Purcell Enhancement of a Single T Center Coupled to a Silicon Nanophotonic Cavity

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Abstract: We demonstrate Purcell enhancement of a single T center integrated in a silicon photonic crystal cavity, increasing the fluorescence decay rate by a factor of 6.89 and achieving a photon outcoupling rate of 73.3 kHz.

In recent years, optically interfaced solid-state spins have risen as promising candidates for various quantum technologies [1]. Among them, T centers in silicon possess attractive properties for quantum networking applications, including optical transitions in the telecommunication O-band that allow for low-loss photon transmission through optical fibers, as well as long-lived electronic and nuclear spin manifolds [2]. Additionally, they can benefit from the technologically mature silicon platform, enabling their integration with on-chip photonic and electronic devices. In spite of recent advances for the generation of single T centers in nanophotonic structures to improve the photon extraction efficiency [3, 4], challenges remain to enhance the T centers' weak and slow coherent emission at the zero phonon line (ZPL). Here, by integrating a single T center with a low-loss, small mode-volume silicon photonic crystal (PC) cavity [5], we demonstrate the Purcell enhancement of its fluorescence decay rate by a factor $F = 6.89$, as well as a high ZPL photon outcoupling rate of 73.3 kHz.

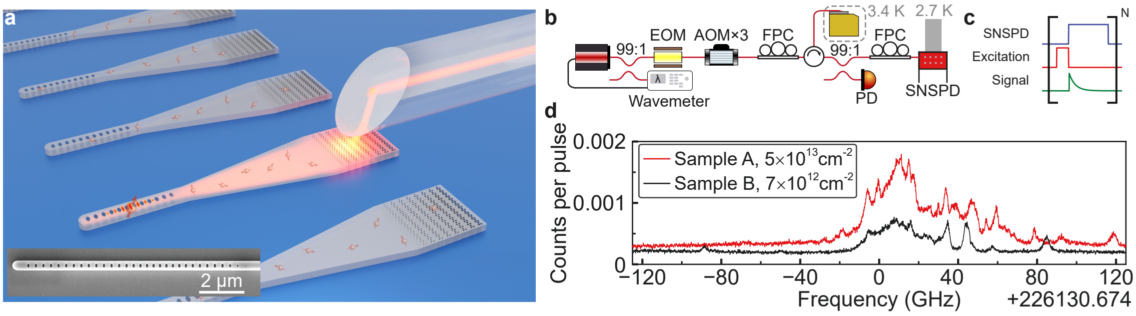

Fig. 1: **a.** Illustration of nanophotonic devices with integrated T centers (solid red balls with arrows) being excited by laser pulses delivered via an angle-polished fiber through grating couplers. The inset shows a scanning electron microscope image of a typical PC cavity. **b.** Simplified schematic of the experimental setup. **c.** Pulse sequence for the PLE spectroscopy. **d.** PLE spectra of two devices with different implantation fluences when the PC cavity is far-detuned (> 200 GHz) from the frequency scanning range.

T centers are generated in the device layer of silicon-on-insulator (SOI) samples via ion implantation [6], with a 1:1 implantation fluence ratio of ^{12}C and ^{1}H. Nanophotonic devices are subsequently fabricated, with each device consisting of a subwavelength grating coupler (GC) and a one-dimensional PC cavity, connected by a linearly tapered waveguide (Fig. 1a). Optical coupling is achieved using an angle-polished fiber via the GC with a one-way coupling efficiency of $\eta_{GC} = 46.1\%$ at 1326 nm. The PC cavity used in this work has a linewidth of 5.22 ± 0.04 GHz, which corresponds to a quality factor $Q = 4.3 \times 10^4$. Devices are mounted on the cold finger of a closed-cycle cryostat at $T = 3.4$ K, and the T centers' fluorescence is detected by a fiber-coupled superconducting nanowire single photon detector (SNSPD) (Fig. 1b). We perform time-resolved photoluminescence excitation (PLE) spectroscopy to probe T centers using the pulse sequence shown in Fig. 1c.

Figure. 1d shows the measured PLE spectra for devices with different implantation fluences when the PC cavity is far-detuned from the scan range. The spectra reveal an inhomogeneous distribution linewidth $\Gamma_{inh} \approx 29$ GHz. Isolated T center peaks can be identified away from the inhomogeneous distribution center, which have an average linewidth and fluorescence lifetime of 2.40 ± 0.86 GHz and 836.8 ± 57.3 ns, respectively. When the PC cavity is tuned in-range by N_2 gas condensation, a T center peak located at around 11 GHz emerges (Fig. 2a) with a fluorescence intensity significantly surpassing other isolated peaks (Fig. 1d). At a low input power, this cavity-coupled single T center reveals a linewidth of $\Gamma = 3.81 \pm 0.07$ GHz. To verify the single-emitter nature of this cavity-coupled T center, we measure the second-order autocorrelation function $g^{(2)}$ of its fluorescence after each excitation pulse, which shows a strong antibunching with $g^{(2)}(0) = 0.024 \pm 0.018$ (Fig. 2b).

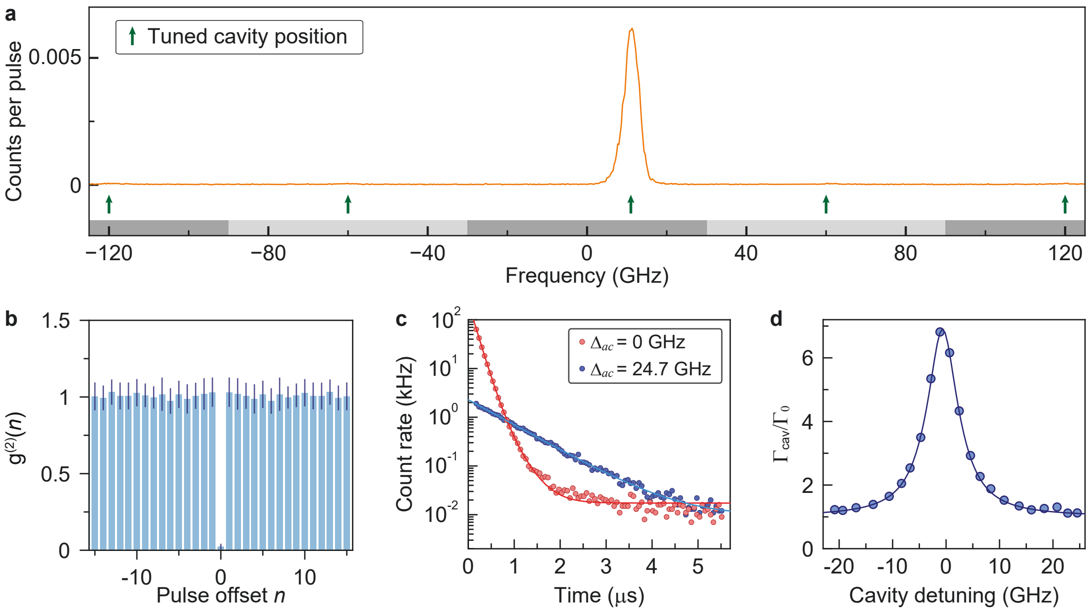

Fig. 2: **a.** PLE spectrum of the device with an implantation fluence of 7×10^{12} cm^{-2} (sample B). The PC cavity is tuned within the scanning range. The green arrows indicate the cavity position for each scanning range shaded in the x-axis below the arrows. **b.** Second-order autocorrelation measurement for the cavity-coupled T center with a laser excitation power $P_{\text{in}} = 2.47$ nW. **c.** Time-resolved fluorescence decay under saturation ($P_{\text{in}} = 17.01$ nW) at different cavity detunings (Δ_{ac}), with fitted decay lifetimes (solid lines) of 136.4 ± 0.6 ns and 835.2 ± 3.1 ns for $\Delta_{ac} = 0$ GHz and $\Delta_{ac} = 24.7$ GHz, respectively. **d.** Cavity-coupled T center decay rate as a function of Δ_{ac} under $P_{\text{in}} = 1.21$ nW. The solid line shows the results from the numerical calculations by solving the Lindblad master equation.

When the cavity is tuned into resonance with the T center ZPL, its fluorescence lifetime is shortened to 136.4 ± 0.6 ns (Fig. 2c), which is 6.89 ± 0.03 times faster than the bulk lifetime of $1/\Gamma_0 = 940$ ns [2]. Under this resonance condition, the saturated average ZPL outcoupling rate is 73.3 kHz. To confirm the decay rate enhancement originates from the cavity coupling, we measure the fluorescence decay rate (Γ_{cav}) at different cavity detunings (Fig. 2d), which can be described as $\Gamma_{\text{cav}}/\Gamma_0 = P_t/[1 + (2\Delta_{ac}/\tilde{\kappa})^2] + \Gamma_\infty/\Gamma_0$, where $P_t = 5.88\pm0.04$ is the Purcell factor, $\Gamma_\infty = (1.03\pm0.02)\Gamma_0 \approx \Gamma_0$ is the decay rate at large detunings, and $\tilde{\kappa}/2\pi = 7.11 \pm 0.09$ GHz is the characteristic linewidth. This linewidth has contributions from the cavity linewidth κ, as well as from the dephasing rate Γ_{d} and spectral diffusion Γ_{sd}. By solving the Lindblad master equation for this coupled system, we achieve a good agreement between the experimental data and the numerical calculations, which reveals the cavity-QED parameters $(g, \kappa, \Gamma_0) = 2\pi\times(42.4$ MHz, 5.22 GHz, 169.3 kHz$)$, $2\Gamma_{\text{d}} = 2\pi \times 1.29$ GHz and $\Gamma_{\text{sd}} = 2\pi \times 1.69$ GHz. The results also enable us to put a lower bound on the quantum efficiency $\eta_{\text{QE}} \geq 23.4\%$ for the single T center.

In summary, we demonstrate the Purcell enhancement of a single T center coupled to a low-loss, small mode-volume silicon photonic cavity. This work represents an important step towards utilizing T centers in a scalable silicon photonic platform for quantum information processing and networking applications.

References

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