Daniel Riedel

Patrick Maletinsky, Quantum Sensing Group, University of Basel

Richard J. Warburton, Nano Optics Group, University of Basel

Enhancement of resonant transitions via coupling to a fully tunable Fabry-Pérot microcavity

DR et al., submitted (2017)

(arXiv:1703.00815)

Motivation

NV center: Optically addressable, highly coherent spin

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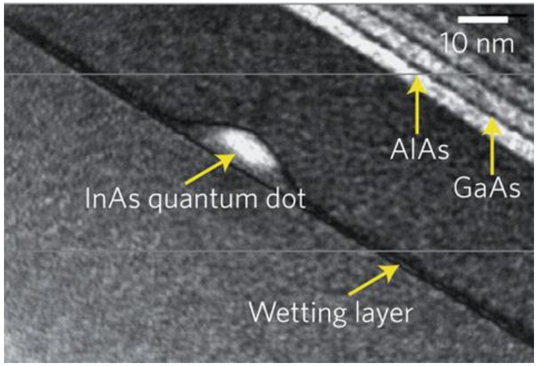
NV center: Optically addressable, highly coherent spin

Self assembled quantum dots



Warburton, Nat. Mater. **12**, 483 (2013)

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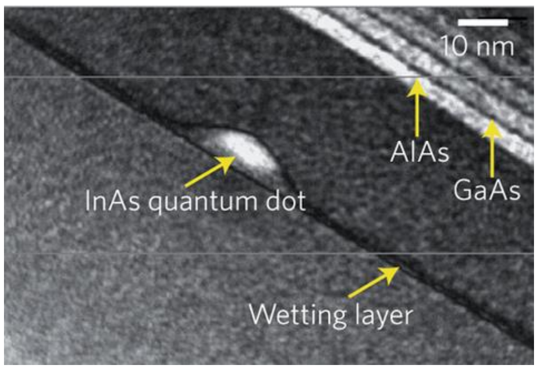
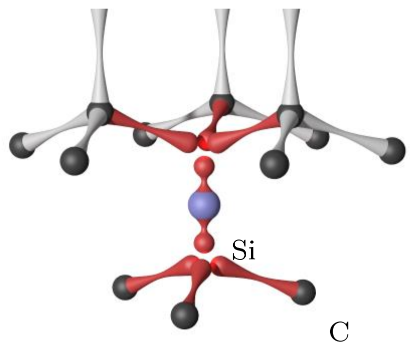


Warburton, Nat. Mater. **12**, 483 (2013)

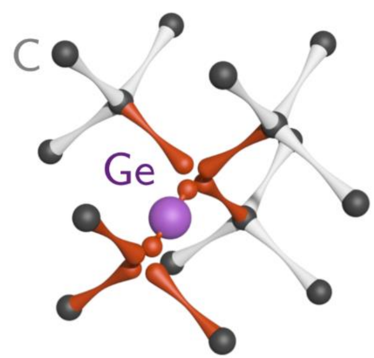
Colour centres

<u>diamond</u>



SiV

Rogers et al. PRL **113**, 263602 (2014)
Sipahigil et. al, Science **354**, 847 (2016)



GeV

Siyushev et al., arXiV: 1612.02947
Bhaskar et al., arXiV: 1612.03036

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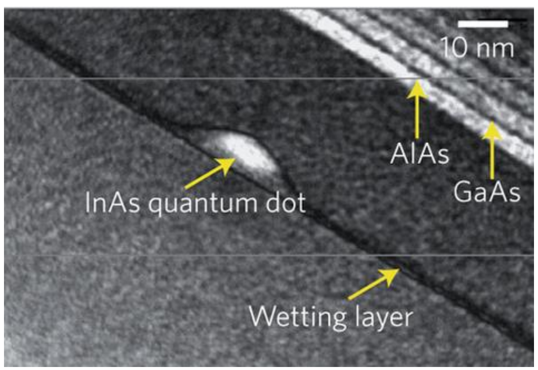

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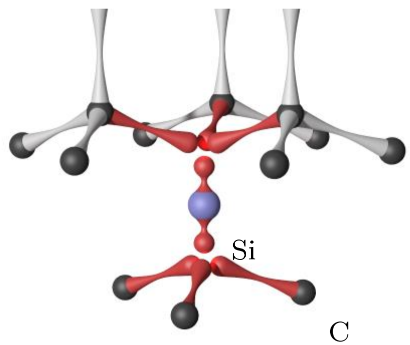

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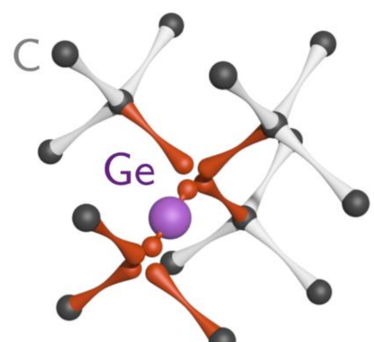

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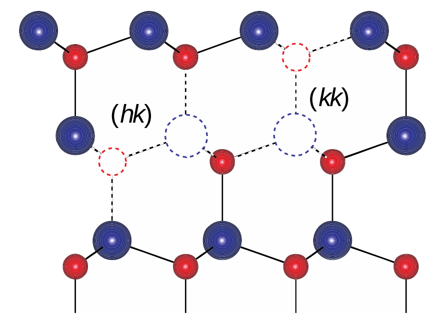
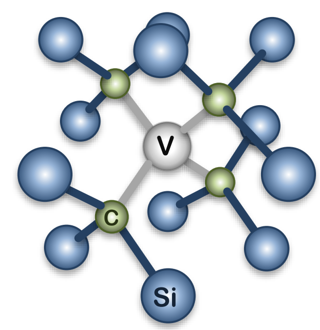
silicon carbide



$V_{Si}V_C$

Christle et al., Nat. Mater. **14**, 160 (2015)
Koehl et al., Nature **479**, 84 (2011)



V_{si} / T_V

DR et al., PRL **109**, 226402 (2012)
Widmann et al., Nat. Mater. **14**, 164 (2015)

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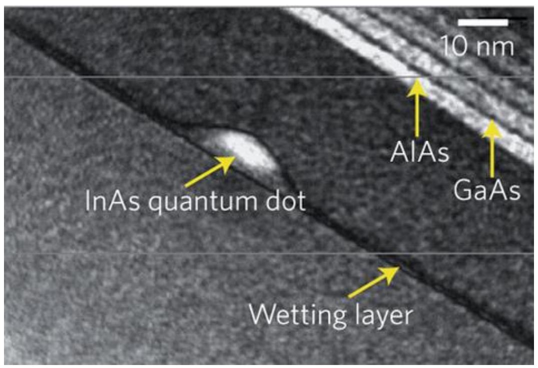
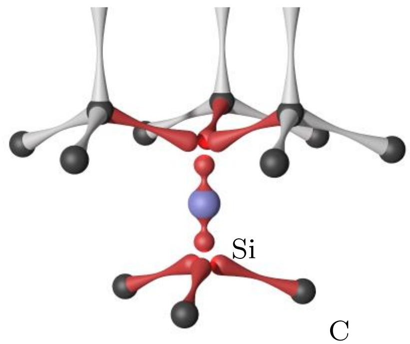


Warburton, Nat. Mater. **12**, 483 (2013)

Both spin and photon should be highly coherent

Colour centres

diamond



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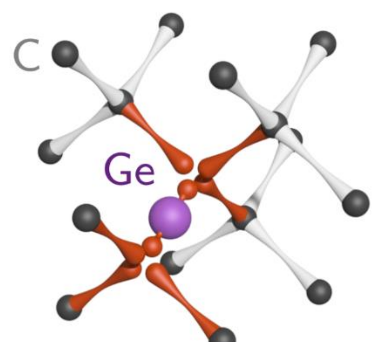

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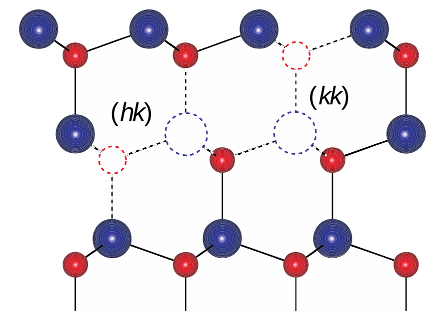

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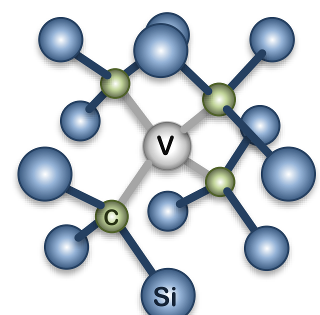

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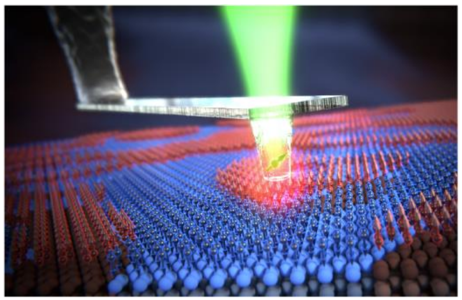
Magnetic sensing



Appel et al., New J. Phys. **17**, 112001 (2015)
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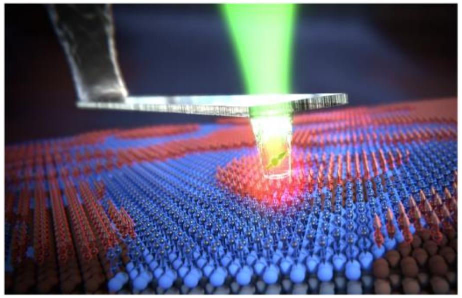

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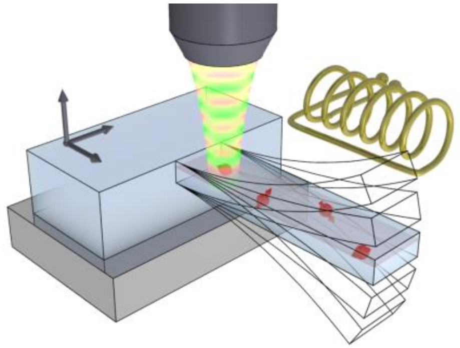
Optomechanics



Teissier et al., PRL **113**, 020503 (2014)
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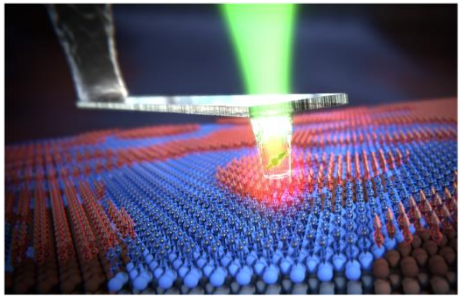

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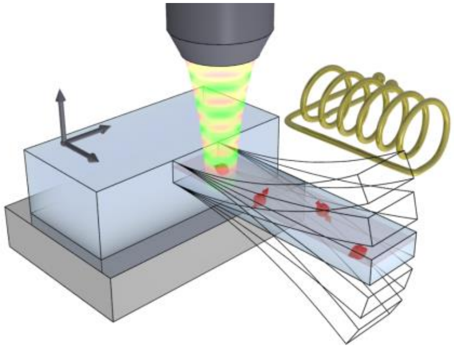

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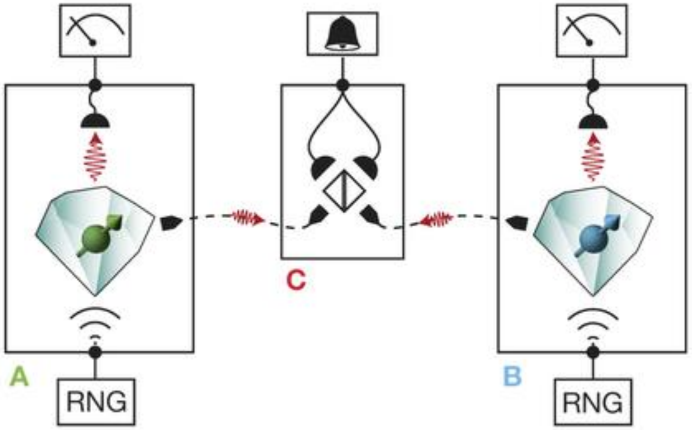
Quantum information

Long distance spin-spin entanglement



Hensen et al., Nature **526**, 682 (2015)

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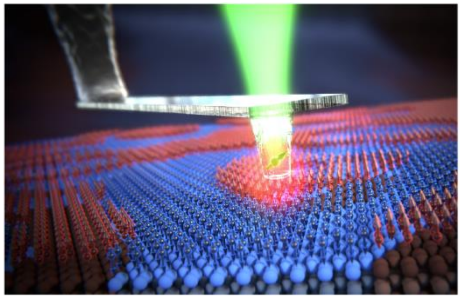

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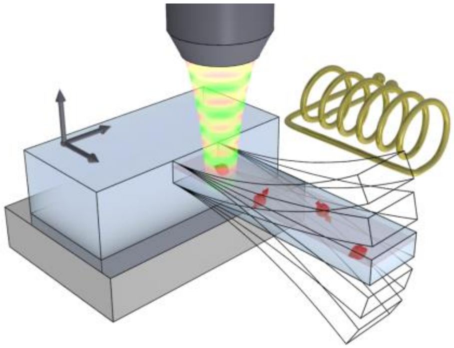

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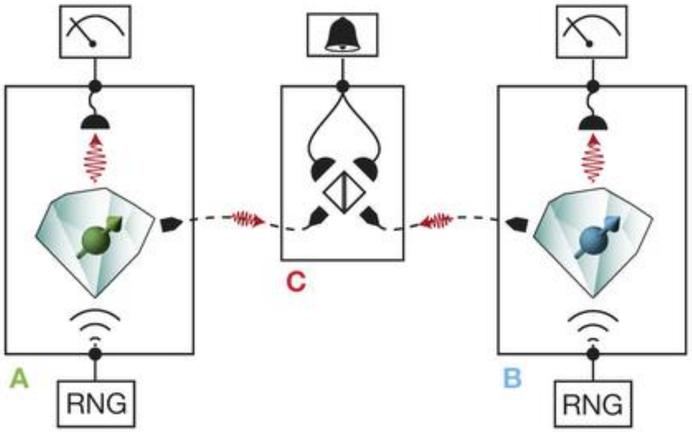


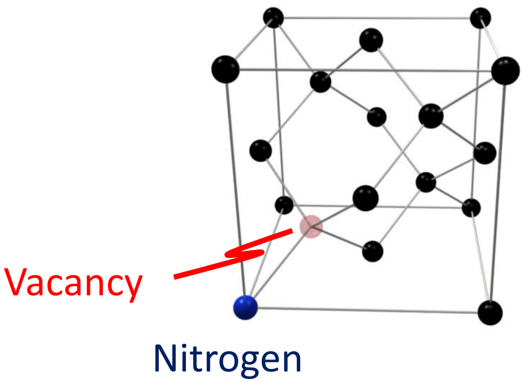
Hensen et al., Nature **526**, 682 (2015)

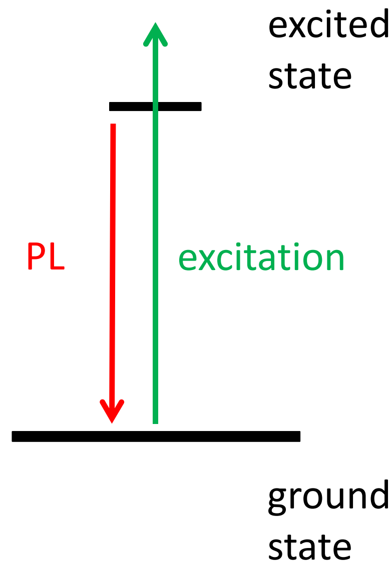
➢ **limited by the detection rate of coherent photons (~ mHz)**

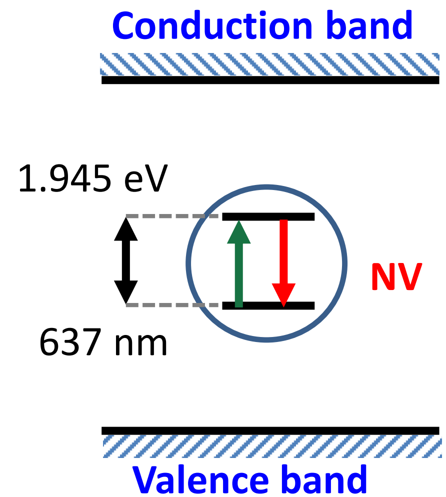
Outline

- Motivation
- NV centres in diamond
- Optical cavities
- Fully tunable Fabry-Pérot microcavity
- Experimental results and analysis
- Summary and Outlook

NV centres in diamond - advantages



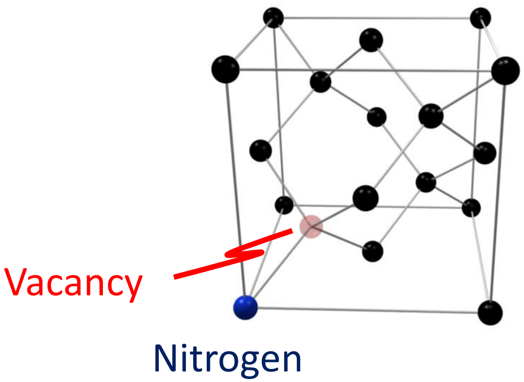


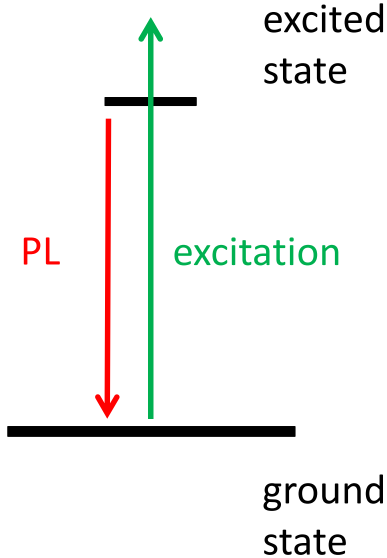


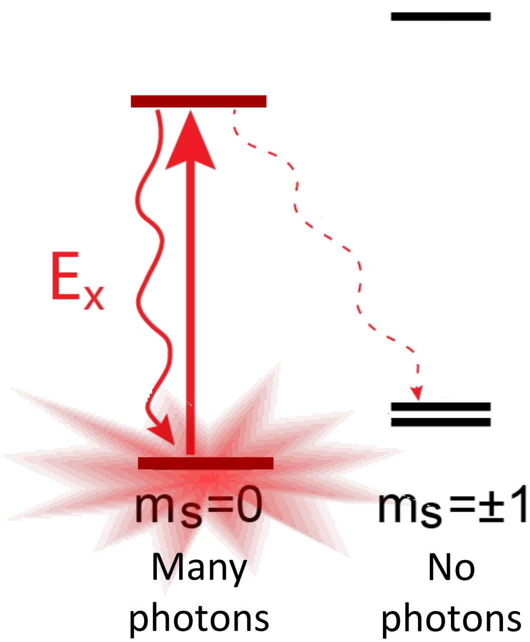
Key features:

- long spin coherence times (> 1 ms) } @RT — Balasubramanian et al., Nat. Mater. **8**, 383 (2009)
- nuclear quantum memory (> 1s) } @RT — Maurer et al., Nature **8**, 383 (2009)
- fast one- and two- qubit gates — Fuchs et al., Science **326**, 1520 (2009)
- ground state spin control via external fields

NV centres in diamond - advantages





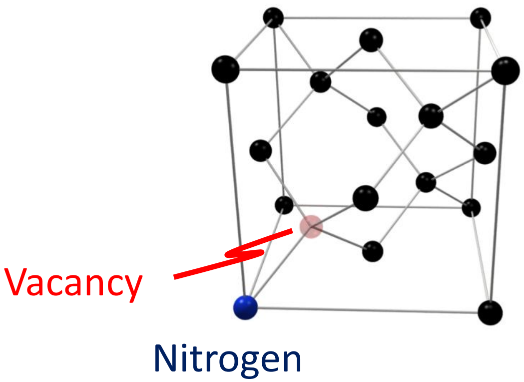


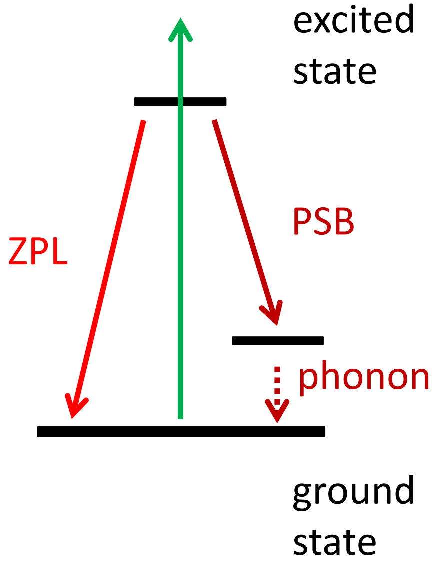
Key features:

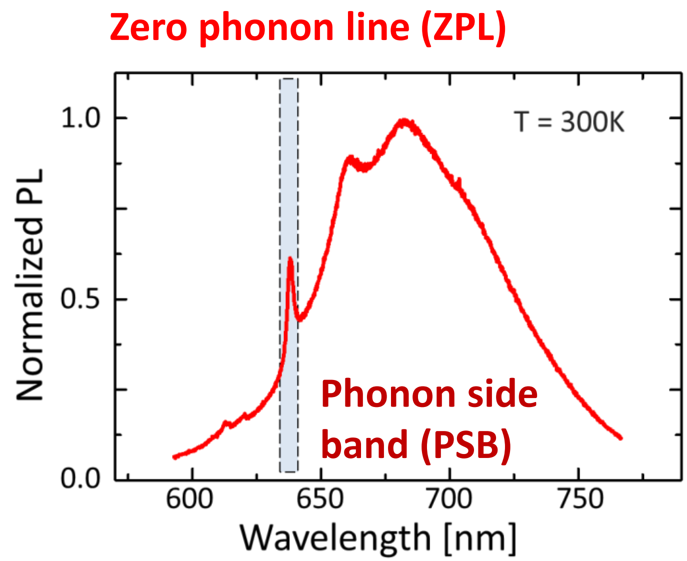
- spin-readout via spin-state dependent photoluminescence (PL) intensity
- spin-selective / cycling transitions
- optical lambda-system: requirement for spin-photon entanglement

Togan et al., Nature **466**, 730 (2010)

NV centres in diamond - challenges



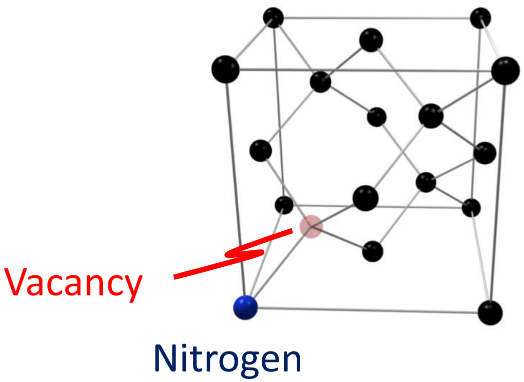


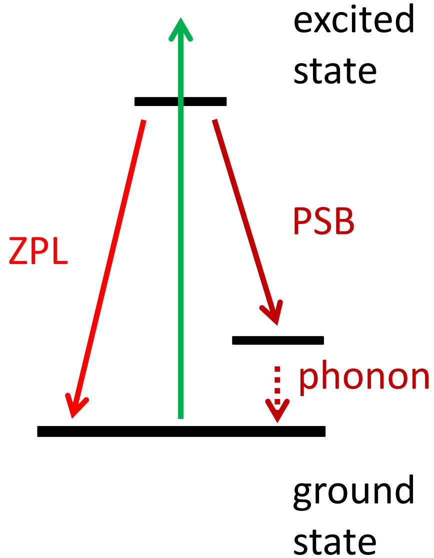


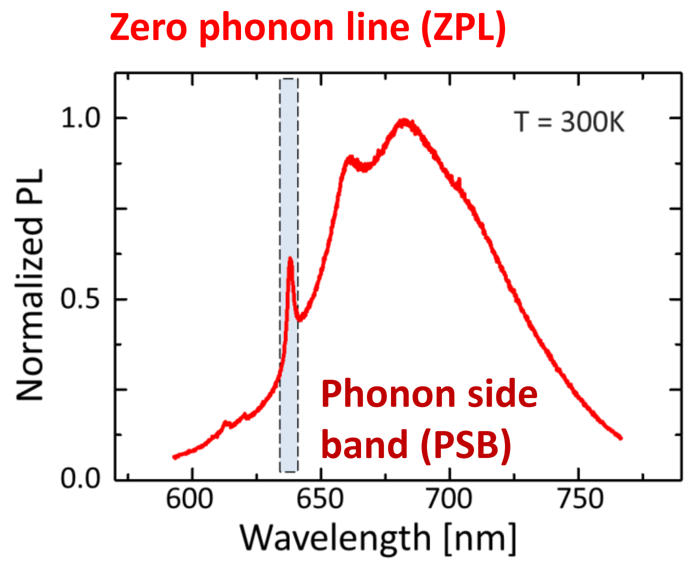
Key challenge: light extraction

1. small extraction efficiency out of bulk diamond
2. long radiative lifetime: ~ 12 ns
3. small fraction of PL emission at ZPL (637 nm): ~ 3%

NV centres in diamond - challenges







Key challenge: light extraction

1. small extraction efficiency out of bulk diamond
2. long radiative lifetime: ~ 12 ns
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→ solve all 3 problems with cavity

Optical cavity - Purcell enhancement

Transition rate for spontaneous emission:

$$\gamma_{12} = \frac{2\pi}{\hbar^2} < \vec{p} \cdot \vec{E}_{\mathrm{vac}} >^2 g(\omega)$$

Optical cavity - Purcell enhancement

Transition rate for spontaneous emission:

electric dipole

density of states

$$\gamma_{12} = \frac{2\pi}{\hbar^2} < \vec{p} \cdot \vec{E}_{\mathrm{vac}} >^2 g(\omega)$$

vacuum electric field

Optical cavity - Purcell enhancement

Transition rate for spontaneous emission:

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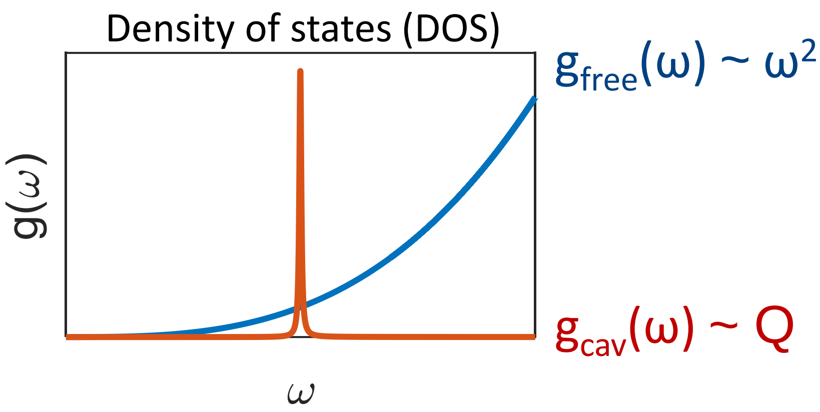
$\sim Q$

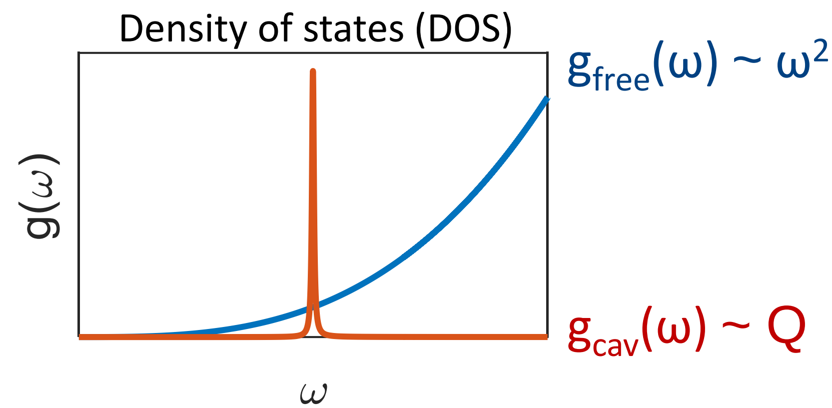


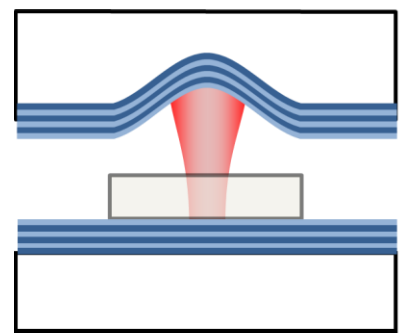
Optical cavity - Purcell enhancement

Transition rate for spontaneous emission:

$$\gamma_{12} = \frac{2\pi}{\hbar^2} \left< \vec{p} \cdot \vec{E}_{\mathrm{vac}} \right>^2 g(\omega)$$

$\sim 1 / V$ $\qquad$ $\sim Q$





Mode volume of vacuum fluctuation:

$V \sim \mu m^3$

Energy of vacuum fluctuation:

$\int \varepsilon_0 \varepsilon_R E^2 \, dV = \hbar\omega / 2$

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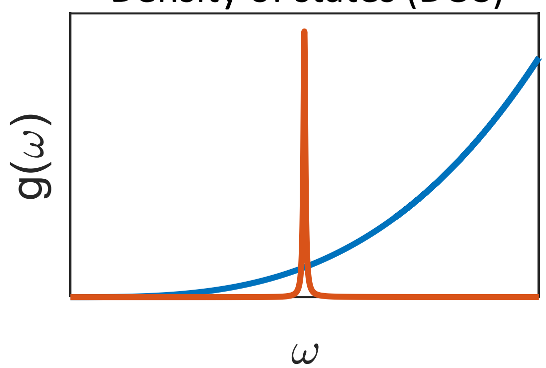
$$\gamma_{12} = \frac{2\pi}{\hbar^2} \boxed{< \vec{p} \cdot \vec{E}_{\text{vac}} >^2} \boxed{g(\omega)}$$

~ 1 / V   ~ Q

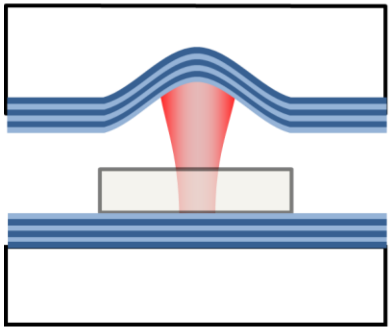


Relative transition rate enhancement:

$$\frac{\gamma_{\text{cav}}}{\gamma_{\text{free}}} \sim \frac{Q}{V}$$ (Purcell enhancement)

constant

Increased DOS - High Q
Confined E_{vac} - Small V



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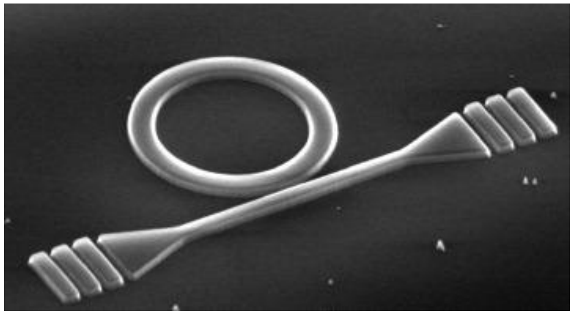
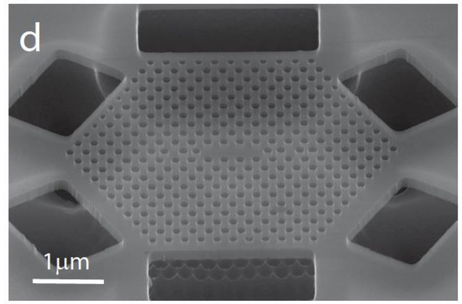
Diamond cavities

micro-ring resonator



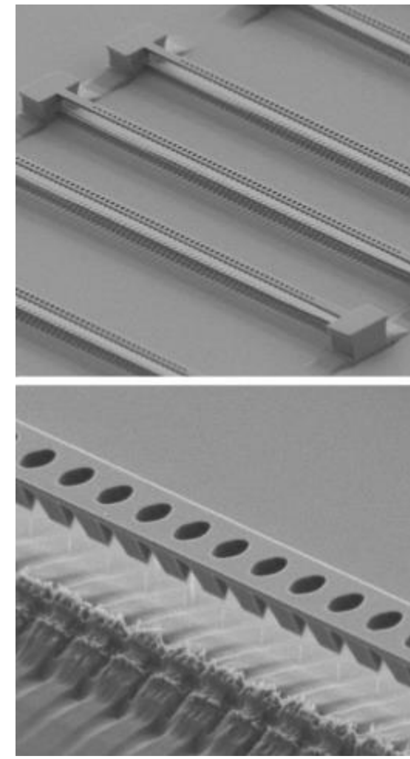
Faraon et al., New J. Phys. **15** 025010 (2013)
Faraon et al., Nat. Photon. **5**, 301 (2011)

2D photonic crystal



Faraon et. al, PRL **109**, 033604 (2012)
Riedrich-Möller et al.,
Appl. Phys. Lett. **106**, 221103 (2015)

nanobeam photonic crystal



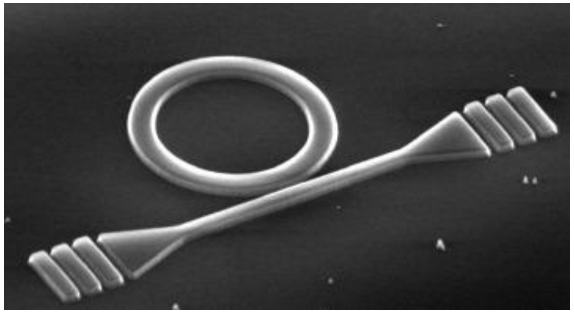
Hausmann et al., Nano Lett. **13**, 5791 (2013)
Burek et al., Nat. Commun. **5**, 5718 (2014)
Li et al., Nat. Commun. **6**, 6173 (2015)
Sipahigil et. al, Science 354, **847** (2016)

Key result:

- up tp 70-fold enhancement of emission rate

Diamond cavities

micro-ring resonator



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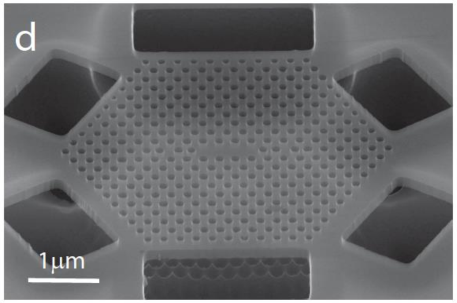

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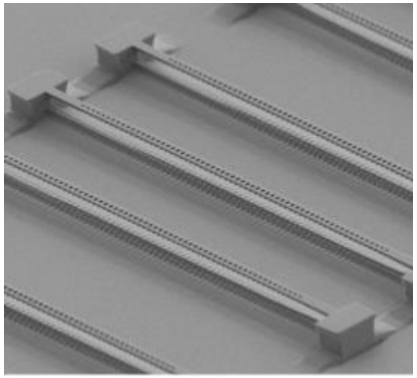

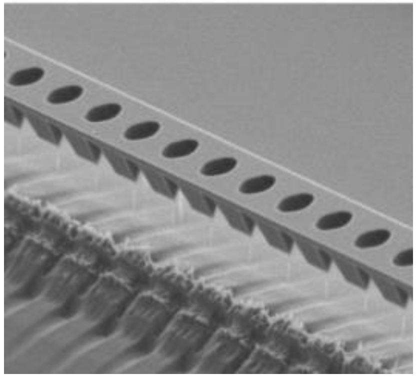

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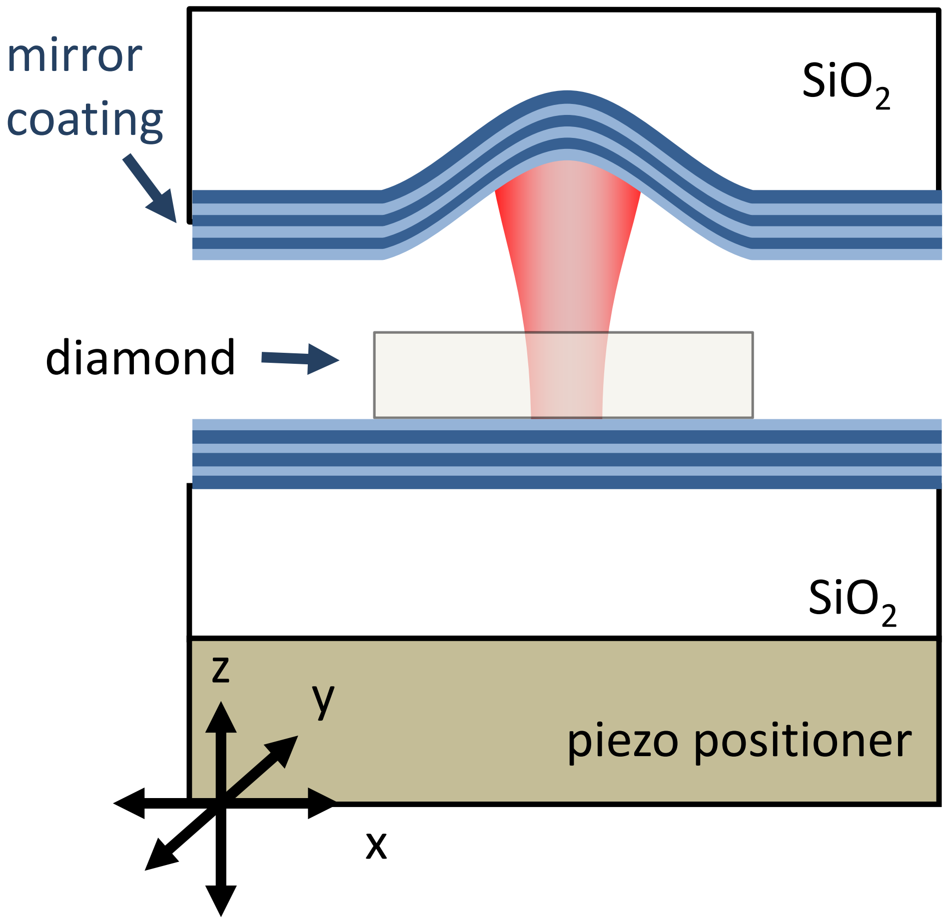
Challenges:

- spatial and spectral overlap
- high Q-factors
- efficient outcoupling
- emitter stability

Fully tunable microcavity design



Experiments on quantum dots:

Barbour et al., J. Appl. Phys. **110**, 053107 (2011)
Greuter et al., Appl. Phys. Lett. **105**, 121105 (2014)
Greuter et al., Phys. Rev. B **92**, 045302 (2015)

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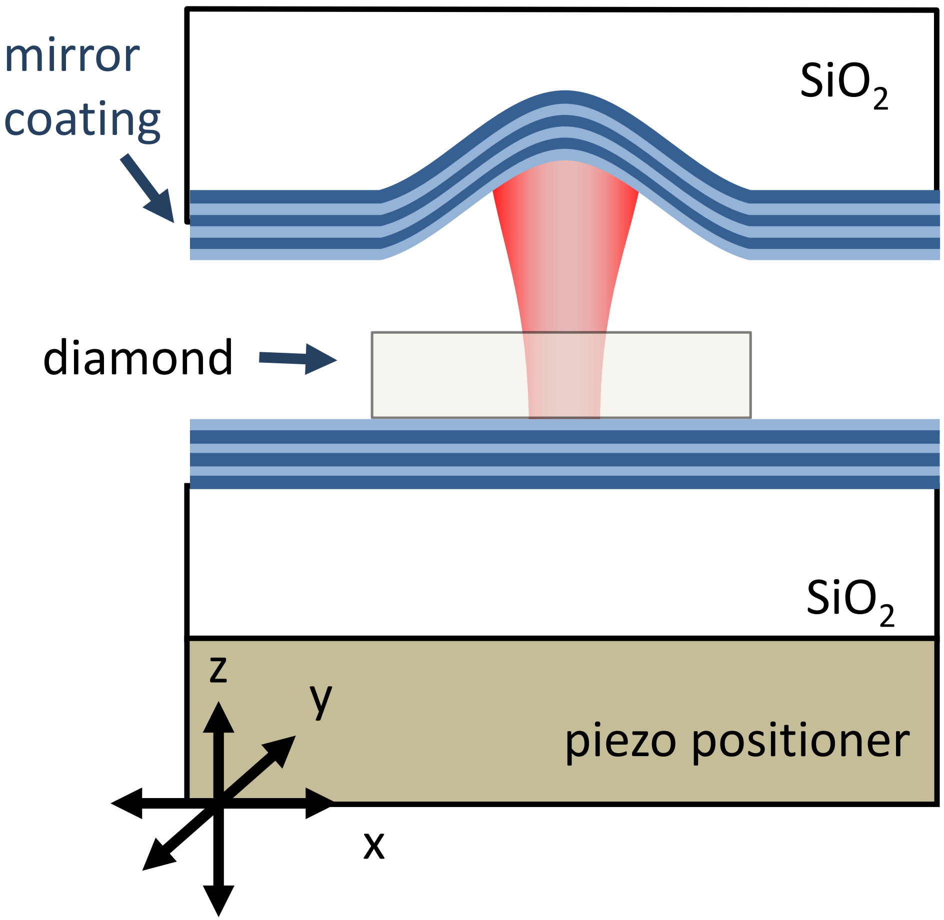

Advantages of microcavity design:

- minimal diamond processing

  (low spectral fluctuations)
- well-defined Gaussian output mode
- full *in situ* tunability:
  - resonance wavelength
  - spatial overlap
  - select favourable NV
- small mode volume V
- high Q factor

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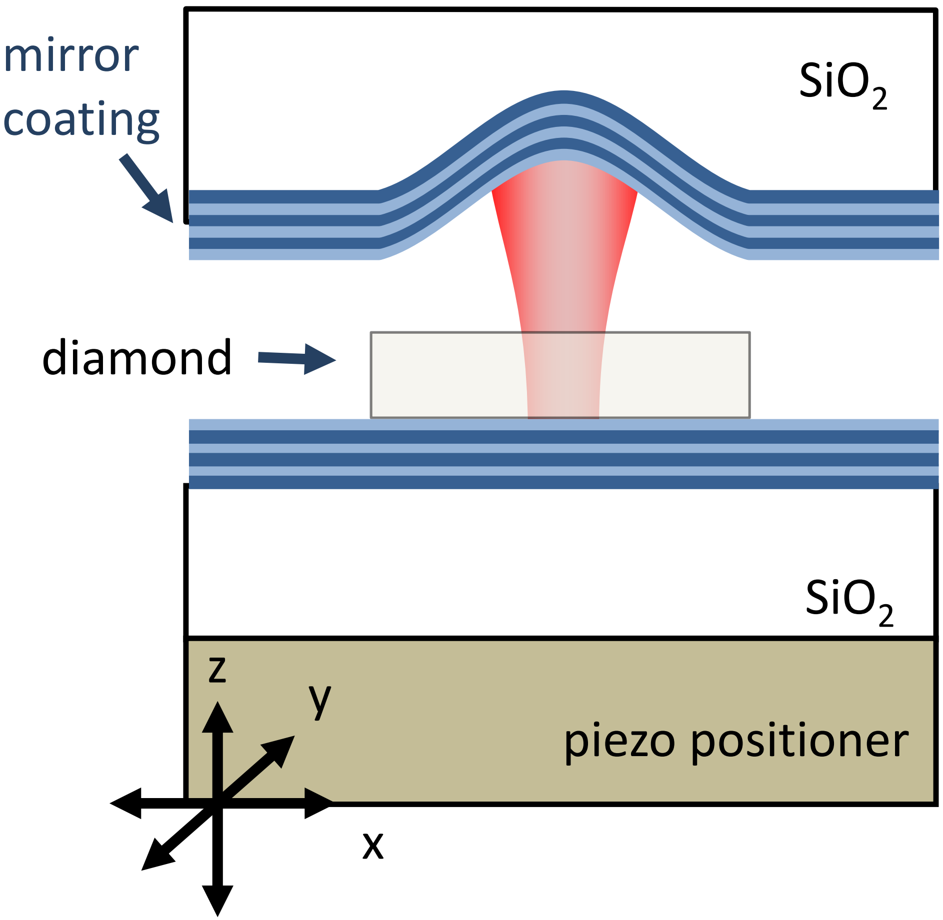

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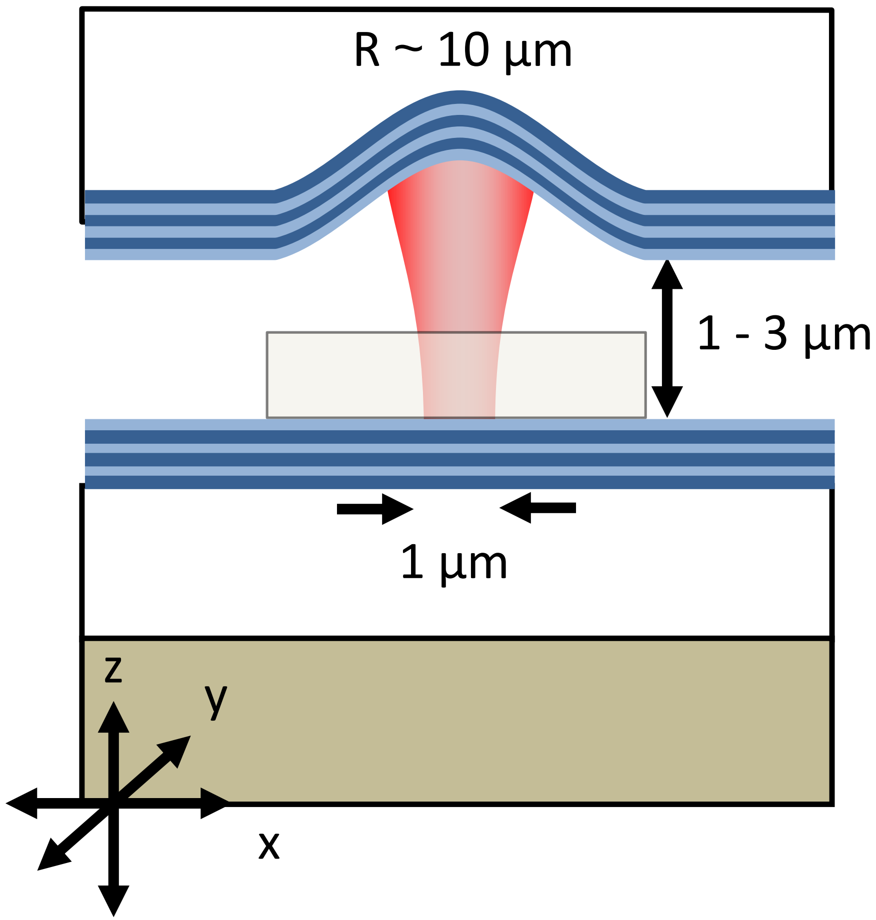
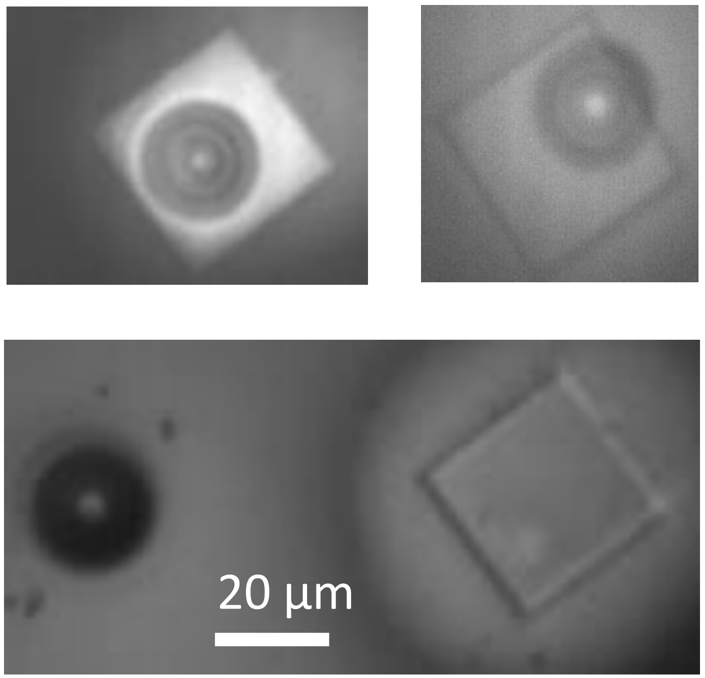
Proof of concept using nanodiamonds:

Albrecht et al., PRL **110**, 243602 (2013)
Johnson et al., New J. Phys. **17**, 122003 (2015)
Kaupp et al., Phys. Rev. Applied **6**, 054010 (2016)

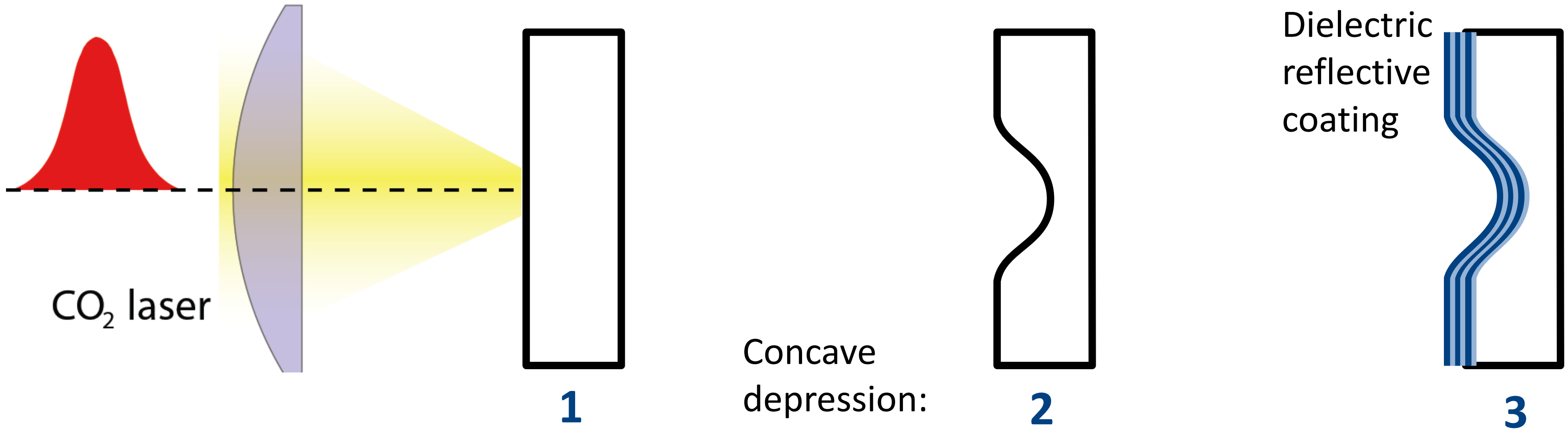
Fully tunable microcavity design





Integration of a microscopic diamond membrane into microcavity

Fabrication of curved mirror templates



Hunger et al., AIP Adv. **2**, 012119 (2012)
Najer et al., Appl. Phys. Lett. **110**, 011101 (2017)

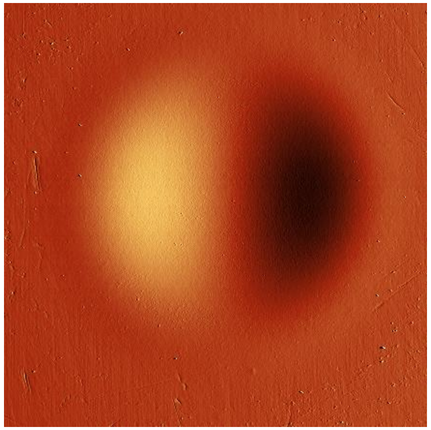
Pulsed CO_2 – laser radiation:

- surface atomically smooth

  high Q factor

- small radius of curvature

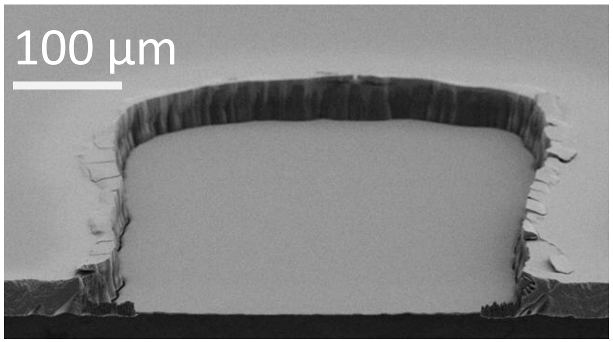
  small mode volume V



AFM – phase image

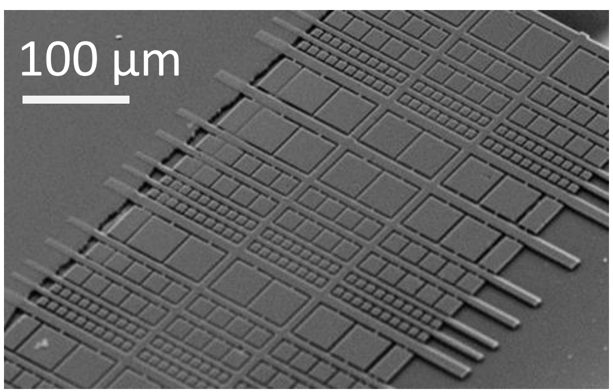
Fabrication of diamond membranes

Commercially available diamond and nitrogen implantation + annealing

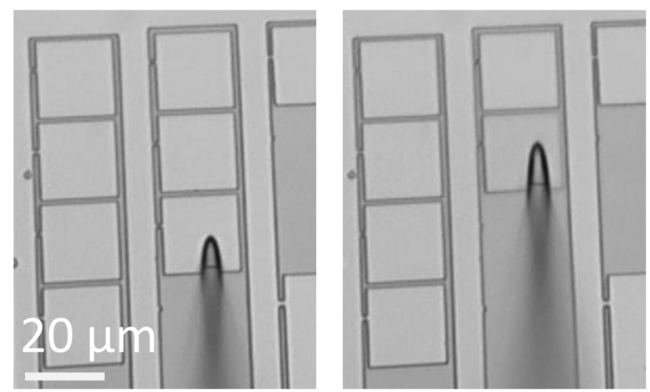


ICP etching

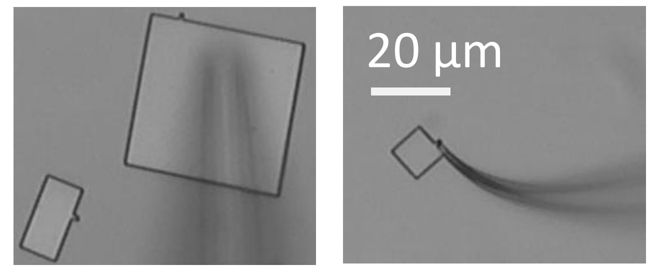
electron beam lithography



micro manipulator



van der Waals bonding

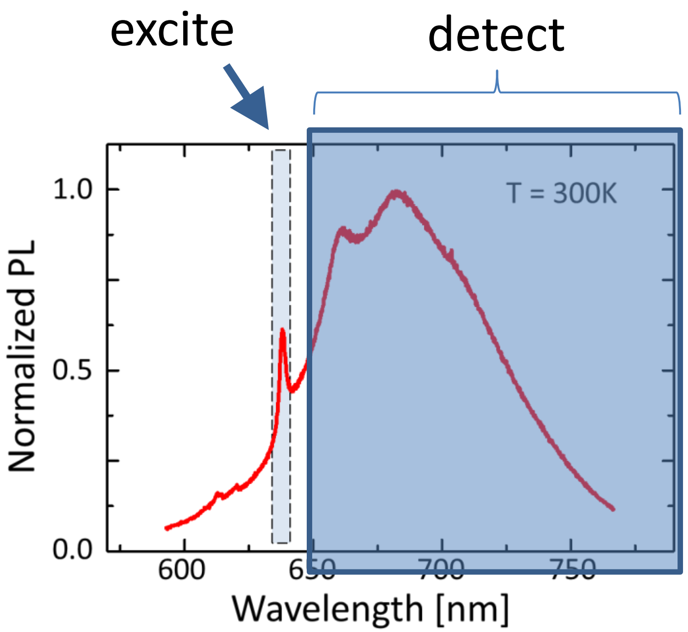


Appel et al., Rev. Sci. Instrum. **87**, 063703 (2016)
Maletinsky et al., Nat. Nanotechnol. **7**, 320 (2012)

DR et al., Phys. Rev. Appl. **2**, 064011 (2014)

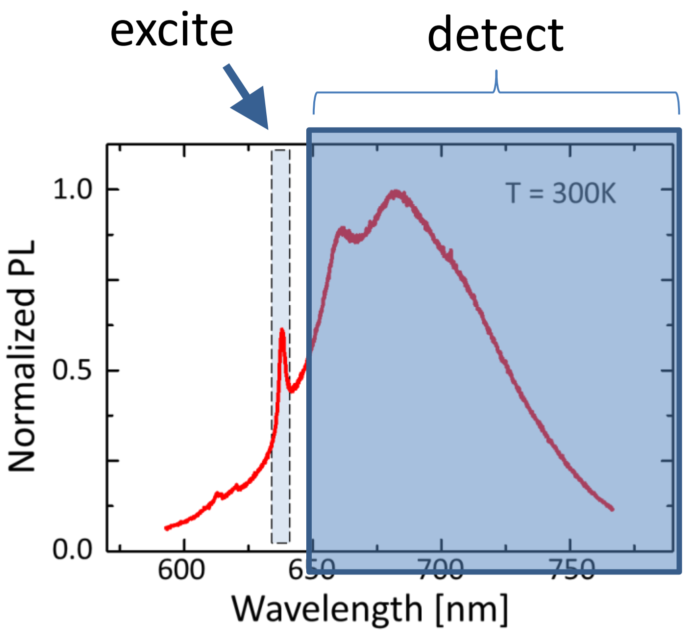
Linewidth measurements

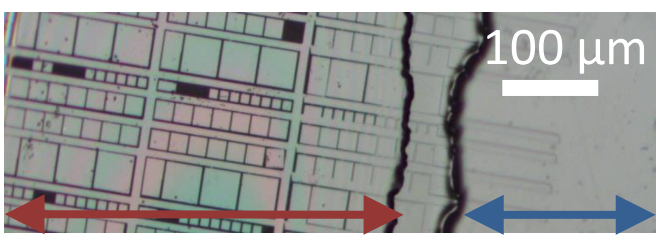
Photoluminescence excitation measurement



Linewidth measurements

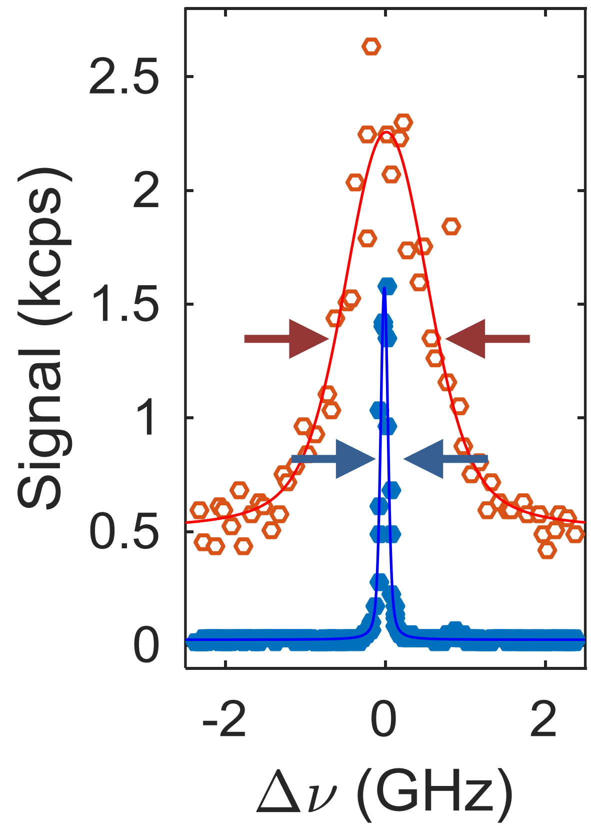
Photoluminescence excitation measurement





membrane
d ~ 1 µm

"bulk"
d ~ 40 µm



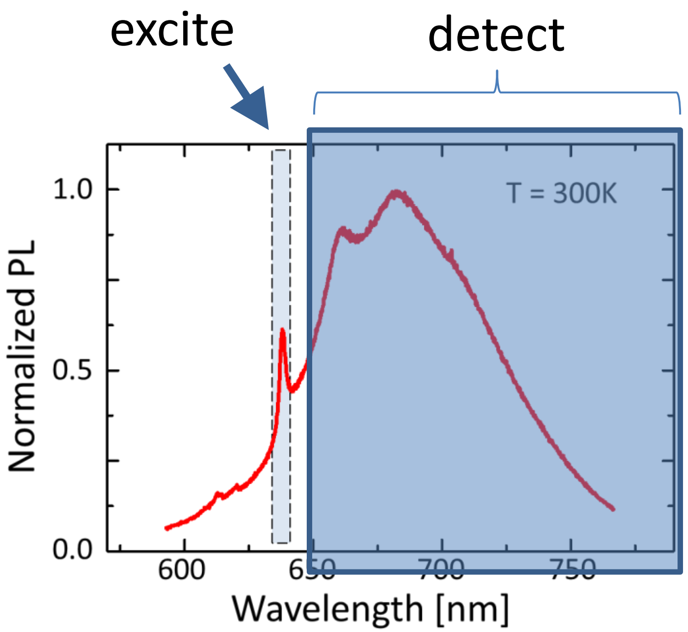
membrane:
1 GHz

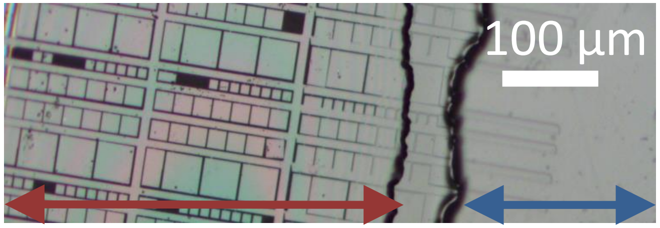
"bulk“:
100 MHz

Chu et. al, Nano Lett. **14**, 1982 (2014)

Linewidth measurements

Photoluminescence excitation measurement





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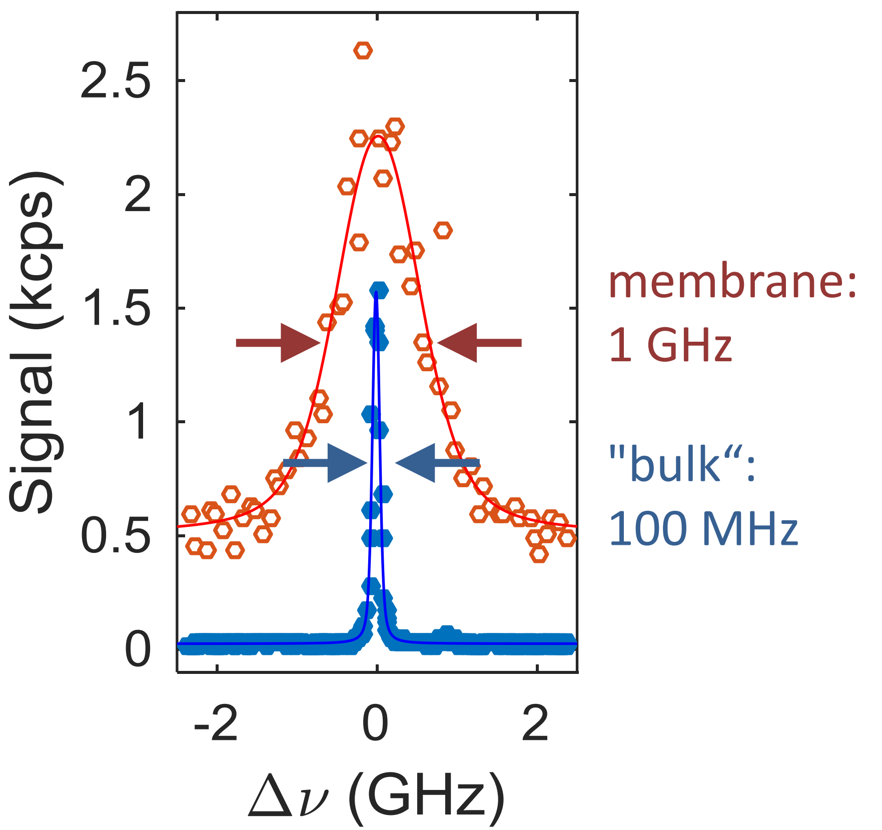
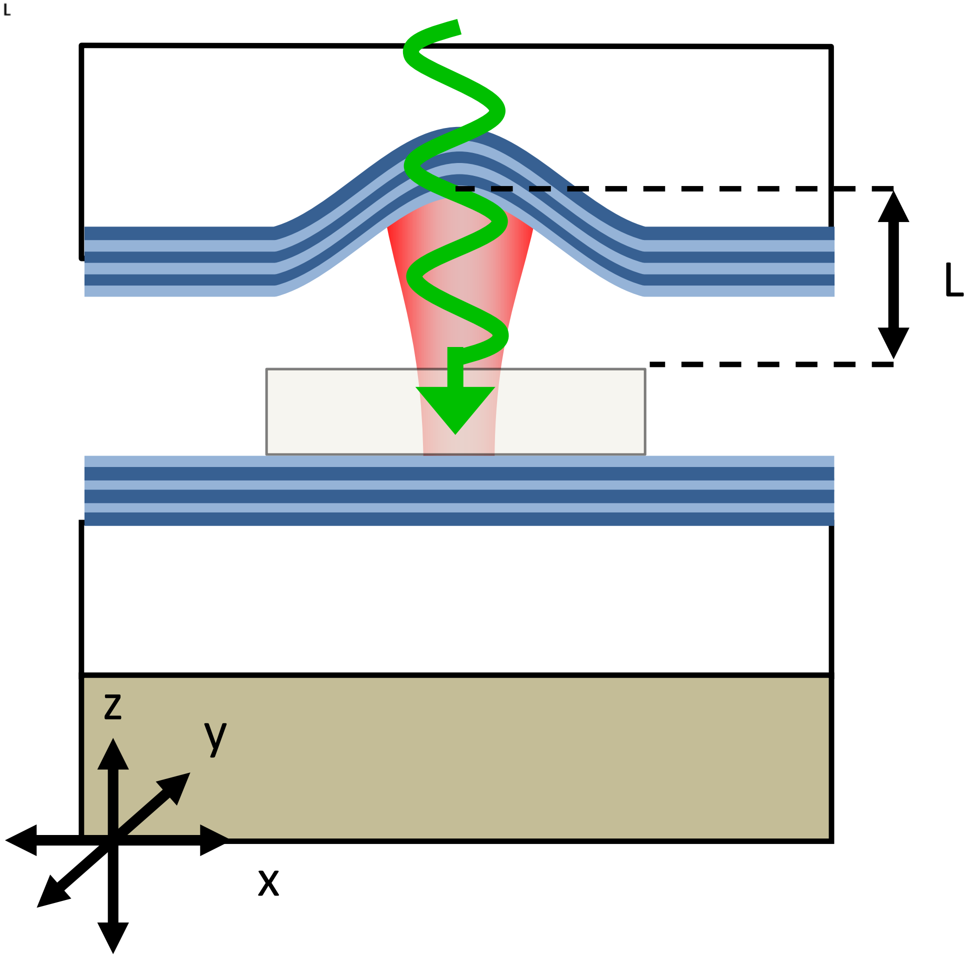


linewidth smaller than ground state spin splitting: 2.87 GHz

Chu et. al, Nano Lett. **14**, 1982 (2014)

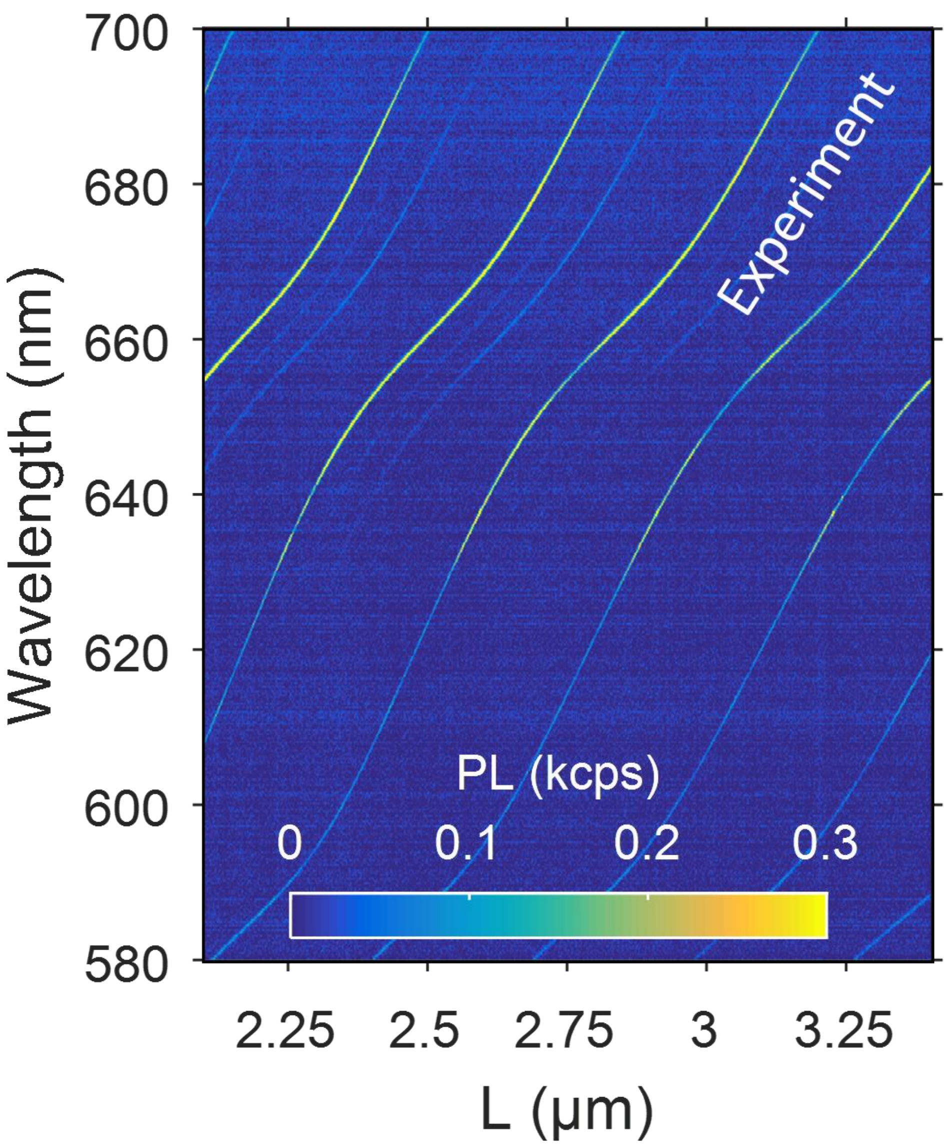
Cavity characterization



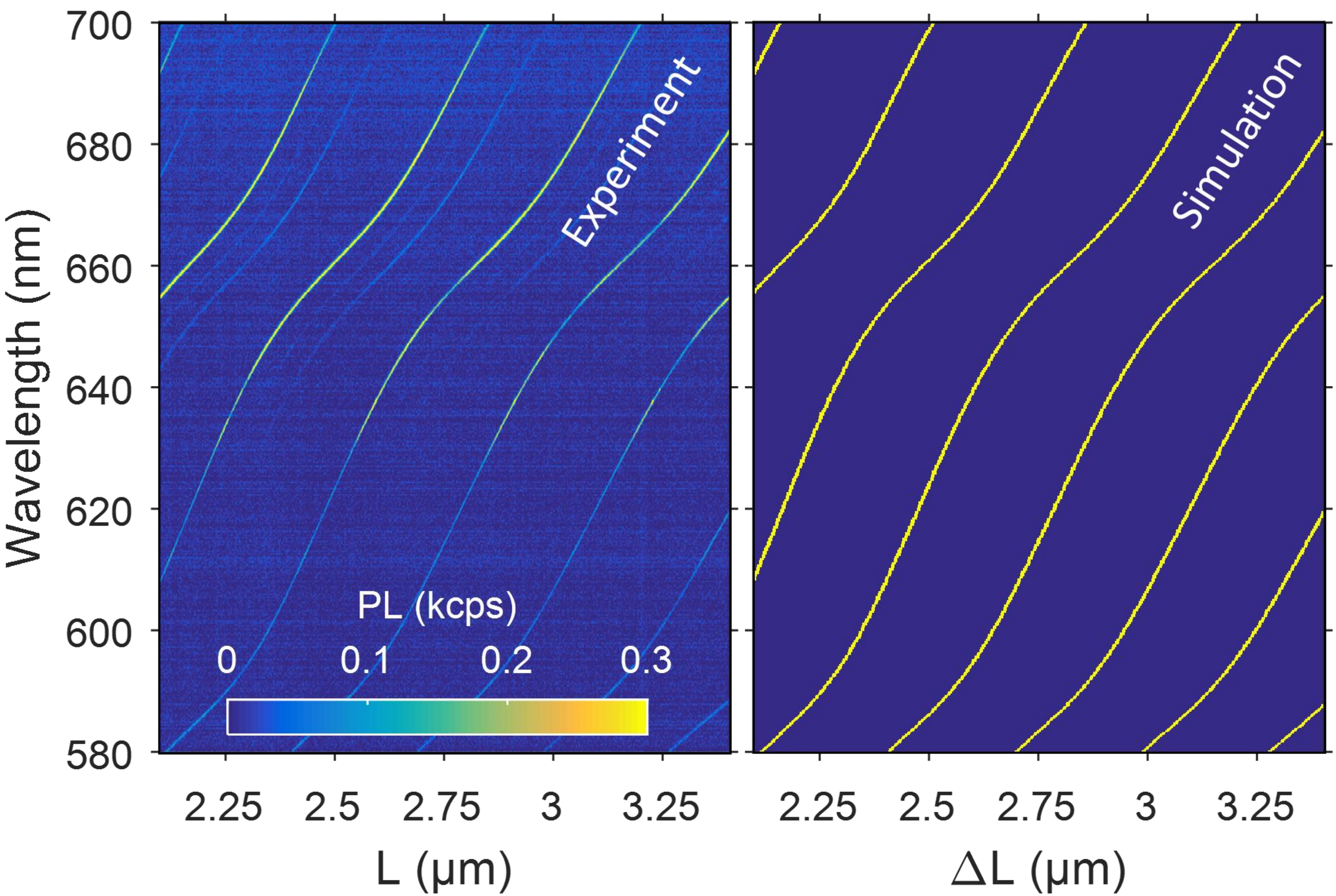
Analyze cavity mode structure:

- couple green laser
- tune width of air gap L
- record photoluminescence (PL) spectra for different L

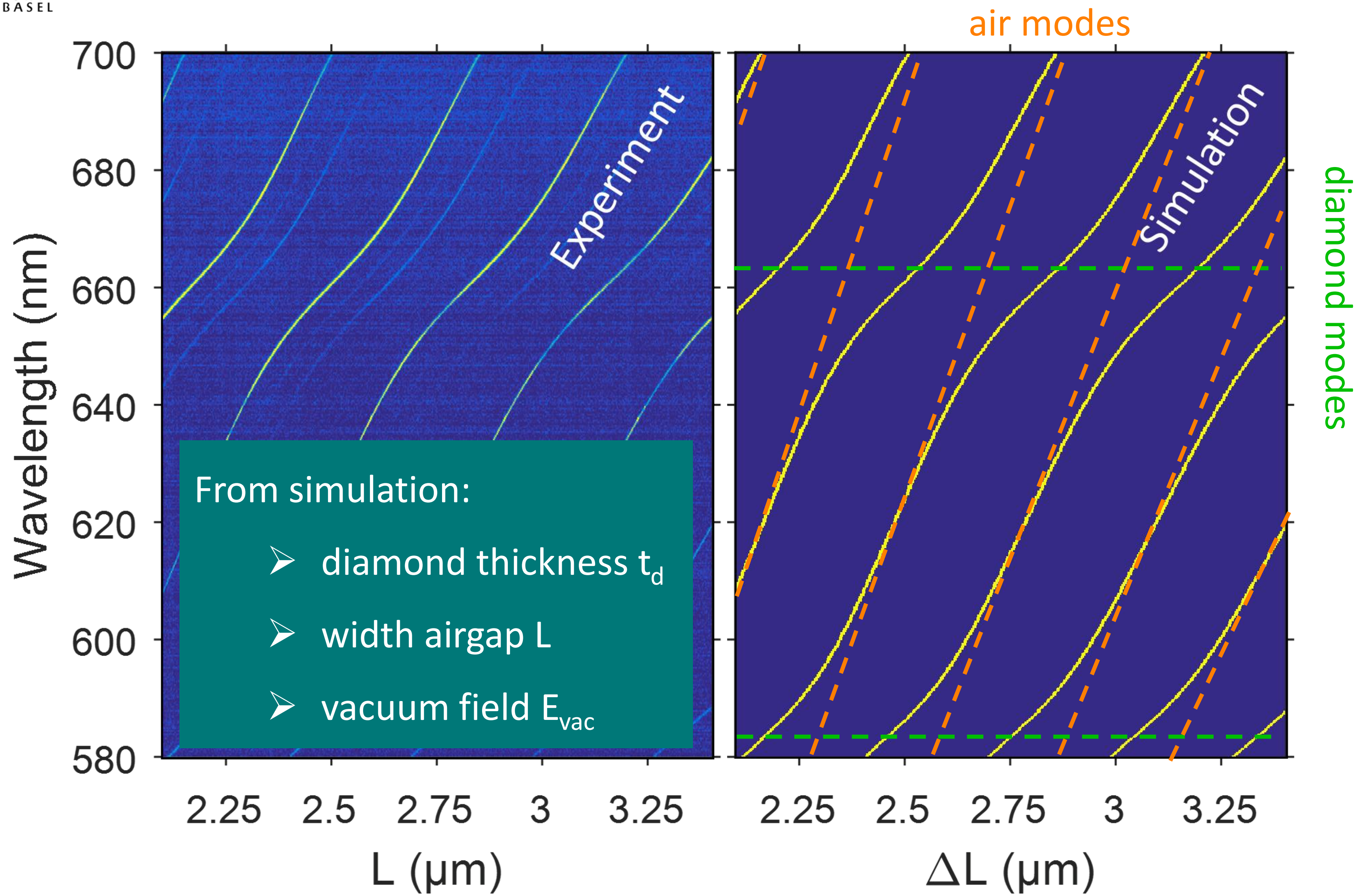
PL vs. air gap width L



PL vs. air gap width L



PL vs. air gap width L

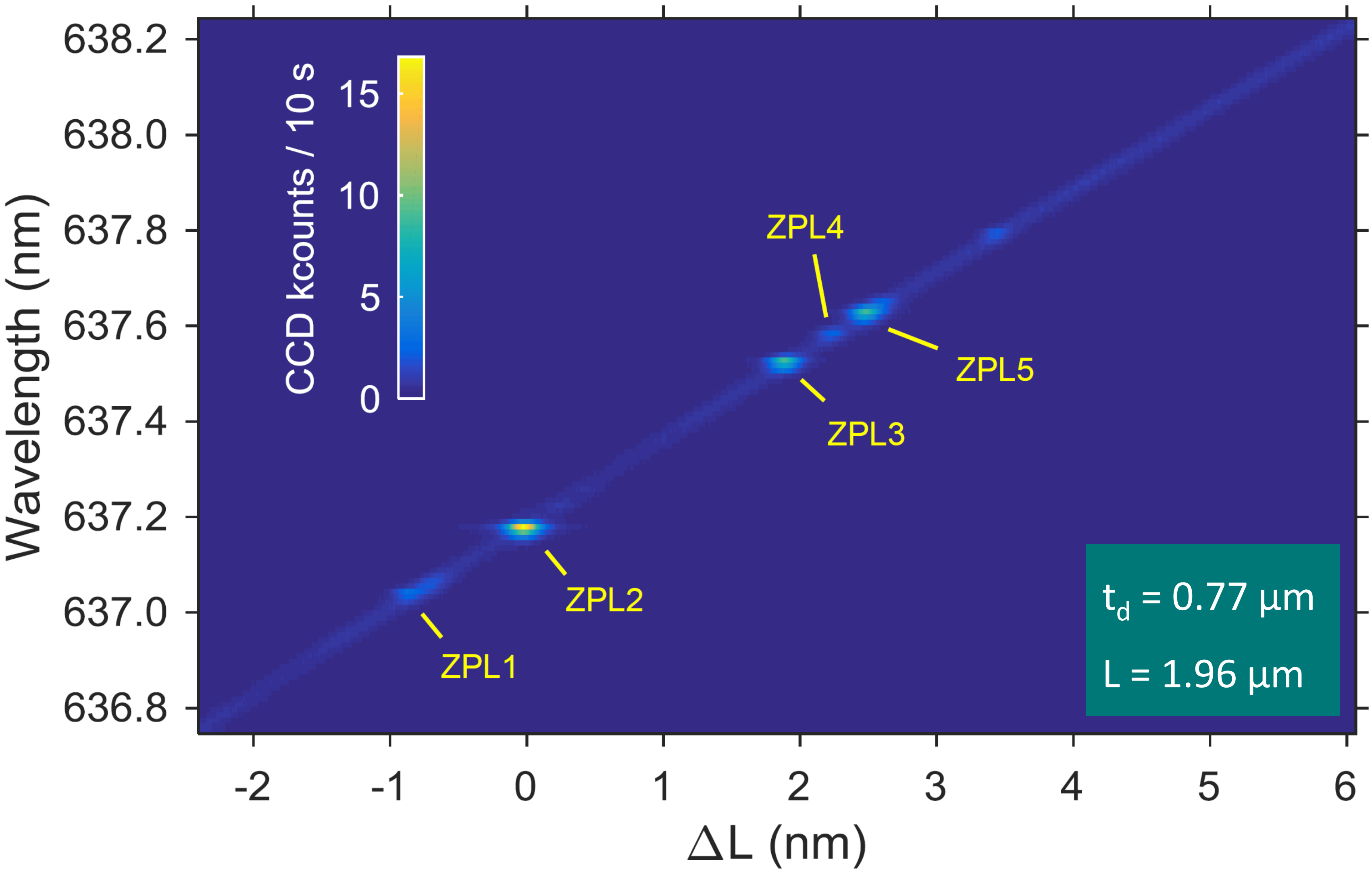


From simulation:

- diamond thickness t_d
- width airgap L
- vacuum field E_{vac}

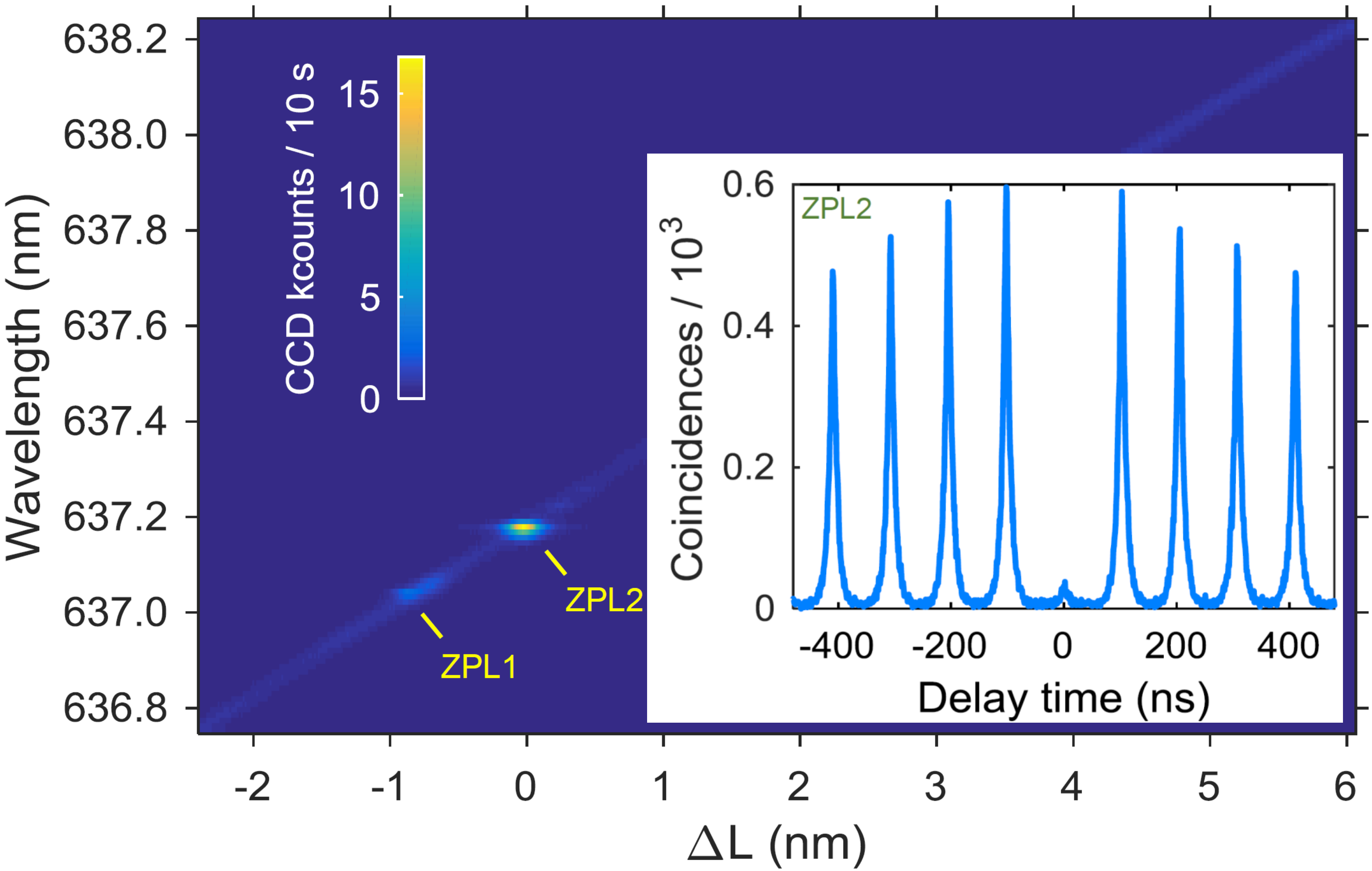
Janitz et. al, Phys. Rev. A **92**, 043844 (2015)

PL vs. relative detuning ΔL



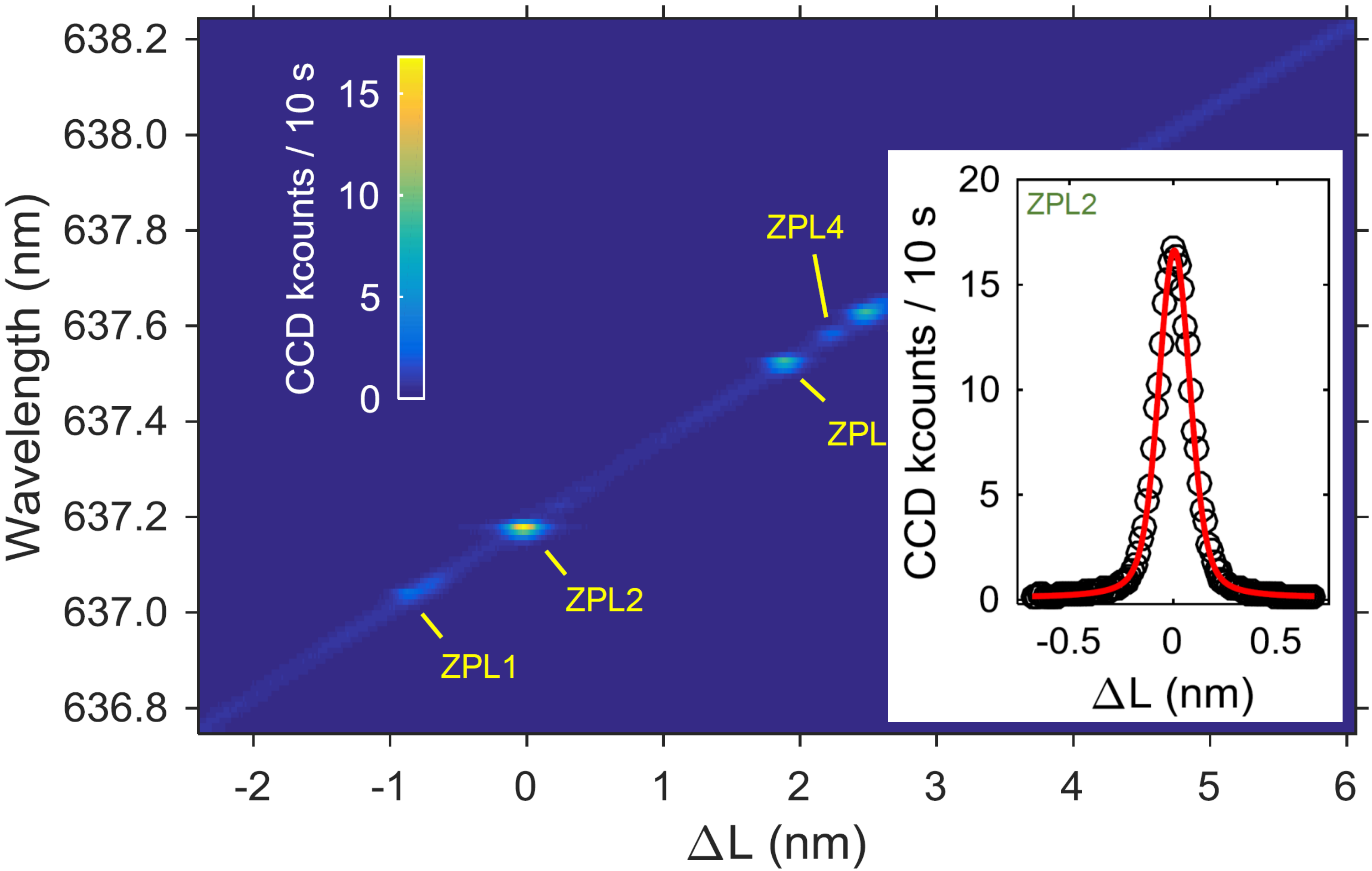
PL vs. relative detuning ΔL

➢ Clear single emitter signature in photon autocorrelation

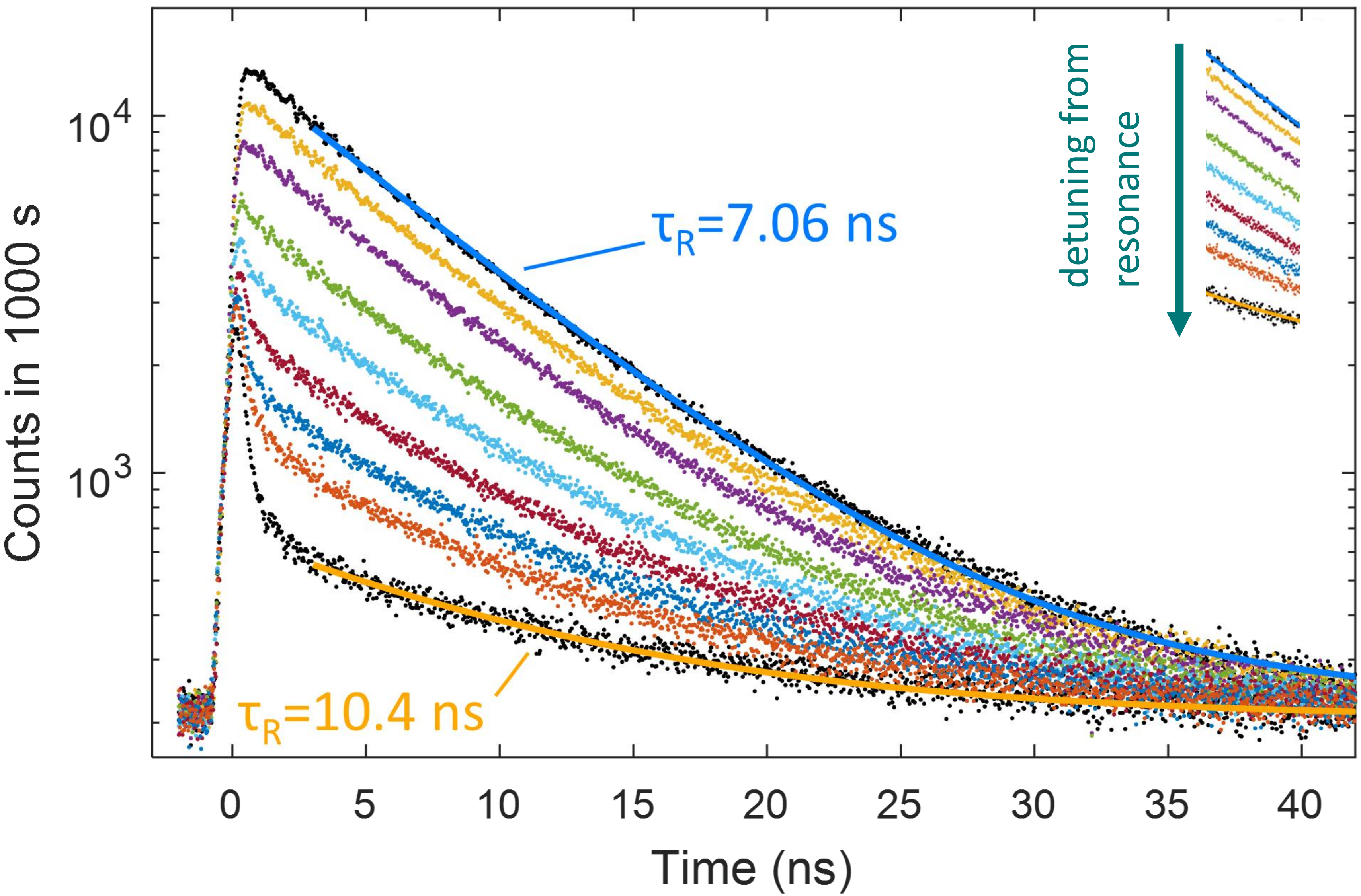


PL vs. relative detuning ΔL

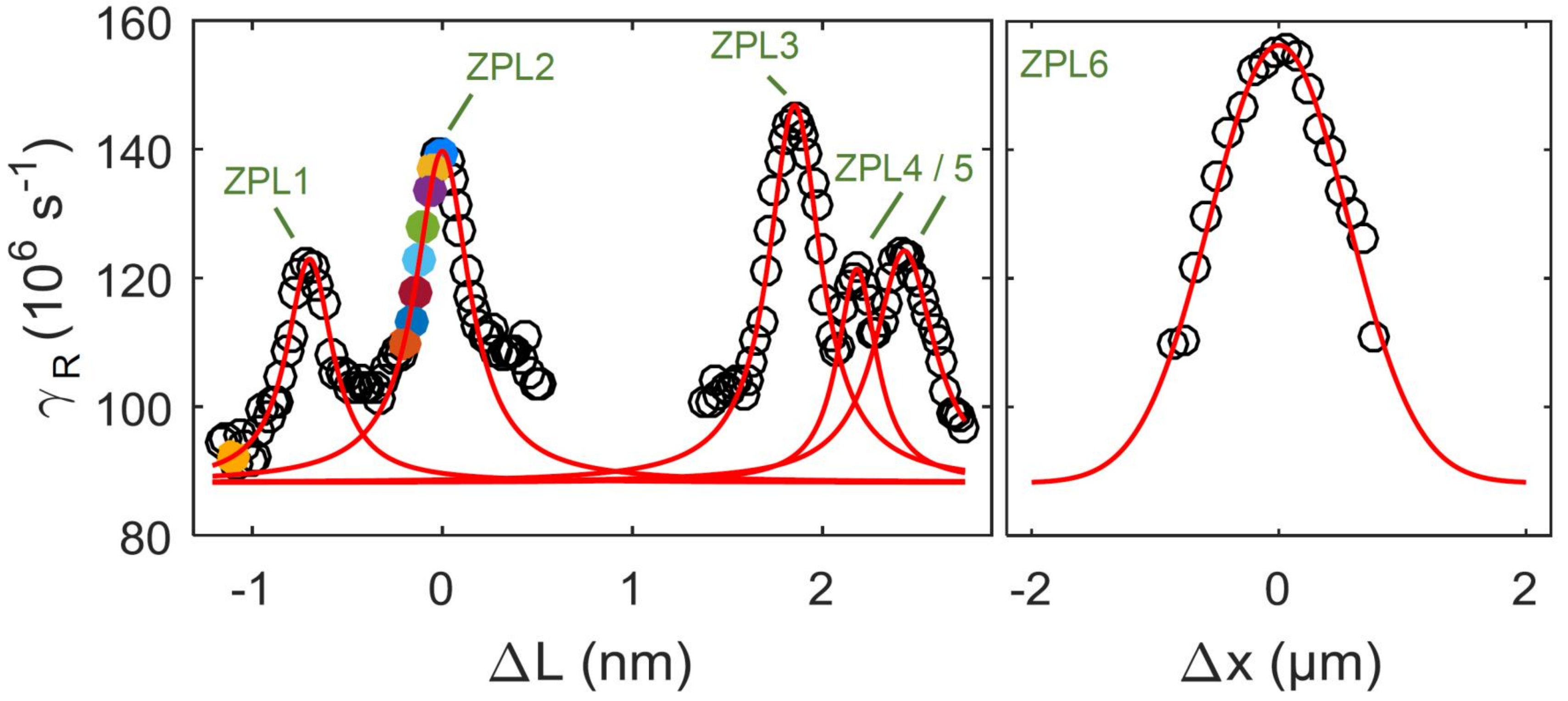
- Q factor: 58500 $\kappa = \omega / Q = 5.06 \cdot 10^{10}\ s^{-1}$



Lifetime NV2: spectral detuning

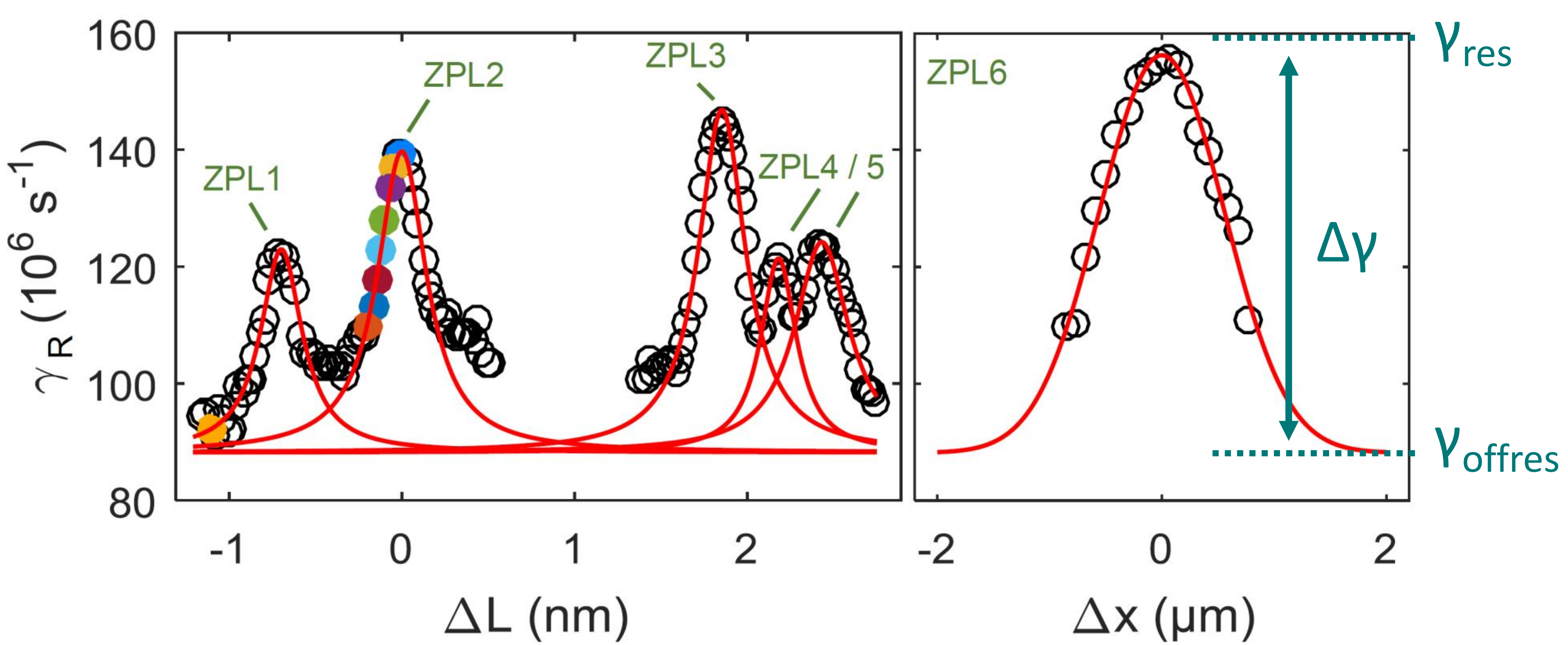


Lifetime NV2: spectral + spatial detuning



Full *in situ* control of the cavity system

Lifetime NV2: spectral + spatial detuning



Full *in situ* control of the cavity system

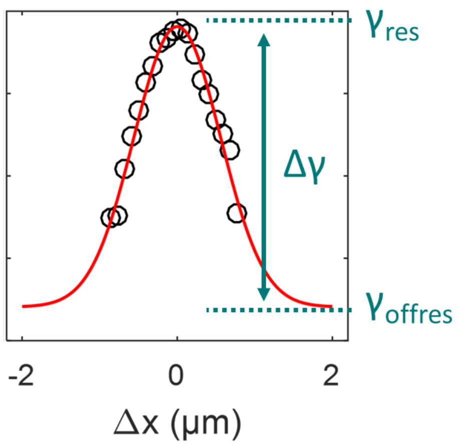
$\gamma_{res} = 158 \cdot 10^6\, s^{-1}$ $\gamma_{offres} = 88.2 \cdot 10^6\, s^{-1}$ $\Delta\gamma = 69.8 \cdot 10^6\, s^{-1}$

Results

Experimental results:

$\gamma_{res} = 158 \cdot 10^6\, s^{-1}$, $\gamma_{offres} = 88.2 \cdot 10^6\, s^{-1}$, $\Delta\gamma = 69.8 \cdot 10^6\, s^{-1}$

$\gamma_{NV} = 79.4 \cdot 10^6\, s^{-1}$ (measurement without top mirror)



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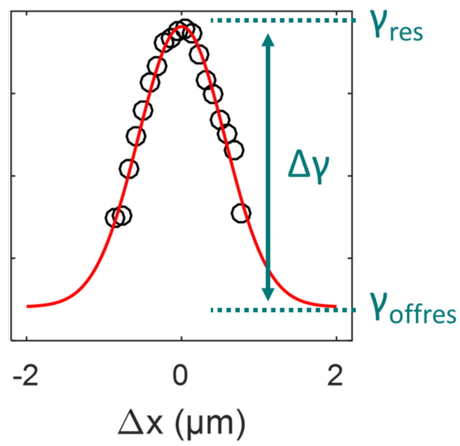
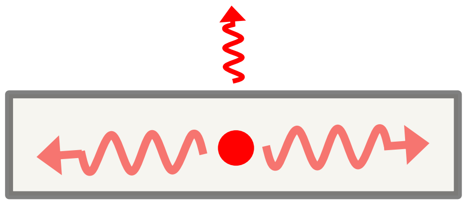
$\gamma_{NV} = 79.4 \cdot 10^6\, s^{-1}$ (measurement without top mirror)

Overall enhancement:

$F_P = \gamma_{res} / \gamma_{NV} = 2.0$





waveguide effect

Results

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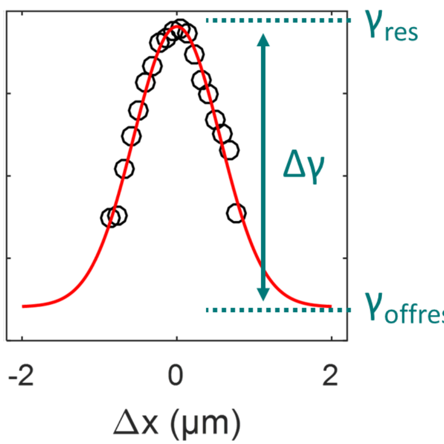


Overall enhancement:

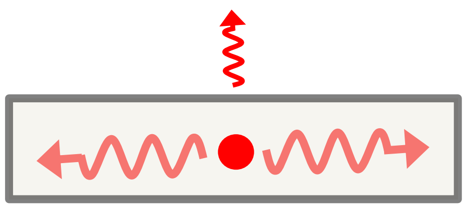
$F_P = \gamma_{res} / \gamma_{NV} = 2.0$

Purcell enhancement of ZPL:

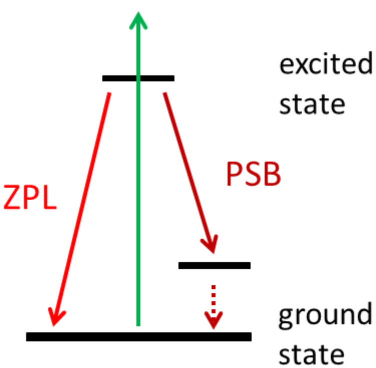
Fraction of ZPL emission in bulk: ~ 3%

$\gamma_{ZPL} = 2.38 \cdot 10^6\, s^{-1}$

$F_{P,ZPL} = \Delta\gamma / \gamma_{ZPL} + 1 = 30.3$



waveguide effect



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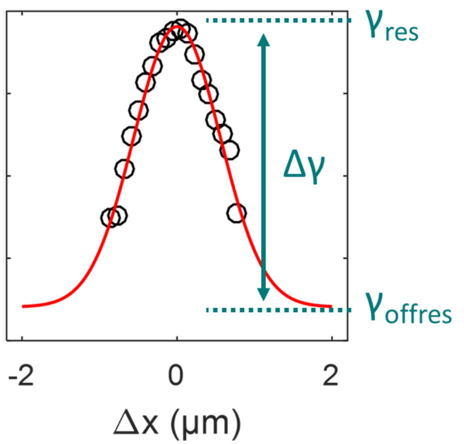

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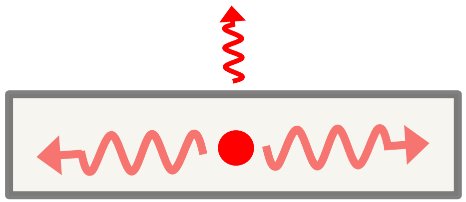
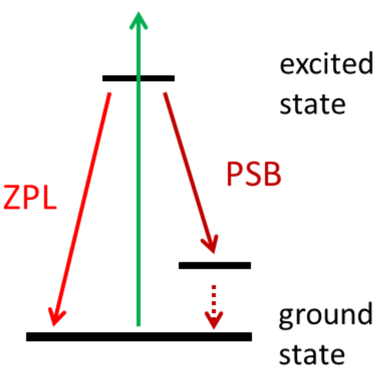


$\gamma_{ZPL} = 2.38 \cdot 10^6\, s^{-1}$

$F_{P,ZPL} = \Delta\gamma / \gamma_{ZPL} + 1 = 30.3$



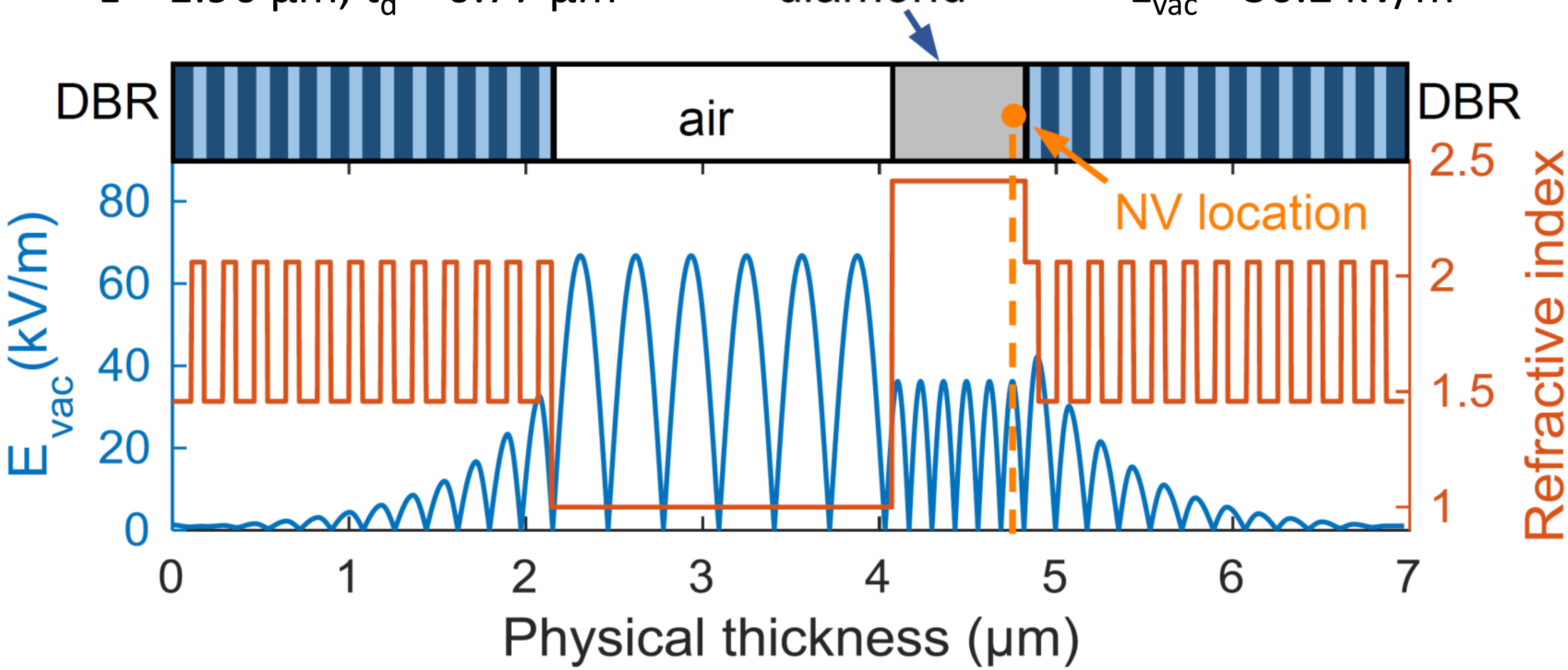
Fraction of ZPL emission in cavity:

$\eta = (\Delta\gamma + \gamma_{ZPL}) / \gamma_{res} = 45.7\%$

before: ~ 3%

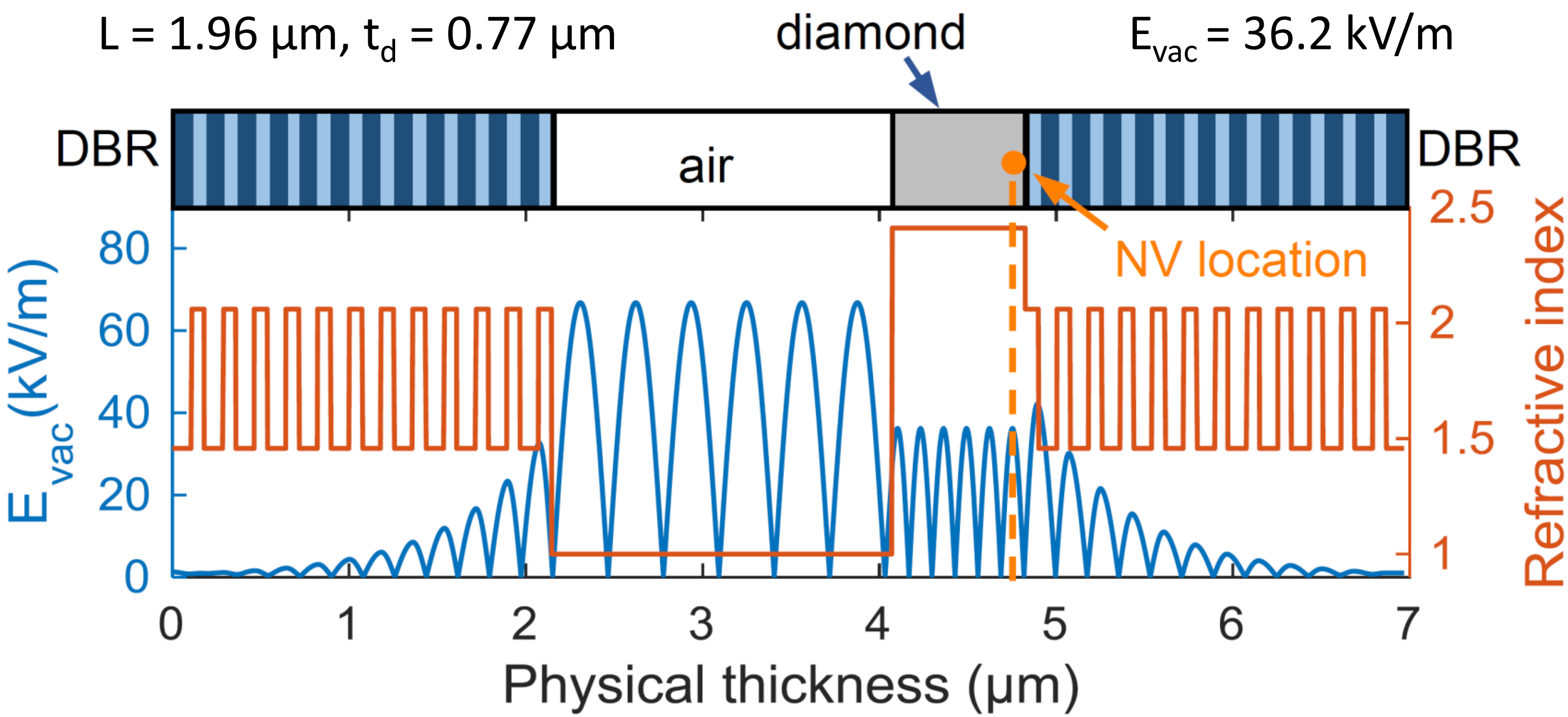
Calculation of expected Purcell enhancement

$L = 1.96\ \mu m$, $t_d = 0.77\ \mu m$ diamond $E_{vac} = 36.2$ kV/m



1D-transfer matrix calculation + Gaussian lateral confinement

Calculation of expected Purcell enhancement



1D-transfer matrix calculation + Gaussian lateral confinement

$\gamma_{NV} = 79.4 \cdot 10^6\ s^{-1}$ $\kappa = 5.06 \cdot 10^{10}\ s^{-1}$ $g = 5.97 \cdot 10^9\ s^{-1}$

Theoretical Purcell enhancement:
$F_P = 4\ g^2 / (\kappa\ \gamma_{NV}) = 35.5$

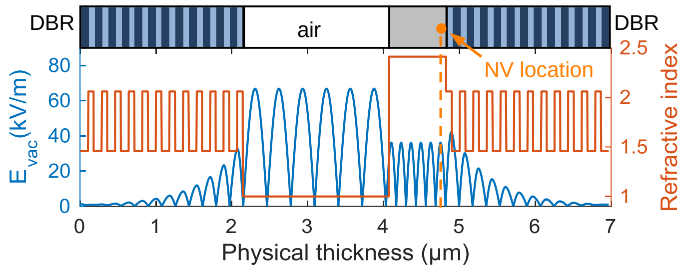
Outlook

Current experiment:

$\gamma_{NV} = 79.4 \cdot 10^{6}\, s^{-1}$

$\kappa = 5.06 \cdot 10^{10}\, s^{-1}$

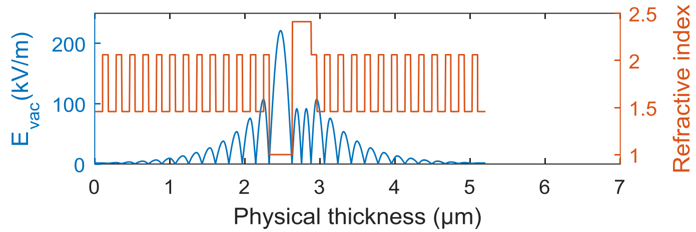
$g = 5.97 \cdot 10^{9}\, s^{-1}$



Best air-confined cavity:

$g = 1.41 \cdot 10^{10}\, s^{-1}$, $\kappa = 2g$

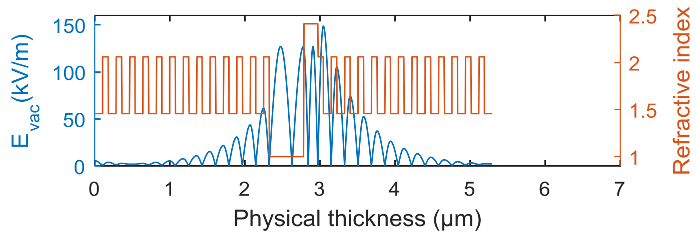
$F_{P,air} = 356$



Best diamond-confined cavity:

$g = 2.09 \cdot 10^{10}\, s^{-1}$, $\kappa = 2g$

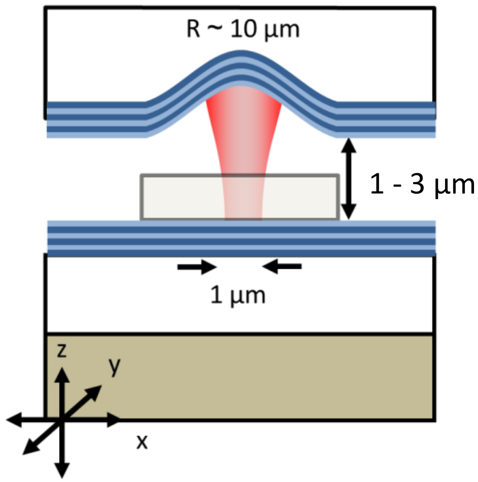
$F_{P,dia} = 527$



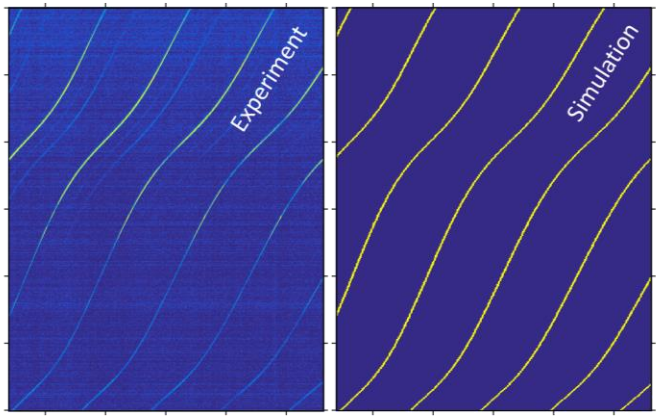
Potential enhancement of entanglement rate: 10^{6}

Bogdanovic et al., arXiV: 1612.02164

Conclusion and outlook

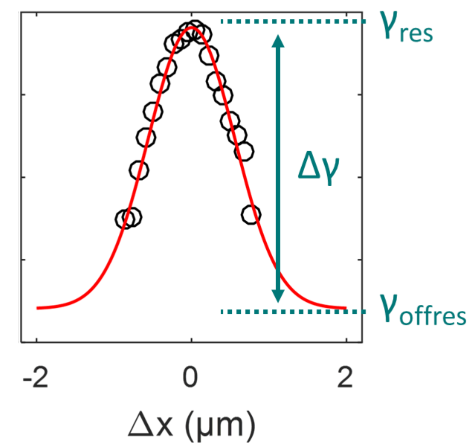


✓ Fully tunable microcavity



✓ Theoretical model

D. Riedel et al., submitted



✓ Purcell enhancement

Outlook:

- integrate microwave for spin control of NV centers
- improve Q/V - enhancement > 500 feasible
- other colour centres in diamond (SiV, GeV), silicon carbide, ...

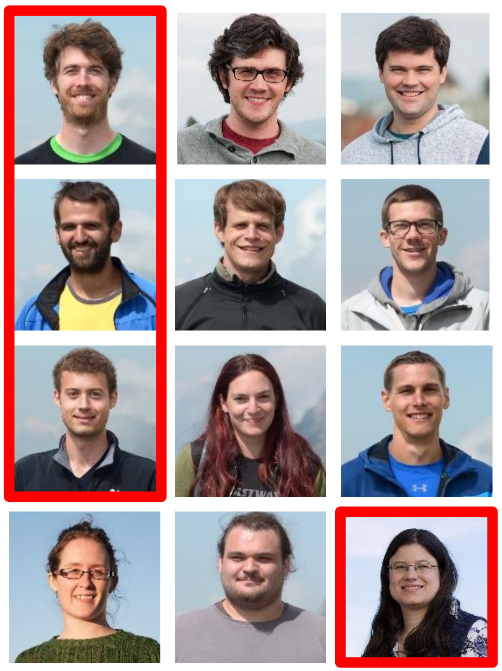
Neu et. al, New J. Phys **13**, 025012 (2011)
Rogers et al. PRL **113**, 263602 (2014)
Sipahigil et. al, Science 354, **847** (2016)

Siyushev et al., arXiV: 1612.02947
Bhaskar et al., arXiV: 1612.03036

DR et al., PRL **109**, 226402 (2012)
Widmann et al., Nat. Mater. **14**, 164 (2015)
Christle et al., Nat. Mater. **14**, 160 (2015)

Acknowledgements

Patrick Maletinsky



Uni Saarbrücken

https://quantum-sensing.ch/

Universität Basel

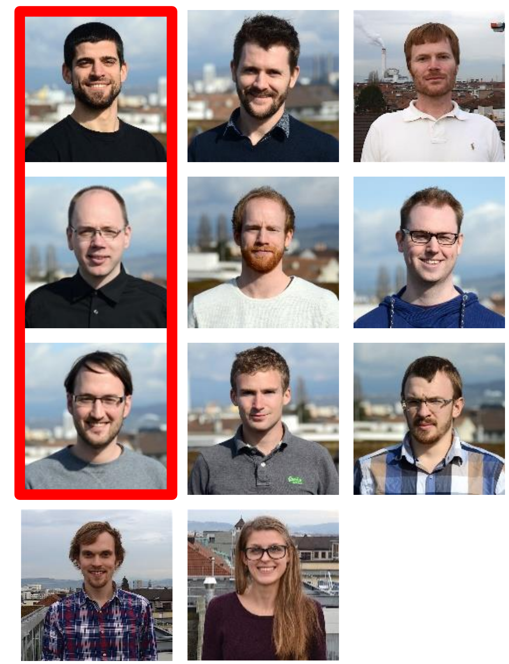
QSIT Quantum Science and Technology

National Centre of Competence in Research

SNI SWISS NANOSCIENCE INSTITUTE

EINE INITIATIVE DER UNIVERSITÄT BASEL UND DES KANTONS AARGAU

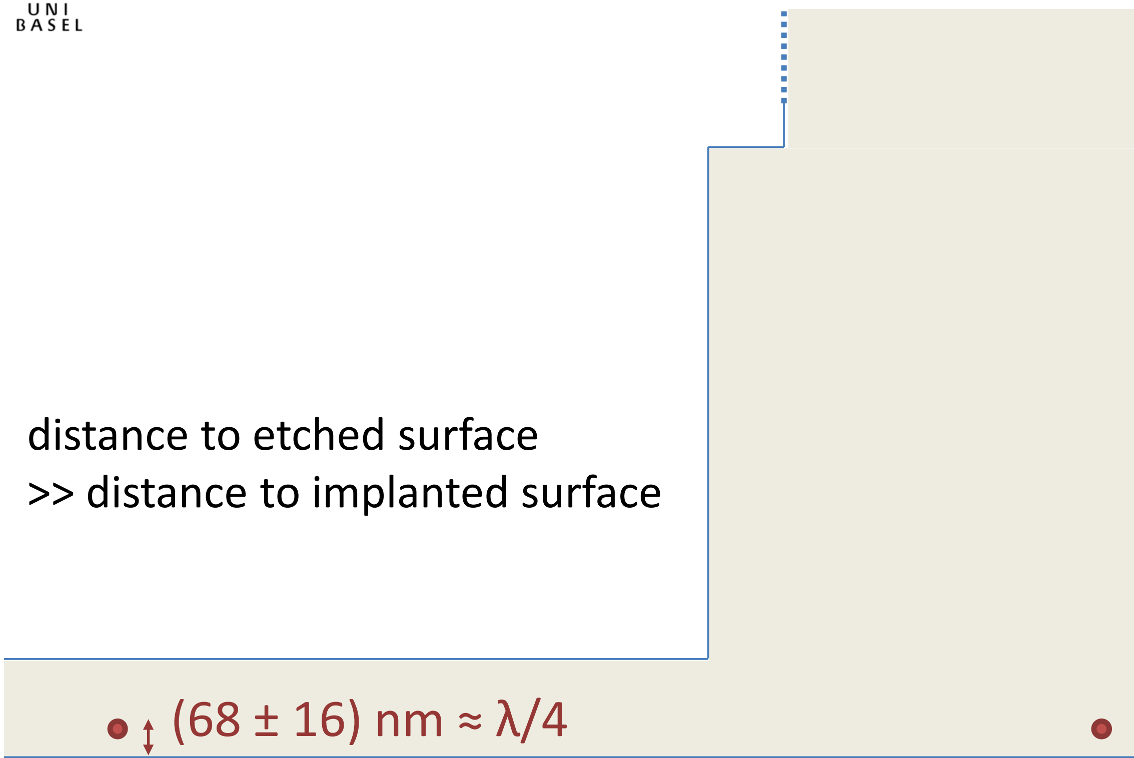
Richard J. Warburton

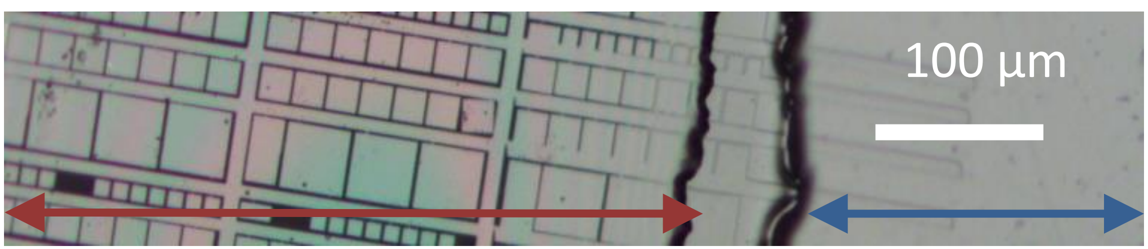


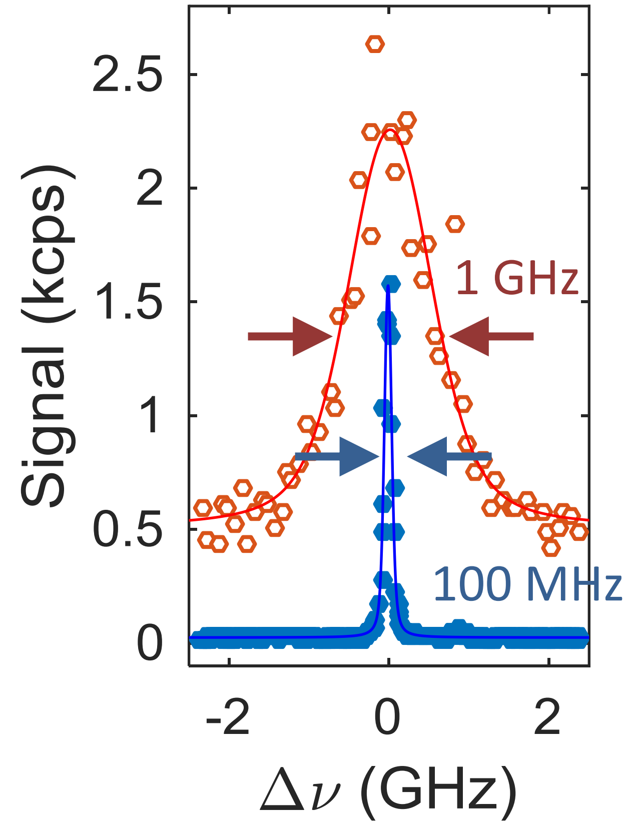
https://nano-photonics.unibas.ch/

Linewidth measurements

distance to etched surface
>> distance to implanted surface



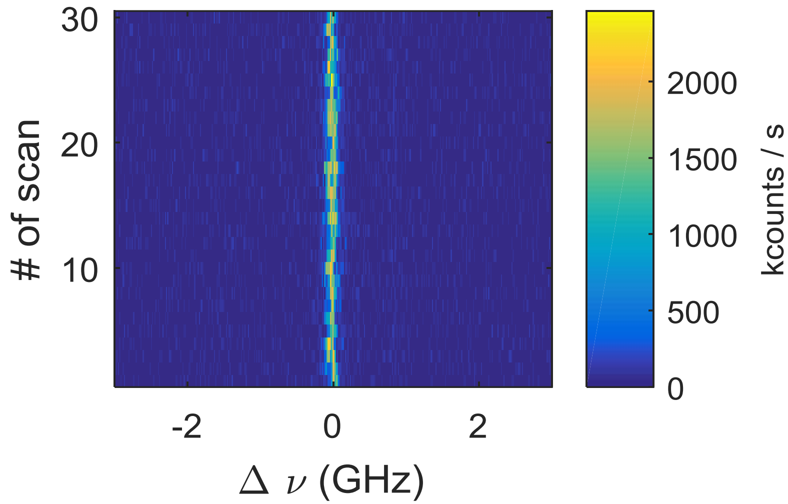


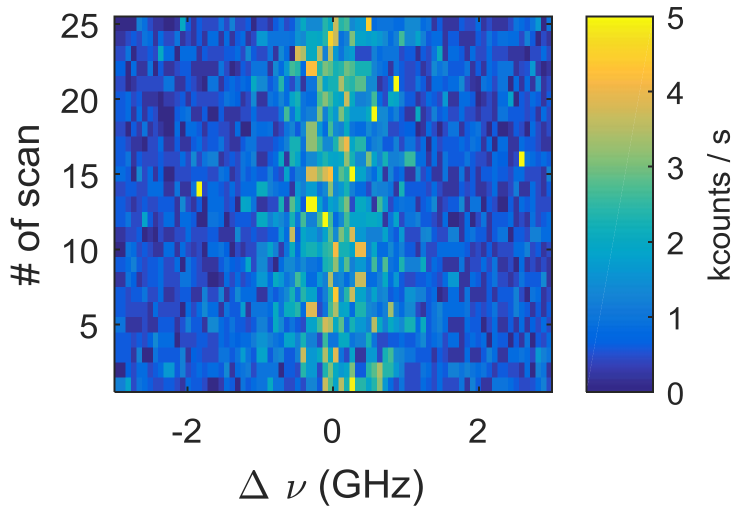


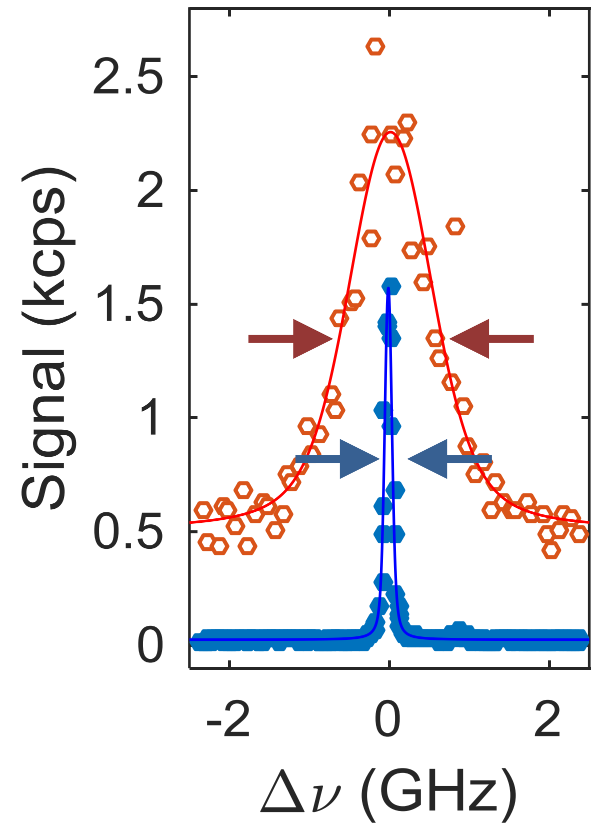
membrane
d ~ 1 µm

"bulk“
d ~ 40 µm

Linewidth measurements

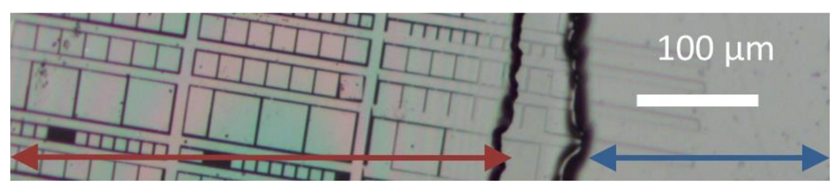






membrane: 1 GHz

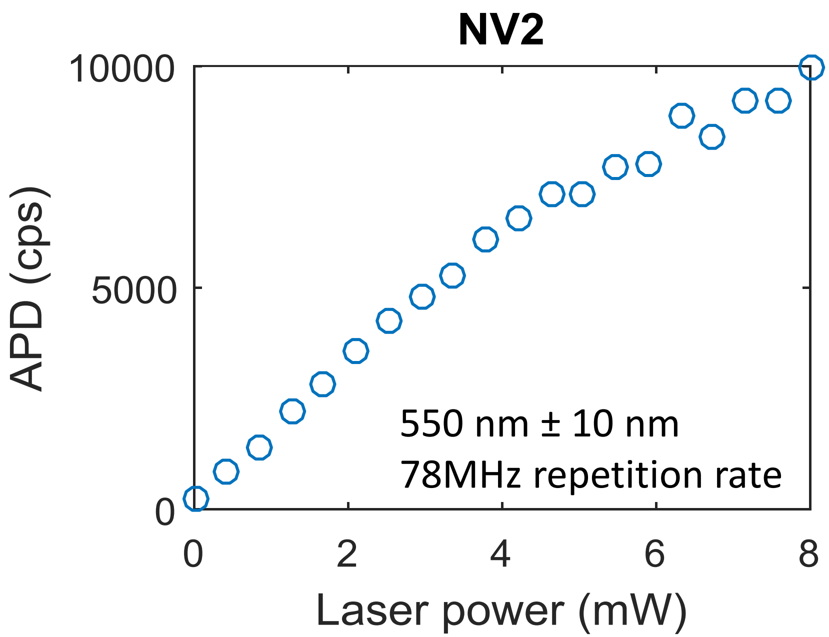
"bulk“: 100 MHz



membrane
d ~ 1 µm

"bulk“
d ~ 40 µm

Power saturation



Low count rate due to losses:

T = 1 - R - A

(T:= Transmissivity of mirror coating)
(R:= Reflectivity of mirror coating)
(A:= Absorption and scattering losses)

Transmission of tunable red diode laser:
~ 4%

Ideal transmission: 100%

→ Factor of 25 for lossless mirrors / no scattering, no absorption

Optical cavity - Purcell enhancement

$$\frac{W_{\mathrm{cav}}}{W_{\mathrm{free}}} = F_{\mathrm{P}} = \frac{3}{4\pi^2}\left(\frac{\lambda_{\mathrm{cav}}}{n}\right)^3 \frac{Q}{V_{\mathrm{cav}}}$$

Transition rate for spontaneous emission:

$$W_{12} = \frac{2\pi}{\hbar^2}|M_{12}|^2 g(\omega)$$

Increased DOS - High Q
Confined E_{vac} - Small V

Transition matrix element:

$$|M_{12}|^2 = < \vec{p}\cdot\vec{E}_{\mathrm{vac}} >^2$$

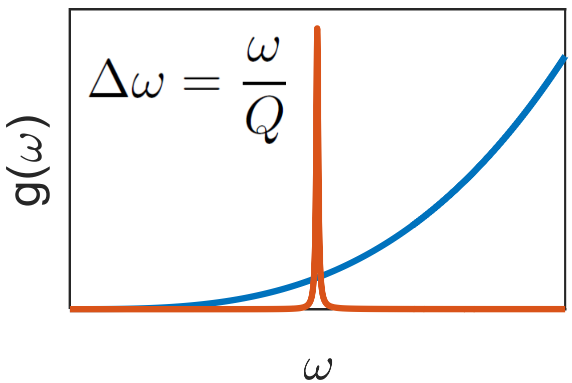
$$E_{\mathrm{vac}} = \sqrt{\frac{\hbar\omega}{2\epsilon_0 V}}$$

single photon mode volume

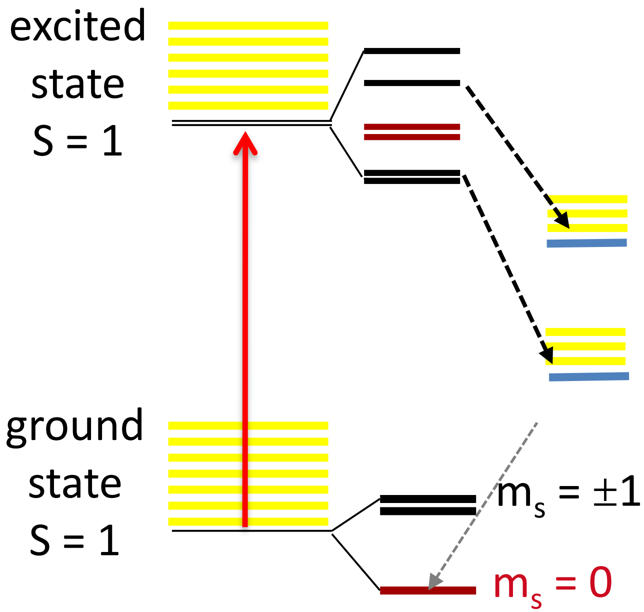
Photon density of states:

$$g_{\mathrm{free}}(\omega) = \frac{\omega^2 V}{\pi^2 c^3}$$

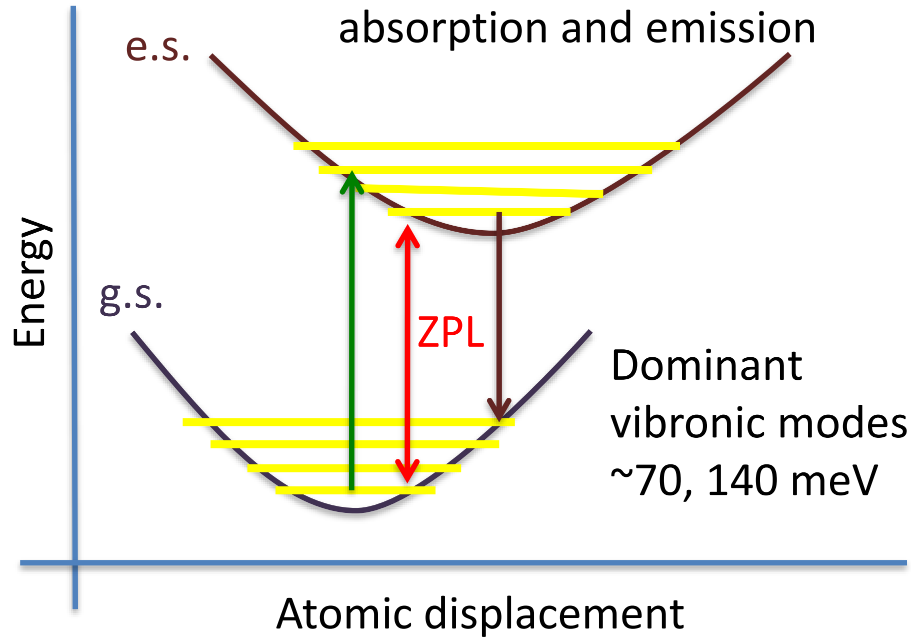
$$g_{\mathrm{cav}}(\omega) = \frac{2}{\pi\Delta\omega}\frac{\Delta\omega^2}{4(\omega-\omega_{\mathrm{c}})^2+\Delta\omega^2}$$

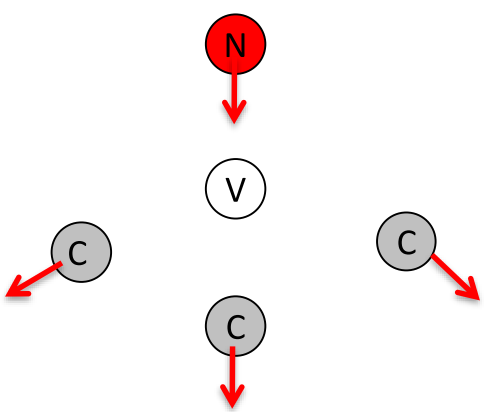


Vibronic structure of the NV center



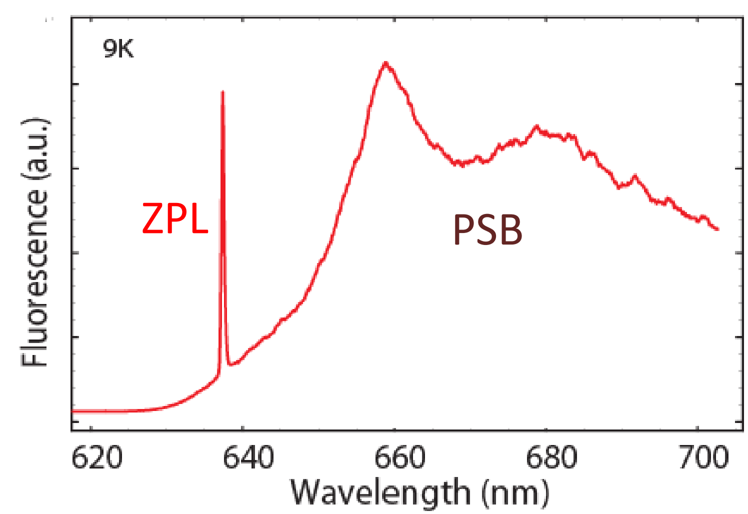
"Phonon sidebands" in both absorption and emission



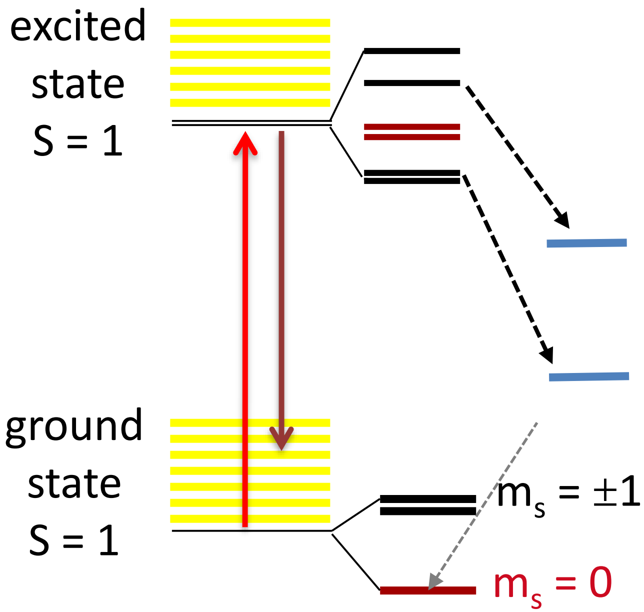


Different equilibrium positions in the ground and excited states (*ab initio* calculations)

Ma et al. 2010 PRB
Gali et al. 2011 NJP
Zhang et al. 2011 PRB
Abtew et al. 2011 PRL
Toyli et al. 2012 PRX



Strain effects at low temperatures

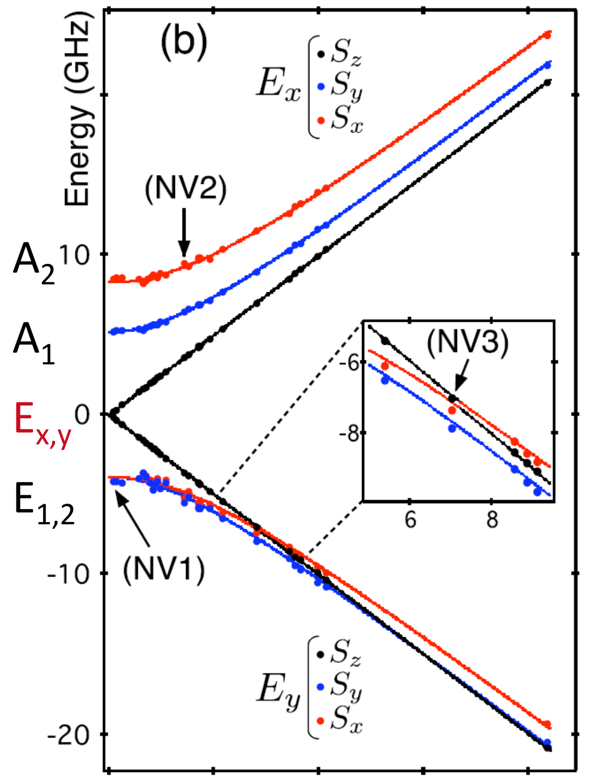


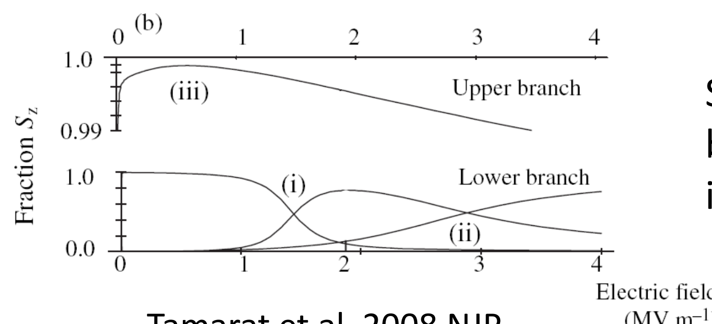
Zero strain:
C_{3v} symmetry

Axial strain shifts all the energy levels together

Electric fields have the same effect as strain

Batalov et al. 2009 PRL





Tamarat et al. 2008 NJP

High transverse strain:

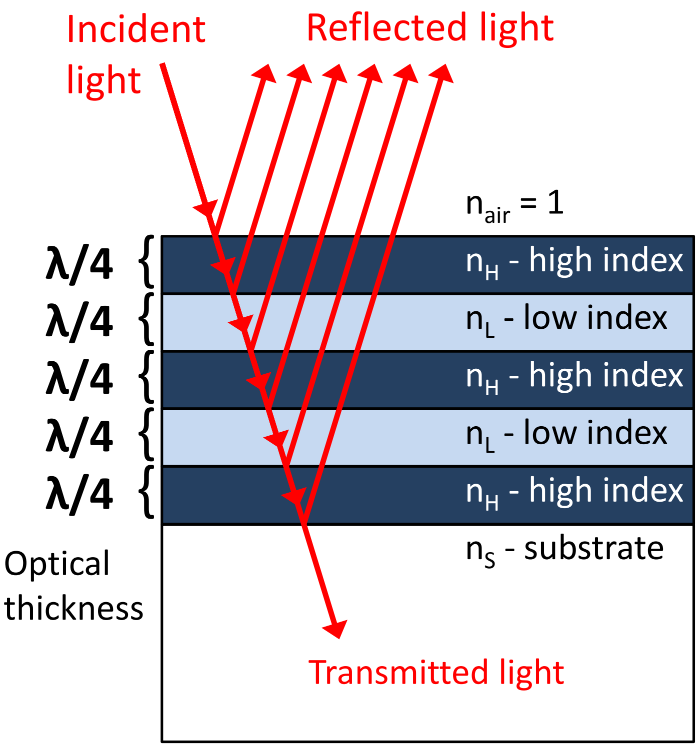
Two S=1 orbital branches

Linearly polarized emission, spin conserving in the limit of high strain

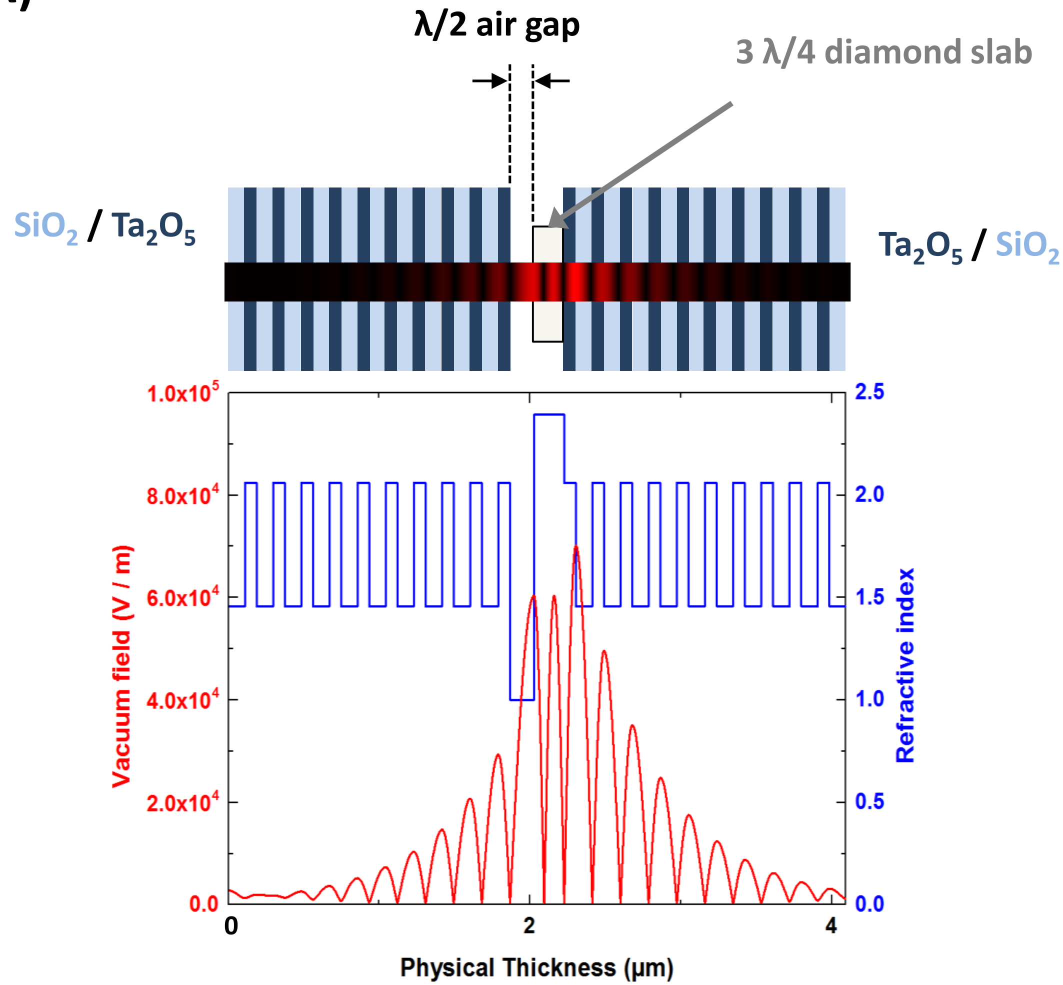
Significant mixing between spin states in lower branch

Results

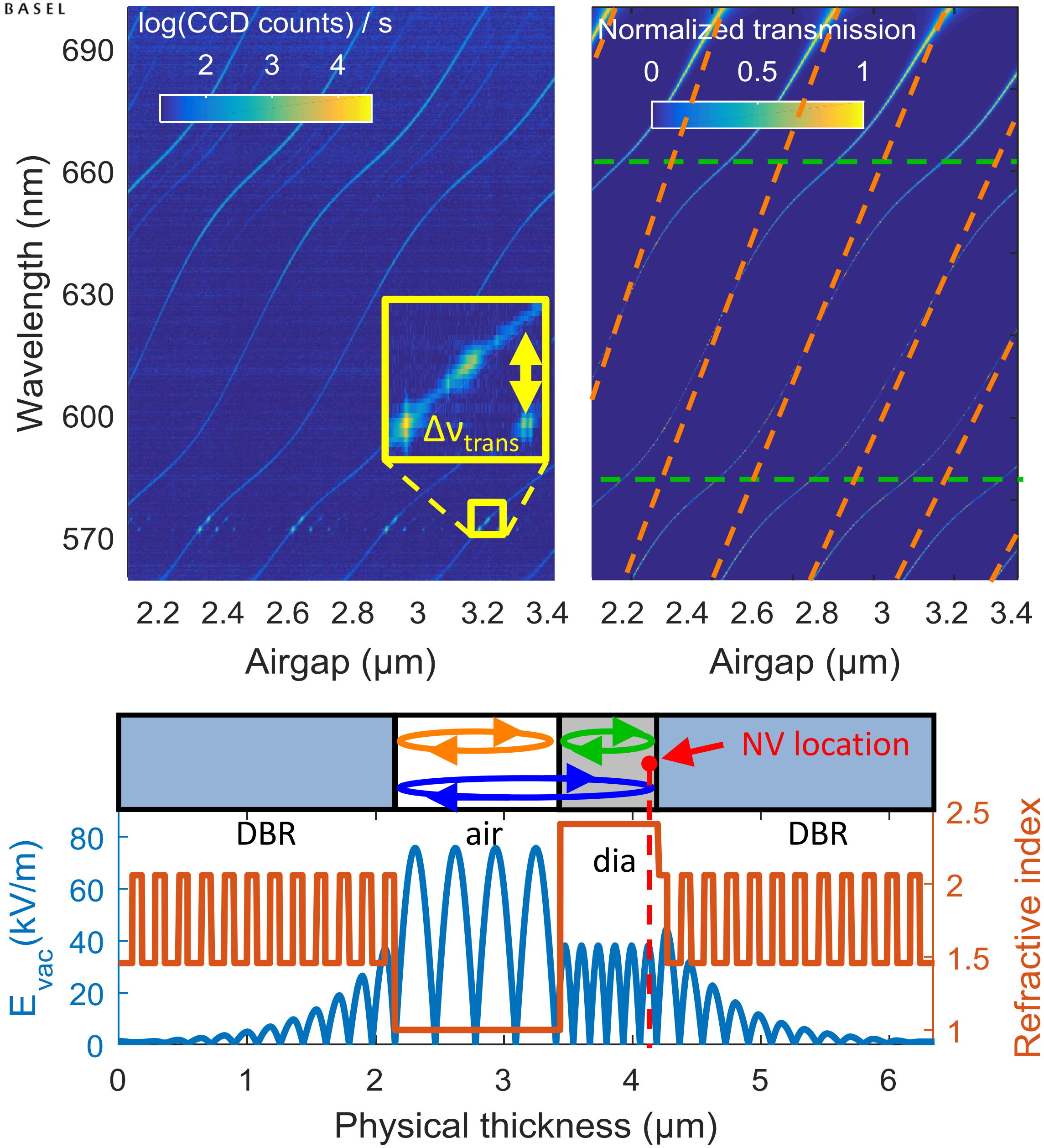
Distributed Bragg Reflector (DBR)
R > 99.99% @ 637nm



SiO_2:	n = 1.457
Ta_2O_5:	n = 2.060
Diamond:	n = 2.393



Results



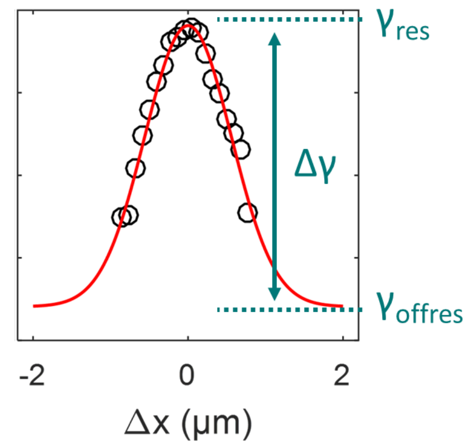
Mode structure:

- Two hybridized cavites:
  - air modes
  - diamond modes
- From simulation:
  - Diamond thickness
  - Width airgap
  - Vacuum field at NV
- Higher order mode spacing
  - Radius of curved mirror

Results

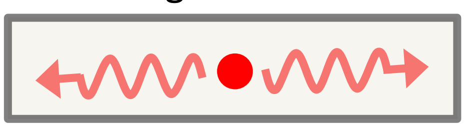
Experimental results:

$\gamma_{res} = 158$ MHz, $\gamma_{offres} = 88$ MHz, $\Delta\gamma = 70$ MHz



Transition rate without top mirror:

$\gamma_0 = 78.4$ MHz

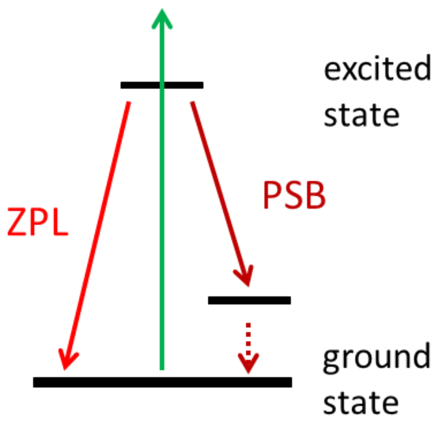


Fraction of ZPL emission:

$\gamma_{ZPL} = \zeta \cdot \gamma_0$, with $\zeta = 2\% \ldots 5\%$

$\Delta\gamma = F_P \cdot \gamma_{ZPL} = F_P \cdot \zeta \cdot \gamma_0$

$\zeta = \Delta\gamma / (F_P \cdot \gamma_0) = 2.2\%$



ZPL enhancement: ~ 40