

Enhanced Light-Matter Interactions for a Single T Center in a Silicon Nanocavity

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Abstract: We investigate light-matter interactions for a single T center coupled to a silicon photonic crystal cavity. By solving Lindblad master equation, we extract the cavity-QED parameters for the coupled system. © 2024 The Author(s)

Color centers in silicon have been investigated recently as promising candidates for quantum information applications. Their compatibility with the technologically mature silicon platform enables a tantalizing system scaling capability. In particular, T centers in silicon hold great promise due to their telecom O-band optical transitions, the doublet ground state spin manifold, and the long spin coherence time [1]. To advance the T centers in silicon platform, challenges remain to enhance their weak and slow zero phonon line (ZPL) transitions. We have performed photoluminescence excitation (PLE) spectroscopy and demonstrated the Purcell enhancement of the fluorescence decay rate for a single T center [2] in a low-loss, small mode-volume silicon photonic crystal (PC) cavity (Fig. 1). To elucidate the process of the cavity-enhanced light-matter interactions for the single T center, we build a numerical model based on solving the Lindblad master equation to describe the cavity-QED of the coupled system. The work will lay the foundation for designing cavity-mediated multi-qubit gates for single T centers towards quantum information and networking applications.

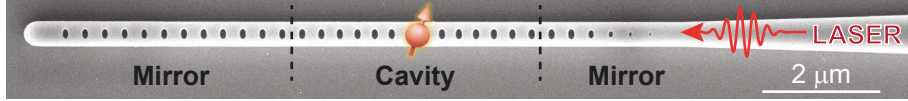


Fig. 1: Illustration of a T center, which acts like an artificial atom with two energy levels, coupled to a single-sided silicon PC cavity. The pulsed laser excitation enters the cavity from the right side.

The dynamics of the coupled system can be well described by the Jaynes-Cummings model with the rotation wave approximation and in the rotating frame of the laser field (ω_L),

$$H/\hbar = \Delta_a \sigma_+ \sigma_- + \Delta_c \hat{a}^\dagger \hat{a} + g(\sigma_+ \hat{a} + \sigma_- \hat{a}^\dagger) + \frac{\Omega}{2}(\sigma_+ + \sigma_-), \quad (1)$$

where $\hat{a}$ and σ_- are the annihilation operators for the cavity mode and the T center ZPL transition, $\Delta_a = \omega_a - \omega_L$ and $\Delta_c = \omega_c - \omega_L$ are respectively the detunings of the laser from the T center ZPL transition ω_a and from the cavity resonance ω_c , and g is the coupling strength between the single T center and the cavity. The optical Rabi frequency $\Omega = 2g\sqrt{N_{\text{ph}}}$, where the intracavity photon number relates to the laser excitation power by the equation [3],

$$N_{\text{ph}} = \frac{P_{\text{in}}}{\hbar\omega_L} \frac{4\eta_{\text{cav}}/\kappa}{1 + (2\Delta_c/\kappa)^2}, \quad (2)$$

where $\eta_{\text{cav}} = \kappa_{\text{wg}}/\kappa$, P_{in} is the input power to the cavity, κ_{wg} is the photon coupling rate between the waveguide and the cavity. To solve the dynamics of this open quantum system, we utilize the QuTip [4] package to solve the Lindblad master equation:

$$\dot{\rho}(t) = -\frac{i}{\hbar} [H, \rho(t)] + \sum_{\omega, i} \left(C_i(\omega) \rho(t) C_i^\dagger(\omega) - \frac{1}{2} \{ C_i^\dagger(\omega) C_i(\omega), \rho(t) \} \right), \quad (3)$$

where $\rho(t)$ is the density matrix, C_i are the jump operators describing different loss mechanisms. We adopt three major losses in the system: cavity photon loss $C_{sc} = \sqrt{\kappa}\hat{a}$, T center spontaneous decay $C_{sp} = \sqrt{\Gamma_0}\sigma_-$, where Γ_0 is spontaneous emission rate in bulk silicon, and dephasing $C_d = \sqrt{\Gamma_d/2}\sigma_z$, where Γ_d is the pure dephasing rate. To take into account the spectral diffusion (Γ_{sd}) of the single T

center, we perform a weighted average of the numerical calculation results assuming Δ_a takes a range of values with each weight determined by a Gaussian distribution with a full width half maximum linewidth of $2\Gamma_{sd}$. To extract the cavity-QED parameters, we perform a multi-parameter global fitting of the single T center saturation (Fig. 2a), power-dependent linewidth (Fig. 2b), and detuning-dependent fluorescence decay rate (Fig. 2c) results. The fitting reveals the full set of cavity-QED parameters $(g, \kappa, \Gamma_0) = 2\pi \times (42.4 \text{ MHz}, 5.22 \text{ GHz}, 169.3 \text{ kHz})$, as well as an excited-state dephasing rate $2\Gamma_d = 2\pi \times 1.29 \text{ GHz}$ and a spectral diffusion $\Gamma_{sd} = 2\pi \times 1.69 \text{ GHz}$. The characteristic linewidth of the detuning-dependent decay rate $\tilde{\kappa}/2\pi = 7.11 \pm 0.09 \text{ GHz}$ has contributions from the Γ_d and Γ_{sd} beyond the cavity linewidth κ . In a hypothetical case with a negligible Γ_{sd} , the linewidth $\tilde{\kappa} \approx \kappa + 2\Gamma_d$. Based on the extracted system parameters, we predict the single T center's PLE spectra (Fig. 3a) and fluorescence emission (Fig. 3b) at different atom-cavity detuning Δ_{ac} , both of which match well with the experimental results.

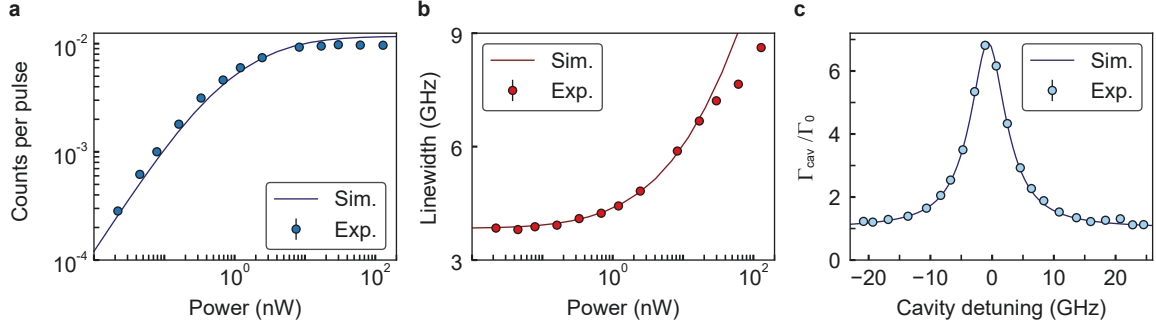


Fig. 2: **a.** Saturation of the single T center emission under the condition $\Delta_a = \Delta_c = 0$. **b.** Gaussian-fitted spectrum linewidth when atom-cavity detuning $\Delta_{ac} = 0$. **c.** Cavity-enhanced fluorescence decay rate at different cavity detunings. The excitation laser power is $P_{in} = 1.21 \text{ nW}$.

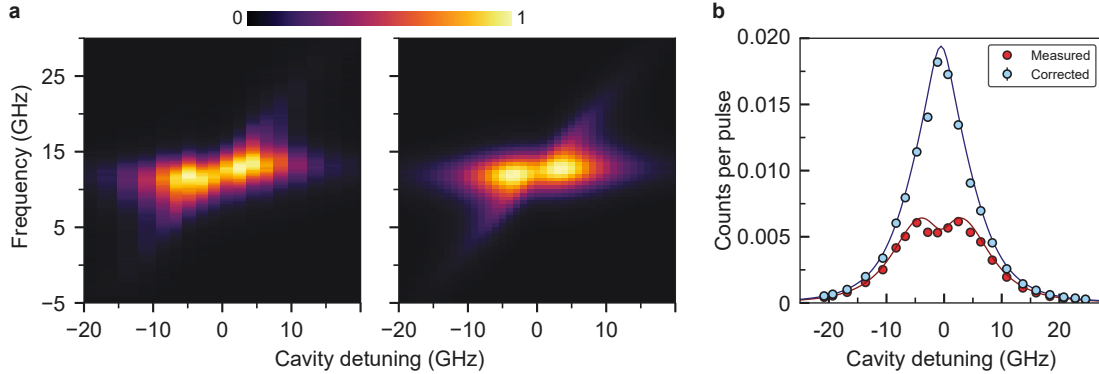


Fig. 3: **a.** Measured (left) and simulated (right) PLE spectra at different Δ_{ac} with $P_{in} = 1.21 \text{ nW}$. **b.** T center fluorescence measured when $\Delta_a = 0$. Due to technical difficulties, the first 170 ns of the fluorescence cannot be collected, causing lower counts when the cavity is near-resonant. The blue dots are corrected counts by assuming all counts can be collected. Solid lines are from numerical calculation results.

In summary, we have developed a numerical model that describes the cavity-QED of the single T center coupled to a silicon nanophotonic cavity. With the realistic improvement of the cavity quality factor and single T center linewidth, the coupled system can reach the strong coupling regime with a large atom-cavity cooperativity $C \geq 29$. The theoretical framework discussed here can be implemented to investigate the enhanced light-matter interactions in such a regime, which can enable future applications of high-fidelity dispersive spin readout and cavity-mediated multi-qubit gate operations.

References

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