Coupling color centers in diamond to fiber-based Fabry-Pérot microcavities

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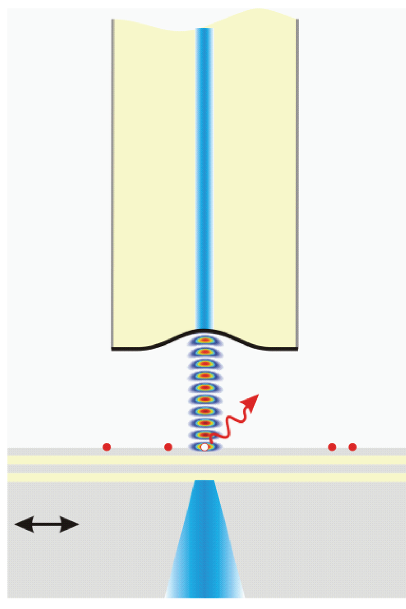
1. Abstract

Optical fibers with machined and coated end facets can serve as high reflectivity micro-mirrors to build low loss optical resonators with free space access [1]. These microcavities feature a very small mode volume on the order of a few tens of cubic wavelengths and a very large Finesse of up to 10^5, corresponding to quality factors of several millions. Thus, the Purcell factor being proportional to the ratio of quality factor and mode volume can be as high as 10^4, enhancing the emission rate of an emitter inside the cavity. The cavity length and thus the spectral position of the resonances can be tuned freely.

We use the microcavities to couple solid state based emitters such as color centers in diamond to the cavity mode in order to study and enhance their optical properties. Two particular defects have drawn our attention:
First, the Nitrogen-vacancy (NV) center which exhibits a short excited state lifetime and a stable emission in the visible. Its emission can be channelled and enhanced by the cavity.
Even more promising the Silicon-Vacancy (SiV) center is brighter and has a spectral fluorescence width of only 1 nm making it an ideal candidate as a single photon source.



Fabry-Pérot cavity from optical fiber and plane mirror with emitters

2. Fiber-based Fabry-Pérot cavities for strong light matter interaction

Basic parameters

+ small r and d for small w_0: (w_0 = 1.5 - 3 µm) $\quad w_0^2 = \frac{\lambda}{2\pi}\sqrt{2rd - d^2}$

=> small mode Volume $\quad V_m = \frac{\pi}{4} w_0^2 d$

+ low loss coating for high Finesse $\quad \mathcal{F} = \frac{2\pi}{Losses}$

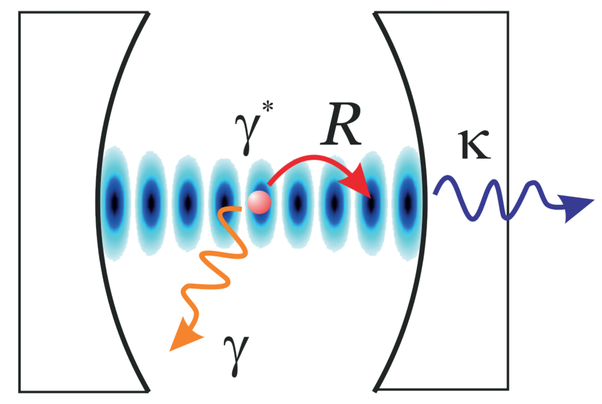
Purcell enhancement

- modification of spont. emission $\quad \gamma_c = F_P \cdot \gamma_0$

by Purcell factor $\quad F_P = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V_m} \propto \frac{\mathcal{F}}{w_0^2}$

- for broadband emitters $\quad F_{P,eff} = \zeta \cdot F_P \propto V_m^{-1}, \; \zeta = \delta\upsilon / \Delta$
(δυ: cavity linewidth, Δ: emitter bandwidth)

- probability to emit into cavity: $\quad p_c \approx \frac{\zeta F_P}{1+\zeta F_P}$

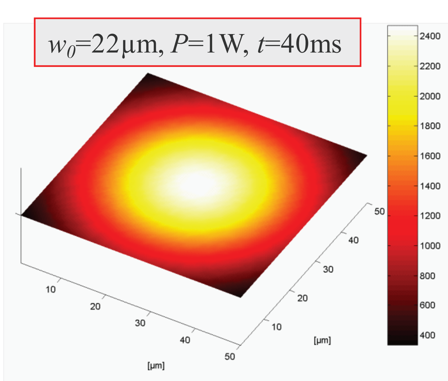


Effective coupling rate for solid state emitters: Nitrogen- and Silicon-Vacancies, Rare-Earths, ...

$$R = \frac{4g^2}{\gamma + \gamma^* + \kappa} \qquad F_P = R/\gamma$$

@ low T => $F_P \sim 10^4$
$g_{0,NV} \sim 0.5\,\mathrm{GHz} \sim \gamma^* >> \kappa, \gamma$
$g_{0,SiV} \sim 10\,\mathrm{GHz} \sim \gamma^* >> \kappa, \gamma$
$g_{0,Tm^{3+}} \sim 20\,\mathrm{MHz} \sim \kappa >> \gamma, \gamma^*$

3. Fabrication

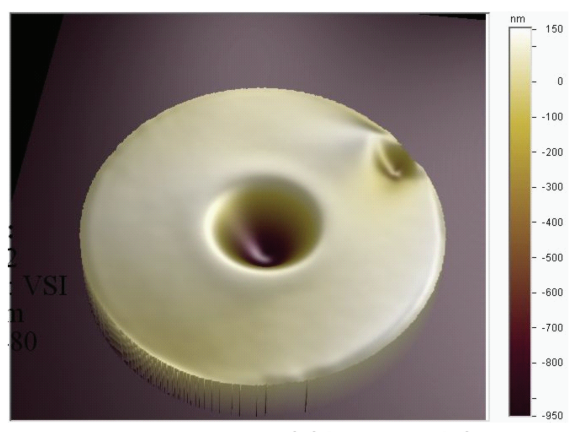


CO_2 laser machining

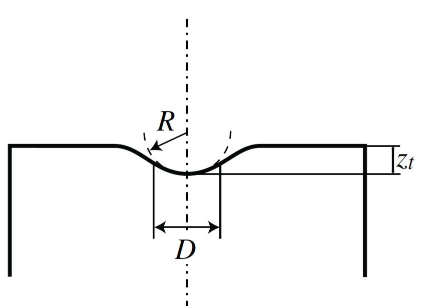
+ laser induced heating of surface intensity profile => temperature profile

+ thermal evaporation temperature profile => depth profile

+ low viscosity + surface tension removes roughness



AFM image of fiber end face

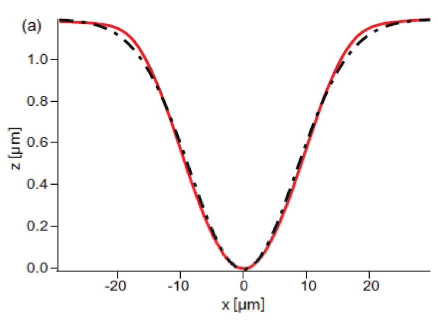


Fabricated geometries

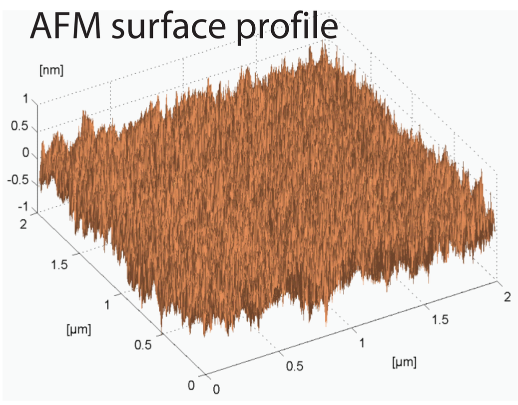
+ radii of curvature $R \sim$ 30 µm - 2 mm

+ diameters $D \sim$ 20 - 60 µm $\quad z_t \approx \frac{D^2}{8R}$

+ structure depths $z_t \sim$ 0.5 - 3 µm



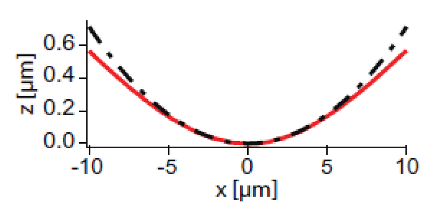
AFM surface profile



+ surface roughness σ ~ 0.14 nm rms

+ roughness induced scattering loss:

$$S \approx \left(\frac{4\pi\sigma}{\lambda}\right)^2 \approx 5 \text{ ppm}$$



4. Cavity Characterization

$$\mathcal{F} = \frac{FSR}{\delta\upsilon} = \frac{c\Delta\lambda}{\lambda^2 \cdot \delta\upsilon}$$

Dielectric mirror coating by Ion Beam Sputtering designed for **780 nm**:

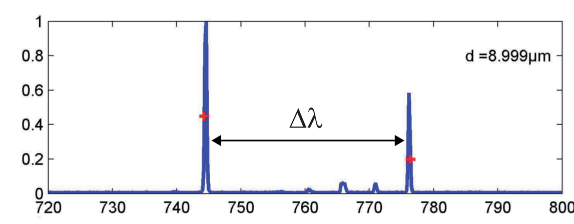
~31 layers (SiO_2 n= 1.46 / Ta_2O_5 n=2.1)

> transmission $T \sim$ 10 ppm,
absorption $A \sim$ 6 ppm,
scattering $S <$ 5 ppm

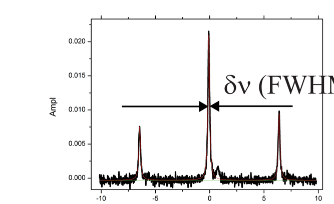
total loss = 2(T+A+S)=42 ppm

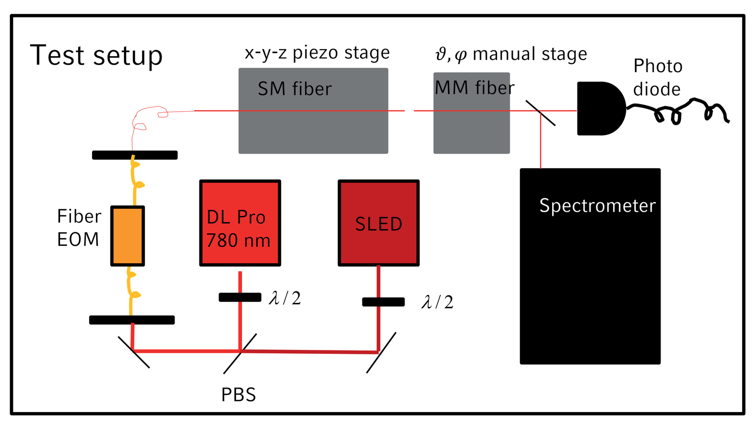
=> $\mathcal{F}_{theo}$ > 150000

Cavity spectrum from superluminescent diode

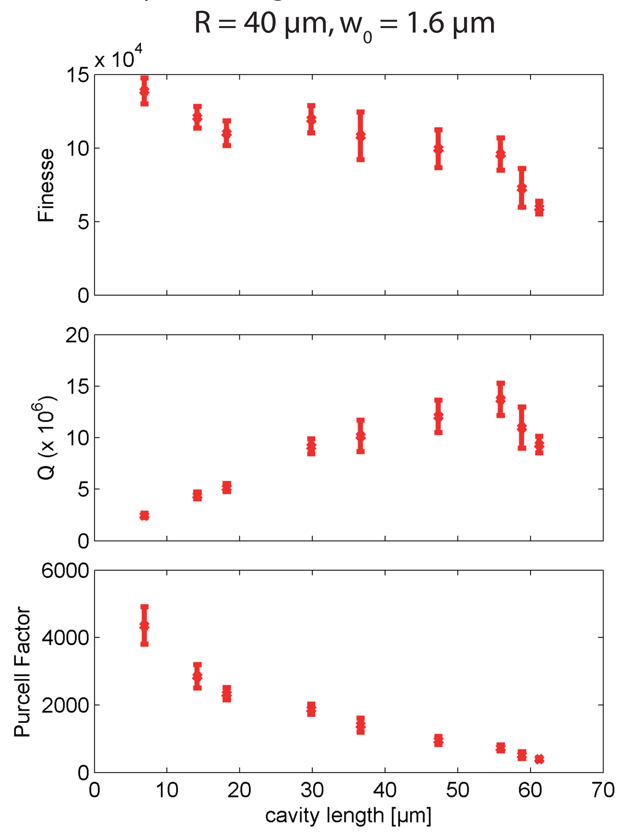


Resonace with side bands @ 4GHz



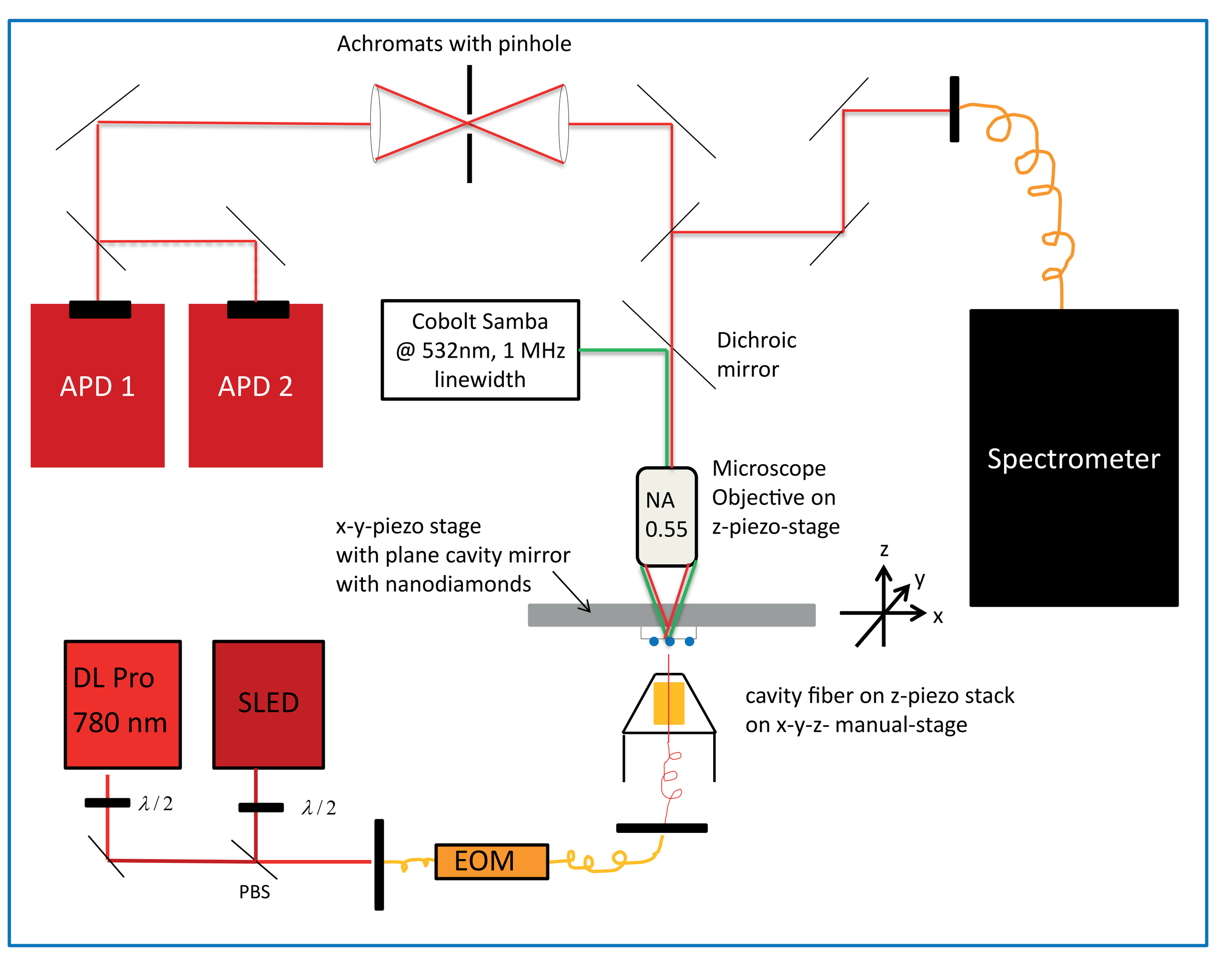


Test cavity with single mode and multi mode fibers
R = 40 µm, w_0 = 1.6 µm



$\mathcal{F}$ = 140000
$V_m = 20\ \lambda^3$

5. Experimental setup



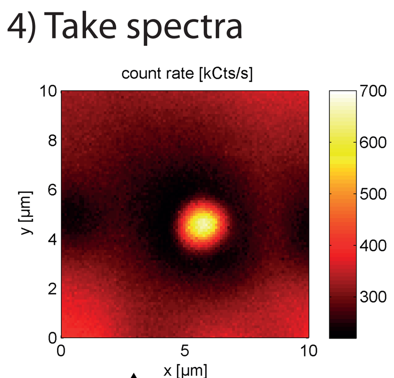
Experimental procedure:

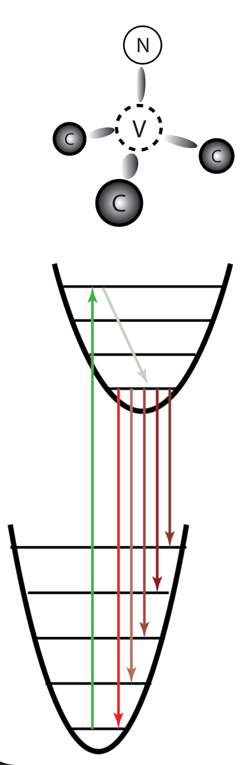
1) Spincoating of nanodiamonds on macroscopic mirror

2) Take confocal scan to locate NV centers, hold position

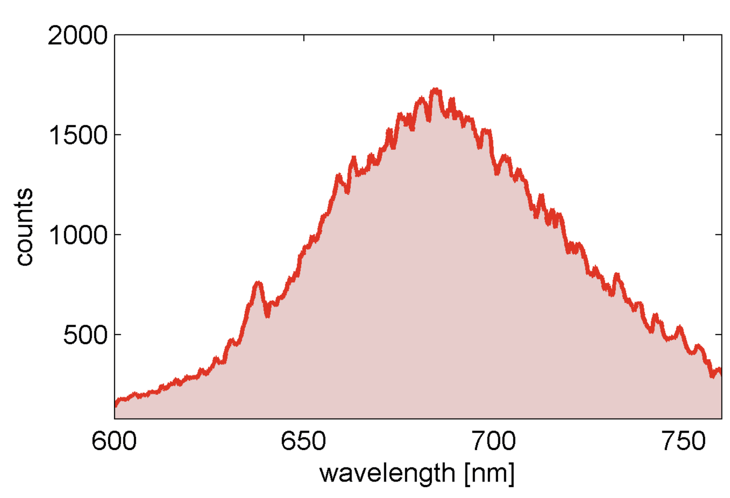
3) Move fiber towards NV to build cavity

4) Take spectra

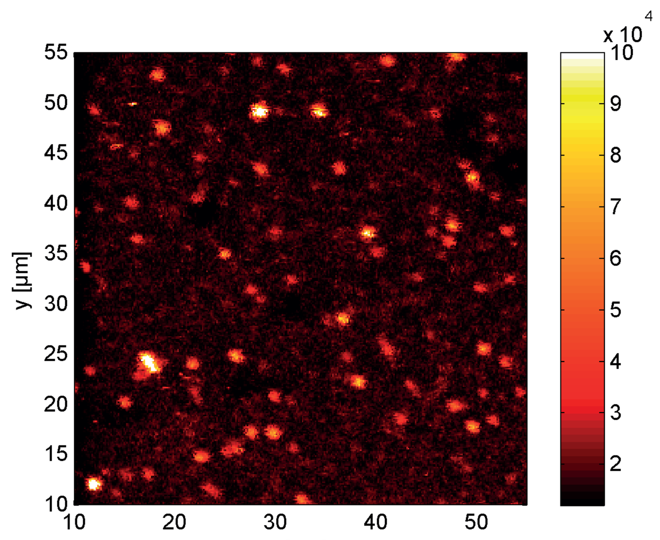




spectrum (100 nm diamonds)



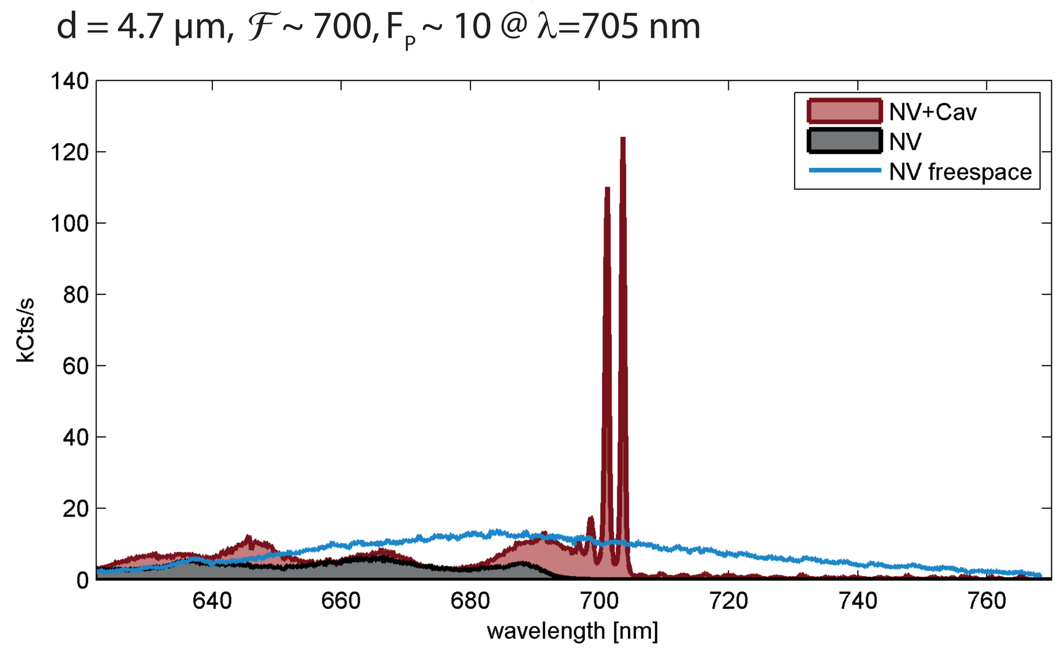
confocal scan (10 nm, 100 nm diamonds)



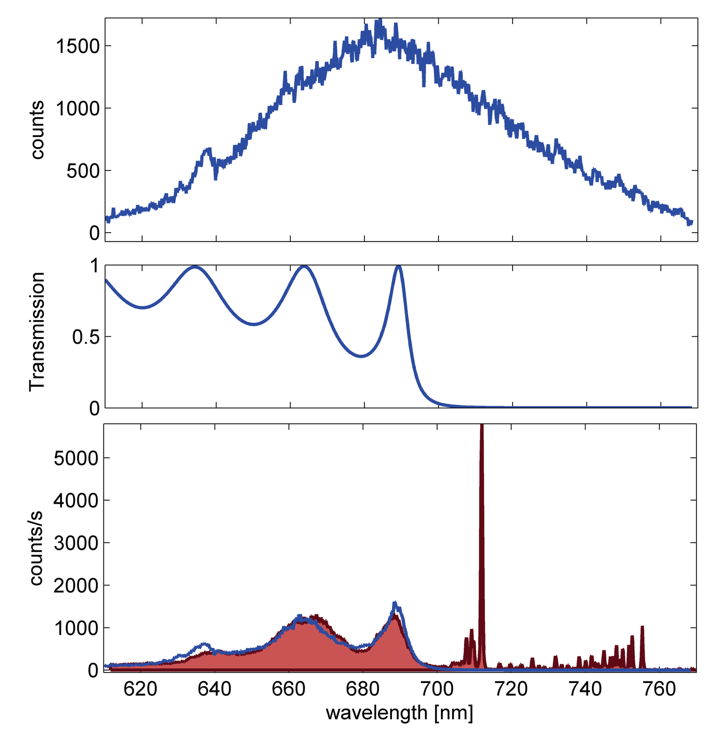
6. First results

NV centers in 100nm diameter nanodiamonds, $\mathcal{F}$ ~ 30000 @ λ=780nm

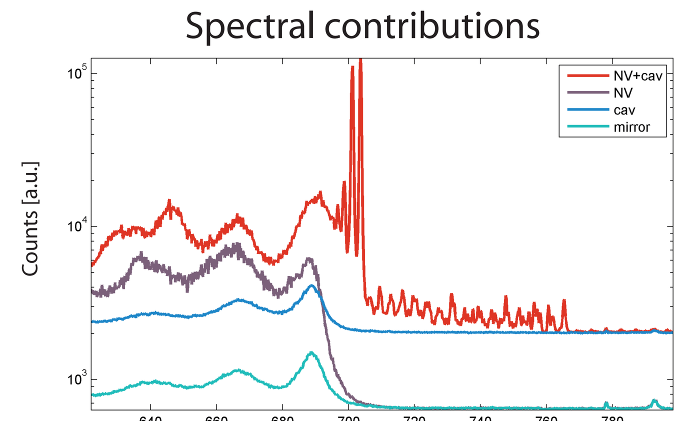
Resonances of NV inside cavity
d = 4.7 µm, $\mathcal{F}$ ~ 700, F_p ~ 10 @ λ=705 nm



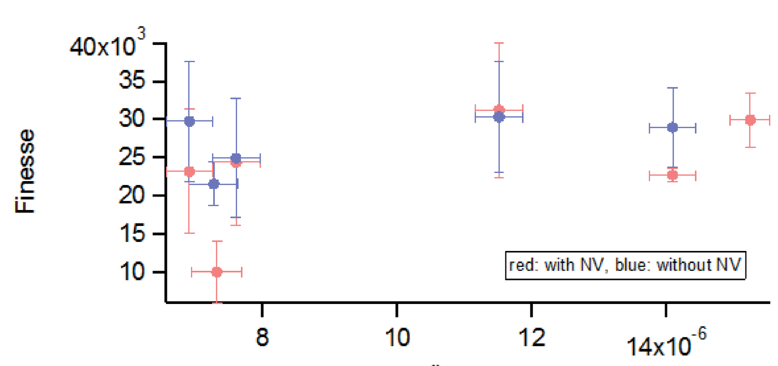
Effect of mirror coating
d = 6.7 µm, $\mathcal{F}$ ~ 3000, F_p ~ 50 @ 715 nm



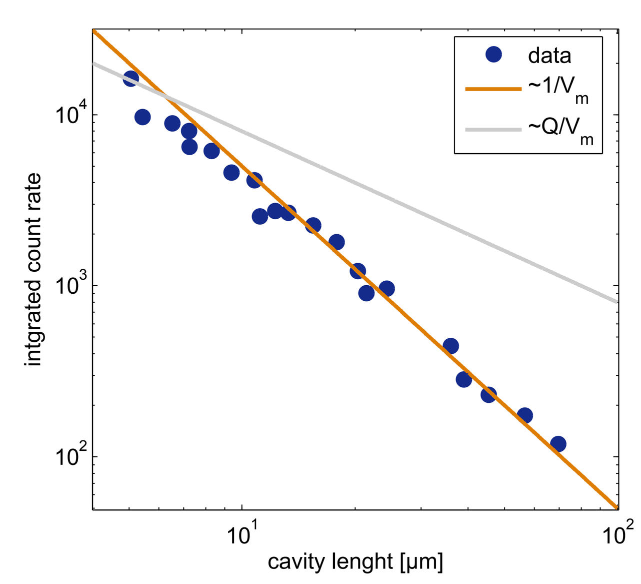
Spectral contributions



Finesse @ 780 nm



Scaling of peak area @ 710 nm



References:
[1] Hunger et al., *A fiber Fabry-Perot cavity with high finesse*, **NJP 12, 065038** (2010)
[2] Hunger et al., *Laser micro-fabrication of concave, low roughness features in silica*, **AIP Advances 2, 012119** (2012)