

Laser-Induced Spectral Diffusion and Excited-State Mixing of Silicon T Centers

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To find practical application as photon sources for entangled optical-resource states or as spin-photon interfaces in entangled networks, semiconductor emitters must produce indistinguishable photons with high efficiency and spectral stability. Nanophotonic cavity integration increases efficiency and bandwidth but it also introduces environmental charge instability and spectral diffusion. Among various candidates, silicon color centers have emerged as compelling platforms for integrated-emitter quantum technologies. Here, we investigate the dynamics of spectral wandering in nanophotonics-coupled individual silicon T centers using spectral correlation measurements. We observe that spectral fluctuations are driven predominantly by the near-infrared excitation laser, consistent with a power-dependent Ornstein-Uhlenbeck process, and we show that the spectrum is stable for up to 1.5 ms in the dark. We demonstrate a factor-of-35 narrowing of the emitter linewidth to 110 MHz using a resonance-check scheme and discuss the advantage for pairwise entanglement rates and optical-resource-state generators. Finally, we report laser-induced spin mixing in the excited state and discuss potential mechanisms common to both phenomena. These effects must be considered in calibrating T-center devices for high-performance entanglement generation.

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I. INTRODUCTION

Semiconductor point defects are a versatile platform for quantum technologies [1]; they can function as single-photon sources for quantum communication and as resource-state generators for optical quantum computers [2]. If the emitter couples single photons to a local spin qubit, then it may also function as a spin-photon interface (SPI), with applications including quantum repeater networks [3,4] and hybrid spin-photon quantum computing [5–7]. Semiconductor emitters may be integrated directly into nanophotonic optical resonators to enhance their emission rate and coherence through the Purcell effect [8,9].

In turn, these optical resonators can be connected by photonic integrated circuits to prepare large entangled states on chip [10]. However, integration also exposes the emitter to material interfaces and crystal damage that produce charge noise and cause the emission frequency to fluctuate in time [11,12]. Such spectral diffusion (SD, also called spectral wandering) is a critical challenge for practical quantum technologies.

Recently, silicon color centers have emerged as an intriguing category of emitters harnessing the advanced material and nanofabrication capabilities of silicon [13–18]. The silicon T center, for example, is the focus of ongoing commercial efforts to build a spin-photon quantum computer [5,19]. Silicon combines global microelectronics and nanophotonics foundry capabilities with extremely high chemical and isotopic purities [20]. Owing to the mass homogeneity, strain-free environment, and high-quality lattice of their “semiconductor-vacuum” host, the optical transitions of silicon color centers in bulk ²⁸Si crystals can have remarkably low inhomogeneous broadening and spectral diffusion. Popular silicon color centers

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including C and T have demonstrated inhomogeneous linewidths below 60 MHz and the G center can be nearly lifetime limited [21,22]. However, spectral diffusion has proven to be significant in the first generation of silicon color-center devices [13,18,19,23] and increasing the spectral stability closer to their performance in bulk is a critical challenge.

Interference-based entanglement protocols require spectrally matched stable emitters [24,25]. Resonant excitation using a shared narrow-linewidth laser acts as a frequency filter, selecting only emitters that are spectrally aligned. However, spectral diffusion reduces the probability of such alignment by a factor of approximately η_{SD}^2 , where $\eta_{SD} = \Gamma_{\text{hom}} / \Gamma_{SD}$ is the ratio of the SD and homogeneous linewidths. For example, in Ref. [19], SD is shown to decrease the entanglement rate between remote T-center devices by 3 orders of magnitude. Techniques for reducing or mitigating spectral diffusion have been widely explored for other semiconductor emitters. Resonance-check (RC) techniques can confirm both the charge state of diamond color centers (e.g., N-*V*, Si-*V*, and Sn-*V*) and mutual resonance between remote emitters [26,27]. In wide-band-gap semiconductors, spectral diffusion is relatively slow (approximately seconds) [28,29], and hundreds of entanglement attempts may follow a single RC [30]. In contrast, resonantly driven silicon color centers exhibit emission correlations typical of short SD timescales of 5–10 μs [13,19].

In this paper, we investigate spectral diffusion processes in single, cavity-coupled silicon T centers, shown schematically in Fig. 1. We show through spectrally resolved two-photon correlations in the device luminescence that spectral diffusion of the TX_0 transition is driven predominantly by the interaction of the NIR laser and the material. We show that RCs can dramatically narrow the effective linewidth of T centers in devices and that they remain effective for up to 1.5 ms of wait time in the dark. We explore the conditions under which they can achieve a practical speedup for entangled-state generation. Finally, we investigate the effect of NIR laser on the spin of the optically excited bound-exciton state TX_0 . Together, these results illustrate the mechanism of laser-induced spectral diffusion and demonstrate a promising approach to mitigate spectral diffusion in T-center devices. These results have immediate relevance for near-term T-center quantum processors and network demonstrations.

II. SPECTRAL DIFFUSION OF DEVICE-INTEGRATED T CENTERS

We characterize the spectral diffusion dynamics of integrated single T centers with and without near-infrared (NIR) excitation. The T center is a silicon color center combining telecommunications-band optical emission, a ground-state electron spin qubit, and an intrinsic register

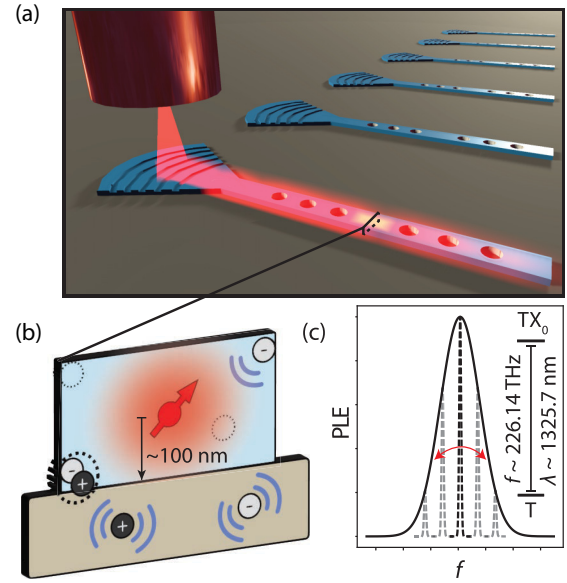


FIG. 1. Spectral diffusion in integrated color-center devices. (a) A one-dimensional silicon photonic crystal cavity is addressed by a resonant laser through an above-chip optical fiber and a grating coupler. (b) A cross-section view showing an integrated T center at the device center. The laser resonates in the single-mode cavity (red). Charge traps at surfaces, interfaces, impurities, and vacancies within the silicon device layer and oxide insulator generate electric fields that perturb the color-center emission frequency. We expect the closest interface to a T center in a cavity to be less than 100 nm away. (c) An illustration of spectral diffusion. The T-center emission frequency fluctuates as the charge environment is reconfigured.

of between one and three nuclear spin qubits depending on isotopic composition [22]. Since it was first proposed for quantum technologies in 2020, it has been integrated with silicon nanophotonics [13,32], Purcell enhanced in nanocavities [14,18,19,33,34], and embedded in *p-i-n* diode devices for electrical control [34,35]. Moreover, these devices exhibit strong qubit performance: one- and two-qubit gates have been realized using the electron and hydrogen nuclear spins; nuclear coherence times exceeding 200 ms have been demonstrated; and indistinguishable emission has been observed between devices in separate cryostats [19]. In high-purity isotopically enriched bulk ^{28}Si samples, the inhomogeneous linewidth of the T center (including static spatial inhomogeneity and SD) is as low as 33 MHz [22], just 15 times the lifetime limit of Purcell-enhanced T centers in devices [19]. However, the typical SD linewidth of integrated T centers observed to date is much larger, at 0.4–4.0 GHz [13,14,18,36].

The centers in our study are integrated in one-dimensional silicon photonic crystal cavities on a silicon-on-insulator (SOI) chip and resonantly excited to the bound-exciton ground state TX_0 . We report results from two devices, T centers I and II, with moderate cavity

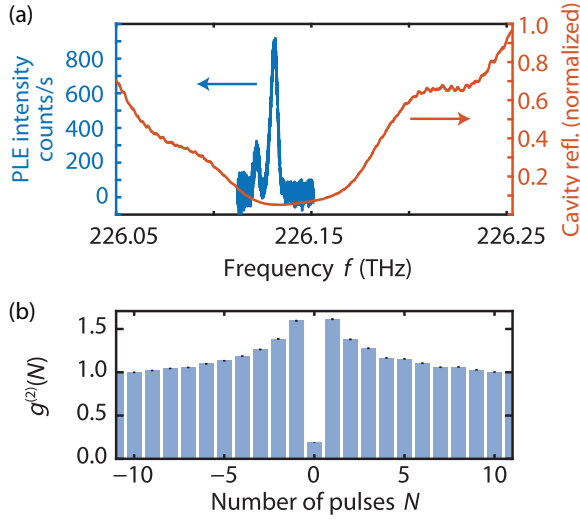


FIG. 2. A representative integrated T-center device (T center II). (a) The photoluminescence excitation (PLE) spectrum at zero magnetic field (blue) and the cavity spectrum measured in reflection (orange). (b) Correlation measurements of the center luminescence under pulsed resonant excitation exhibit a high degree of antibunching with $g^{(2)}(0) = 0.186(4) \ll 1$, confirming that the emission is dominated by a single center. $g^{(2)}(N)$ shows a positive correlation at low pulse separation number N , consistent with spectral diffusion [31].

quality factors $Q_I = 880(40)$ and $Q_{II} = 1743(2)$ such that the cavities can be excited on or off resonance from the T centers. The devices are operated at either 0.27–0.4 K or 1.45–2.5 K in one of two cryostats and addressed by cryogenic optical-fiber arrays (for more details, see the Appendix). In Fig. 2, we show the photoluminescence excitation (PLE) spectrum and $g^{(2)}$ of T center II. Details of the devices reported in this study are provided in the Supplemental Material [37].

A. Two-color correlation

We measure the spectral dynamics using frequency-resolved photon correlation measurements. For this experiment, we choose a device (T center I) with a PLE full width at half maximum linewidth $\Gamma = 1.694(5)$ GHz (standard deviation $\sigma = 0.723(2)$ GHz). Spectral hole-burning measurements of the homogeneous linewidth, Γ_{hom} (see the Supplemental Material [37]) confirm a temporal inhomogeneous broadening factor of $1/\eta_{\text{SD}} = \Gamma/\Gamma_{\text{hom}} = 100(15)$. With the sample at 1.45 K, we detune two submegahertz-linewidth excitation lasers from the PLE peak by frequencies δ_1 and δ_2 . We measure correlations between photons emitted in detection bins corresponding to each of the two excitation frequencies and separated by an interpulse delay of $\tau = 160$ ns, using the pulse sequence in Fig. 3(a). Each pulse is 900 ns in duration and is followed by a 1375-ns collection window. We

fix δ_1 at the center frequency and vary δ_2 across four values as shown in Fig. 3(a). When the detuning difference $\delta_2 - \delta_1 = 0$ (i.e., single-laser PLE), detections in consecutive windows are positively correlated, as observed in the $g^{(2)}$ measurement. The emitter has a spectral diffusion time larger than the pulse sequence length and if it is resonant for the first pulse, it is more likely to be resonant for the second. On the other hand, if the two lasers are separated by 0.97σ , emission into consecutive time bins is anticorrelated, since a finite time is required for the emitter to wander from frequency δ_1 to δ_2 . We model the spectral diffusion as an Ornstein-Uhlenbeck (O-U) process that is active during the excitation pulse [solid lines in Figs. 3(b)–3(d)], parametrized solely by the SD rate, α , and the ratio of background counts to total counts, β [38]. We use a closed-form expression for the correlations and connect it to a discrete-charge microscopic model (details in the Supplemental Material [37]). We obtain β by comparing the uncorrelated PLE count rate as a function of frequency to our background rate. Finally, we extract the SD rate $\alpha = 0.050(2) \mu\text{s}^{-1}$ by jointly fitting the correlation data taken at 1.45 K across multiple detuning values, $\delta_2 - \delta_1 = 0, 0.49\sigma, 0.97\sigma, 1.46\sigma$, and extract a per-pulse rate of $A = \int_{\text{pulse}} \alpha dt = 0.045(2)$. In the short-time limit, α can be understood as an effective diffusion constant [37]. We repeat the measurements at 2.5 K and find a similarly good match to the model (see the Supplemental Material [37]).

To test the SD mechanism, we next investigate how the correlation measurements depend on the laser power [Fig. 3(c)]. Here, we keep $\delta_2 - \delta_1 = 0$ and change between two powers, P_{sat} and $2.86P_{\text{sat}}$, where P_{sat} is the calibrated saturation power. We observe that the correlation amplitude drops with increasing power, consistent with an increase in the SD rate. Hole-burning measurements (see the Supplemental Material [37]) verify that the homogeneous linewidth is effectively constant over this power range. The O-U model (solid lines) agrees well with the ratio of fitted charge-reconfiguration rates, $A(P_{\text{sat}})/A(2.86P_{\text{sat}}) = 0.025(1)/0.079(2) = 0.32(2)$, matching the ratio of powers (0.35), which suggests that the fraction of charges reconfigured per pulse scales with the incident intensity. We further observe that adding a near-resonant laser has the same effect as increasing the resonant power (see the Supplemental Material [37]), indicating that the effect is consistent with a broadband interaction with the host material.

Finally, we increase the delay τ between the two-color pulses from $\tau = 160$ ns to 2560 ns. The resulting correlation curves, shown in Fig. 3(d), differ when plotted as a function of absolute time but show close agreement when the data are plotted as a function of the pulse number, indicating that spectral wandering is negligible during the dark interpulse time. Fitting each data set with a fixed value of

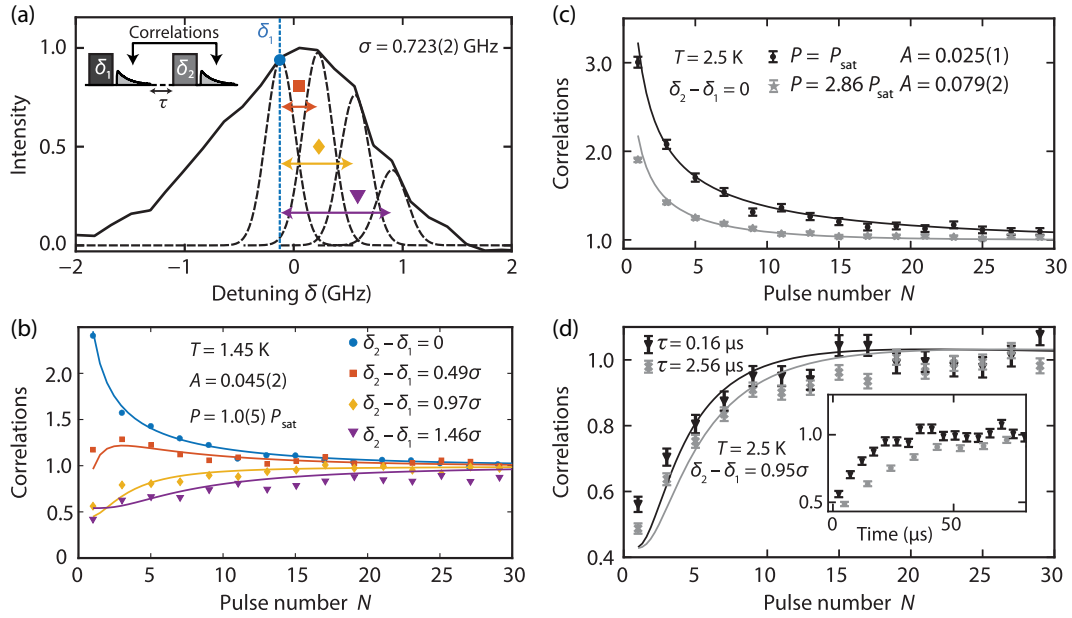


FIG. 3. Two-color correlation measurement. (a) Laser detunings $\delta_{1,2}$ from the center of the inhomogeneous line (solid) and modeled homogeneous lines (dashed). The vertical blue line indicates δ_1 . The inset illustrates the pulse sequence, showing consecutive excitation pulses at detunings $\delta_{1,2}$. Correlations are calculated between photons emitted in detection windows indicated by the gray luminescence transients. (b) Correlations between frequencies $\delta_{1,2}$ as a function of the number of intermediate pulses. The solid lines display a joint single-parameter (A) fit to an O-U model of spectral diffusion. (c) The power dependence of the two-color correlation for two different powers. The correlation amplitude reduces with higher power. (d) The dark-time dependence of the two-color correlation. The curves show closer agreement when plotted as a function of the pulse number compared to when they are plotted as a function of time (inset).

β , we extract $A(\tau = 160 \text{ ns}) = 0.024(2)/\text{pulse}$ and $A(\tau = 2560 \text{ ns}) = 0.019(2)/\text{pulse}$. The fact that A scales with the pulse number and power, rather than time, indicates that the diffusion is driven by the energy delivered by each excitation pulse. This is consistent with the findings of van de Stolpe *et al.*, who have identified laser-induced spectral diffusion in emitters in silicon carbide [39], and analogous behavior observed in Sn- V centers [40]. The slow spectral diffusion of the T center in the absence of optical excitation suggests a strategy for multiemitter alignment: after a successful RC, waiting in the dark may preserve the spectral position of the emitter for long enough to synchronize multiple T centers.

B. Resonance-check spectroscopy

We investigate a RC scheme [26,39] as an initialization step for preceding resource-state generation or bipartite-entanglement attempts. We choose a second device on the same chip (T center II; see the Supplemental Material [37]) at temperature $T = 0.4 \text{ K}$ and apply a series of pulses detuned by δ_1 to prepare the T center at a target optical frequency. Following a photon detection that heralds resonance with the “check” laser, we proceed with the target application. In this case, we perform PLE measurements conditioned on the RC by sending a low-power “probe” pulse at frequency δ_2 after a delay τ , as illustrated in

Fig. 4(a). If SD between the check and probe pulses is negligible, the RC-conditioned PLE linewidth measured by the probe pulse should be narrower than the raw PLE spectrum. Indeed, at the lowest-power setting, check (probe) power $P_{\delta_1} = 0.016P_{\text{sat}}$ ($P_{\delta_2} = 0.008P_{\text{sat}}$), we observe a linewidth of 110(10) MHz, 35 times narrower than the raw PLE linewidth, as shown in Fig. 4(b). Following the RC, the photon-detection probability increases by a factor of 6 (see the Supplemental Material [37]). It is possible that with improvements in detection efficiency, an improvement in RC linewidths may be realized by increasing the number of prerequisite successful check pulses [39].

To test for spectral diffusion in the absence of excitation, we vary the dark interval τ and monitor the RC linewidth at low temperatures, $T = 0.27 \text{ K}$. To improve count rates, we increase the powers for the check and probe lasers to $P_{\delta_1} = 0.19P_{\text{sat}}$ and $P_{\delta_2} = 0.11P_{\text{sat}}$. At these powers, the $\tau = 0$ RC-conditioned linewidth is 1.2(1) GHz and shows no significant broadening out to $\tau = 1.5 \text{ ms}$ [Fig. 4(c)]. However, we observe a small increase in linewidth at $\tau \gtrsim 2.5 \text{ ms}$ (see the Supplemental Material [37]). Independent T-center devices can therefore be prepared by RCs and remain stable for milliseconds—sufficient time to prepare additional devices.

RC schemes offer considerable advantages in scaling SPIs to generate large optical-resource states [41–43] by preparing N qubits with identical optical frequencies.

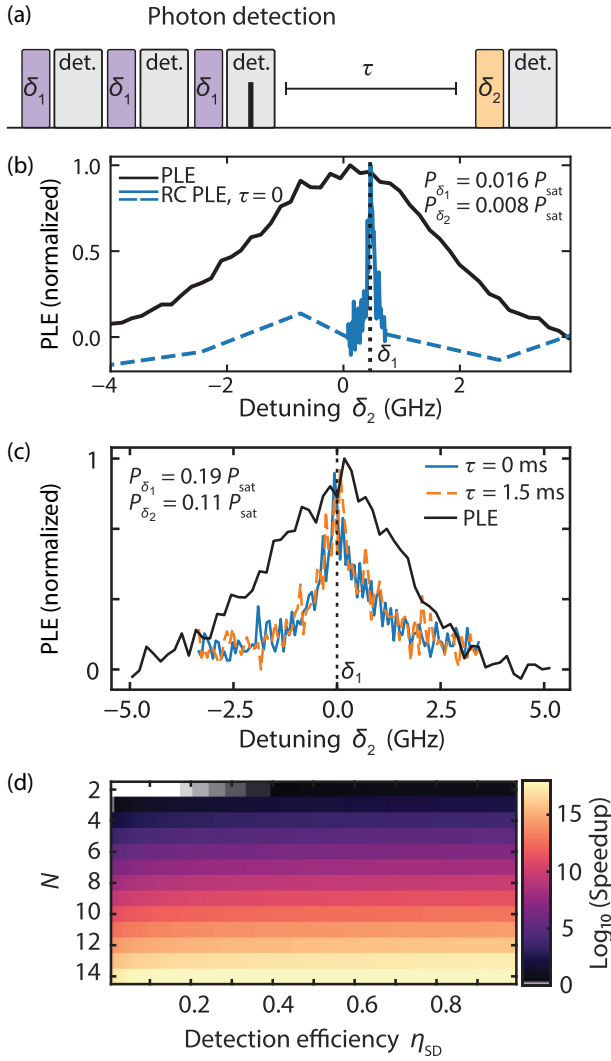


FIG. 4. The resonance-check (RC) PLE scheme. (a) The experimental pulse sequence. We excite at check frequency δ_1 until a photon is detected, which triggers a probe pulse at frequency δ_2 after delay τ . (b) Background-subtracted RC PLE (solid blue, high resolution; dashed blue, low resolution) compared to regular PLE (black), showing the linewidth narrowing to $\Gamma = 110(10)$ MHz. (c) RC PLE with dark wait time, τ . We measure broadening in the absence of laser excitation as a function of the wait time and observe no significant broadening out to 1.5 ms. (d) Simulated N -qubit entangled-state preparation using parallel RC PLE, with parameters corresponding to T center II. The speedup, defined as τ^*/τ_{RC} , where τ_{RC} is the time required to obtain N resonant photons from N independent T centers prepared with RC PLE and τ^* is the time it takes to obtain N resonant photons from N independent T centers prepared conventionally. White indicates the region in which no speedup is expected.

Interference-based remote entanglement schemes such as the Barrett-Kok protocol [24], demonstrated with T-center devices in Ref. [19], require $N = 2$ spectrally indistinguishable qubits, but optical-resource-state-generator

schemes can require many simultaneously resonant emitters. In the example scheme proposed by Wein *et al.*, 12 SPIs are first entangled by pairwise operations, before all $N = 12$ are required to emit simultaneously at the target frequency [44].

We derive the expected number of attempts T required to prepare N qubits by RC:

$$\mathbb{E}[T] = \sum_{j=1}^N (-1)^{j+1} \binom{N}{j} \frac{1}{1 - (1 - \eta_{\text{SD}}\eta_{\text{det}})^j}, \quad (1)$$

where η_{det} is the detection efficiency. If the effective linewidth ratio under the RC scheme is given by η'_{SD} , the resulting speedup in preparing N qubits is

$$\text{Speedup} = \frac{(\eta'_{\text{SD}}/\eta_{\text{SD}})^N}{1 + \mathbb{E}[T]}, \quad (2)$$

which is shown as a function of N and η_{det} in Fig. 4(d). Even for small N , the improvement can be many orders of magnitude. Moreover, the RC scheme also offers benefits in protocols that involve long spin-control sequences or sequential photon generation, where each step depends on the success of prior emission events [45].

III. LASER-INDUCED EXCITED-STATE SPIN MIXING

We observe a second laser-driven effect causing TX_0 spin mixing, which disrupts the cyclicity of otherwise spin-conserving transitions and reduces the fidelity of repeated spin-photon entanglement cycles. We apply a magnetic field $B = 755$ mT along [110] to T center II with a superconducting Helmholtz-coil pair to lift the spin degeneracy, as shown in Fig. 5(a), and operate at $T = 0.4$ K to reduce postpulse thermal effects. We prepare either of the two TX_0 states $|h \uparrow\rangle$ (red) and $|h \downarrow\rangle$ (purple) by spin-selective excitation and align a fiber Fabry-Perot interferometer to filter spin-selective luminescence from the C transition, which allows us to measure the population in $|h \uparrow\rangle$. In Fig. 5(b), we show the $|h \uparrow\rangle$ population as a function of time for both spin-preparation schemes, where n_1 and n_2 are the populations following preparation of $|h \downarrow\rangle$ and $|h \uparrow\rangle$, respectively. The left panel shows relative populations for low-power preparation ($P = 0.045 P_{\text{sat},B}$), while the right panel shows high-power preparation ($P = 10.2 P_{\text{sat},B}$), where $P_{\text{sat},B}$ is the at-field saturation power. Single exponential fits match the decay with no measurable indication of post-pulse thermalization. The two closest transitions, B and C , have a peak-to-peak separation of 11.05(3) GHz compared to the Gaussian inhomogeneous linewidth of 4.10(1) GHz at $P = 11.2 P_{\text{sat},B}$. We rule out confounding effects of off-resonant driving by measuring PLE spectra at powers higher than $10.2 P_{\text{sat},B}$ (for details, see the Supplemental Material [37]).

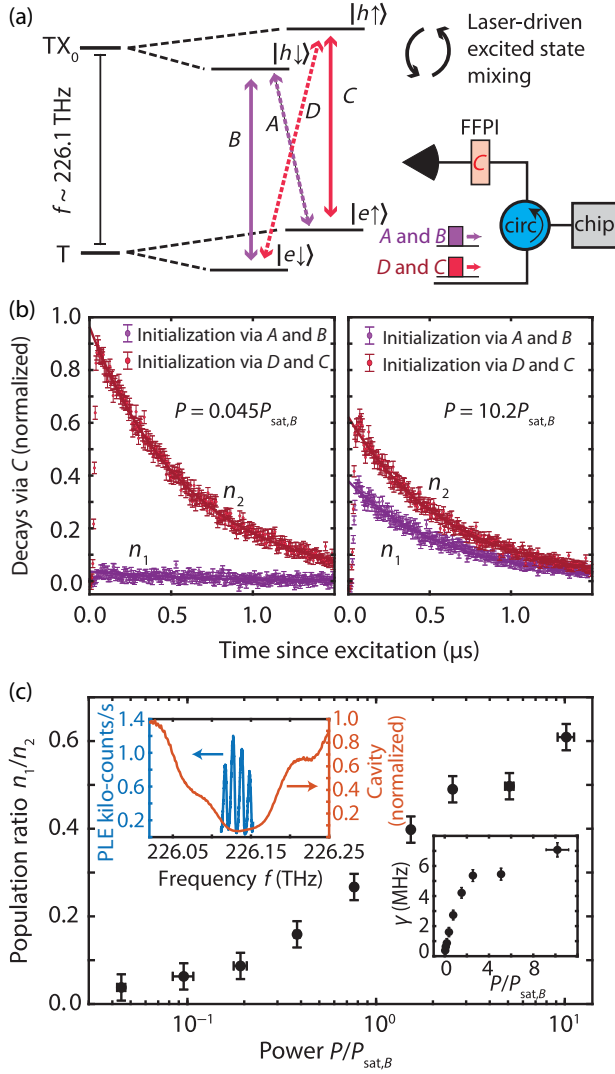


FIG. 5. The TX_0 spin populations as mixed by laser power. (a) The level diagram of T center II under an applied field and the experiment schematic. (b) Time-resolved decay measurements showing the populations converging at higher excitation powers, indicating increased spin mixing. Powers are quoted in the at-field saturation power, $P_{\text{sat},B}$. (c) The population ratio n_1/n_2 as a function of the excitation power. The insets show the at-field PLE spectrum for this T center (top) and the extracted mixing rate γ versus the power (bottom).

The ratio n_1/n_2 corresponds to the degree of spin mixing (given equal mixing rates, as shown in the Supplemental Material [37]) and increases from 0 (no mixing) to approximately 0.6 with increasing excitation power, as shown in Fig. 5(c). Assuming perfect spin-state initialization and uniform excitation during the pulse, we define an effective mixing rate

$$\gamma = \frac{1}{2T} \ln \left(\frac{n_2 + n_1}{n_2 - n_1} \right), \quad (3)$$

plotted in the inset of Fig. 5(c). Finally, we find that excited-state spin mixing is not a resonant effect. When the experiment is repeated at low resonant powers with additional high-power off-resonant light, we observe similar levels of mixing (see the Supplemental Material [37]). Electric field coupling to hole g factors has been observed in quantum dots [46–48]. We speculate that analogous mechanisms may be present in the bound T-center exciton, where local charges that reconfigure the spectral diffusion environment may also couple to the hole g factor, inducing a finite spin-flip rate. This mixing effect reduces the optical cyclicity, C , the average number of optical cycles before the spin-state flips, of T-center devices below the dipole branching-ratio limit [49]. This means that the spin-flip error-channel probability per emitter per π -pulse is $1/C$, with consequences for quantum nondemolition readout by resonant excitation and for remote entanglement schemes requiring cyclic transitions [24].

IV. DISCUSSION AND CONCLUSIONS

Our results establish the significance of laser-induced effects for silicon color-center emitters and SPIs. We find that the spectral diffusion of T centers in nanophotonic devices is primarily induced by the NIR excitation laser and, using an RC scheme, we achieve a factor-of-35 reduction in effective linewidth to 110(10) MHz. We expect that the RC linewidth can be further reduced toward the homogeneous limit (32 MHz; for information on the homogeneous linewidth, see Table I in the Supplemental Material [37]) by optimizing the check and probe pulses. We find that the RC linewidth remains stable for up to approximately 1.5 ms, long enough for practical advantage. Along with concurrent work in Ref. [50], this is the first demonstration of a functional RC scheme for silicon color centers to our knowledge.

Effective RCs enhance the feasibility of interference-based silicon color-center quantum technologies, increasing emission efficiencies for resource-state generation and other protocols requiring spectrally matched emitters or photons. Under a wide range of conditions, RCs can improve the performance of even pairwise ($N = 2$) entanglement schemes [51]. We anticipate that the scheme introduced here can be applied to improve the entanglement rate of prototype T-center repeaters, network hubs, and spin-photon processors [5,19].

Finally, we observe laser-induced spin mixing in the optically excited bound-exciton state TX_0 . We suggest that these two laser-induced effects have the same root cause. A broad low-intensity band, likely a superposition of donor- and acceptor-pair bands, is common to radiation-damaged silicon photoluminescence and underlies the sharp emitter lines of T and other silicon color centers. This band may be due to donor- and acceptorlike damage centers. We observe that the NIR excitation laser,

detuned from the T center or any other sharp lines, drives luminescence from this broad band. This indicates that the laser is weakly photoneutralizing these ionized defects so that they can recombine and luminesce. Such laser-driven charge fluctuations would cause T-center spectral wandering and could also couple to the TX_0 hole state to induce spin-state mixing.

Photoinduced spectral diffusion has been extensively studied in quantum dots [52–54]. These studies identify surface traps and charge traps in surrounding oxide layers as major contributors to spectral diffusion [55,56] and the same mechanisms may be present at the interfaces and oxide layers of our devices. Efforts to passivate quantum dot surfaces have led to significant improvements in spectral stability [56] and the same engineering approaches may, in the longer term, reduce the silicon color-center spectral diffusion closer to their performance in bulk, and perhaps make RCs redundant. Whether surface charges or volume charges dominate the spectral diffusion may be answered as smaller mode volume cavities are explored: as mode volumes become smaller, the power density at surfaces may also decrease. The results described in this paper are critical for understanding and mitigating laser-driven processes that limit the fidelity and success rate of multiqubit entanglement sequences with silicon T centers and should be relevant to a broad class of emerging devices, as well as electronically similar silicon color centers [57].

Note added. We have recently become aware of related work by Zhang *et al.* [50].

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DATA AVAILABILITY

The data that support the findings of this paper are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX: METHODS

1. Sample

T centers are generated in a float-zone *p*-type SOI chip using a multistage implant-and-anneal process following MacQuarrie *et al.* [36]. The photonic devices are patterned by electron-beam lithography and etched into the chip. We use quadratically tapered L0 nanobeam cavities ([58]) with the cavity axis along [110] to enhance our T-center emission rate through the Purcell effect. We find quality factors of $Q = 600$ –2000. Single-mode waveguides couple the nanobeam cavities to on-chip diffraction-grating couplers with 6 THz bandwidths centered between 223.7 THz and 228.9 THz that couple light into and out of the chip via optical fibers.

2. Apparatus

For the two-color spectroscopy, two fiber-coupled tunable continuous-wave lasers (Toptica CTL) are pulsed independently and combined. Each laser is frequency locked to a Bristol wave meter. Pulsing is achieved using a booster optical amplifier (BOA) and an electro-optical modulator (EOM). We adjust the power of each laser using a combination of manual variable optical attenuators (VOAs) and electrically variable optical attenuators (EVOAs). The two lasers are combined using a fiber-coupled 50:50 beam splitter and then a circulator connects them to polarization-maintaining fibers that feed into a custom cryogenic fiber array to deliver light to the sample held at temperatures between 1.45 and 2.5 K in an ICE Oxford He flow cryostat. Reflected laser light and T-center emission are collected through the same fiber path and routed to superconducting nanowire single-photon detectors (SNSPDs) housed in a separate cryostat (IDQ 281). The excitation pulse length (t_{exc}) for the correlation measurements taken at 1.45 K was 800 ns. At 2.5 K, $t_{\text{exc}} = 800$ ns.

The configuration for the RC measurements is the same as for the two-color correlation measurements with two additional components: an AOM is placed in the excitation path between the EOM and the circulator to improve the pulse extinction ratio, and an AOM is inserted in the collection path between the circulator and the SNSPDs to prevent detector saturation during the excitation pulse. In this experiment, the samples are housed in a Bluefors LD400 dilution refrigerator, with the devices thermally

anchored to a mixing plate held at 0.27 K. For the RC measurements, $t_{\text{exc}} = 100$ ns.

The configuration for the $g^{(2)}$ measurement is the same as for the RC measurements except that an additional 50:50 beam splitter is placed in the collection path after the AOM. Each output of the 50:50 beam splitter is sent to separate SNSPD channels in the same cryostat. For T centers I, II, and III, we have used $t_{\text{exc}} = 900$, 100, and 800 ns, respectively.

The configuration for the laser-induced hole-spin mixing is the same as the RC measurements without the AOM in the excitation path and operating at 0.4 K. A 50:50 beam splitter is placed in the collection path after the collection AOM. One output of the 50:50 beam splitter passes through a fiber-coupled temperature-tunable Fabry-Perot interferometer with a bandwidth of 0.985 GHz and a free spectral range of 102.4 GHz (LUNA Innovations). Two optical isolators are placed before and after the interferometer to suppress reflections. The signal at the output of the isolator is then sent to one SNSPD. The other output of the 50:50 beam splitter is connected directly to a second SNSPD in the same cryostat. For the laser-induced hole spin mixing, $t_{\text{exc}} = 100$ ns.

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