Frequency Tunable Single-Photon Emission From a Single Atomic Defect in a Solid

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Abstract: We demonstrate generation of frequency tunable single-photon emission based on cavity-enhanced Raman emission from a single silicon-vacancy center in diamond. The demonstrated frequency tuning range (100 GHz) significantly exceeds the spectral inhomogeneity of the emitters.

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1. Introduction

Integration of solid-state quantum emitters with nanophotonic structures offers a scalable quantum photonics platform that is essential for photonic quantum simulation, quantum metrology, quantum repeaters, and quantum networks. However, despite significant progress with single solid-state qubits [1-4], a scalable quantum photonic circuit consisting of many quantum emitters remains an outstanding challenge. One major obstacle toward this goal is the spectral inhomogeneity of solid-state quantum emitters, which limits their prospects in realizing many-body interactions through exchange of photons. The ability to tune the emission frequency of a solid-state quantum emitter across the full range of inhomogeneous broadening remains a key missing ingredient in developing scalable quantum photonic circuits.

Color centers in solids have recently shown great promise for applications in scalable quantum photonic circuits, largely owing to their narrow spectral inhomogeneity. One of the candidates that has attracted significant interests in recent years is the negatively charged silicon-vacancy (SiV^-) center in diamond. The SiV^- centers possess narrow inhomogeneous broadening on the order of 1 GHz in high quality diamond. They also exhibit many excellent spin and optical properties that make them promising as optically accessible quantum memories. However, once embedded in nanostructures, SiV^- centers typically display a much larger spectral inhomogeneity (>20 GHz) than bulk. This large spectral inhomogeneity remains a major limiting factor for photon-mediated many-body interactions.

In this paper, we demonstrate cavity-enhanced Raman emission from a single color center [5]. We show that an optical cavity enables a frequency tuning range of 100 GHz for Raman emission from a single SiV^- center in diamond, which significantly exceeds the typical spectral inhomogeneity of the SiV^- centers in nanostructures. In addition, we show that the cavity can selectively suppress the spontaneous emission and only enhance the Raman photon generation. Our results represent an important step towards the implementation of scalable quantum circuits and quantum networks that involve multiple solid-state quantum emitters in an integrated nanophotonic platform.

2. Working Principle

Figure 1(a) shows the energy level structure of a single SiV^- center. We utilize the Λ-system formed by the lower excited state (labeled as $|e\rangle$) and the two ground states (labeled as $|g_1\rangle$ and $|g_2\rangle$) to generate tunable Raman emission. We optically drive transition $|g_1\rangle \leftrightarrow |e\rangle$ using a continuous-wave laser with a Rabi frequency given by Ω, and couple transition $|g_2\rangle \leftrightarrow |e\rangle$ to a cavity with a coupling strength given by g (vacuum Rabi frequency of $2g$). We set the detuning between the driving laser and transition $|g_1\rangle \leftrightarrow |e\rangle$ to be identical to the detuning between the cavity and transition $|g_2\rangle \leftrightarrow |e\rangle$ (both are given by Δ) in order to achieve Raman resonance. Under this configuration, we are able to generate a single photon by first pumping the ground state from $|g_1\rangle$ to the virtual excited state, followed by an emission of a single photon into the cavity. The frequency of the emitted photon is tunable since the actual excited state is not populated during the whole process.

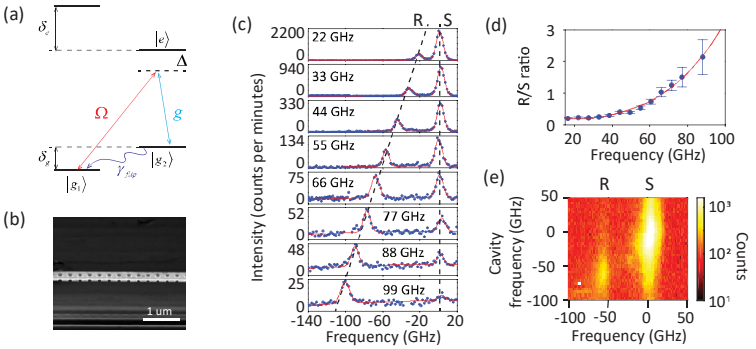

Figure 1 | (a) Energy level structure of a SiV^- center; (b) Scanning electron microscope image of a fabricated nanobeam photonic crystal cavity in diamond. (c) Cavity emission spectra as we vary the excitation detuning Δ. (d) Ratio between the Raman and spontaneous emission intensity as we vary the excitation detuning Δ. (d) Cavity emission spectra as we tune the cavity across both the spontaneous and Raman emission peaks.

3. Device fabrication and characterization

We couple a single SiV^- center with a monolithic diamond nanobeam photonic crystal cavity [6]. Figure 1(b) shows a scanning electron microscope image of the fabricated cavity. The device fabrication starts with homoepitaxial growth of a thin layer of diamond on a single-crystal diamond substrate using microwave plasma chemical vapor deposition (MPCVD). We place a silicon wafer underneath the diamond substrate to generate silicon atoms in the growth chamber through hydrogen plasma etching, which then form SiV^- centers due to plasma diffusion [7]. We then fabricate nanobeam photonic crystal cavities using electron beam lithography followed by angled etching of the bulk diamond to create a nanobeam. We perform all the measurements in a closed-cycle cryostat at 4 K. We perform sample excitation and collection using a home-built confocal microscope, which has an objective lens with a numerical aperture of 0.9.

4. Results

Figure 1(c) shows the measured emission spectrum as we vary the detuning Δ. We observe two distinct peaks in the measured spectra, labeled as *R* and *S* respectively. The emission peak *R* continuously red shifts as we increase the detuning Δ, corresponding to the cavity-enhanced Raman emission. The emission peak *S* remains centered around the natural frequency of $|g_2\rangle \leftrightarrow |e\rangle$, which is originated from incoherent excitation of the system into the state $|e\rangle$ followed by spontaneous emission via transition $|e\rangle \rightarrow |g_2\rangle$. We are able to achieve a tuning range of 99 GHz for the Raman emission, which significantly exceeds the typical spectral inhomogeneity of the SiV^- centers in nanostructures. Besides an unprecedented tuning bandwidth, the cavity also enables selective enhancement of Raman emission as we spectrally detune the Raman emission away from the emitter resonance. To quantitatively show this effect, we extract the ratio between the Raman and spontaneous emission intensity (referred as the R/S ratio) at each detuning, as shown in Fig. 1(d). The R/S ratio increases by a factor of 10 when we increase the detuning from 15 GHz to 88 GHz. Figure 1(e) verifies that the selective enhancement at large detuning originates from the cavity.

5. Discussion

In conclusion, we have demonstrated cavity-enhanced Raman emission from a single SiV^- center. The cavity enables an unprecedented frequency tuning range of 99 GHz, which significantly exceeds the typical spectral inhomogeneity of SiV^- centers in nanostructures. We also demonstrate that the cavity selectively enhances only the Raman emission, which is critical for achieving high-fidelity photon-mediated many-body interactions. Ultimately, our results represent an important step towards developing chip-integrated quantum circuits and quantum networks that employ multiple solid-state qubits mediated by single photons in a nanophotonic platform.

6. Acknowledgement

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7. References

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