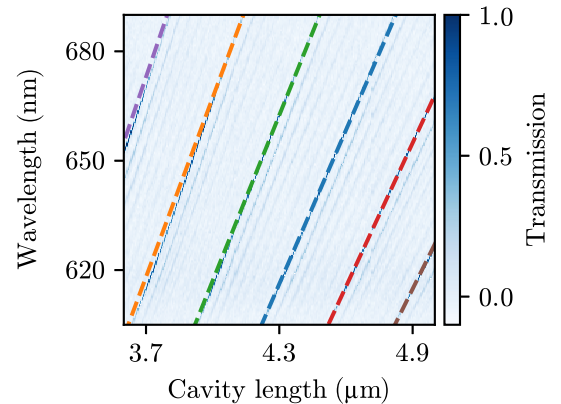


FIG. 8. Cavity transmission spectra with the integrated ND probed by a WLED showing the wavelength-dependent position of the cavity resonances at different cavity lengths. Dashed lines are the simulated cavity resonances.

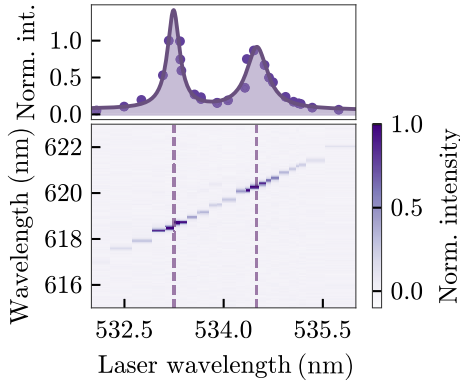


FIG. 9. PL spectrum probing at 100 K. Upper panel: averaged counts from all the spectra. Lower panel: cavity-modulated PL spectra at 100 K as a function of the excitation-laser wavelength. The dashed lines represent the laser wavelength used in the main paper to be on resonance with optical transitions C and D: (533.25 ± 0.03) or (534.50 ± 0.03) nm, respectively.

dashed vertical lines mark the positions of the excitation laser obtained from the Lorentzian fit (533.25 ± 0.03) and (534.50 ± 0.03) nm for transitions C and D, respectively. The laser wavelength obtained for the C transition is used in the main text for measurements resonant with the emitter, without detuning.

APPENDIX E: BAD-EMITTER REGIME

The total spontaneous decay rate (γ) of an emitter can be expressed as the sum of the emitter's natural linewidth (γ_0), determined by its radiative lifetime, and the pure dephasing rate (γ^*) arising from interactions with phonons, $\gamma = \gamma_0 + \gamma^*$. At 100 K, the phonon population in the host lattice is still substantial, leading to significant

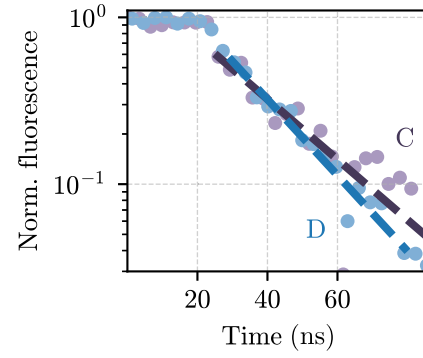


FIG. 11. Pulsed lifetime measurement of transitions C and D coupled to a higher-order cavity mode. The resulting lifetime values from the linear fit are (23 ± 3) ns and (22 ± 2) ns, respectively.

pure dephasing. In this regime, the dephasing rate dominates over the lifetime-limited contribution ($\gamma^* \gg \gamma_0$), and we approximate $\gamma \sim \gamma^*$. Thus, we assume that the spontaneous decay rate is equal to the FWHM of the PL spectrum acquired at 100 K. This corresponds to $\gamma_C^* = (210 \pm 20)$ GHz and $\gamma_D^* = (410 \pm 20)$ GHz.

Due to the broad emitter linewidth ($\gamma \gg \kappa$), only a fraction (κ/γ^*) of the total emission is spectrally resonant with the cavity mode and effectively couples into it [64]. In this regime, the Purcell factor can be approximated as [25]

$$F_{\text{bad-emitter}} \approx \frac{4g^2}{\kappa + \gamma_0} \times \frac{\kappa}{\gamma^*}. \quad (\text{E1})$$

Since in the bad-emitter regime $\gamma^* > g$, we expect $F_{\text{bad-emitter}} < 1$. As a consequence, the cavity would not alter the emitter's lifetime but rather channel the emission into a well-defined cavity mode [25]. With this model,

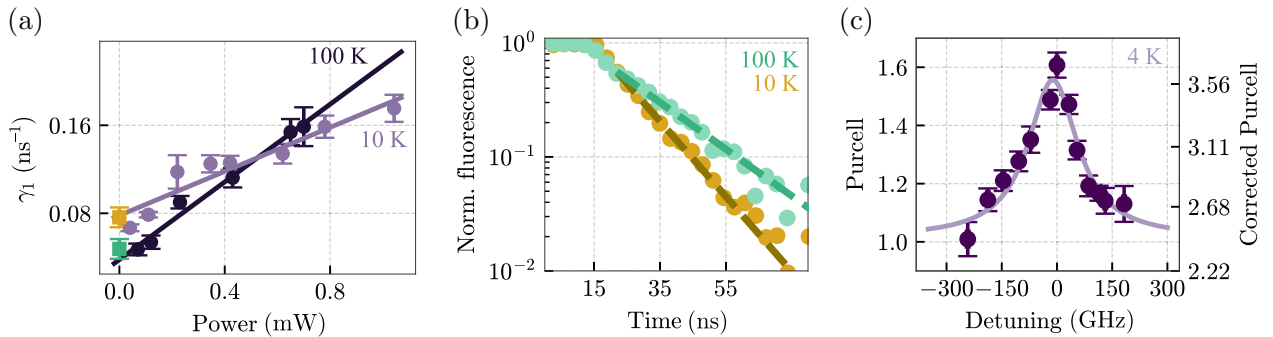


FIG. 10. Cavity-induced enhancement of the spontaneous decay rate of optical transition D across different temperatures. (a) Decay rate (γ_1), extracted from fitting $g^2(t)$ functions measured under varying excitation powers. The solid line represents the linear fit. The estimated lifetime values are (13 ± 1) ns at 30 K and (21 ± 6) ns at 100 K. The green and yellow squares are the lifetime values estimated from the pulse measurements. (b) Logarithmic scale of pulsed lifetime measurements at three different temperatures (4, 40, and 100 K). The dashed lines are the linear fits to extrapolate the lifetime values. The obtained lifetime values are (13.1 ± 0.3) ns at 4 K and (21 ± 2) ns at 100 K. (c) Purcell factor, estimated as the ratio between the free-space and cavity-modulated lifetimes as a function of cavity detuning. The cavity length varies between fully off resonance and on resonance.

TABLE IV. Summary of the main parameters.

Parameter	Condition	Symbol	Value	Units	Origin
Emitter Properties					
ZPL	297 K	ZPL	620.1 ± 0.1	nm	Gaussian fit
Free-space lifetime	297 K	τ_0	21.7 ± 0.3	ns	Pulsed lifetime measure
C transition	100 K	$ZPL_{C,100K}$	618.6 ± 0.1	nm	Spectrum
C transition linewidth	100 K	γ	210 ± 20	GHz	Lorentzian fit
C transition	4 K	$ZPL_{C,4K}$	618.54 ± 0.03	nm	Lorentzian fit
D transition	100 K	$ZPL_{D,100K}$	620.3 ± 0.1	nm	Spectrum
D transition linewidth	100 K	γ_D	410 ± 20	GHz	Lorentzian fit
D transition	4 K	$ZPL_{D,4K}$	620.22 ± 0.03	nm	Spectrum
Mirror					
Radius of curvature x		ROC_x	25	μm	AFM
Radius of curvature y		ROC_y	22	μm	AFM
Transmission	618 nm	T_{618}	650	ppm	Data from Laseroptik
Transmission	533 nm	T_{533}	6400	ppm	Data from Laseroptik
Cavity					
Theoretical finesse	618 nm	$F_{ideal,618}$	4800		Data from Laseroptik
Measured finesse	618 nm	F_{618}	4600 ± 500		Cavity scan
Theoretical finesse	533 nm	$F_{ideal,533}$	400		Data from Laseroptik
Measured finesse	533 nm	F_{533}	400 ± 100		Cavity scan
Theoretical quality factor		Q_{ideal}	56400		F_{618}, m_{det}
Beam waste		ω_0	1.31	μm	ROC, L_{eff}
Mode volume		V_{mode}	21	λ^3	ω_0, L_{eff}
Ideal Purcell		F_{cav}	205		$Q_{ideal}, \omega_0, V_{mode}$
Measured linewidth		κ	15	GHz	Lorentzian fit
Measuring cavity parameters					
Effective cavity length		L_{eff}	3.7	μm	WLED spectrum
Detection mode number		m_{det}	12		WLED spectrum, m
Excitation mode number		m_{exc}	14		WLED spectrum
Purcell enhancement C transition					
Measured quality factor	4 K	Q_{exp}	3100 ± 600		Lorentzian Fit
Vibration-limited Purcell	4 K	F_{vib}	10 ± 2		Q_{exp}
Measured Purcell	4 K	F_p	1.78 ± 0.04		Eq. (2)
Measured Purcell	40 K	$F_{p,40K}$	1.55 ± 0.04		Eq. (2)
Cavity-emitter lifetime	4 K	τ_{4K}	12.2 ± 0.3	ns	Pulsed lifetime measure
Cavity-emitter lifetime	40 K	τ_{40K}	15.8 ± 0.2	ns	Pulsed lifetime measure
Cavity-emitter lifetime	100 K	τ_{100K}	21 ± 1	ns	Pulsed lifetime measure
Purcell enhancement D transition					
Measured quality factor	4 K	Q_{exp-D}	3900 ± 700		Lorentzian Fit
Vibration-limited Purcell	4 K	F_{vib}	12		Q_{exp}
Measured Purcell	4 K	F_p	1.67		Eq. (2)
Cavity-emitter lifetime	4 K	τ_{4K}	13.1 ± 0.3	ns	Pulsed lifetime measure
Cavity-emitter lifetime	100 K	τ_{100K}	21 ± 2	ns	Pulsed lifetime measure

we can explain the observation of no lifetime reduction in either optical transition.

APPENDIX F: PURCELL ENHANCEMENT OF D OPTICAL TRANSITION

For optical transition C, we investigate the interaction between the cavity electric field and the D optical transition. The Purcell enhancement is estimated with Eq. (2). The cavity-modulated lifetime (τ_p) is estimated through power-dependent second-order autocorrelation functions ($g^2(t)$) and pulsed lifetime measurements.

From the linear form of the obtained γ_1 values, lifetime values of (13 ± 1) and (21 ± 6) ns are observed at temperatures of approximately 10 and 100 K, respectively [Fig. 10(a)]. The resulting lifetime values from pulsed lifetime measurements are $\tau_{10K,D} = (13.1 \pm 0.3)$ ns at 10 K and $\tau_{100K,D} = (21 \pm 2)$ ns at 100 K [Fig. 10(b)]. The measured pulsed lifetime [yellow and green squares in Fig. 10(a)] intersects with the linear extrapolation of the power-dependent values at zero excitation power, confirming the reliability of the extracted lifetimes.

At 100 K, no lifetime reduction is observed, consistent with the operation of the cavity in the bad-emitter regime.

In contrast, at approximately 10 K, we measure a lifetime reduction leading to a Purcell factor of $F_P = 1.67$. Further deviations from the ideal Purcell enhancement arise from nonunity quantum efficiency (approximately 80% [16]) and a limited Debye-Waller factor (around 56%). Each of these factors reduces the fraction of emission coupled into the D optical transition. Accounting for all these effects, we estimate a corrected Purcell enhancement of $F_{P,ZPL} = 3.72$. By detuning the cavity resonance from the Sn- V^- center frequency and performing pulsed lifetime measurements [Fig. 10(c)], we measure a cavity-field decay rate of $\kappa_D = (120 \pm 30)$ GHz, resulting in a quality factor of $Q_{\text{exp-D}} = (3900 \pm 700)$. This value agrees with $Q_{\text{exp-C}}$ (Table IV) reported in the main text, confirming both the results and the degradation of the cavity due to vibrations. Taking into account the cavity $Q_{\text{exp-D}}$ and the position of the nanodiamond within the hemispherical cavity structure, we estimate a maximum achievable Purcell factor (F_{vib}), under experimental conditions, of 12. From the ratio between F_P and F_{vib} , we estimate an alignment of the D transition with the electric field of the cavity mode of 31% [Eq. (3)]. This includes both the dipole misalignment and the reduction in effective coupling strength due to the branching ratio.

APPENDIX G: COUPLING TO HIGHER-ORDER MODE

As shown in Fig. 2(b), the Sn- V^- center, for a cavity length of 3.4 μm , couples to a higher-order cavity mode.

To investigate whether this coupling leads to a Purcell enhancement of the spontaneous emission rate for optical transition C (or D), the OPO laser wavelength is fixed to excite transition C (D) through the cavity mode $m_{\text{exc}} = 13$ and detect ZPL counts through this higher-order mode. Achieving this double-resonance condition requires setting the effective cavity length to $L_{\text{eff}} = 3.4 \mu\text{m}$. As in Sec. IV, the OPO is pulsed off with an EOM while recording the fluorescence decay rate. During the acquisition time, the cavity is kept in resonance with the emitter frequency by actively adjusting the cavity length to compensate for temperature-induced drifts during the measurement. The resulting histogram is fitted with a single exponential function, yielding lifetime values of (23 ± 3) ns for optical transition C and (22 ± 2) ns for optical transition D (Fig. 11). The larger uncertainties arise from the lower number of detected photons due to reduced coupling efficiency to the higher-order mode. Comparing these lifetimes with the free-space lifetimes reported in Appendix A shows no measurable reduction, indicating the absence of significant Purcell enhancement in this configuration. Although the emitter is coupled to a higher-order cavity mode at a shorter cavity length, the coupling strength remains too weak to substantially modify the spontaneous

emission rate. As a result, the cavity does not noticeably affect the emitter lifetime under these conditions.

-
- [1] H. J. Kimble, The quantum internet, *Nature* **453**, 1023 (2008).
 - [2] H. David, I. V. Inlek, V. Grahame, C. Clayton, D. Shantanu, S. M. Clark, and M. Christopher, Modular entanglement of atomic qubits using photons and phonons, *Nat. Phys.* **11**, 37 (2015).
 - [3] M. Ruf, N. H. Wan, H. Choi, D. Englund, and R. Hanson, Quantum networks based on color centers in diamond, *J. Appl. Phys.* **130**, 070901 (2021).
 - [4] S. Wehner, D. Elkouss, and R. Hanson, Quantum internet: A vision for the road ahead, *Science* **362**, eaam9288 (2018).
 - [5] L. J. Rogers, K. D. Jahnke, M. H. Metsch, A. Sipahigil, J. M. Binder, T. Teraji, H. Sumiya, J. Isoya, M. D. Lukin, and F. Jelezko, All-optical initialization, readout, and coherent preparation of single silicon-vacancy spins in diamond, *Phys. Rev. Lett.* **113**, 263602 (2014).
 - [6] T. Iwasaki, Chapter Eight - Color centers based on heavy group-IV elements, in *Diamond for Quantum Applications Part I, Semiconductors and Semimetals*, edited by C. E. Nebel, I. Aharonovich, N. Mizuochi, and M. Hatano (Elsevier, 2020), Vol. 103, pp. 237–256.
 - [7] I. B. W. Harris and D. Englund, Coherence of group-IV color centers, *Phys. Rev. B* **109**, 085414 (2024).
 - [8] D. Chen, N. Zheludev, and W.-B. Gao, Building blocks for quantum network based on group-IV split-vacancy centers in diamond, *Adv. Quantum Technol.* **3**, 1900069 (2020).
 - [9] I. B. Harris, C. P. Michaels, K. C. Chen, R. A. Parker, M. Titze, J. Arjona Martínez, M. Sutula, I. R. Christen, A. M. Stramma, W. Roth, C. M. Purser, M. H. Appel, C. Li, M. E. Trusheim, N. L. Palmer, M. L. Markham, E. S. Bielejec, M. Atatüre, and D. Englund, Hyperfine spectroscopy of isotopically engineered group-IV color centers in diamond, *PRX Quantum* **4**, 040301 (2023).
 - [10] U. F. S. D’Haenens-Johansson, A. M. Edmonds, B. L. Green, M. E. Newton, and D. J. Twitchen, Optical properties of the neutral silicon split-vacancy center in diamond, *Phys. Rev. B* **84**, 245208 (2011).
 - [11] T. Iwasaki, F. Ishibashi, Y. Miyamoto, Y. Doi, S. Kobayashi, T. Miyazaki, K. Tahara, T. Makino, S. Yamasaki, R. Morimoto, M. Hatano, F. Jelezko, H. Yamaguchi, and N. Mizuochi, Germanium-vacancy single color centers in diamond, *Sci. Rep.* **5**, 12882 (2015).
 - [12] C. Qiu, H.-X. Deng, S. Geng, and S.-H. Wei, Origin of structure and zero-phonon-line anomalies of XV centers in diamond ($x = \text{Si, Ge, Sn, Pb}$), *Phys. Rev. B* **107**, 214110 (2023).
 - [13] L. D. Santis, M. E. Trusheim, K. C. Chen, and D. R. Englund, Investigation of the Stark effect on a centrosymmetric quantum emitter in diamond, *Phys. Rev. Lett.* **127**, 147402 (2021).
 - [14] C. Hepp, T. Müller, V. Waselowski, B. P. J. N. Becker, H. Sternschulte, D. Steinmüller-Nethl, A. Gali, J. R. Maze, M. Atatüre, and C. Becher, Electronic structure of the silicon vacancy color center in diamond, *Phys. Rev. Lett.* **112**, 036405 (2014).

- [15] A. E. Rugar, H. Lu, C. Dory, S. Sun, P. J. McQuade, Z.-X. Shen, N. A. Melosh, and J. Vučković, Generation of tin-vacancy centers in diamond via shallow ion implantation and subsequent diamond overgrowth, *Nano Lett.* **20**, 1614 (2020).
- [16] T. Iwasaki, Y. Miyamoto, T. Taniguchi, P. Siyushev, M. H. Metsch, F. Jelezko, and M. Hatano, Tin-vacancy quantum emitters in diamond, *Phys. Rev. Lett.* **119**, 253601 (2017).
- [17] A. E. Rugar, C. Dory, S. Sun, and J. Vučković, Characterization of optical and spin properties of single tin-vacancy centers in diamond nanopillars, *Phys. Rev. B* **99**, 205417 (2019).
- [18] S. D. Tchernij, T. Herzig, J. Forneris, J. Küpper, S. Pezzagna, P. Traina, E. Moreva, I. P. Degiovanni, G. Brida, N. Skukan, M. Genovese, M. Jakšić, J. Meijer, and P. Olivero, Single-photon-emitting optical centers in diamond fabricated upon Sn implantation, *ACS Photonics* **4**, 2580 (2017).
- [19] G. M. H. Thiering and A. Gali, Ab initio magneto-optical spectrum of group-IV vacancy color centers in diamond, *Phys. Rev. X* **8**, 021063 (2018).
- [20] K. N. Tolazzi, B. Wang, C. Ianzano, J. Neumeier, C. J. Villas-Boas, and G. Rempe, Continuous quantum light from a dark atom, *Commun. Phys.* **4**, 57 (2021).
- [21] D. Press, S. Götzinger, S. Reitzenstein, C. Hofmann, A. Löffler, M. Kamp, A. Forchel, and Y. Yamamoto, Photon antibunching from a single quantum-dot-microcavity system in the strong coupling regime, *Phys. Rev. Lett.* **98**, 117402 (2007).
- [22] K. Hennessy, A. Badolato, M. Winger, D. Gerace, M. Atatüre, S. Gulde, S. Fält, E. L. Hu, and A. Imamoglu, Quantum nature of a strongly coupled single quantum dot-cavity system, *Nature* **445**, 896 (2007).
- [23] M. Fox, in *Oxford Master Series in Condensed Matter Physics No. 3*, 2nd ed. (Oxford University Press Inc., New York, 2012).
- [24] C. Saavedra, D. Pandey, W. Alt, H. Pfeifer, and D. Meschede, Tunable fiber Fabry-Perot cavities with high passive stability, *Opt. Express* **29**, 974 (2021).
- [25] R. Albrecht, A. Bommer, C. Deutsch, J. Reichel, and C. Becher, Coupling of a single nitrogen-vacancy center in diamond to a fiber-based microcavity, *Phys. Rev. Lett.* **110**, 243602 (2013).
- [26] C. Sames, H. Chibani, C. Hamsen, P. A. Altin, T. Wilk, and G. Rempe, Antiresonance phase shift in strongly coupled cavity QED, *Phys. Rev. Lett.* **112**, 043601 (2014).
- [27] D. Riedel, I. Söllner, B. J. Shields, S. Starosielec, P. Appel, E. Neu, R. J. Warburton, and P. Maletinsky, Deterministic enhancement of coherent photon generation from a nitrogen-vacancy center in ultrapure diamond, *Phys. Rev. X* **7**, 031040 (2017).
- [28] S. Johnson, P. R. Dolan, T. Grange, A. A. P. Trichet, G. Hornecker, Y. C. Chen, L. Weng, G. M. Hughes, A. A. R. Watt, A. Auffèves, and J. M. Smith, Tunable cavity coupling of the zero phonon line of a nitrogen-vacancy defect in diamond, *New J. Phys.* **17**, 122003 (2015).
- [29] R. Høy Jensen, E. Janitz, Y. Fontana, Y. He, O. Gobron, I. P. Radko, M. Bhaskar, R. Evans, C. D. Rodríguez Rosenblueth, L. Childress, A. Huck, and U. Lund Andersen, Cavity-enhanced photon emission from a single germanium-vacancy center in a diamond membrane, *Phys. Rev. Appl.* **13**, 064016 (2020).
- [30] M. Ruf, M. Weaver, S. van Dam, and R. Hanson, Resonant excitation and Purcell enhancement of coherent nitrogen-vacancy centers coupled to a Fabry-Perot microcavity, *Phys. Rev. Appl.* **15**, 024049 (2021).
- [31] V. Yurgens, Y. Fontana, A. Corazza, B. J. Shields, P. Maletinsky, and R. J. Warburton, Cavity-assisted resonance fluorescence from a nitrogen-vacancy center in diamond, *npj Quantum Inf.* **10**, 112 (2024).
- [32] J. Benedikter, H. Kaupp, T. Hümmer, Y. Liang, A. Bommer, C. Becher, A. Krueger, J. M. Smith, T. W. Hänsch, and D. Hunger, Cavity-enhanced single-photon source based on the silicon-vacancy center in diamond, *Phys. Rev. Appl.* **7**, 024031 (2017).
- [33] D. Hunger, T. Steinmetz, Y. Colombe, C. Deutsch, T. W. Hänsch, and J. Reiche, A fiber Fabry-Perot cavity with high finesse, *New J. Phys.* **12**, 065038 (2010).
- [34] R. Zifkin, C. D. Rodríguez Rosenblueth, E. Janitz, Y. Fontana, and L. Childress, Lifetime reduction of single germanium-vacancy centers in diamond via a tunable open microcavity, *PRX Quantum* **5**, 030308 (2024).
- [35] Y. Herrmann, J. Fischer, J. M. Brevoord, C. Sauerzapf, L. G. Wienhoven, L. J. Feije, M. Pasini, M. Eschen, M. Ruf, M. J. Weaver, and R. Hanson, Coherent coupling of a diamond tin-vacancy center to a tunable open microcavity, *Phys. Rev. X* **14**, 041013 (2024).
- [36] A. E. Rugar, S. Aghaeimeibodi, D. Riedel, C. Dory, H. Lu, P. J. McQuade, Z.-X. Shen, N. A. Melosh, and J. Vučković, Quantum photonic interface for tin-vacancy centers in diamond, *Phys. Rev. X* **11**, 031021 (2021).
- [37] R. Berghaus, S. Sachero, G. Bayer, J. Heupel, T. Herzig, F. Feuchtmayr, J. Meijer, C. Popov, and A. Kubanek, Cavity-enhanced emission and absorption of color centers in a diamond membrane with selectable strain, *Phys. Rev. Appl.* **23**, 034050 (2025).
- [38] L. Antoniuk, N. Lettner, A. P. Ovvyan, S. Haugg, M. Klotz, H. Gehring, D. Wendland, V. N. Agafonov, W. H. Pernice, and A. Kubanek, All-optical spin access via a cavity-broadened optical transition in on-chip hybrid quantum photonics, *Phys. Rev. Appl.* **21**, 054032 (2024).
- [39] K. G. Fehler, L. Antoniuk, N. Lettner, A. P. Ovvyan, R. Waltrich, N. Gruhler, V. A. Davydov, V. N. Agafonov, W. H. P. Pernice, and A. Kubanek, Hybrid quantum photonics based on artificial atoms placed inside one hole of a photonic crystal cavity, *ACS Photonics* **8**, 2635 (2021).
- [40] A. D. Greentree, Nanodiamonds in Fabry-Perot cavities: A route to scalable quantum computing, *New J. Phys.* **18**, 021002 (2016).
- [41] P. Diamonds, MSY Diamond Micrograins Datasheet (2023), https://pureon.com/wp-content/uploads/2023/08/MSY_datasheet_en_2023-08-06.pdf.
- [42] E. Corte, A. Bortone, E. N. Hernández, C. Ceresa, G. Provatas, K. I. Nizić, M. Jaksic, E. Vittone, and S. D. Tchernij, The development of IBIC microscopy at the 100 kV ion implanter of the University of Torino (LIUTo) and the application for the assessment of the radiation hardness of a silicon photodiode, *Eur. Phys. J. Plus* **140**, 609 (2025).

- [43] S. Sachero, R. Waltrich, E. Corte, J. Fuhrmann, S. D. Tchernij, F. Jelezko, and A. Kubanek, Creation of negatively charged GeV and SnV centers in nanodiamonds via ion implantation, *Carbon* **247**, 121054 (2026).
- [44] F. Feuchtmayr, R. Berghaus, S. Sachero, G. Bayer, N. Lettner, R. Waltrich, P. Maier, V. Agafonov, and A. Kubanek, Enhanced spectral density of a single germanium vacancy center in a nanodiamond by cavity-integration, *Appl. Phys. Lett.* **123**, 024001 (2023).
- [45] J. Görlitz, D. Herrmann, G. Thiering, P. Fuchs, M. Gandil, T. Iwasaki, T. Taniguchi, M. Kieschnick, J. Meijer, A. G. Mutsuko Hatano, and C. Becher, Spectroscopic investigations of negatively charged tin-vacancy centres in diamond, *New J. Phys.* **22**, 013048 (2020).
- [46] M. Fujiwara, M. Otori, F. T. K. So, Y. Makino, N. Morioka, I. Ohki, R. Igarashi, M. Nishikawa, and N. Mizuochi, Single tin-vacancy center in nanoscale diamond, *Discover Nano* **20**, 81 (2025).
- [47] H. Takashima, K. Shimazaki, H. Abe, T. Ohshima, and S. Takeuchi, Creation of single tin-vacancy color centers in small nanodiamonds, *ACS Photonics* **12**, 4950 (2025).
- [48] J. Stortebom, P. Dolan, S. Castelletto, X. Li, and M. Gu, Lifetime investigation of single nitrogen vacancy centres in nanodiamonds, *Opt. Express* **23**, 11327 (2015).
- [49] E. Neu, D. Steinmetz, J. Riedrich-Möller, S. Gsell, M. Fischer, M. Schreck, and C. Becher, Single photon emission from silicon-vacancy colour centres in chemical vapour deposition nano-diamonds on iridium, *New J. Phys.* **13**, 025012 (2011).
- [50] S. Lindner, A. Bommer, A. Muzha, A. Krueger, L. Gines, S. Mandal, O. Williams, E. Londero, A. Gali, and C. Becher, Strongly inhomogeneous distribution of spectral properties of silicon-vacancy color centers in nanodiamonds, *New J. Phys.* **20**, 115002 (2018).
- [51] A. Mohtashami and A. Femius Koenderink, Suitability of nanodiamond nitrogen-vacancy centers for spontaneous emission control experiments, *New J. Phys.* **15**, 043017 (2013).
- [52] M. Klotz, K. G. Fehler, R. Waltrich, E. S. Steiger, S. Häußler, P. Reddy, L. F. Kulikova, V. A. Davydov, V. N. Agafonov, M. W. Doherty, and A. Kubanek, Prolonged orbital relaxation by locally modified phonon density of states for the SiV^- center in nanodiamonds, *Phys. Rev. Lett.* **128**, 153602 (2022).
- [53] F. A. Inam, A. M. Edmonds, M. J. Steel, and S. Castelletto, Tracking emission rate dynamics of nitrogen vacancy centers in nanodiamonds, *Appl. Phys. Lett.* **102**, 253109 (2013).
- [54] X. Cheng, A. Thurn, G. Chen, G. S. Jones, M. Coke, M. Adshead, C. P. Michaels, O. Balci, A. C. Ferrari, M. Atatüre, R. Curry, J. M. Smith, P. S. Salter, and D. A. Gangloff, Laser activation of single group-IV colour centres in diamond, *Nat. Commun.* **16**, 5124 (2025).
- [55] M. Zahedian, J. Liu, R. Vidrio, S. Kolkowitz, and J. T. Choy, Modeling of radiative emission from shallow color centers in single crystalline diamond, *Laser Photon. Rev.* **17**, 2200529 (2023).
- [56] H. K. King and A. W. Lawson, Crystal structure and lattice constants of diamond, *J. Res. Natl. Bur. Stand.* (1934) **30**, 101 (1938).
- [57] M. Klotz, A. Tangemann, and A. Kubanek, Ultra-high strained diamond spin register with coherent optical control, *npj Quantum Inf.* **11**, 91 (2025).
- [58] J. M. Brevoord, L. G. C. Wienhoven, N. Codreanu, T. Ishiguro, E. van Leeuwen, M. Iuliano, L. De Santis, C. Waas, H. K. C. Beukers, T. Turan, C. Errando-Herranz, K. Kawaguchi, and R. Hanson, Large-range tuning and stabilization of the optical transition of diamond tin-vacancy centers by in situ strain control, *Appl. Phys. Lett.* **126**, 174001 (2025). special Collection: Quantum Networks.
- [59] E. I. Rosenthal, C. P. Anderson, H. C. Kleidermacher, A. J. Stein, H. Lee, J. Grzesik, G. Scuri, A. E. Rugar, D. Riedel, S. Aghaeimeibodi, G. H. Ahn, K. Van Gasse, and J. Vučković, Microwave spin control of a tin-vacancy qubit in diamond, *Phys. Rev. X* **13**, 031022 (2023).
- [60] D. A. Steck, *Quantum and Atom Optics* (Daniel Adam Steck, Eugene, Oregon, 2019).
- [61] N. G. Basov, A. N. Oraevskii, and G. M. Khodovoi, Saturation of the absorption of radiation by a two-level system, *Sov. Phys. JETP* **17**, 828 (1963). originally published in *ZhETF*, Vol. 44, p. 1233 (1963).
- [62] E. Janitz, M. K. Bhaskar, and L. Childress, Cavity quantum electrodynamics with color centers in diamond, *Optica* **7**, 1232 (2020).
- [63] M. Berthel, O. Mollet, G. Dantelle, T. Gacoin, S. Huant, and A. Drezet, Photophysics of single nitrogen-vacancy centers in diamond nanocrystals, *Phys. Rev. B* **91**, 035308 (2015).
- [64] H. Kaupp, C. Deutsch, H.-C. Chang, J. Reichel, T. W. Hänsch, and D. Hunger, Scaling laws of the cavity enhancement for nitrogen-vacancy centers in diamond, *Phys. Rev. A* **88**, 053812 (2013).
- [65] T. Grange, G. Hornecker, D. Hunger, J.-P. Poizat, J.-M. Gérard, P. Senellart, and A. Auffèves, Cavity-funnelled generation of indistinguishable single photons from strongly dissipative quantum emitters, *Phys. Rev. Lett.* **114**, 193601 (2015).
- [66] S. Häußler, G. Bayer, R. Waltrich, N. Mendelson, C. Li, D. Hunger, I. Aharonovich, and A. Kubanek, Tunable fiber-cavity enhanced photon emission from defect centers in hBN, *Adv. Opt. Mater.* **9**, 2002218 (2021).
- [67] D. Englund, D. Fattal, E. Waks, G. Solomon, B. Zhang, T. Nakaoka, Y. Arakawa, Y. Yamamoto, and J. Vučković, Controlling the spontaneous emission rate of single quantum dots in a two-dimensional photonic crystal, *Phys. Rev. Lett.* **95**, 013904 (2005).
- [68] K. C. Chen, I. Christen, H. Raniwala, M. Colangelo, L. D. Santis, K. Shtyrkova, D. Starling, R. Murphy, L. Li, K. Berggren, P. B. Dixon, M. Trusheim, and D. Englund, A scalable cavity-based spin-photon interface in a photonic integrated circuit, *Opt. Quantum* **2**, 124 (2024).
- [69] G. Bayer, R. Berghaus, S. Sachero, A. B. Filipovski, L. Antoniuk, N. Lettner, R. Waltrich, M. Klotz, P. Maier, V. Agafonov, and A. Kubanek, Optical driving, spin initialization and readout of single SiV^- centers in a Fabry-Pérot resonator, *Commun. Phys.* **6**, 300 (2023).
- [70] M. Ruf, M. J. Weaver, S. B. v. Dam, and R. Hanson, Resonant excitation and Purcell enhancement of coherent nitrogen-vacancy centers coupled to a Fabry-Pérot microcavity, *Phys. Rev. Appl.* **15**, 024049 (2021).

- [71] J. Görlitz, D. Herrmann, P. Fuchs, T. Iwasaki, T. Taniguchi, D. Rogalla, D. Hardeman, P.-O. Colard, M. Markham, M. Hatano, and C. Becher, Coherence of a charge stabilised tin-vacancy spin in diamond, *npj Quantum Inf.* **8**, 45 (2022).
- [72] L. Li, T. Schröder, E. H. Chen, M. Walsh, I. Bayn, J. Goldstein, O. Gaathon, M. E. Trusheim, M. Lu, J. Mower, M. Cotlet, M. Markham, D. J. Twitchen, and D. Englund, Coherent spin control of a nanocavity-enhanced qubit in diamond, *Nat. Commun.* **6**, 6173 (2015).
- [73] N. Lettner, L. Antoniuk, A. P. Ovvyan, H. Gehring, D. Wendland, V. N. Agafonov, W. H. P. Pernice, and A. Kubanek, Controlling all degrees of freedom of the optical coupling in hybrid quantum photonics, *ACS Photonics* **11**, 696 (2024).
- [74] M. Pallmann, T. Eichhorn, J. Benedikter, B. Casabone, T. Hümmer, and D. Hunger, A highly stable and fully tunable open microcavity platform at cryogenic temperatures, *APL Photonics* **8**, 046107 (2023).
- [75] R. Debroux, C. P. Michaels, C. M. Purser, N. Wan, M. E. Trusheim, J. Arjona Martínez, R. A. Parker, A. M. Stramma, K. C. Chen, L. de Santis, E. M. Alexeev, A. C. Ferrari, D. Englund, D. A. Gangloff, and M. Atatüre, Quantum control of the tin-vacancy spin qubit in diamond, *Phys. Rev. X* **11**, 041041 (2021).
- [76] A. Khalid, K. Chung, R. Rajasekharan, D. W. Lau, T. J. Karle, B. C. Gibson, and S. Tomljenovic-Hanic, Lifetime reduction and enhanced emission of single photon color centers in nanodiamond via surrounding refractive index modification, *Sci. Rep.* **5**, 11179 (2015).
- [77] F. Trojánek, K. Hamráček, M. Hanák, M. Varga, A. Kromka, O. Babčenko, L. Ondič, and P. Malý, Light emission dynamics of silicon vacancy centers in a polycrystalline diamond thin film, *Nanoscale* **15**, 2734 (2023).
- [78] M. E. Trusheim, B. Pingault, N. H. Wan, M. Gündoğan, L. De Santis, R. Debroux, D. Gangloff, C. Purser, K. C. Chen, M. Walsh, J. J. Rose, J. N. Becker, B. Lienhard, E. Bersin, I. Paradeisanos, G. Wang, D. Lyzwa, A. R.-P. Montblanch, G. Malladi, H. Bakhru, A. C. Ferrari, I. A. Walmsley, M. Atatüre, and D. Englund, Transform-limited photons from a coherent tin-vacancy spin in diamond, *Phys. Rev. Lett.* **124**, 023602 (2020).
- [79] I. Y. Eremchev, A. O. Tarasevich, M. A. Kniazeva, J. Li, A. V. Naumov, and I. G. Scheblykin, Detection of single charge trapping defects in semiconductor particles by evaluating photon antibunching in delayed photoluminescence, *Nano Lett.* **23**, 2087 (2023).