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Quantum Non-linear Optics with a Diamond Tin-Vacancy Center in a Fiber-based Microcavity

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Abstract: We demonstrate coherent coupling of a single diamond Tin-Vacancy center to a fiber-based microcavity, showing a cavity transmission dip of 50 % on resonance, and altered photon statistics in cavity transmission. © 2024 The Author(s)

1. Introduction

Quantum networks are interesting for application like secure communication or distributed quantum computing, as well as for experiments in fundamental sciences. One of the central challenges is the realization of a coherent interface between a single stationary qubit and a flying qubit, to distribute entanglement between the network nodes. Utilizing their spin as a stationary qubit, quantum networking has been demonstrated with color centers in diamond [1], but their optical properties are limiting the performance and scalability. However, optical cavities can be used to dramatically improve the efficiency of this interface [2,3]. Due to their full spectral and spatial tunability, fiber-based microcavities are a promising platform to realize such a cavity-enhanced spin-photon interface. We demonstrate the integration of a micrometer-thin diamond membrane, hosting implanted Tin-Vacancy (SnV) centers into a microcavity. The microcavity is composed of a fiber tip with a concave mirror [4], and a flat macroscopic mirror, to which the diamond membrane is bonded. We operate the system in a closed-cycle cryostat with a sample temperature reaching 8 K. The coupling of SnV centers is shown in Fig. 1, where the tunablity of the cavity is employed to sweep its resonance frequency, which allows to couple to a specific SnV center.

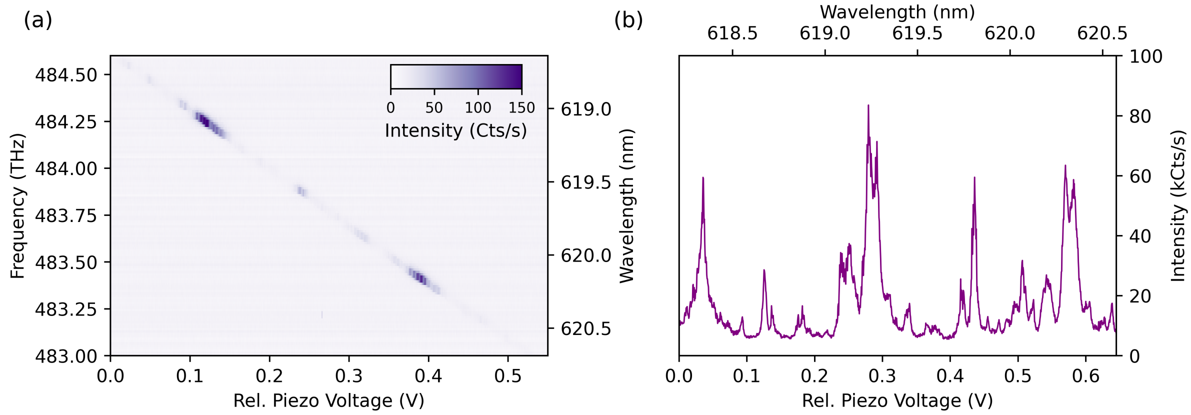

Fig. 1. Coupling SnV centers to the microcavity. (a) Off-resonant excitation of the cavity and zero-phonon line detection of the coupled SnV centers with a spectrometer. Once the cavity resonance (straight line) becomes resonant with the 619 nm or 620 nm transition of a SnV center, fluorescence is observed. (b) The detection light is filtered and sent to a single photon detector. Multiple emission lines from various SnV centers can be observed. The full tunability of the cavity can be used to selectively enhance an individual SnV center.

2. Results

The high quality factor Q of the microcavity of about 7×10^4 and the simulated mode volume of $V = 55\lambda^3$ enables a Purcell factor of 7. We confirm this by measuring the corresponding Purcell-broadening of the SnV linewidth. With these parameters, a coherent cooperativity of $C_{\mathrm{coh}} = 0.69\pm0.07$ can be evaluated [5], which puts the system in the regime of coherent coupling and makes it possible to measure quantum non-linear effects for the first time with SnV centers. We demonstrate this by showing a SnV-modulated microcavity transmission signal, measured in the low-power regime (shown in Fig. 2). The cavity-emitter system is very well explained by a Lindblad master equation approach, and described by the parameters $\{g,\kappa,\gamma\}/2\pi = \{0.30, 6.86, 0.032\}$GHz, with g being the single photon Rabi frequency, κ the total loss rate of the cavity and γ the SnV centers lifetime-limited linewidth. We characterize the microcavity transmission dip dependent on detuning and excitation power and show the altered photon statistics for transmitted light.
The versatility of the platform allows to transfer these methods to other solid-state emitters like the Nitrogen-Vacancy center or defects in Silicon Carbide. Furthermore, an improved microcavity would allow to reach the regime of strong coupling and this system can be supplemented with the recently demonstrated spin qubit control of SnV centers [6] in strained nanometer-thin diamond membranes to an efficient spin-photon interface.

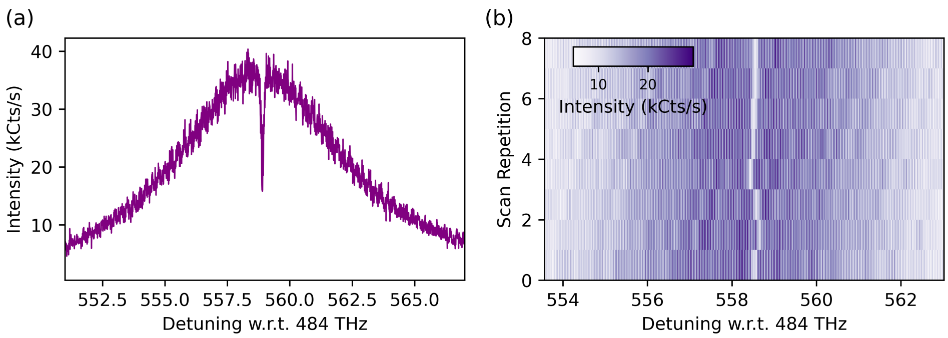

Fig. 2. Quantum Non-linear effects. (a) The cavity resonance is probed with a resonant laser. A transmission dip, reaching a contrast of 50 % can be observed once the excitation laser becomes resonant with the SnV transition. (b) The cavity transmission is resonantly scanned, showing the spectral wandering of the single SnV center.

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