A tunable Fabry-Pérot cavity for diamond-based photonics

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By coupling individual NV-centres to a tunable Fabry-Pérot microcavity, we show a reduction in the radiative lifetime from 12 ns to 7 ns, a clear demonstration of a Purcell-effect. Furthermore, we demonstrate a method to efficiently characterize the cavity performance using the Raman transition as a strong internal lighthouse.

The development of highly efficient quantum nodes is essential for the scalability of quantum networks and the development of a quantum internet [1]. These quantum nodes need to provide a storage for a quantum state. Furthermore, a highly efficient interface between the stationary and flying qubits is required for the interconnection of distant nodes [2]. The nitrogen-vacancy centre in diamond constitutes a promising candidate for the stationary qubit due to its highly coherent, optically addressable electron spin. Recent advances in photon-photon [3] and spin-photon entanglement [4] pave the way for a long-distance distributed quantum network based on NV centres via the implementation of remote entanglement protocols [5] and on-demand delivery of entanglement [6]. Yet, the scaling of such a network is limited by moderate NV entanglement rates owing to the low detection rate of coherent photons.

The low entanglement rate is limited by four main factors. Firstly, due to the high contrast in refractive index across the diamond-air interface, the photon extraction efficiency is low. Secondly, only 3% of the NV photons are emitted via the coherent zero-phonon-line (ZPL), while the remaining 97% are accompanied by a rapidly decohering phonon, resulting in a broad phonon-sideband (PSB). Thirdly, the flux of coherent photons is limited by the long radiative lifetime of 12 ns. Finally, electric field fluctuations in the vicinity of the NV centre lead to spectral fluctuations of the ZPL transition which render the ZPL photons emitted from two different quantum nodes distinguishable. However, all these shortcomings can be addressed by coupling NV centres to a small mode-volume Fabry-Pérot tunable microcavity [7]. The ZPL emission is selectively enhanced due to the Purcell effect; the photons emitted from the cavity can be efficiently collected using a single-mode fibre and the microscopic design allows a pure crystalline environment to be achieved.

Our device consists of a high-quality, single-crystalline diamond micro-membrane [8] bonded to a high reflectivity DBR planar mirror, with a laser ablated concave mirror [9] completing the cavity (see Fig. 1(a)). A piezo-electric nano-positioner offers full spatial and spectral tunability, allowing for *in situ* selection of individual NV centres. By tuning the cavity into resonance with the ZPL, we found a reduction of the radiative lifetime from 12 ns in bulk diamond to 7 ns on resonance, a clear demonstration of a Purcell effect [10]. The Purcell enhancement of the ZPL was found to be ~30, resulting in an increased ZPL emission probability from ~3% to ~46% (See Fig. 1(b)).

The coherence of photons emitted from the cavity is presently limited by an inhomogeneous broadening of the NV centres' optical transitions a consequence of fabrication-induced defects. In bulk diamond, we measure optical linewidths ≤100 MHz (Fig. 1 (c)), while in the fabricated membranes we typically find linewidths ~1 GHz. Experimental effort is therefore being made to understand the mechanism behind the broadening of the optical linewidth, and to develop less invasive fabrication techniques.

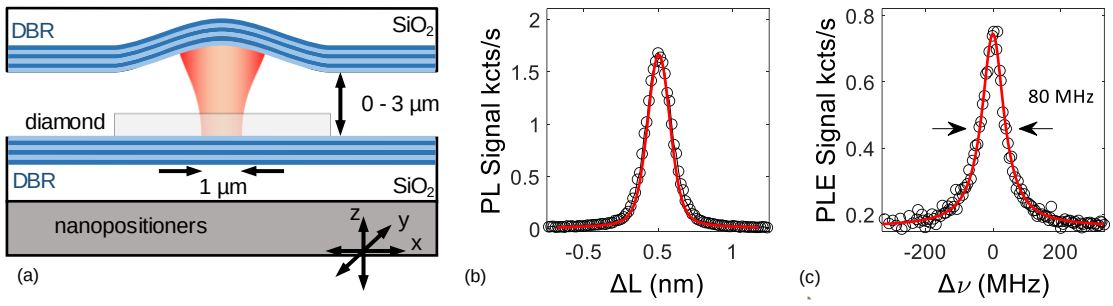

Figure 1: Schematic design of the tunable microcavity. (b) Detected ZPL photons versus the cavity detuning ΔL, a clear indication of a Purcell effect. (c) Photoluminescence excitation scan of a typical ZPL linewidth in unprocessed bulk diamond.

In contrast to monolithic resonators, open-access tunable Fabry-Pérot microcavities require *in situ* alignment of the external fields to the cavity mode. When attempting to couple NV centres to a tunable cavity, the low ZPL fraction constitutes a problem, as appreciable high count rates can only be achieved with close-to-optimal coupling. Due to aberration effects, a confocal alignment of the far detuned excitation at 532 nm and ZPL emission at 637 nm does not routinely yield a good coupling. It is thus advantageous to have an additional narrow-linewidth high-intensity internal lighthouse triggered by the green excitation, which can be used to optimise the fibre coupling efficiency of the collected cavity emission. To this end, we propose to harness the Stokes Raman transition of the diamond crystal [11].

The Raman scattering process is the well-known phenomenon in which a photon is inelastically scattered via the creation (Stokes) or annihilation (anti-Stokes) of an optical phonon of fixed energy. Diamond exhibits unique properties combining a high Raman gain coefficient of ~75 GWcm^{-1} (at 532 nm) and a large Raman shift of 1332 cm^{-1} (40 THz) [12], making diamond a compelling material for Raman scattering experiments. Correlated Stokes, anti-Stokes scattering in diamond has been used to demonstrate non-classical correlations [13-14] and to achieve remote entanglement of macroscopic diamonds [15].

We drive the Raman scattering using an excitation laser at 532 nm, sweep the cavity length over one free spectral range, and record the photoluminescence (PL) from our system (Fig. 2(a)). The bright resonances at λ = 572.7 nm correspond to the Stokes transition (Fig. 2(b)). The Raman light couples to higher transverse modes as well as to the fundamental cavity mode. Replacing the detection optics with a CCD camera, we can directly image the emission pattern of the cavity modes (inset in Fig. 2(b)). We find a linear relation between the excitation power and the Raman signal, as expected for the Stokes Raman process (Fig. 2(c)). By comparing the cavity-enhanced Raman signal (Fig. 2(d)) to the bare diamond signal (Fig. 2(e)), we infer a ~100 fold enhancement of the Raman transition [11].

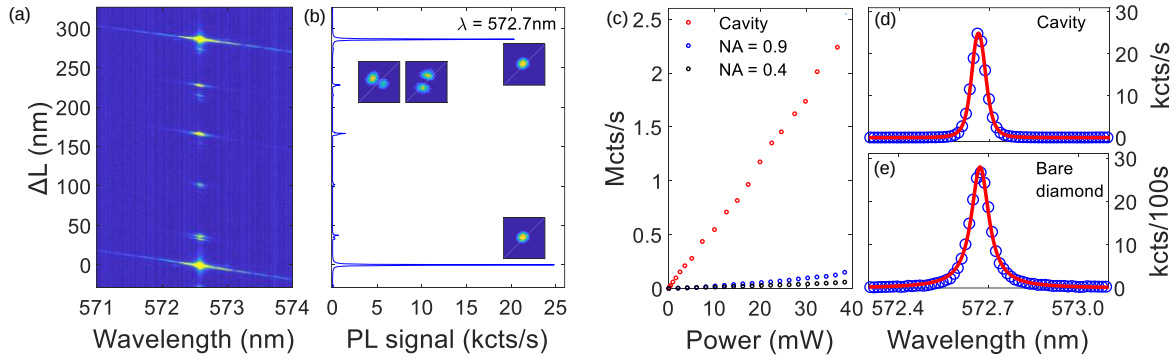

Figure 2: (a) PL spectra recorded for one free spectral range, where the bright resonances correspond to the Raman transition. (b) Line-cut along the Raman transition, where the insets show the spatial shape of the different cavity modes. (c) Power dependence for comparison of the signal strength inside the cavity (d) and from the bare diamond (e).

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