

Spectrally reconfigurable tin-vacancy centers for remote two-photon interference

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Scalable quantum networks rely on optical links between long-lived qubits to distribute entanglement. Tin-vacancy (SnV^-) centers in diamond combine long spin coherence at liquid-helium temperatures with highly coherent, spin-dependent optical transitions, making them promising network qubits. Connecting independent centers, however, requires indistinguishable photons: solid-state inhomogeneity creates frequency mismatch, while inversion symmetry suppresses the first-order electrical response. Here, we establish optical connectivity between two remote SnV^- centers in separate cryogenic nodes. Using local electrodes, we tune the optical transition by up to 4 GHz via the Stark effect while maintaining optical coherence. Bringing the two transitions into resonance yields remote Hong-Ou-Mandel interference with a measured zero-delay visibility of 80(6)% without postprocessing. The same electrodes provide dynamic spectral control, producing resolved Floquet sidebands at drive frequencies up to 1.5 GHz. These results establish a locally reconfigurable optical interface for connecting remote SnV^- quantum-network nodes.

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I. INTRODUCTION

Remote quantum networks require two-photon interference between independently created emitters. Color centers in diamond are attractive building blocks for this task because they combine optically addressable spins with compatibility with nanophotonic devices and scalable network architectures [1–4]. Among them, group-IV vacancy centers are particularly appealing because they combine strong zero-phonon-line emission with inversion-symmetric optical transitions, suppressing first-order sensitivity to electric-field fluctuations [5,6].

SiV^- centers established photon indistinguishability, remote interference, and memory-mediated entanglement [4,7–11]. However, SiV^- spin coherence requires either sub-Kelvin operation or substantial strain engineering [12–14]. Heavier group-IV centers, namely GeV^- , SnV^- , and PbV^- , exhibit larger spin-orbit splittings than SiV^- , which suppress phonon-mediated relaxation while preserving the optical stability associated with inversion symmetry

[15–19]. As a result, SnV^- centers have already shown second-scale spin relaxation, millisecond coherence under dynamical decoupling, and emerging photonic integration [20–23]. For independently fabricated network nodes, however, improved spin coherence must be combined with deterministic frequency control. In previous remote interference and entanglement experiments with SiV^- centers, spectral overlap was obtained by selecting naturally matched emitters, by electro-optic modulation of the emitted photons, or by quantum frequency conversion, rather than by locally tuning each optical transition [4,7,24]. A local tuning interface would turn frequency matching into a scalable node-level operation, avoiding the additional optical loss and filtering overhead associated with tuning photons after emission.

However, this route is nontrivial for group-IV centers. Inversion symmetry suppresses first-order Stark shifts, so electrical tuning requires operation at finite bias, where local field fluctuations are converted into optical-frequency noise. This Stark-noise trade-off appears across group-IV emitters: previous electrical Stark measurements on SiV^- and SnV^- centers observed field-dependent linewidth broadening and spectral diffusion, making it difficult to use electrical tuning for emitter matching without broadening the optical transition [25–27].

This challenge is compounded in SnV^- network nodes by a large static frequency spread. Implantation damage, strain, and local charge disorder can shift optical transitions

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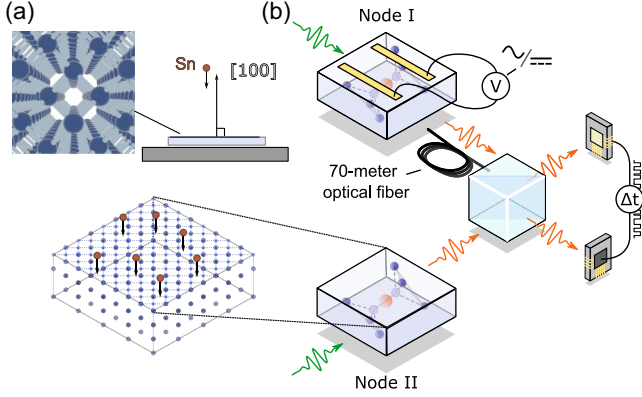


FIG. 1. (a) Sn ions implanted along the [100] crystal channel create SnV^- centers in diamond with reduced local implantation damage. (b) Remote two-photon-interference scheme between independent cryogenic nodes. One node is electrically tuned to match the optical transition of the second node, and photons are combined after propagation through a 70-m fiber link.

by tens to hundreds of gigahertz [17]. Even after high-pressure, high-temperature annealing, residual inhomogeneous broadening of about 4 GHz remains [28,29], more than 2 orders of magnitude larger than the 30 MHz optical linewidth. Bridging this spread electrically is especially demanding because SnV^- is less polarizable than SiV^- : the optically relevant e_u defect orbitals lie deeper in the diamond band gap and are more localized, reducing the effective Stark tunability [6,27,30].

Together, these constraints set a demanding target: bridging a gigahertz-scale frequency spread without sacrificing optical coherence. Here we meet this target by combining channeled Sn implantation [Fig. 1(a)] with local electrodes. The resulting device provides a 4-GHz Stark-tuning branch while retaining coherent driven dynamics. We use this branch to bring a selected pair of emitters in independent cryogenic nodes into resonance and observe remote two-photon interference with a measured zero-delay visibility of 80(6)% [Fig. 1(b)]. Interference persists at 850 MHz detuning, corresponding to more than 20 optical linewidths, with a visibility of 63(8)%, consistent with partial erasure of frequency distinguishability within the detection window. The same electrode platform also produces ac Stark sidebands at gigahertz drive frequencies.

II. ELECTRICAL CONTROL AND LINEWIDTH STABILITY

A. dc Stark tuning and linewidth stability

To accomplish Stark tuning, we select a single SnV^- emitter in a 1.7 μm -gap electrode structure (Sec. 4; Fig. 9 in the Appendix) and characterize the Stark branch used for the remote-interference experiment [Fig. 2(a)]. The optical transition tunes over 4 GHz while retaining

coherent optical dynamics. Rabi oscillations remain visible throughout the voltage sweep [Fig. 2(b)] and are reproduced by a resonantly driven two-level model [31]. To test the photon-matching operating window, we measure PLE linewidths near the voltage where this emitter is tuned close to the remote-emitter frequency. Lorentzian fits give a mean linewidth of 41.6 MHz over 1 GHz of tuning [Fig. 2(c)].

A separate device in another sample exhibits a Stark tuning span of approximately 12 GHz (Fig. 7 in the Appendix). This device-specific result demonstrates the broader electrical tuning range available in this geometry, although the remote-interference experiment uses the 4 GHz branch characterized above.

When the electrode-integrated sample was measured under improved thermalization, PLE linewidths narrowed across the device. An exemplary emitter showed a single-scan linewidth of 31.5 MHz and a 2-hour-averaged linewidth of 31.9 MHz, close to the 28.4 MHz Fourier limit (Fig. 2(d); Secs. 1 and 2 in the Appendix [32]). This device-wide narrowing indicates that the broader lines in the initial cryogenic configuration were dominated by elevated sample temperature rather than by electrode integration.

The linewidth stability under bias reflects a trade-off between Stark tunability and charge-noise sensitivity. For an inversion-symmetric emitter, the first-order Stark response vanishes at the symmetry-protected extremum, while finite bias creates the local Stark slope needed for electrical frequency control. The same slope can transduce nearby electric-field fluctuations into optical-frequency noise, explaining the bias-induced spectral diffusion observed in earlier electrically tuned SnV^- centers [25,26]. In the current device, however, the linewidth remains stable across the measured Stark-tuning window despite the finite susceptibility, demonstrating that the local electrical environment is sufficiently quiet for photon-frequency matching.

B. Implantation environment and charge stability

This stability is consistent with the reduced lattice damage expected from channeled implantation. The Stark-tuned emitter was created by Sn implantation along [100] crystal channels [33,34]. For the 80-keV sample used here, Crystal-TRIM simulations place the emitters about 120 nm below the surface (Fig. 3) [35]. This depth is expected to reduce sensitivity to surface-driven photo-induced drift while still allowing Stark tuning with the lateral electrode field (Fig. 9) [36].

The implantation simulations show that the simulated 80-keV channeled process has a deeper ion range and lower peak damage density than the 300 keV, 7° off-axis reference at the same fluence (Fig. 3). For the common fluence normalization used in this comparison, $1 \times 10^{10} \text{ cm}^{-2}$, converting the simulated peak displacement densities to

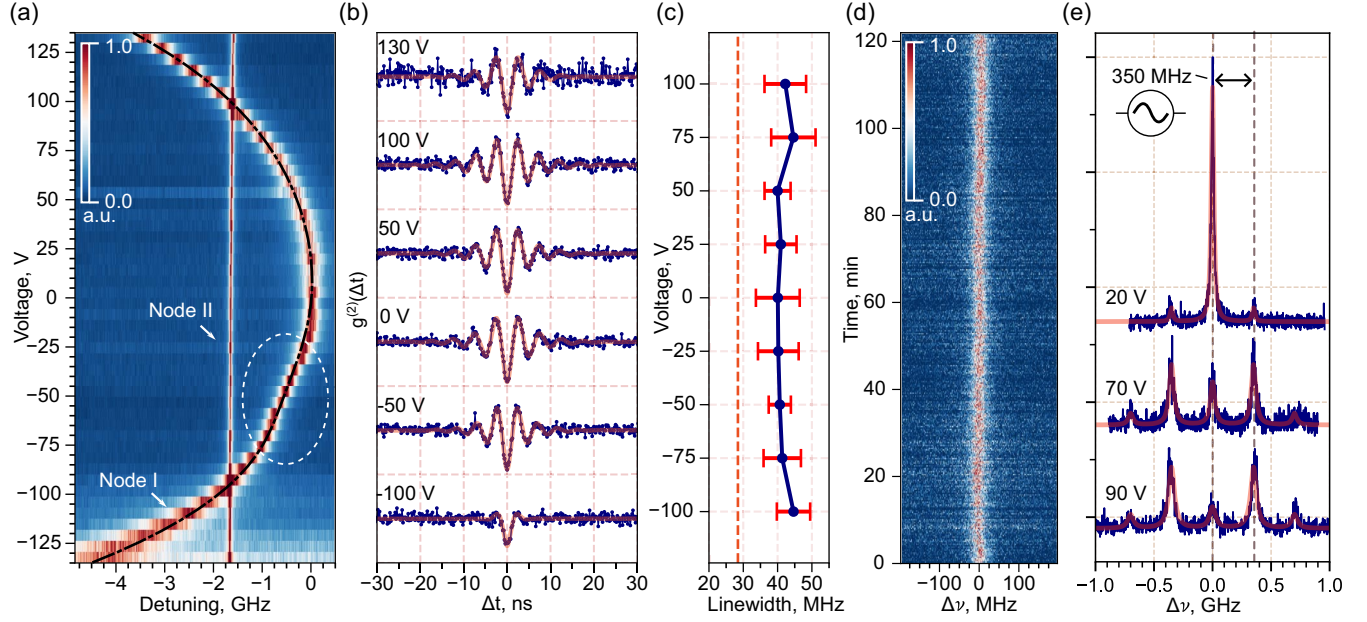


FIG. 2. Electrical tuning and optical-dynamics characterization of low-strain SnV^- centers. (a) PLE intensity as a function of applied voltage and optical detuning, showing dc Stark tuning over 4 GHz. The vertical red line marks the transition frequency of the emitter in the remote node (node II). The black dashed curve is a Stark-shift fit including a nearby two-level charge trap, and the white dash-dotted circle highlights the resulting kink associated with voltage-dependent trap occupation. (b) Intensity autocorrelations $g^{(2)}(\Delta t)$ at selected voltages. The persistence of Rabi oscillations across the voltage sweep shows that coherent optical dynamics are retained during Stark tuning. (c) Lorentzian PLE linewidths measured while sweeping the voltage from -100 to 100 V. Near-Fourier-limited linewidths are maintained over approximately 1 GHz of tuning, with a mean fitted linewidth of 41.6 MHz. The red dashed line marks the 28.4-MHz Fourier limit corresponding to an excited-state lifetime of $T_1 = 5.6$ ns. (d) Repeated PLE scans of a separate emitter in the same electrode-integrated device under improved thermalization. A single scan gives a linewidth of 31.5 MHz, while averaging over 2 h gives 31.9 MHz, demonstrating long-term spectral stability. (e) ac modulation spectra at $\Omega/2\pi = 350$ MHz; dashed lines mark the carrier and first-order sidebands. Displayed voltages denote $|V|$.

volumetric monovacancy-precursor concentrations gives approximately 22 ppm for the 300-keV off-axis case and 7 ppm for the 80-keV channeled case. During annealing,

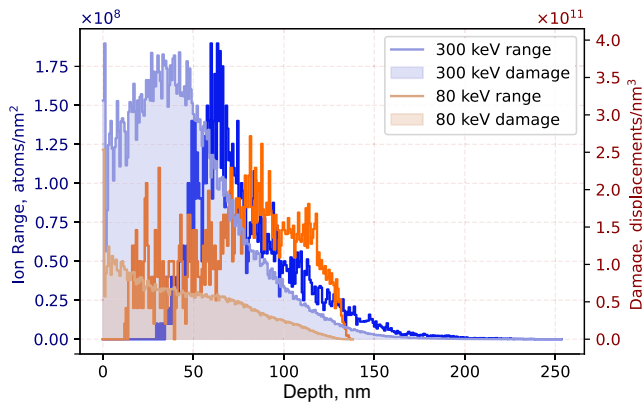


FIG. 3. Crystal-TRIM simulation of the Sn ion range and primary-displacement damage profile for an 80-keV implant aligned along [100] and a 300-keV implant at a 7° off-axis angle. Ion-range profiles are shown as lines, and damage profiles as shaded areas, normalized to a fluence of $1 \times 10^{10} \text{ cm}^{-2}$. The 80-keV channeled process has a deeper peak range and lower peak damage than the off-axis reference.

nearby monovacancies can diffuse and combine into divacancies and larger vacancy complexes. Because this aggregation is bimolecular, the threefold lower precursor density of the channeled process reduces the expected vacancy-complex formation rate by approximately one order of magnitude, providing a direct route to a cleaner local charge environment after annealing [37].

Reduced implantation damage does not, however, imply a trap-free local environment. The kink near 50 V in Fig. 2(a) is consistent with switching of a nearby charge trap. We model the occupied and empty trap states as two Stark branches, $\nu_{\text{occ}}(V)$ and $\nu_{\text{emp}}(V)$, weighted by the voltage-dependent trap occupation (Sec. 7 in the Appendix) [38,39]. This effect is localized in voltage: away from the trap-switching region, narrow linewidths persist over the HOM operating window.

The coexistence of localized trap switching and otherwise stable linewidths suggests that bias plays a dual role: it generates the Stark susceptibility required for tuning while also changing the local charge configuration. The polarity-dependent fluorescence maps in Fig. 8(b) show that the field actively reconfigures the charge-state landscape. The observed response is compatible with redistribution, depletion, or pinning of nearby fluctuators.

Analogous gate-bias control can suppress charge noise in semiconductor quantum emitters [40–42].

C. Bias-enabled ac Stark modulation

The same Stark branch enables ac frequency modulation [Fig. 2(e)]. An ac electric field at $f_{\text{mod}} = \Omega/2\pi$ periodically shifts the optical transition by $\Delta\nu_{\text{ac}}$, generating Floquet sidebands spaced by f_{mod} with weights set by $\beta = \Delta\nu_{\text{ac}}/f_{\text{mod}}$ [43–45]. At $f_{\text{mod}} = 350$ MHz, the fitted modulation index is $\beta = 0.20$ at 20 V and rises to 1.56 and 1.66 at 70 and 90 V; near zero bias the response remains weak ($\beta = 0.14$), as expected for an inversion-symmetric emitter. Additional sweeps resolve sidebands at drive frequencies up to 1.5 GHz. Cryostat heating, rather than the optical response, limited the maximum drive frequency. Thus, 1.5 GHz is a measurement ceiling, not the intrinsic modulation bandwidth (Sec. 8 in the Appendix) [43,46,47].

III. REMOTE TWO-PHOTON INTERFERENCE

With the two-node link established, the electrically controlled Stark branch is used for remote two-photon

interference (Fig. 4). One SnV^- center is electrically tuned onto the transition frequency of a second emitter in the independent cryogenic node. Single photons are generated under off-resonant 520 nm excitation and filtered to the narrow zero-phonon-line transition used for interference (Sec. 1 in the Appendix). At zero detuning, we periodically match spectral overlap and confocal alignment about every 15 min, balance the zero-phonon-line count rates to 4 kcts/s per node, and verify single-photon purity with single-emitter autocorrelations [Fig. 5(b)]. The 9-hour zero-detuning dataset shows a Hong-Ou-Mandel dip with measured central-bin visibility $V_{\text{HOM}} = 0.80 \pm 0.06$. This value is obtained by comparing the zero-detuning central bin with the 1400-MHz central bin, for which no interference feature is resolved and which is therefore used as the distinguishable-photon reference.

The detuned measurements test when spectral mismatch becomes distinguishable. At $\Delta\nu = 850$ MHz, more than 20 natural linewidths, the correlation still exhibits a zero-delay suppression with $V_{\text{HOM}} = 0.63 \pm 0.08$ [Fig. 4(b)]. For photon pairs detected within a short time window, time-resolved detection partially erases the source information encoded by their different frequencies. The

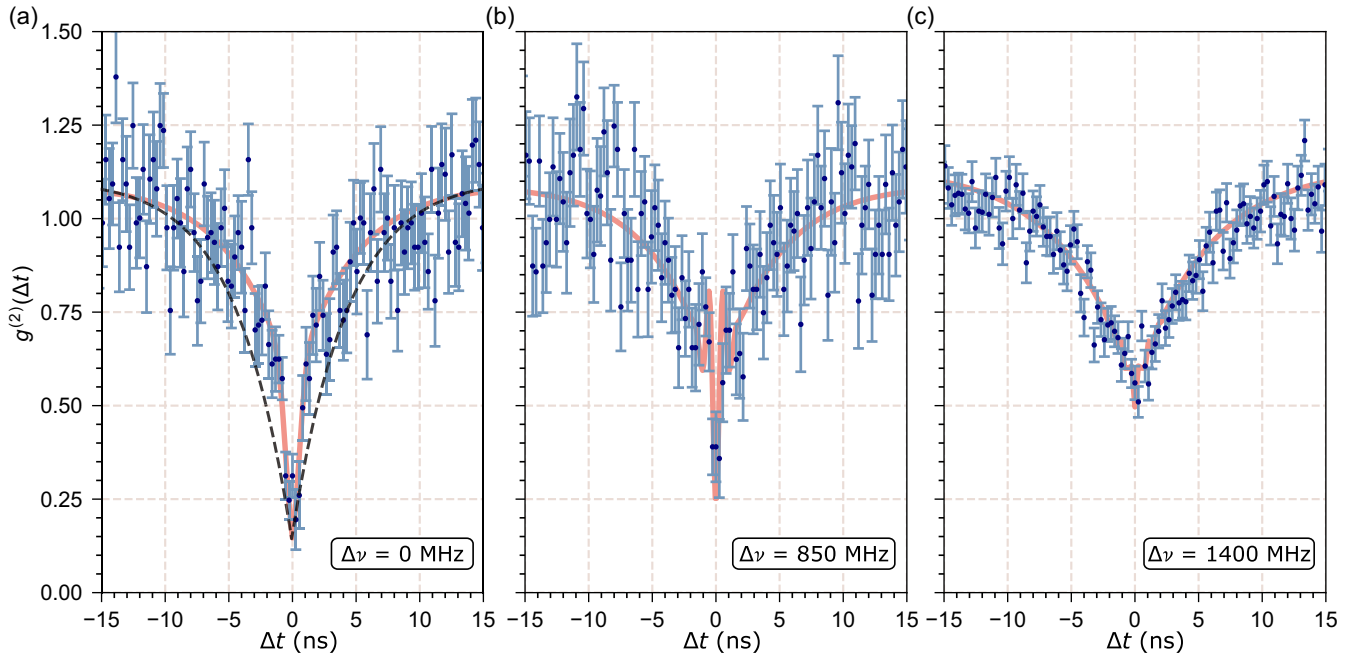


FIG. 4. Detuning-dependent remote two-photon interference between photons emitted by SnV^- centers in independent cryogenic nodes. The second-order cross-correlation $g_{12}^{(2)}(\Delta t)$ is measured at (a) $\Delta\nu = 0$ MHz, where the emitters are tuned into resonance; (b) $\Delta\nu = 850$ MHz, corresponding to more than 20 natural linewidths; and (c) $\Delta\nu = 1400$ MHz, the distinguishable-photon reference. Blue points are the measured data. Red curves are fitting curves from Eq. (A13), combining the independently measured single-emitter dynamics with Gaussian relative-detuning fluctuations representing spectral diffusion. The black dashed curve in (a) shows the idealized resonant response calculated with the same model parameters but zero spectral diffusion. Relative to the 1400-MHz reference, the measured central-bin visibilities are $V_{\text{HOM}}(\Delta\nu = 0 \text{ MHz}) = 0.80 \pm 0.06$ and $V_{\text{HOM}}(\Delta\nu = 850 \text{ MHz}) = 0.63 \pm 0.08$. The zero-delay suppression at 850 MHz demonstrates that two-photon interference persists at finite detuning; in the model, spectral diffusion narrows the temporal interference contribution. At 1400 MHz, no additional HOM interference contribution is resolved.

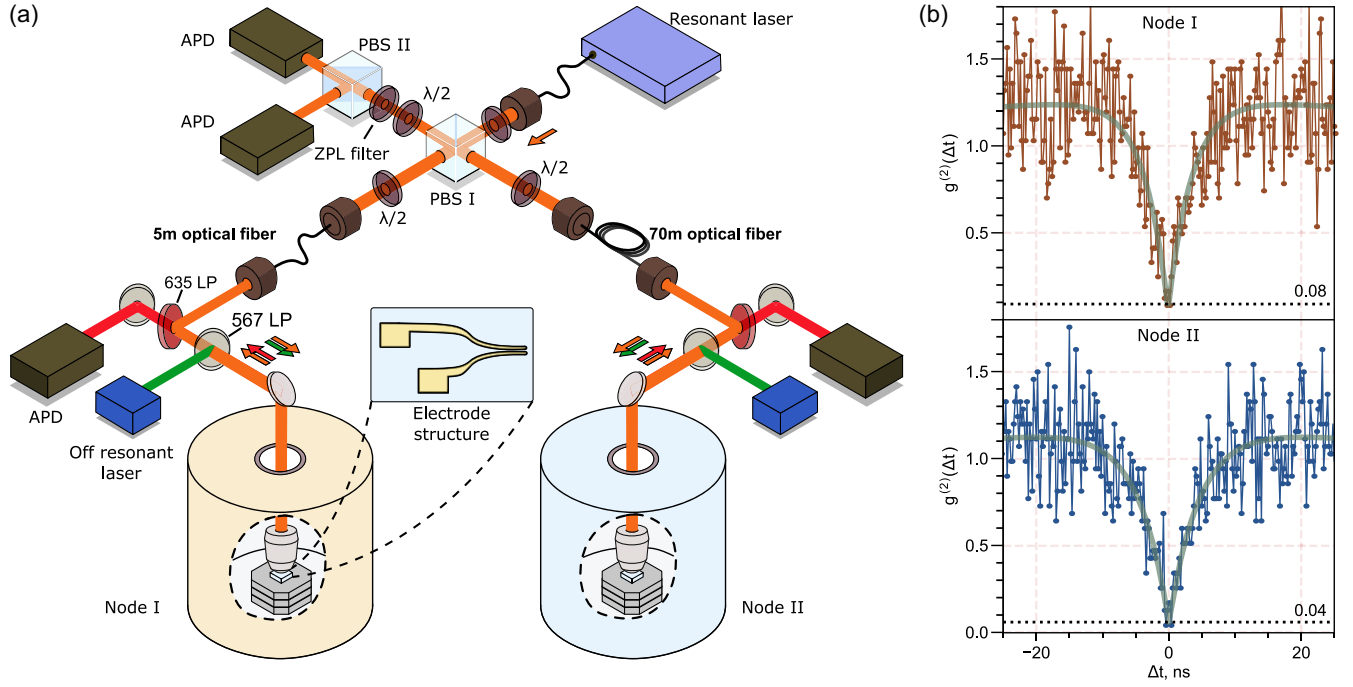


FIG. 5. Two-node tin-vacancy experiment. (a) Optical setup connecting node I and node II, located in separate rooms, through a 70-m polarization-maintaining fiber. Off-resonantly excited zero-phonon-line emission is spectrally filtered, combined at the interferometer, and detected with avalanche photodiodes. (b) Single-emitter autocorrelations measured in the two cryostats, with $g_I^{(2)}(0) = 0.08 \pm 0.06$ and $g_{II}^{(2)}(0) = 0.04^{+0.09}_{-0.04}$, confirming that the remote interference experiment combines photons from two spatially separated single SnV⁻ emitters.

photons therefore remain partially indistinguishable, allowing an interference dip to persist despite the detuning [48–53]. For comparison, the manufacturer’s single-APD timing-jitter specification of 350 ps FWHM corresponds to a reciprocal Fourier scale of $0.44/\Delta t_{\text{FWHM}} \simeq 1.3$ GHz, above the 850-MHz detuning. At 1400 MHz and higher bias, no clear interference feature remains [Fig. 4(c)]. Fits to Eq. (A13) include spectral diffusion as described in Sec. 11 in the Appendix; the dashed zero-diffusion trace in Fig. 4(a) shows the corresponding ideal resonant response.

Because the measured arrival time difference records the detuning-induced phase, this finite-detuning regime is also the feed-forward variable used in different-color entanglement protocols [53,54]. The experiment therefore illustrates three complementary responses to spectral diversity: remove it by dc tuning, reduce its distinguishability through time-resolved detection, or address it dynamically with bias-enabled sidebands.

IV. DISCUSSION AND OUTLOOK

We demonstrate remote Hong-Ou-Mandel interference between independent SnV⁻ centers with a zero-delay visibility of 80(6)%, extending remote two-photon interference to heavier group-IV vacancy centers. Local electrical control enables this frequency matching while

preserving coherent optical dynamics. Finite bias provides the Stark slope required for dc spectral matching and ac modulation without resolvable bias-induced broadening. Crystal-TRIM simulations show that channeled implantation produces less lattice damage, helping to preserve the stable local charge environment observed here.

Building on this stable electrical interface, resonant excitation should reduce photoinduced charge dynamics and eliminate timing jitter from relaxation through higher-lying excited states [55,56]. Integrating the emitters with waveguides, photonic-crystal cavities, nanopillars, or fiber Fabry-Pérot cavities could then increase photon collection, provide Purcell enhancement, and interface directly with optical networks [57–59].

These photonic improvements can be combined with a hybrid electrical-strain tuning architecture. Static strain provides large frequency shifts and mixes the orbital states required for microwave spin control of SnV⁻ centers [20–22]. Strain-based nanoelectromechanical devices additionally provide large SnV⁻ frequency shifts, gigahertz sidebands, and acoustic spin control [44]. Electrical tuning supplies local spectral alignment, feedback, drift correction, and sideband generation without resolvable broadening over the characterized operating window. Such a device could use strain for coarse spectral placement and spin control, and Stark tuning for fast, node-specific frequency control.

Local Stark tuning, remote Hong-Ou-Mandel interference, and bias-enabled Floquet sidebands establish the core elements of an electrically reconfigurable SnV⁻ optical interface. In larger networks, spectral diversity can be managed by tuning emitters into resonance, erasing residual distinguishability through time-resolved detection, or assigning emitters to dynamically addressable frequency channels. These capabilities open a path to frequency-resolved and multiplexed network protocols [53,54].

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The authors declare no competing interests.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX SUPPORTING ANALYSES

1. Detailed optical and timing setup

The two-node setup includes two cryostats: the AttoDry800 (4 K base temperature; node I) and Bluefors LD250 (4 K base temperature; node II) [Fig. 5(a)], located in separate rooms and connected by a 70-m-long polarization-maintaining (PM) fiber. The setup couples the 520-nm excitation into each cryostat with a 567-nm long-pass dichroic mirror, where it is focused by a 0.9 NA, 100× objective (Olympus MPLN). Collected SnV⁻ emission is then routed through a 635-nm long-pass dichroic mirror that separates phonon-sideband photons used for avalanche-photodiode (APD) monitoring (SPCM-AQRH-14-FC, Excelitas Technologies Corp.) from the zero-phonon-line path. The zero-phonon lines are collected via a 70-m PM fiber for node I and a 5 m PM fiber for node II and then coupled into an interferometer. Inside the interferometer, emission from both nodes is combined into a single spatial mode with orthogonal polarizations using half-wave plates and a polarizing beam splitter (PBS I). This mode is further filtered by a tilted 0.5 nm narrow-band-pass filter (LC-HBP630.2/0.5, Alluxa, Inc.), isolating the desired line.

Because of the substantial spectral separation between emission lines stemming from large spin-orbit coupling, a narrow etalon is not required, which allows for coherent transition selection with a commercial spectral filter. The combined and filtered emission is split again by a second polarizing beam splitter. This configuration allows two modes of operation: (1) with a half-wave plate before PBS II maintaining separate polarizations, enabling independent measurements from nodes I and II; and (2) with the half-wave plate rotated by 22.5°, effecting a 45° polarization rotation mixing horizontal and vertical polarizations to observe interference [60]. The independently measured autocorrelations confirm single-photon emission from both selected centers [Fig. 5(b)].

The photon arrival times are analyzed using time-stamping electronics (Timetagger 20, Swabian Instruments). The zero-detuning trace was accumulated for 9 h; each detuned trace was accumulated for approximately 8 h. Additionally, a resonant laser (620 ± 10 nm DLC TA-SHG PRO, TOPTICA Photonics AG) is introduced into the setup through PBS I, coupling into the PM fibers of both nodes. This design allows the collected zero-phonon line emission (from green excitation) to share the spatial mode with the resonant laser, enabling identification of defects under both off-resonant and resonant excitation. The remote control of both nodes was performed using Qudi software [61].

2. Linewidth measurements under different cryogenic conditions

For the linewidth comparison in Sec. II, PLE datasets were acquired from different emitters in the same electrode-integrated device under two cryogenic configurations.

Initial measurements used an AttoDry800 system (Attocube), whereas subsequent measurements used a Bluefors LD250 system with improved thermal anchoring near 4 K. Because the measurements involved different emitters and cryogenic configurations, the observed narrowing does not constitute a controlled isolation of thermal broadening.

3. Sample fabrication

In this work, we fabricated channeled Sn-implantation samples in [100]-oriented CVD-grown diamond at 0° incidence. The 40 and 170 keV samples were implanted at a fluence of $5 \times 10^9 \text{ cm}^{-2}$, while the 80-keV sample used for the two-node HOM measurements was implanted at a fluence of $2 \times 10^{10} \text{ cm}^{-2}$. The 40-keV samples are used for comparative inhomogeneous-distribution characterization. Following implantation, high-temperature annealing at 1500°C was performed for 1 h in vacuum. As a final step, the samples were boiled for 3 h in a three-acid mixture to remove the graphitized surface layer.

4. Electrode fabrication and field simulation

The electrodes are spaced $1.7\ \mu\text{m}$ apart and are $1.8\ \mu\text{m}$ wide. They were created using a liftoff process, with the electrode shape patterned into a double layer of photoresist (LOR3A and Shipley S1805) via optical lithography. The shape begins as two narrow, parallel electrodes that gradually widen and separate until they terminate in wire-bonding pads. The patterned shape is narrower and farther apart than the final electrodes. These adjustments help to prevent the electrodes from fusing due to the proximity effect. Following the patterning, $10\ \text{nm}$ of Cr as an adhesion layer, followed by $100\ \text{nm}$ of Au, were deposited onto the sample by e-beam evaporation at a rate of $0.1\ \text{nm s}^{-1}$. The remaining photoresist was dissolved in *N*-methyl-2-pyrrolidone, which lifts off the unwanted gold, leaving just the electrodes.

5. Periodic check of the ZPL overlap

Software-based periodic alignment of the ZPL transitions and confocal positioning was performed approximately every 15 min. The need for periodic refocusing arose from cryostat instability, which caused spatial drift of the confocal spot. For the 80-keV implanted samples, achieving stable resonance under off-resonant green excitation required prolonged exposure to higher power (3 mW at 520 nm for several hours). We attribute this conditioning step to charge redistribution at the diamond surface, as it was not required for the deeper-implanted 170-keV samples. The residual spectral drift observed during the HOM interference measurements is therefore likely influenced by the periodic refocusing procedure, which changed the illumination position of the off-resonant laser on the diamond surface and, in turn, modified the local surface charge environment acting on the defects.

For spectral overlap, the static node's resonant laser was swept across a 1-GHz window in 2-MHz steps, and the resulting lineshape was fitted with a Lorentzian to extract the center frequency. The tunable node was then aligned by sweeping its bias voltage over $\pm 10\ \text{V}$ in 1 V increments with a 250-ms integration time, maximizing ZPL counts. During this procedure, a continuous low-power 0.3-mW, 520-nm repump laser was applied to account for laser-induced spectral shifts. After the initial conditioning step, the ZPL transitions remained stable on short timescales under continuous off-resonant excitation (Fig. 6).

6. Device-specific electrical-reach benchmark

An additional measurement on a separate device and sample demonstrates an electrical tuning span of approximately 12 GHz in this electrode geometry, illustrating its potential for emitter matching and frequency-channel selection.

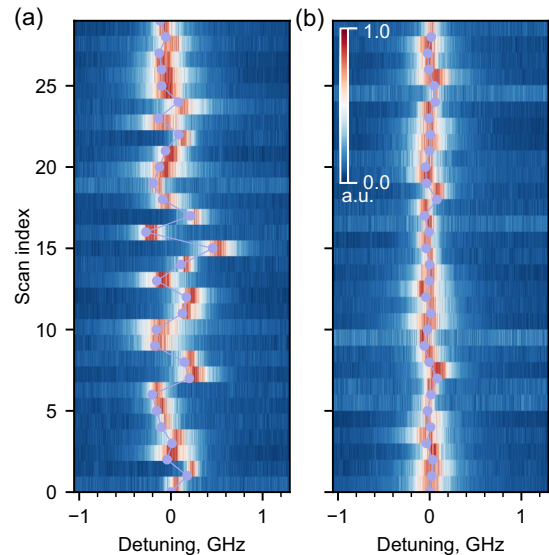


FIG. 6. PLE scans of node I before (a) and after (b) periodic alignment of the c-a resonant transition. The observed zero-phonon-line wandering between alignment steps is consistent with a contribution from slow detuning noise to the two-photon-interference lineshape.

7. Modeling the Stark shift

Figure 8(a) shows the benchmark Stark-tuning trace with a pronounced kink. As discussed in Sec. II, this feature is consistent with a discrete reconfiguration of the local electrostatic environment. The two-branch ansatz below provides a phenomenological interpolation of this local electrostatic switching event.

Figure 8(b) shows that the applied field also changes the charge-state landscape more globally: reversing the bias polarity changes the fluorescence collected from SnV^-

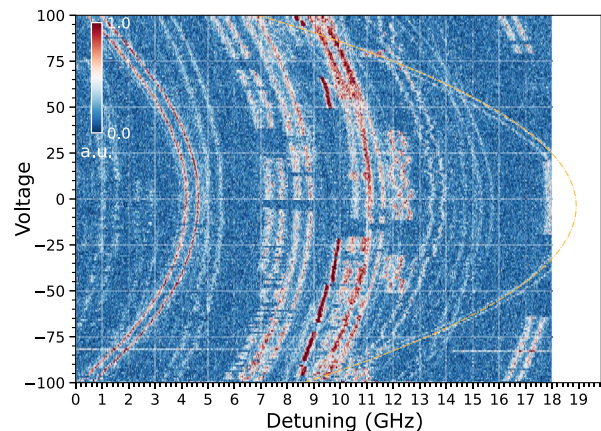


FIG. 7. Device-specific electrical-reach benchmark measured on a SnV^- center in a separate sample. A fit to the tracked Stark curve yields a total tuning span of approximately 12 GHz (orange fit). The fitted branch remains smooth over the accessible bias range and demonstrates the electrical tuning reach of this device.

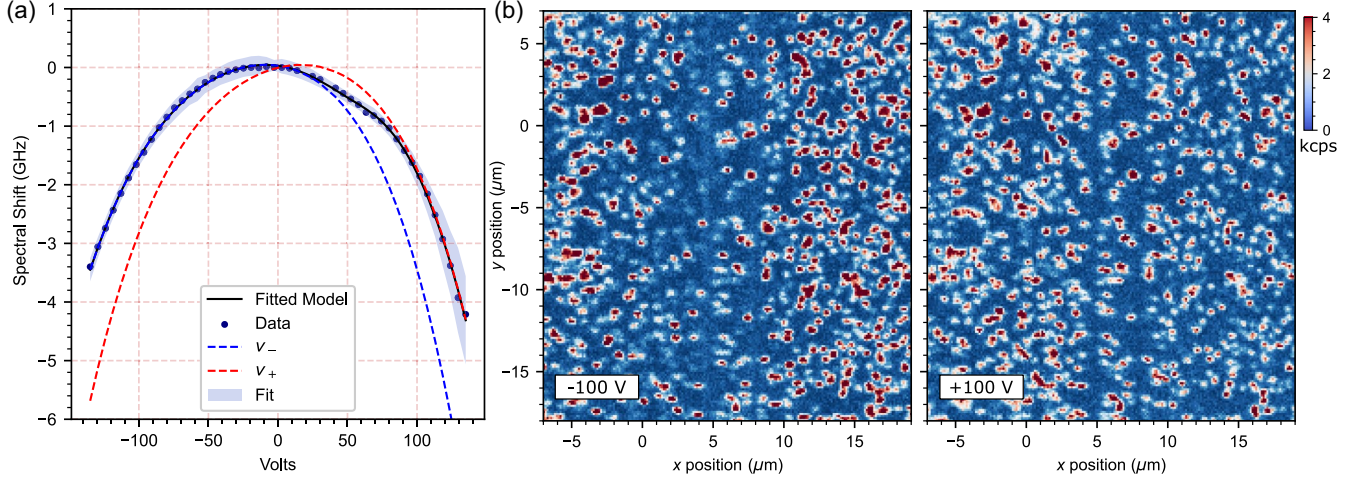


FIG. 8. (a) Benchmark Stark-tuning trace with a pronounced kink. Black dots show the measured transition frequencies; the colored curves denote the two electrostatic branches, $\nu_{\text{occ}}(v)$ and $\nu_{\text{emp}}(v)$, and the shaded region indicates the measured linewidth broadening near the switching region. (b) Confocal scans of the SnV^- centers between the electrodes, measured under off-resonant excitation with photon collection through a 0.5-nm-wide Alluxa filter aligned to the 619.2-nm laser transmission. The left image was recorded with a -100 V bias applied between the electrodes, and the right image was recorded with a $+100$ V bias. The polarity-dependent PL intensity demonstrates bias-driven reconfiguration of bright and dark charge states, consistent with reports for electrically controlled group-IV vacancy centers [62–64].

centers between the electrodes, similar to that observed for contacted SiV^- devices [62,63]. This response establishes active electrical control of the local charge-state landscape and a field-conditioned environment for Stark tuning.

For the discussion here, the relevant susceptibility is simply the local slope of the Stark curve,

$$\chi_v(v) = \frac{d\nu}{dv}. \quad (\text{A1})$$

This derivative controls how voltage- or field-induced charge fluctuations are converted into optical-frequency noise to first order, $\delta\nu \simeq \chi_v \delta v$. For an ideal inversion-symmetric group-IV center, the permanent differential dipole is suppressed, so the Stark curve has an extremum where this susceptibility is small [26,27]. Once the transition is biased away from this extremum, the finite derivative provides the frequency tuning and also sets the sensitivity to local charge noise. Converting χ_v into a field-normalized susceptibility requires the microscopic field at the emitter, which depends on the defect position and orientation. We therefore keep the Stark-fit parameters in the directly measured voltage units of the original analysis and use the COMSOL field only as a nominal field scale.

To interpolate the observed kink, we use a voltage-based phenomenological form. A bistable local charge configuration is represented as an additional offset in the effective voltage seen by the emitter [39]. For the two effective branches, define

$$\mathcal{V}_{\pm} = (v + v_0) \pm v_{\text{trap}}, \quad (\text{A2})$$

and write

$$\nu_{\text{occ}}(v) = \alpha \mathcal{V}_+^2 + \beta \mathcal{V}_+^3 + \gamma \mathcal{V}_+^4 + \delta\mu, \quad (\text{A3})$$

$$\nu_{\text{emp}}(v) = \alpha \mathcal{V}_-^2 + \beta \mathcal{V}_-^3 + \gamma \mathcal{V}_-^4 + \delta\mu. \quad (\text{A4})$$

Here v is the applied electrode voltage; v_0 is the built-in voltage offset; α , β , and γ are the voltage-parametrized Stark coefficients (Table I), $\delta\mu$ is a constant frequency offset, and v_{trap} is the effective voltage separation of the two branches.

We describe their effective weighting with a Fermi-Dirac-like switching function:

$$p(v) = \frac{1}{1 + \exp(\frac{v_{1/2} - v}{k})}, \quad (\text{A5})$$

where $v_{1/2}$ is the midpoint voltage, and k is the characteristic voltage width of the transition. These are interpolation

TABLE I. Stark-shift model parameters.

Parameter	Value	Unit
$\delta\mu$	6.04 ± 0.98	MHz
α	0.42 ± 0.04	MHz/V ²
β	$(4.6 \pm 0.9) \times 10^{-3}$	MHz/V ³
γ	$(1.4 \pm 0.2) \times 10^{-4}$	MHz/V ⁴
v_0	-19.5 ± 2.7	V
v_{trap}	-12.8 ± 2.8	V
k	0.070 ± 0.019	V
$v_{1/2}$	55.4 ± 4.6	V

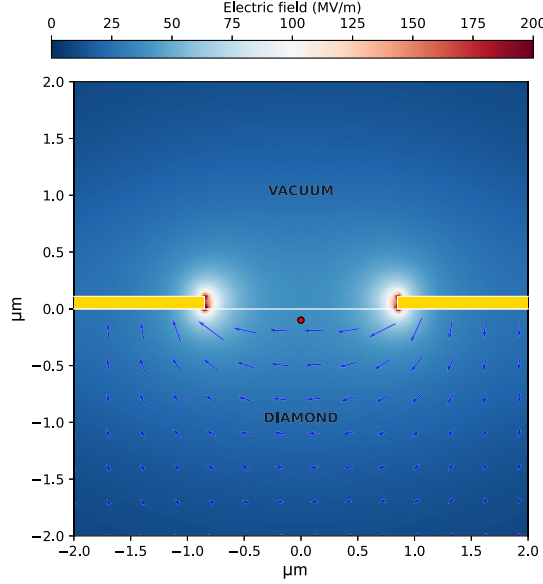


FIG. 9. Simulated electric field distribution around the nanostructure. The color map represents the norm of the electric field vector, $|E|$. For 100-V applied bias and $\epsilon_r = 5.7$, the electric field at the center of the gap is $E_{\text{sim}} \approx 37.4 \text{ MV m}^{-1}$, yielding $\kappa \approx 0.37 \text{ MV m}^{-1} \text{ V}^{-1}$.

parameters rather than independently measured microscopic quantities. The modeled Stark response is then

$$\nu_{\text{model}}(v) = p(v)\nu_{\text{occ}}(v) + [1 - p(v)]\nu_{\text{emp}}(v). \quad (\text{A6})$$

This reproduces the kink near $v \approx v_{1/2}$. Switching between local configurations is one possible microscopic origin of such a feature, but the data do not uniquely determine the mechanism or switching timescale. The parameter set reported in Table I corresponds to the benchmark dataset of Fig. 8(a).

The uncertainties in Table I are the parameter errors returned by the phenomenological fit. They are not intended as independently validated confidence intervals for a microscopic trap model.

To estimate the electric field at the position of the defect, we simulated the electrostatic potential distribution using a finite-element method (COMSOL Multiphysics) in a 2D geometry (see Fig. 9). The model assumes a 100-nm Au electrode on a 10-nm Cr adhesion layer, electrode width $1.8 \mu\text{m}$, spacing $1.7 \mu\text{m}$, on diamond with $\epsilon_r = 5.7$. The defect was assumed to be located at the lateral center of the electrode gap and at a depth of 100 nm below the diamond surface. This position is a nominal geometry used to estimate the field scale; the actual emitter can be displaced laterally within the optical spot and can lie at a different depth within the implantation distribution. At 100 V, the simulated field at this nominal position is $E_{\text{sim}} \approx 37.4 \text{ MV m}^{-1}$, giving $\kappa = E/v \approx 0.37 \text{ MV m}^{-1} \text{ V}^{-1}$.

8. Bias-dependent ac modulation and Floquet fits

The ac-modulation analysis proceeds in two steps. First, we fit the smooth negative-bias Stark branch relevant for the modulation experiment with the no-trap polynomial described above, using only the 0 to -90 V data. This provides a calibrated static response $\nu(v)$ and, in particular, the local slope $\partial\nu/\partial v$ at each dc operating point. Second, we fit the bias-dependent modulation spectra of Fig. 2(e) with a Floquet sideband model. Writing the effective modulation voltage as

$$v(t) = v_{\text{dc}} + v_{\text{ac}} \cos(\Omega t), \quad (\text{A7})$$

the instantaneous optical frequency can be linearized around the operating point as

$$\nu(v(t)) \approx \nu(v_{\text{dc}}) + \left. \frac{\partial\nu}{\partial v} \right|_{v_{\text{dc}}} v_{\text{ac}} \cos(\Omega t), \quad (\text{A8})$$

where $f_{\text{mod}} = \Omega/2\pi$ is the applied modulation frequency. The corresponding phase-modulation index is set by the local Stark slope,

$$\beta = \frac{2\pi\Delta\nu_{\text{ac}}}{\Omega} = \frac{\Delta\nu_{\text{ac}}}{f_{\text{mod}}}, \quad \Delta\nu_{\text{ac}} = \left| \frac{\partial\nu}{\partial v} \right| v_{\text{ac}}. \quad (\text{A9})$$

This is the standard sinusoidal frequency-modulation framework for a periodically driven two-level transition [43,45]. The optical dipole therefore acquires the phase factor

$$e^{i2\pi \int_0^t \Delta\nu_{\text{ac}} \cos(\Omega t') dt'} = e^{i\beta \sin(\Omega t)} = \sum_{n=-\infty}^{\infty} J_n(\beta) e^{in\Omega t}, \quad (\text{A10})$$

so the spectrum consists of Floquet sidebands spaced by f_{mod} with relative weights $|J_n(\beta)|^2$. This framework is qualitatively consistent with the absence of resolved sidebands near the Stark extremum and their appearance at finite bias.

For the 350-MHz data in Fig. 2(e), we fit each spectrum with a carrier and modulation sidebands separated by $f_{\text{mod}} = \Omega/2\pi$. The sideband weights are fixed by the frequency-modulation index β , giving

$$I(\Delta) = I_{\text{bg}} + A \sum_{n=-N}^N \frac{|J_n(\beta)|^2}{1 + [(\Delta - \Delta_0 - n f_{\text{mod}})/\Gamma]^2}, \quad (\text{A11})$$

where β is the fitted modulation index, Δ_0 is the carrier position, and Γ is the common Lorentzian half width at half maximum; the corresponding FWHM is 2Γ [45,47]. The extracted β values reproduce the observed sideband

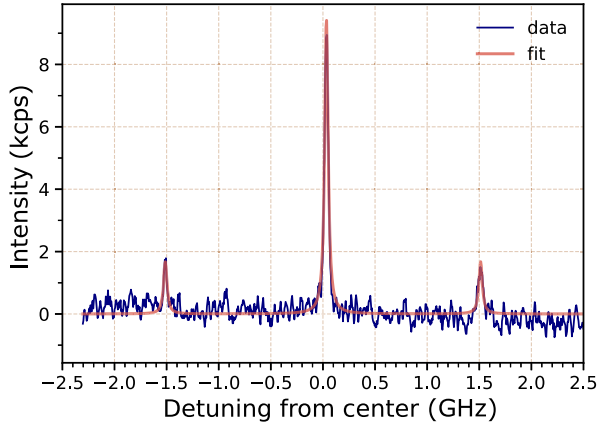


FIG. 10. Representative Floquet fit to the largest resolved sidebands in the modulation-frequency sweep. The plotted trace corresponds to the highest-frequency measured dataset driven at 1.5 GHz and is shown after subtraction of the background. Allowing a small correction to the effective sideband spacing yields $\Omega/2\pi = 1.513$ GHz, $\beta = 0.629$.

weights. The 0-V spectrum shows no resolved sidebands and is omitted from Fig. 2(e) for clarity.

We resolve ac-modulation sidebands at drive frequencies up to $\Omega/2\pi = 1.5$ GHz (Fig. 10). Cryostat heating set the practical ceiling of the present sweep.

9. Crystal-TRIM damage-density calculation

Ion ranges and damage profiles were simulated with Crystal-TRIM [35], which accounts for channeling, electronic stopping, defect accumulation, and thermal vibrations. For the HOM samples, the simulations give projected Sn depths of approximately 120 nm for 80-keV implantation and 250 nm for 170-keV implantation.

Figure 3 compares the 80-keV channeled profile with a 300 keV, 7° off-axis reference implant, both normalized to a fluence of $1 \times 10^{10} \text{ cm}^{-2}$. The channeled profile has a deeper peak range and lower simulated peak primary damage. Because both implantation energy and orientation differ, this comparison illustrates the combined process geometries rather than isolating channeling at fixed energy.

To estimate the local density of implantation-induced V_1 precursors, we converted the Crystal-TRIM displacement profile into a volumetric concentration by scaling the number of displacements per implanted ion and depth bin by the implantation fluence. This density was then normalized to the atomic density of diamond, $n_C \simeq 1.76 \times 10^{23} \text{ cm}^{-3}$, and expressed in ppm.

At a common fluence of $1 \times 10^{10} \text{ cm}^{-2}$, the peak V_1 -precursor concentration is approximately 22 ppm for the 300-keV, 7° off-axis implant and 7 ppm for the 80-keV channeled implant. Since the conversion scales linearly with fluence, the 80-keV HOM sample implanted at

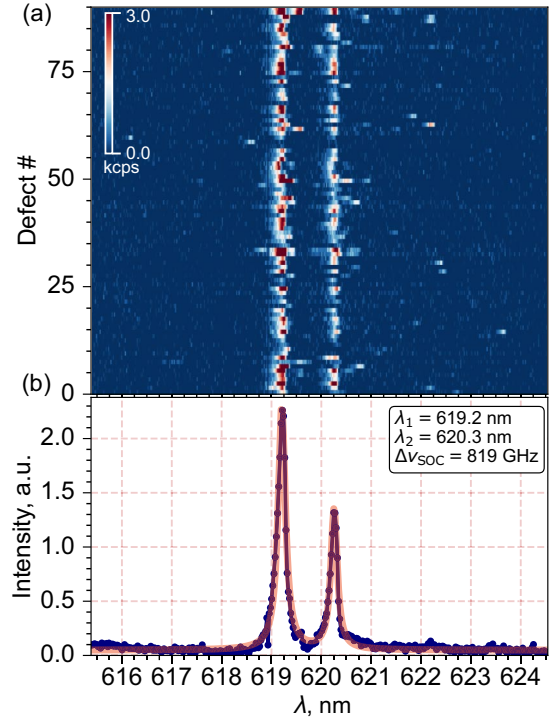


FIG. 11. Spectral characterization of a 170-keV-implanted low-strain SnV^- ensemble. (a) Distribution of zero-phonon-line frequencies for 90 defects. (b) Photoluminescence spectrum averaged over the same area, showing the two spin-orbit-split optical lines at 619.2 and 620.3 nm, separated by 819 GHz.

$2 \times 10^{10} \text{ cm}^{-2}$ would correspond to a peak precursor concentration of about 14 ppm.

10. Low-strain spectral characterization and comparative inhomogeneous distributions

We measured 90 resonant transitions in a 170-keV-implanted area and averaged the photoluminescence spectrum over the same region (Fig. 11). The two zero-phonon lines are centered at 619.2 and 620.3 nm, separated by 819 GHz, and correspond to the two spin-orbit-split SnV^- optical transitions.

We measured the inhomogeneous frequency distributions of SnV^- centers in 40- and 170-keV-implanted areas, both with an ion fluence of $5 \times 10^9 \text{ cm}^{-2}$. Gaussian fits give distribution widths $\sigma = 11.02$ GHz and $\sigma = 13.69$ GHz, respectively (Fig. 12). The gap near 20 GHz results from a mode hop of the resonant laser during the measurement.

11. Model for detuning-dependent two-photon interference

The background-free single-emitter dynamics are represented by the three-level form

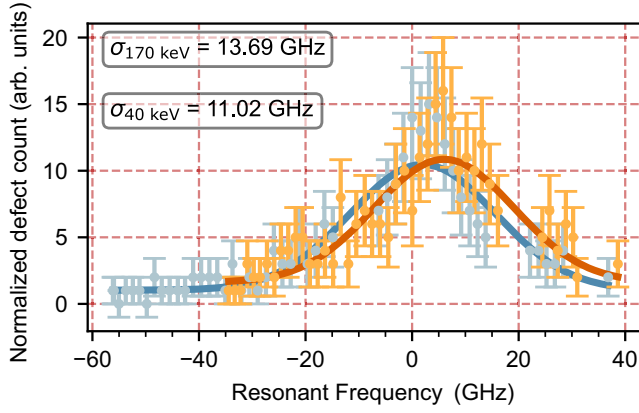


FIG. 12. Inhomogeneous frequency distributions of SnV⁻ centers in 170-keV-implemented (blue) and 40-keV-implemented (orange) areas. Gaussian fits give standard deviations of 13.69 and 11.02 GHz, respectively.

$$g_{ii}^{(2)}(\tau) = 1 - (1 + a_i)e^{-|\tau|/\tau_{1,i}} + a_ie^{-|\tau|/\tau_{2,i}}, \quad (\text{A12})$$

where $\tau_{1,i}$, $\tau_{2,i}$, and a_i are the antibunching time, bunching time, and bunching amplitude, respectively. For Lorentzian optical coherence, $|g_{ii}^{(1)}(\tau)| = e^{-|\tau|/T_{2,i}}$, with $T_{2,i} = 1/(\pi\Delta\nu_i)$ for Lorentzian FWHM $\Delta\nu_i$ and $T_{2,i} = 2T_{1,i}$ at the transform limit [31].

Following Refs. [55,65], Gaussian relative-detuning fluctuations give

$$\begin{aligned} g_{12}^{(2)}(\tau; \Delta\nu) &= c_1^2 g_{11}^{(2)}(\tau) + c_2^2 g_{22}^{(2)}(\tau) \\ &+ 2c_1 c_2 [1 - \eta_{\text{eff}}(\Delta\nu) e^{-|\tau|(1/T_{2,1} + 1/T_{2,2})} \\ &\times e^{-2\pi^2 \sigma_\nu^2 \tau^2} \cos(2\pi\Delta\nu\tau)]. \end{aligned} \quad (\text{A13})$$

Here $c_i = I_i/(I_1 + I_2)$, $\Delta\nu = \nu_1 - \nu_2$, and σ_ν is the standard deviation of the relative-detuning fluctuations. The Gaussian factor is the analytic result of averaging the beat term over a normal detuning distribution. The PLE-derived $T_{2,i}$ parametrizes the Lorentzian component,

TABLE II. Parameters used in the HOM line-shape model.

Parameter	Value(s)
a_i	0.3
$\tau_{1,i}$	5 ns
$\tau_{2,i}$	50 ns
$T_{2,i}$	$1/(\pi\Delta\nu_i)$
$\Delta\nu$	0, 850, and 1400 MHz 0.80 (0 MHz); 0.63 (850 MHz);
η_{eff}	0 (1400 MHz)
c_1, c_2	0.5, 0.5
I_i	4.2 kcps
σ_ν	234 MHz

whereas σ_ν parametrizes the slower relative-frequency wandering accumulated during the multi-hour cross-correlation measurements.

The detuning-dependent amplitude η_{eff} includes residual background, spatial and polarization mismatch, detector timing jitter, and finite histogram-bin width. Detector averaging suppresses beats that are not resolved in time, so η_{eff} is allowed to vary with detuning. The phase factor $\cos(2\pi\Delta\nu\tau)$ maps detuning onto the measured arrival-time difference; real-time protocols can track and compensate for this phase [53,54].

The 1400-MHz trace serves as the distinguishable-photon reference. The reported zero-delay visibility is calculated directly from the central bins:

$$V_{\text{HOM}} = \frac{g_{12,\text{ref}}^{(2)}(0) - g_{12}^{(2)}(0)}{g_{12,\text{ref}}^{(2)}(0)}, \quad (\text{A14})$$

$$g_{12,\text{ref}}^{(2)}(\tau) \equiv g_{12}^{(2)}(\tau; \Delta\nu = 1400 \text{ MHz}). \quad (\text{A15})$$

For $c_1 = c_2 = 0.5$ and the background-free three-level form, $g_{12,\text{ref}}^{(2)}(0) = 0.5$ and $V_{\text{HOM}} = \eta_{\text{eff}}$. The resulting curves are shown in Fig. 4.

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