

A Cavity QED System Coupling Nitrogen Vacancy Centers in a Diamond Nanopillar to a Silica Microsphere

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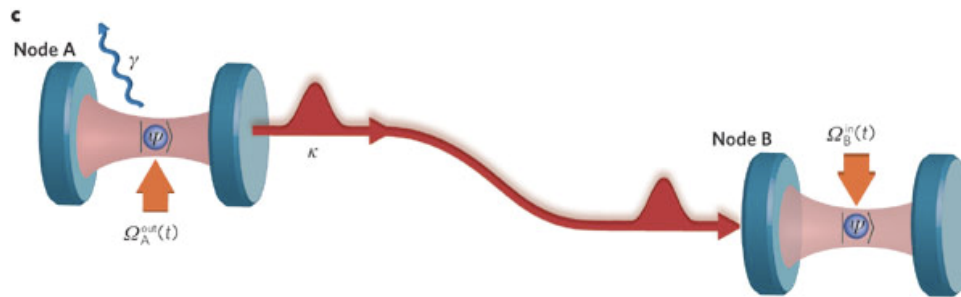
University of Oregon, Oregon Center for Optics



Support from: DARPA, NSF-GK12, and the
Swedish Research Council

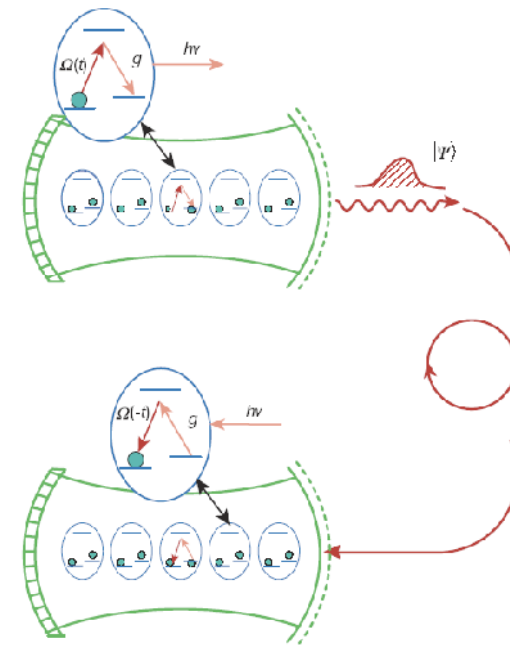


Motivation: Quantum Networking



H. J. Kimble, The quantum internet, Nature 453, 1023-1030

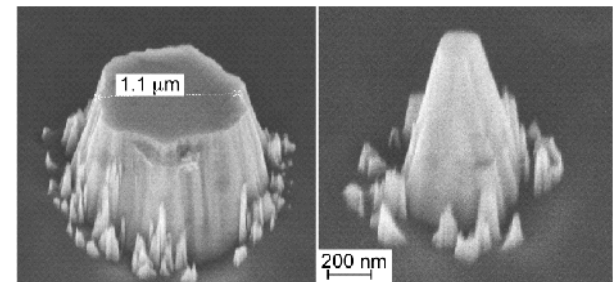
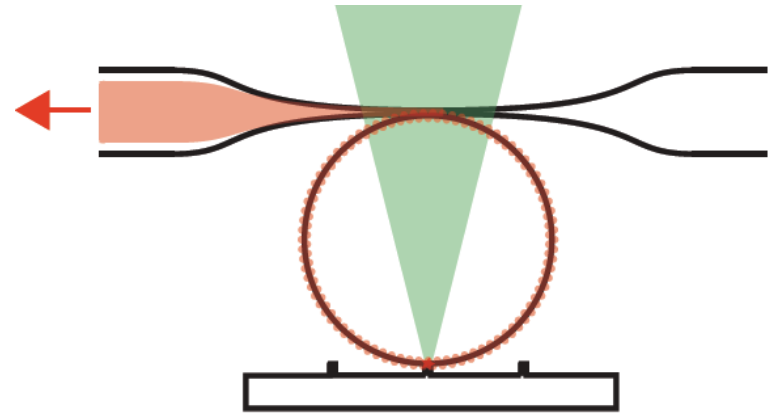
Cavity QED systems can play an integral role in quantum networks to distribute and process quantum information.



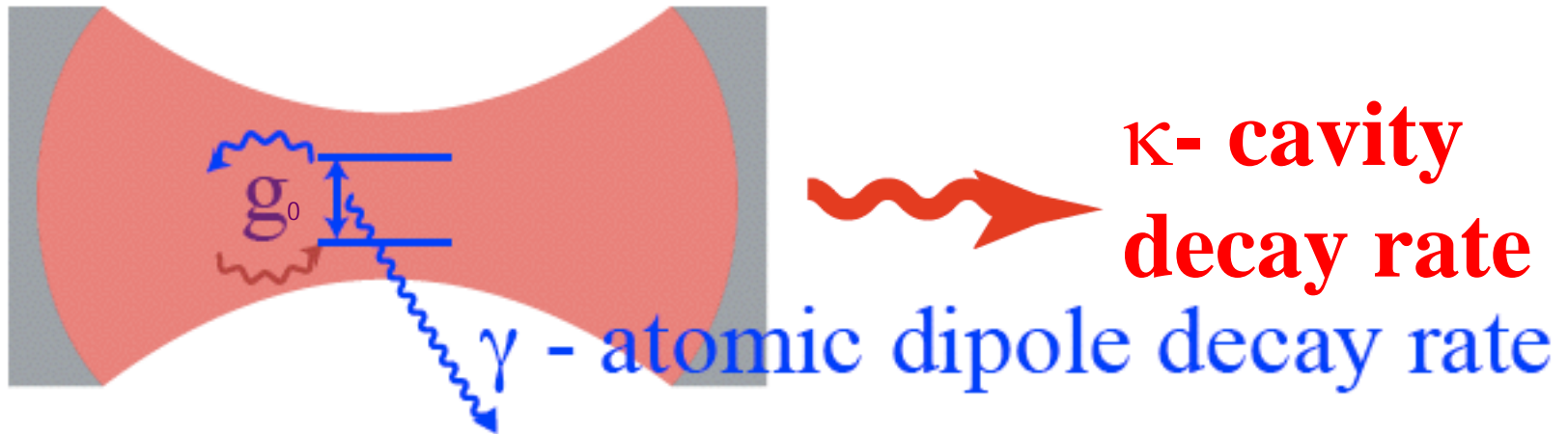
Cirac, Zoller, Kimble, Mabuchi, Phys. Rev. Lett. 78, 3221 (1997);
Van Enk, Cirac, Zoller, Science 279, 205 (1998).

Outline

- Cavity QED Systems
- Our system
 - Fused Silica Microsphere
 - NV Centers in Diamond
- Experimental Set-up & Results
- Analysis
- Future Work/Preliminary Results
- Conclusion



A Cavity QED System

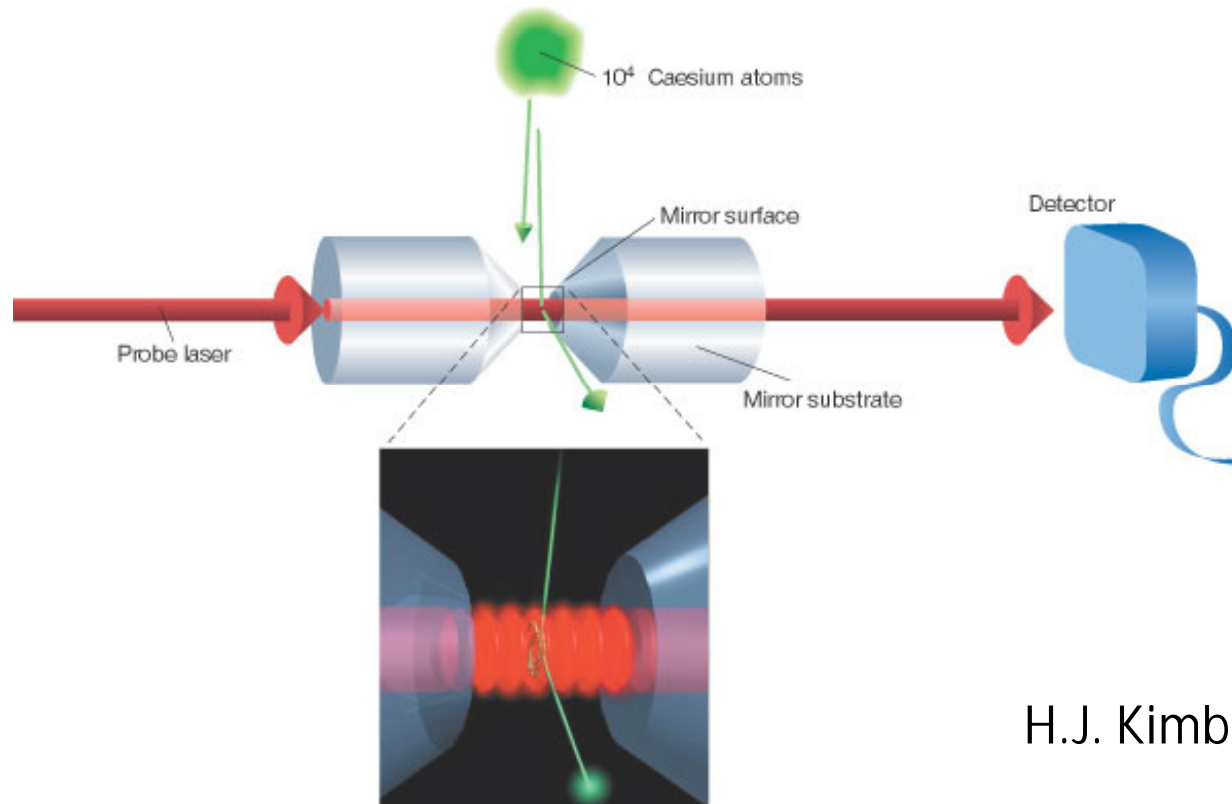


$g_0 = \frac{\vec{\mu} \cdot \vec{E}_{vac}}{h}$ is the vacuum Rabi frequency.

We can have a cavity QED system in two regimes:

- a) $g_0 < (\gamma, \kappa)$ weak coupling
- b) $g_0 > (\gamma, \kappa)$ strong coupling

Cavity QED Systems: Cold Atoms and Fabry-Perot Cavity



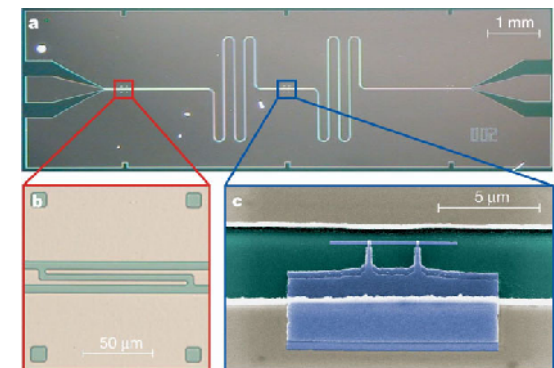
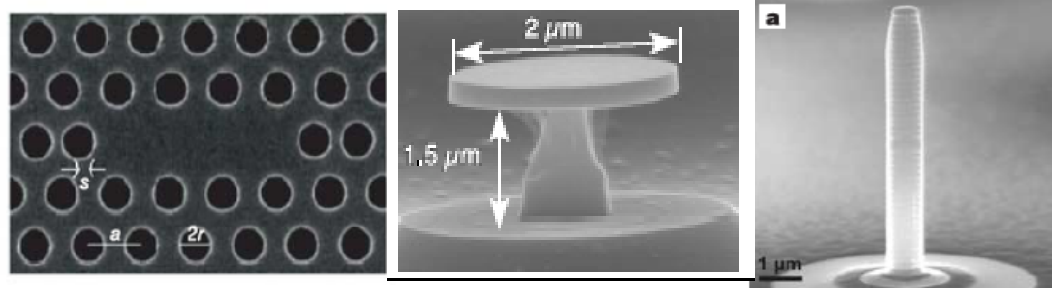
H.J. Kimble, Caltech

Cavity QED with Artificial Atoms

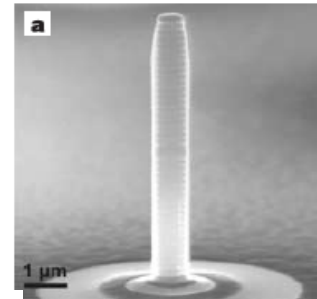
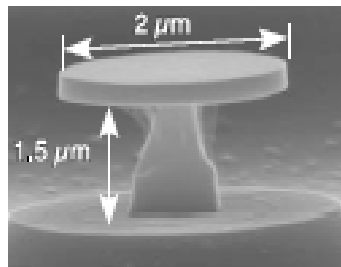
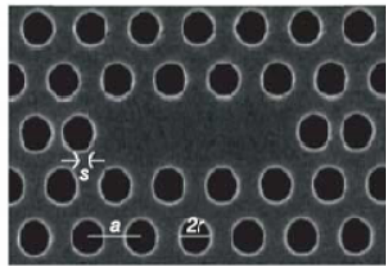
- Circumventing the complexities of trapping single atoms in an optical microresonator.
- Possibility of integration and scaling up to a quantum network.
- Artificial atoms:
 - Quantum dots, defect centers, Cooper pair boxes

Reithmaier et al., Nature 432, 197 (2004).
Wallraff et al., Nature 431, 162 (2004).
Le Thomas et al., Nano Lett. 6, 557 (2006).
Press et al., PRL 117402 (2007).
Hennessey et al., Nature 445, 896 (2007).

Yoshie et al., Nature 432, 200 (2004).
Peter et al., PRL 95, 067401 (2005).
Park et al., Nano Lett. 6, 2075 (2006).
Srinivasan et al., Nature 450, 862 (2007).
Englund et al., Nature 450, 7171 (2007).



Semiconductor Microresonators



Geometry:

1. Photonic crystals
2. Microdisks
3. Micro-pillar Fabry-Perot cavities

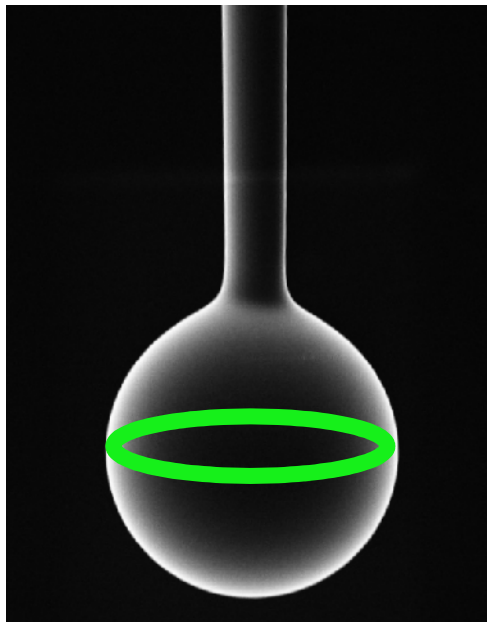
Advantages:

Extremely small mode volume.

Disadvantages:

Relatively small quality factor (Q) cavities

Silica Microresonators

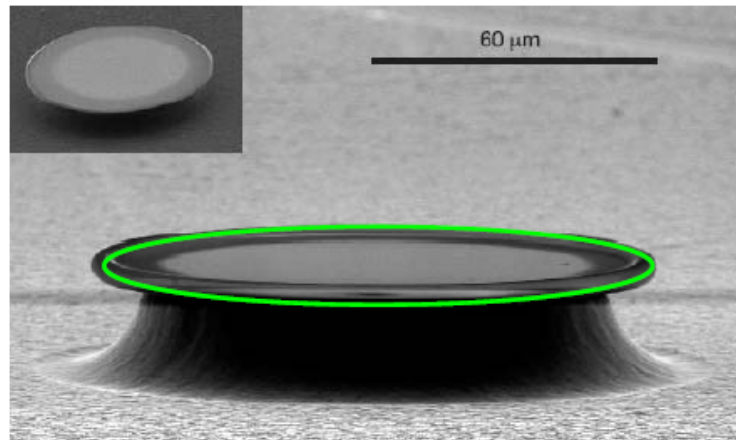


30 μ

Whispering gallery modes form via total internal reflections.

Best figure of merit in terms of strong coupling cavity QED:

1. Silica microsphere
Buck and Kimble, Phys. Rev. A 67, 033806 (2003).
2. Silica microtoroid
Spillane et al., Phys. Rev. A 71, 013817 (2005).



Vahala,
Nature 424,
839 (2003).

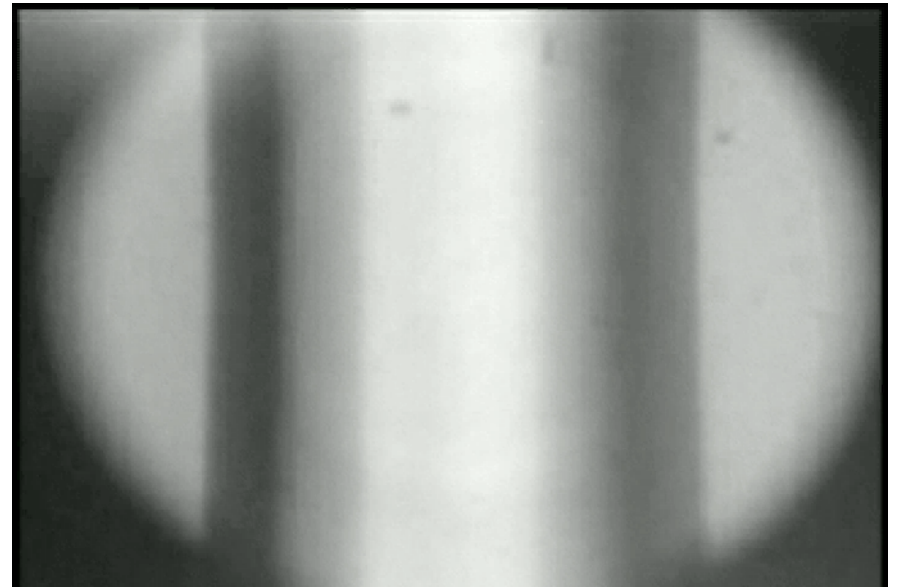
Silica Microsphere

Linewidth of a few MHz \Leftrightarrow Q-factors $> 10^8$

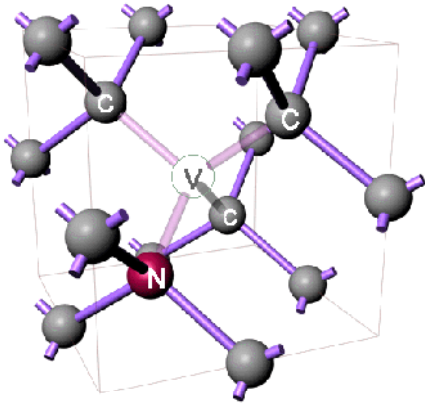
High purity silica features extremely small absorption and scattering loss are minimize due to the extremely smooth silica surface.

Braginsky et al., Phys. Lett. 137, 393 (1989).

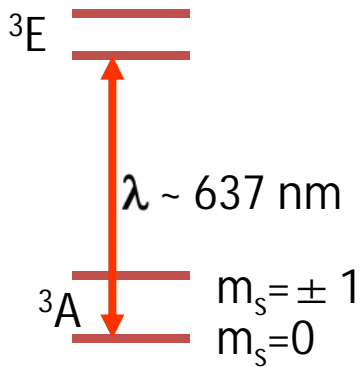
Inexpensive and easy to fabricate with telecommunication grade optical fiber and a CO₂ laser.



NV Centers

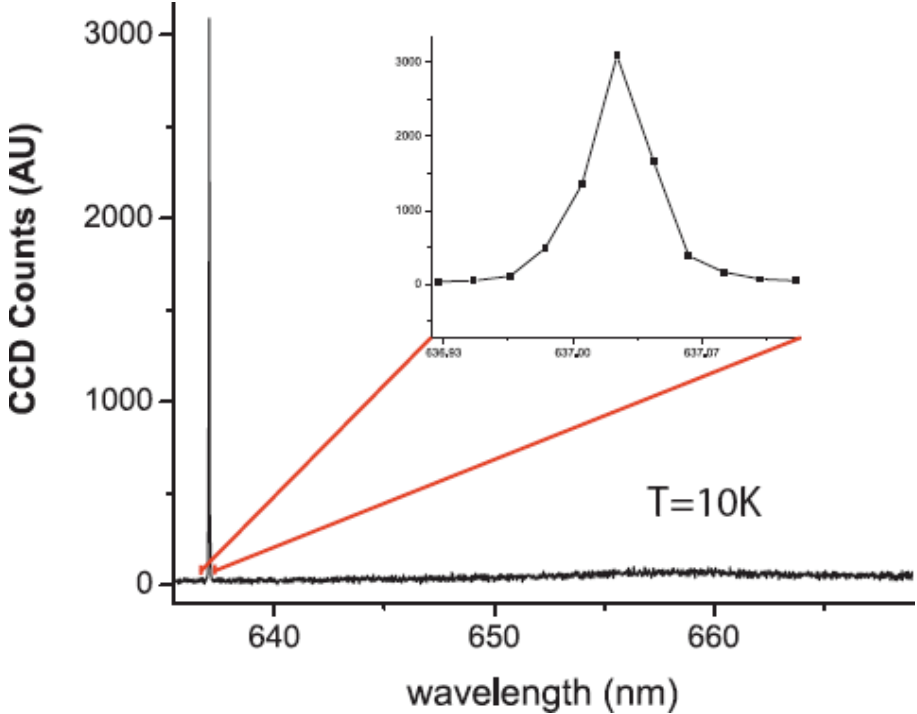


F. Jelezko, J. Phys.: Condens. Matter
18: S807-S824 (2006)



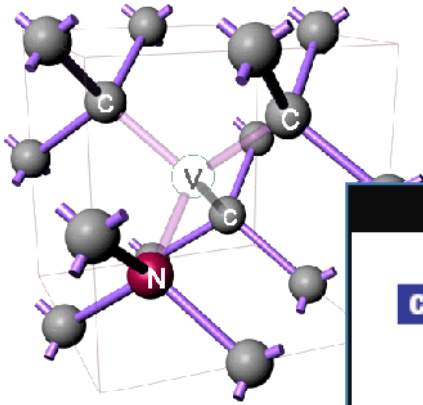
NV centers feature robust triplet spin states as the ground states, which is ideal for using the spin as a qubit.

Can be created in high purity single crystal diamond by Nitrogen or electron irradiation followed by annealing.

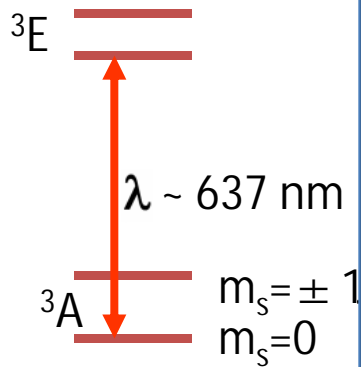


UCSB, Stuttgart, Harvard, HP Labs,
Texas A&M, Univ. Melbourne, ...

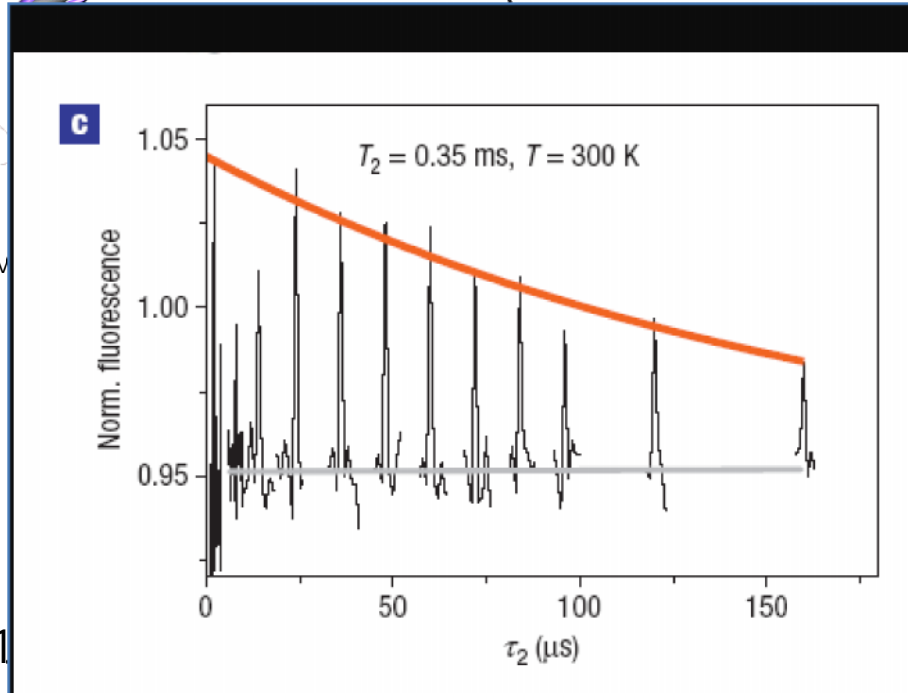
NV Centers



F. Jelezko, J. Phys.: Condens. M
18: S807-S824 (2006)



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Gaebel *et al.*, Nature Physics 2, 409 (2006).

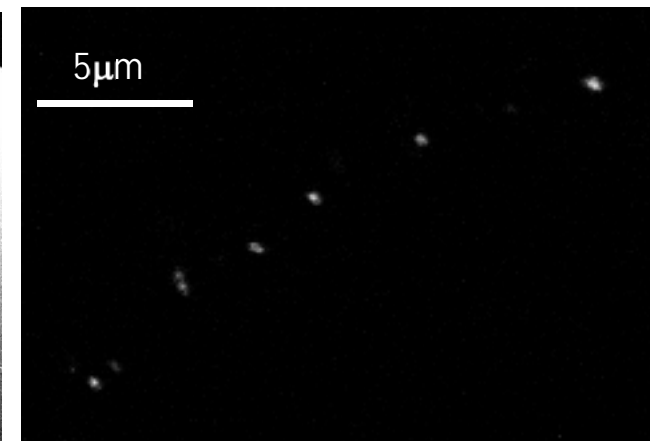
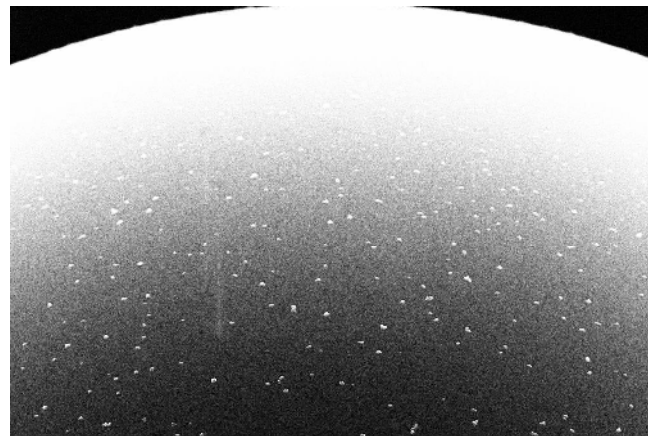
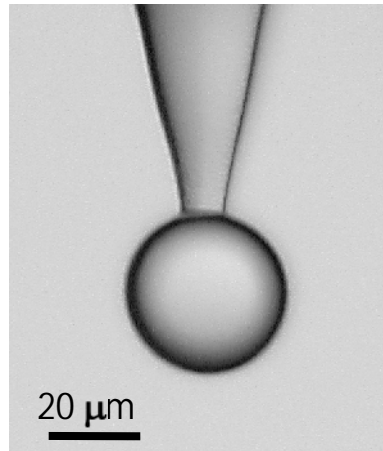
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Composite NV nanocrystal-microsphere

Diamond nanocrystals are dispersed on the surface of a silica microsphere through solution deposition.



Strong-coupling regime: $g_0 > (\kappa, \gamma)$

Cavity QED with Diamond Nanocrystals and Silica Microspheres

Young-Shin Park, Andrew K. Cook, and Hailin Wang*

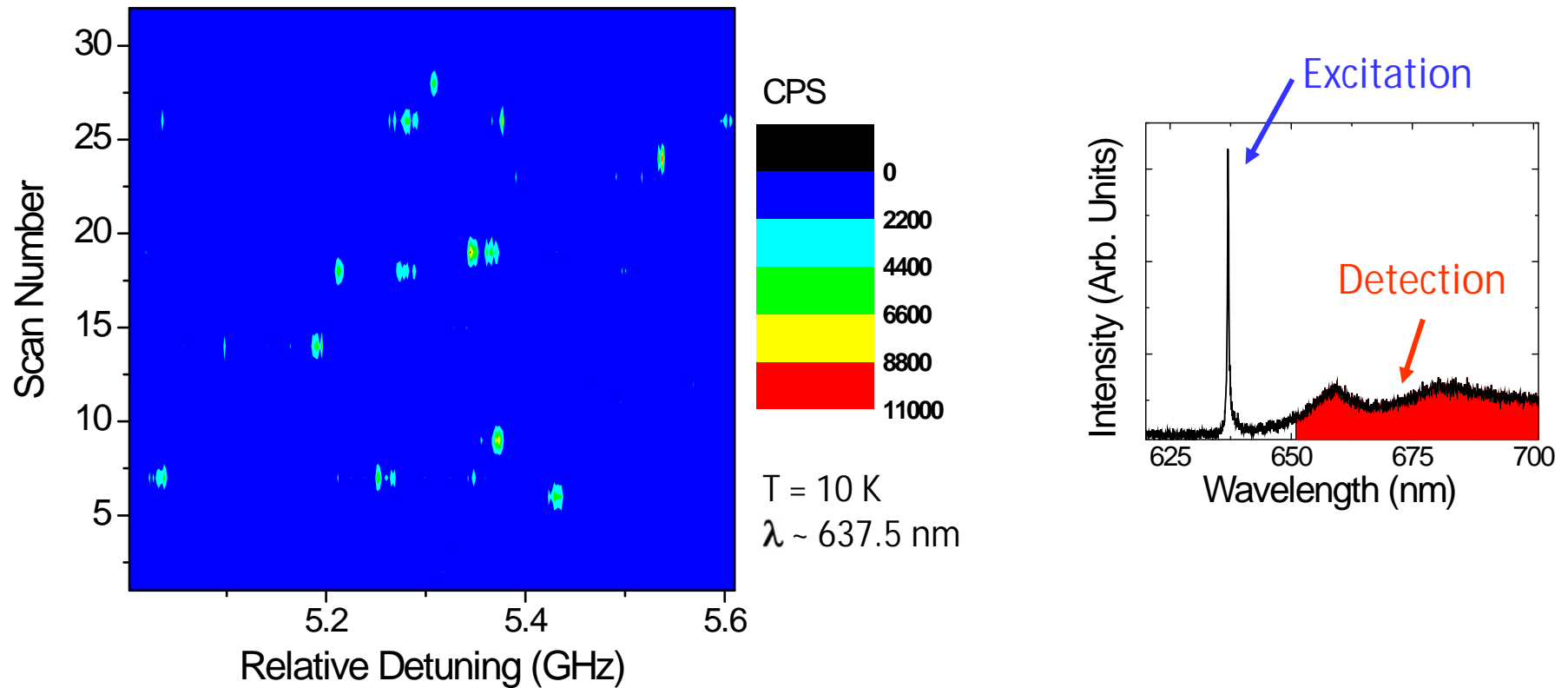
Nano Lett., Vol. 6, No. 9, 2006

Decoherence rate: $\gamma/2\pi \sim 10$ MHz

Cavity decay rate: $\kappa/2\pi \sim 10$ MHz

Dipole coupling rate: $g_0/2\pi \sim 50$ MHz

Excitation Spectra of Single NVs in Nanocrystals



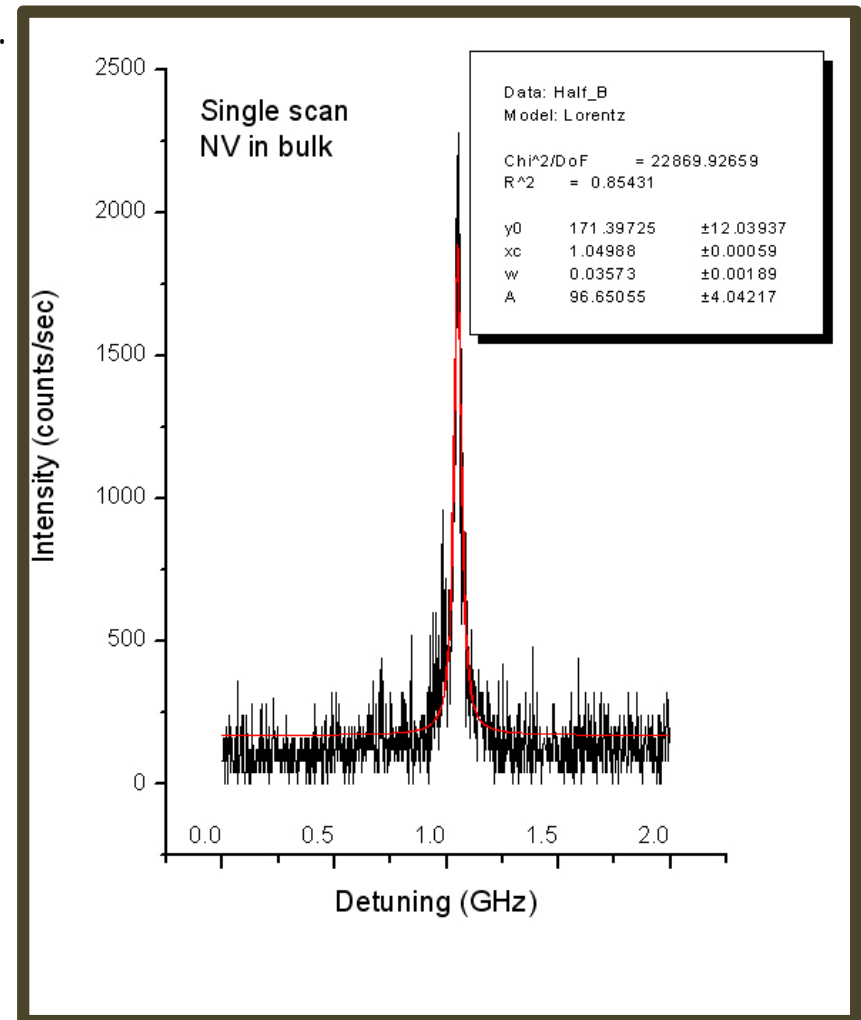
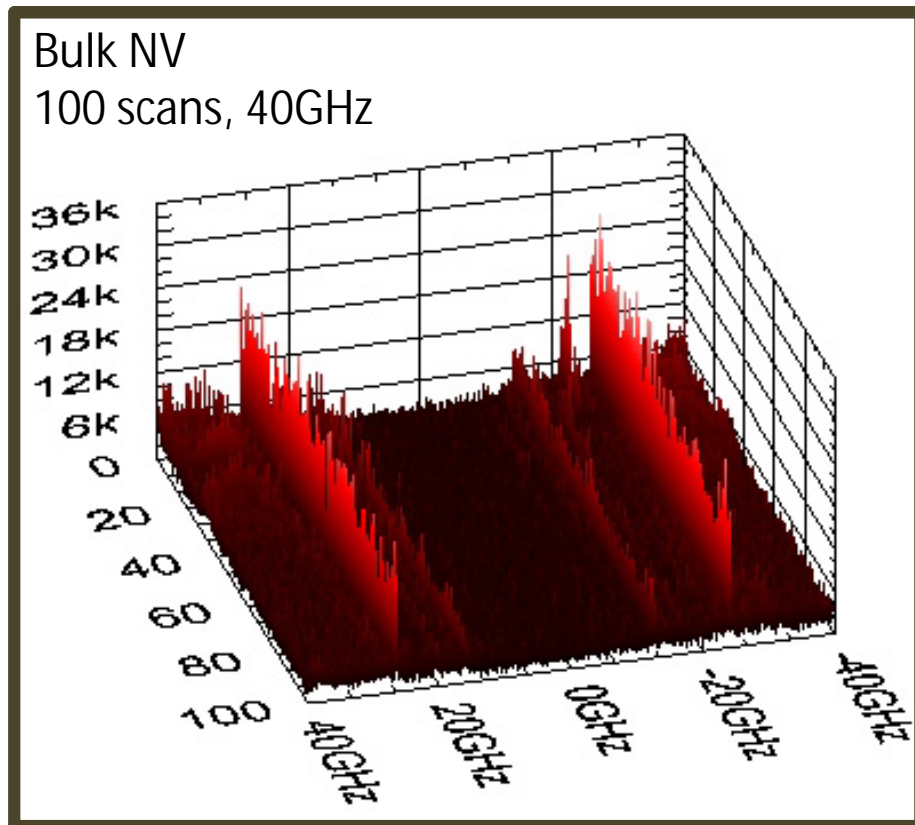
- Large spectral fluctuations in NV transition frequencies.
- Typical NVs spend significant amount of time in dark states.

Excitation Spectra of Single NVs in Bulk Crystals

NV centers found in bulk crystal are spectrally stable and exhibits atomic like linewidths.

Ph. Tamarat et al., Phys. Rev. Lett. 97, (8), (2006)

A Gruber et al., Science 276, 5321, (1997)

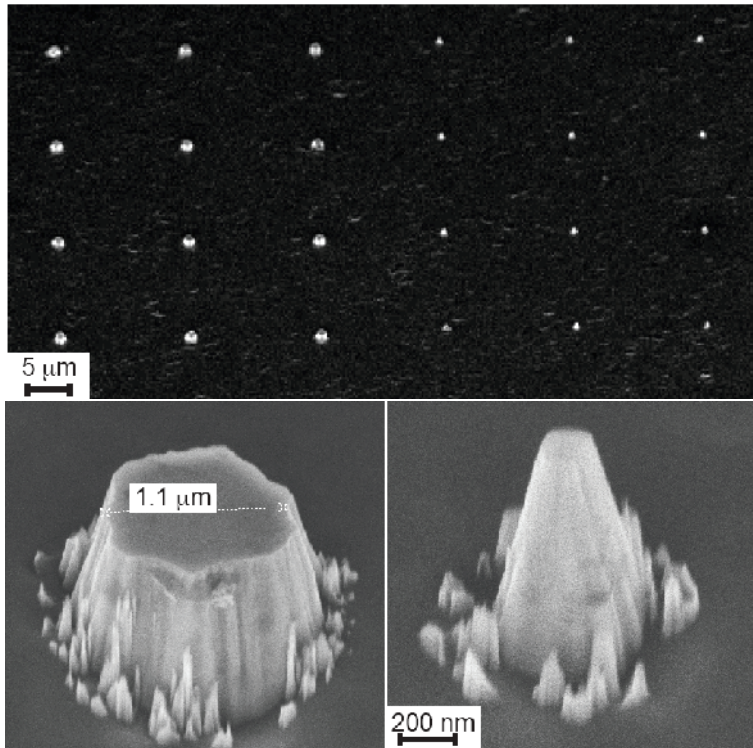


Pillar Fabrication

Problems of using diamond nanocrystals in cavity QED:

Difficult to control the spatial position of nanocrystals.

Spectral fluctuations and blinking of NV centers in diamond nanocrystals, which are believed to be due to ionization of electrons of nitrogen impurities and seem to be minimized in high purity diamond crystals.

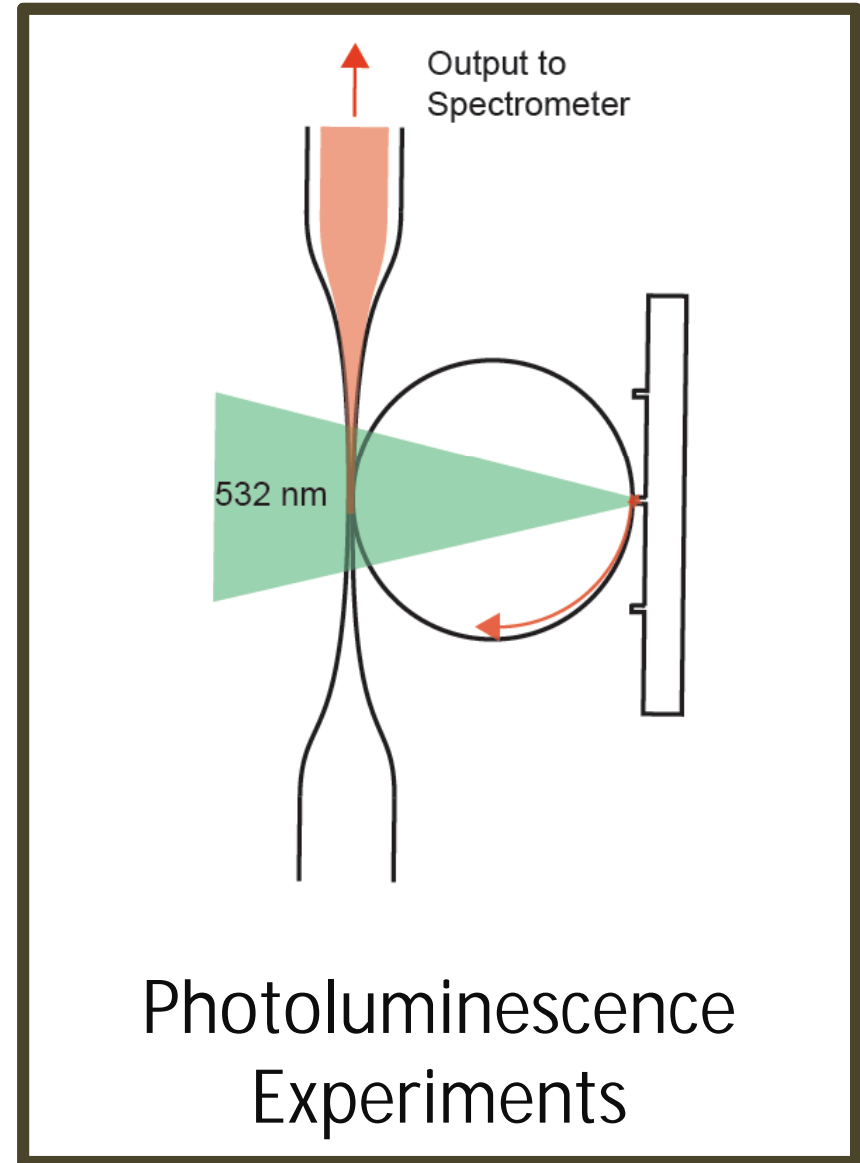
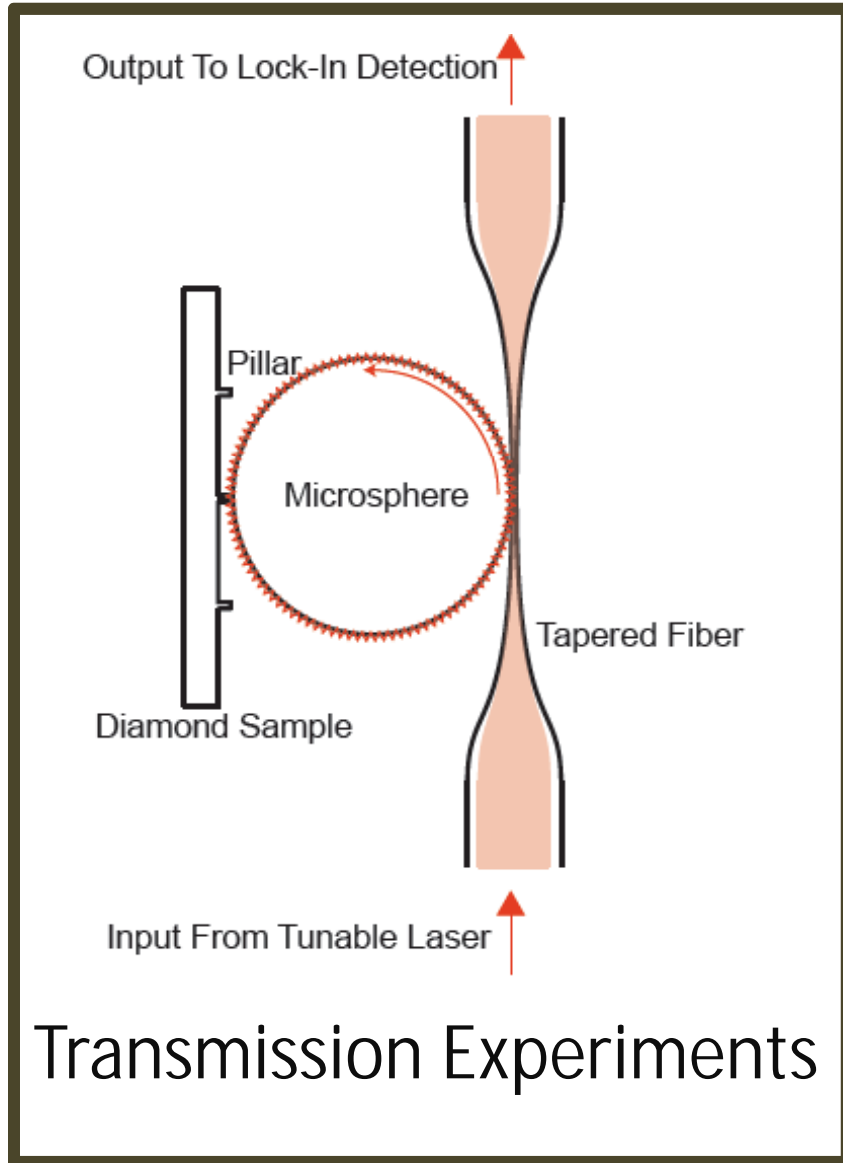


Diamond nanopillars:

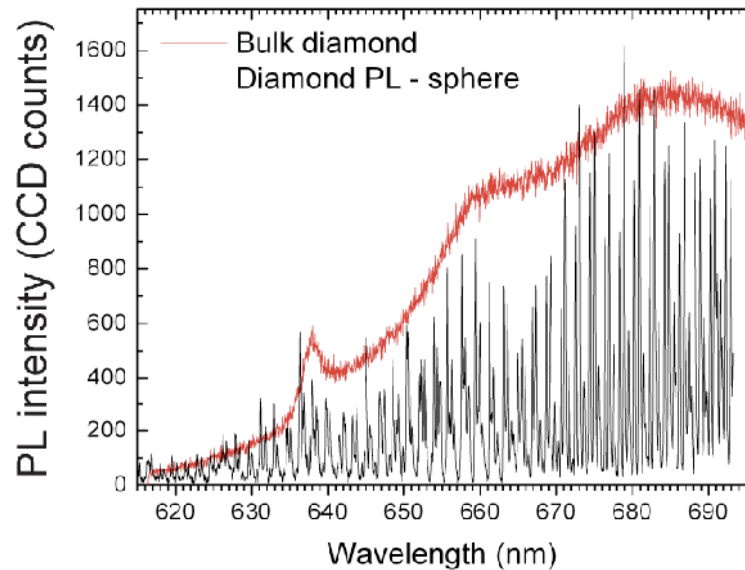
An aluminum mask is patterned on the diamond surface with EBL and liftoff.

Pillars are fabricated by reactive ion etching the exposed diamond.

Experimental Set-Up

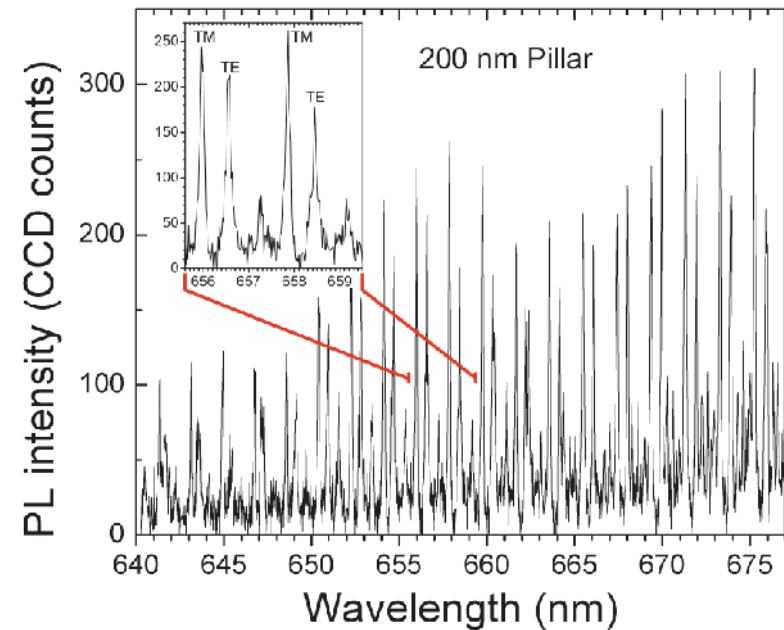


Photoluminescence Results



Direct PL measurement (red) and PL coupled through microsphere (black) in direct contact with bulk surface.

Room temperature photoluminescence (PL)

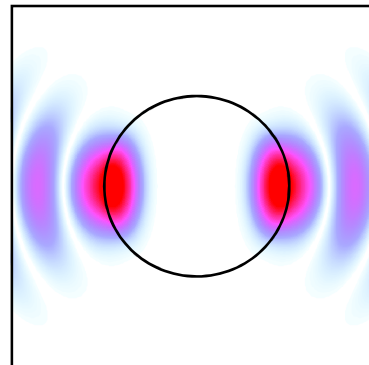
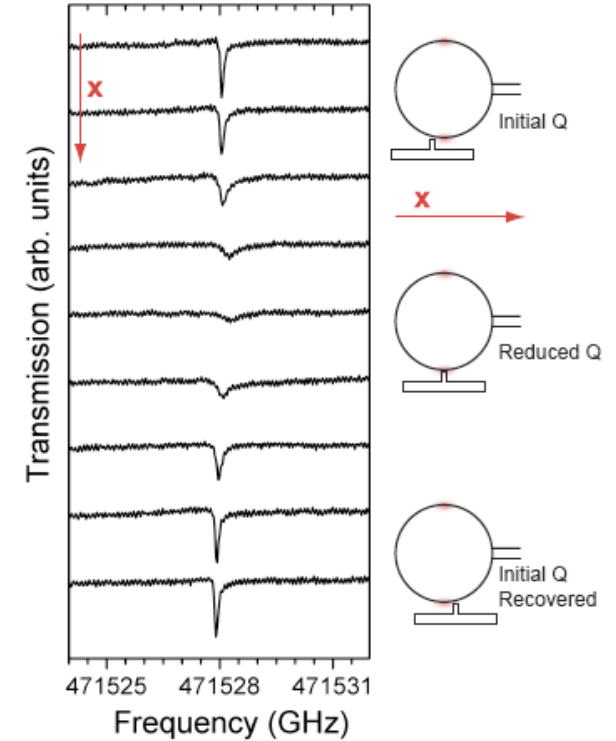
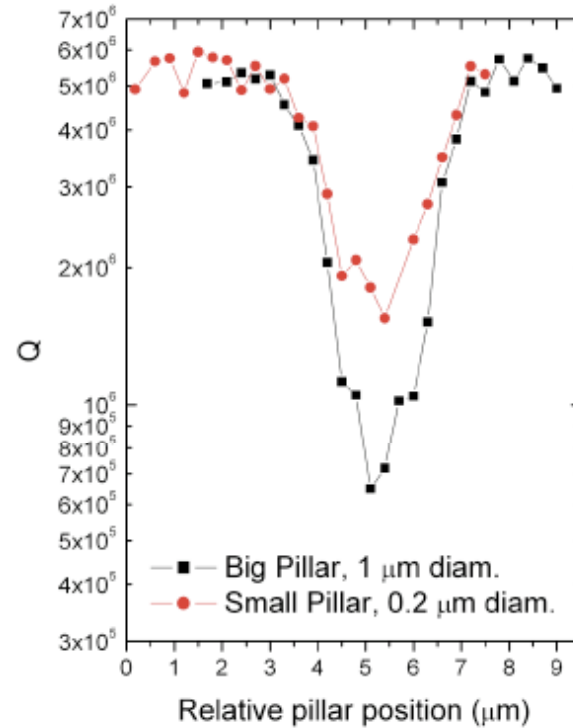
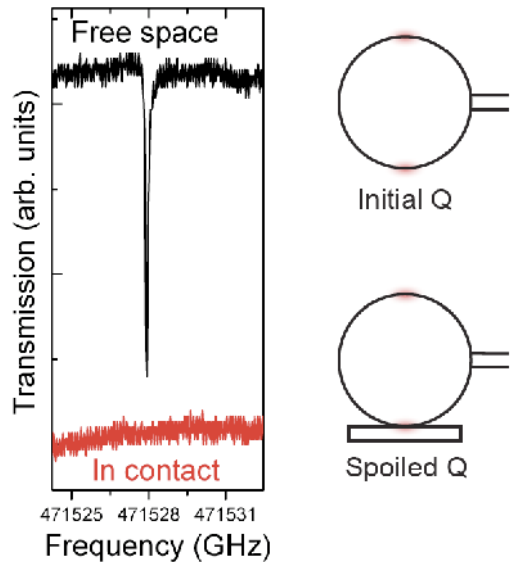


PL coupled from through microsphere from NV centers in a 200 nm diamond pillar.

Type Ib diamond (High Nitrogen Concentration)

Transmission Results

The coupling between the pillar and resonator depends sensitively on the position of the pillar.



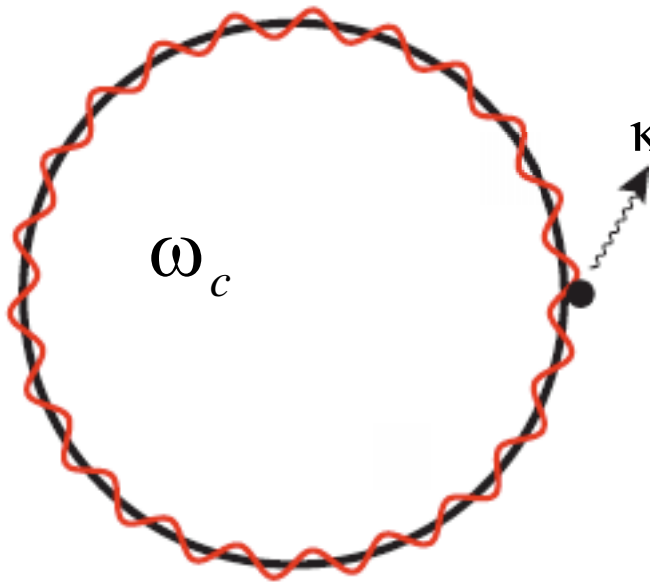
$$p=1, l=16, m=16$$

WGM confined on the equator of the sphere.

Mode is completely spoiled when the sphere is in contact with bulk diamond.

Analysis of Scattering

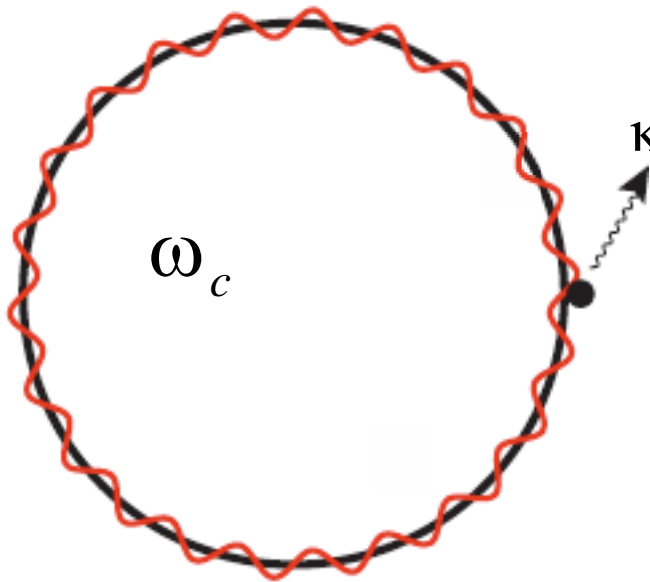
$g_0 \approx 2\pi(50\text{MHz})$ } Ideally we want $\kappa \approx \gamma$ for pursuing strong coupling cavity QED with NV
 $\gamma \approx 2\pi(10\text{MHz})$ } centers, where $\kappa = \kappa_0 + \kappa_{sc}$.



$$\kappa_{sc} = \frac{\alpha^2 f(\vec{r}) \omega_c^4}{6\pi c^3 V_c} \text{ with polarizability } \alpha = 4\pi r_{sc}^3 \left| \frac{\epsilon - 1}{\epsilon + 2} \right|.$$

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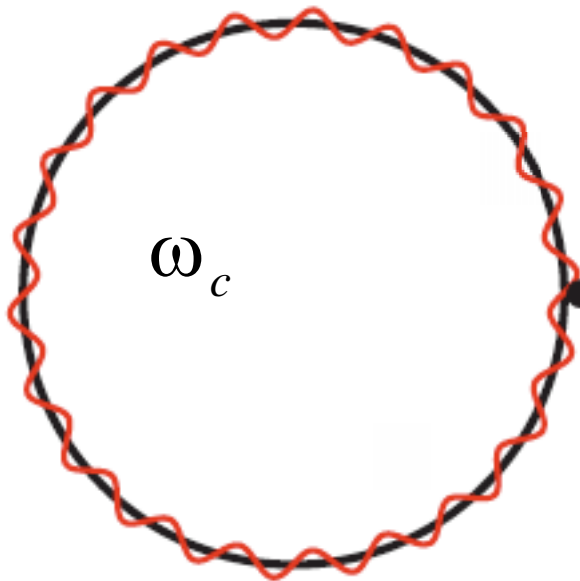


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$$\kappa_{200nm} = \kappa - \kappa_0 = 2\pi(80\text{MHz})$$

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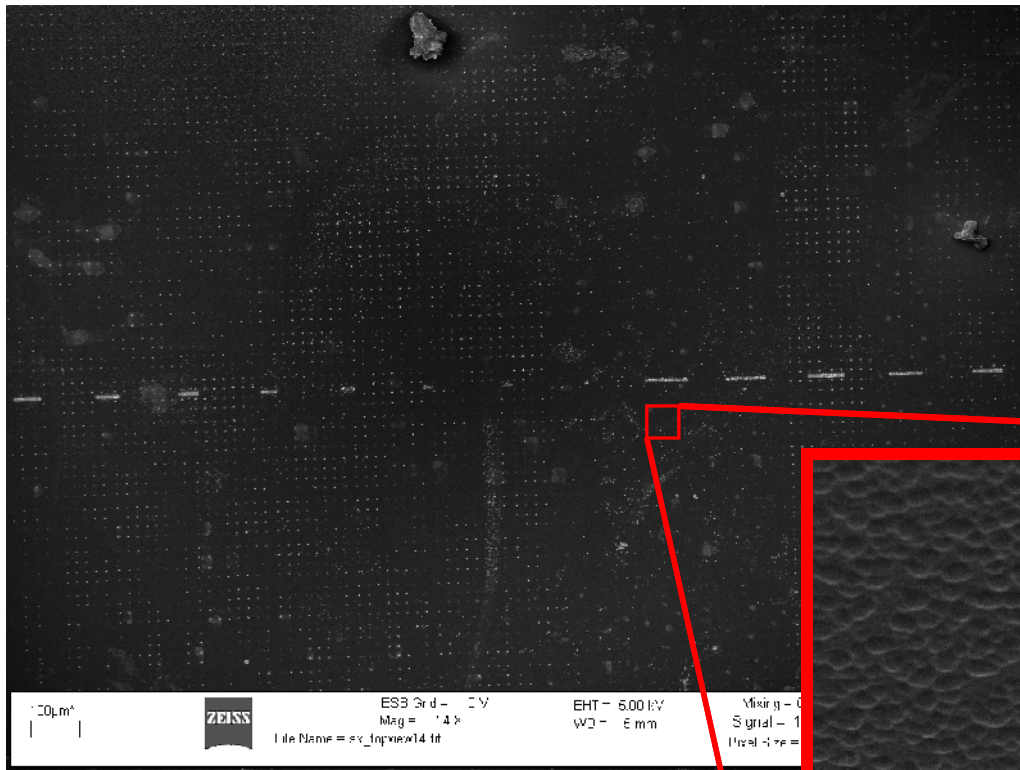
$$\kappa_{200nm} = \kappa - \kappa_0 = 2\pi(80\text{MHz})$$

$$\frac{\kappa_\gamma}{\kappa_{200nm}} = \frac{r_\gamma^6}{r^6} \Rightarrow r_\gamma = 200nm \left(\frac{10\text{MHz}}{80\text{MHz}} \right)^{\frac{1}{6}} \approx 140nm$$

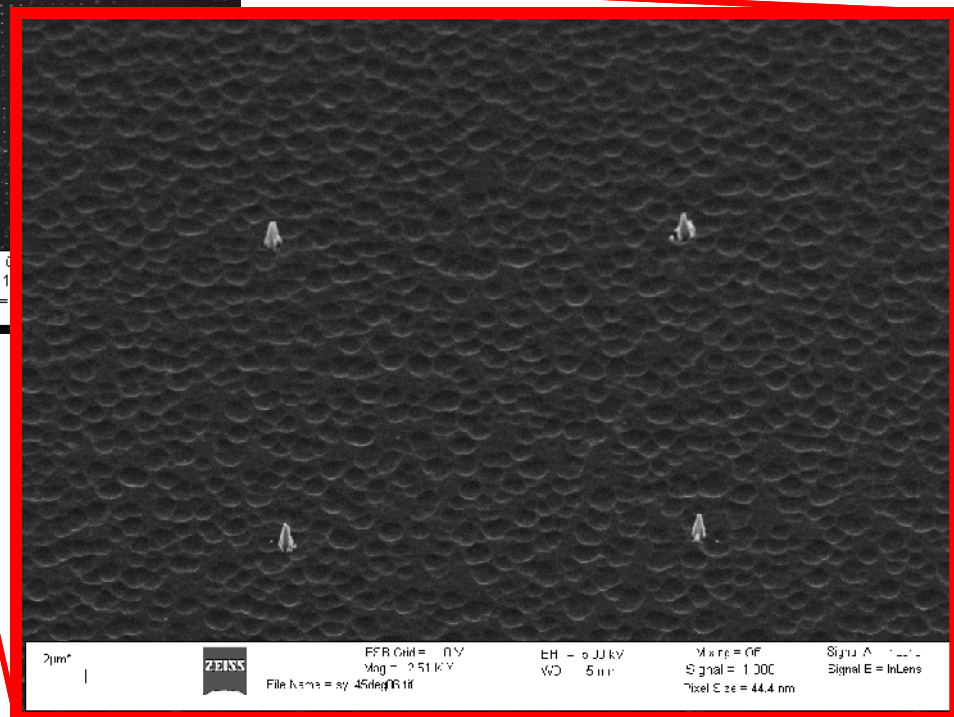
Future Work

- Reduce pillar diameter < 140 nm and use high purity diamond to reduce the number of NVs in the nanopillar.
- Irradiate high purity samples and produce stable NVs near the diamond surface.
- Couple a single NV to a microsphere and demonstrate a strong coupled cavity QED system.

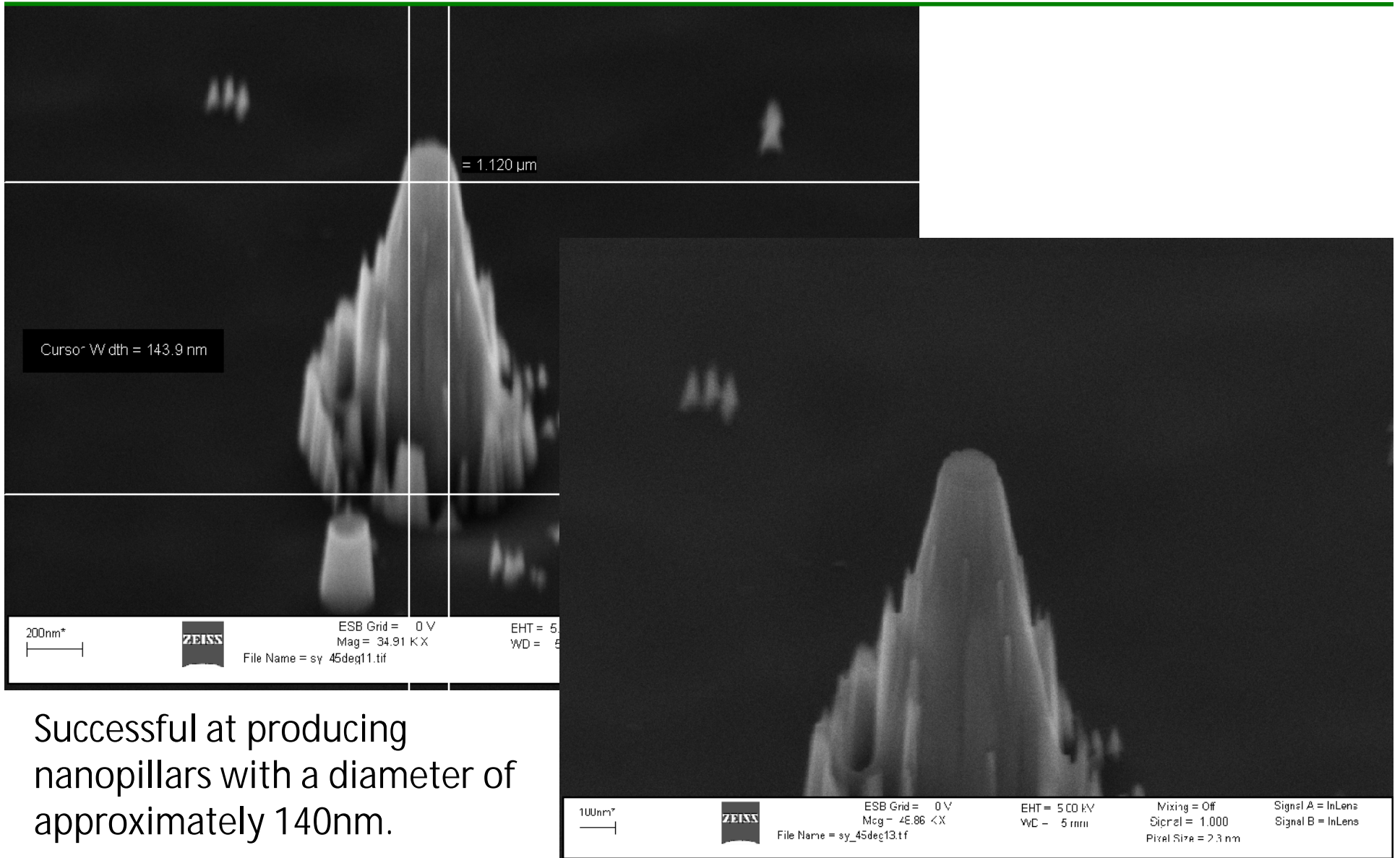
Preliminary Results



Produced arrays of pillars, with varying diameters, from high purity (< 1ppb N) diamond which was irradiated with 100 keV N⁺ ions to create NVs 100nm from the surface of the pillar.

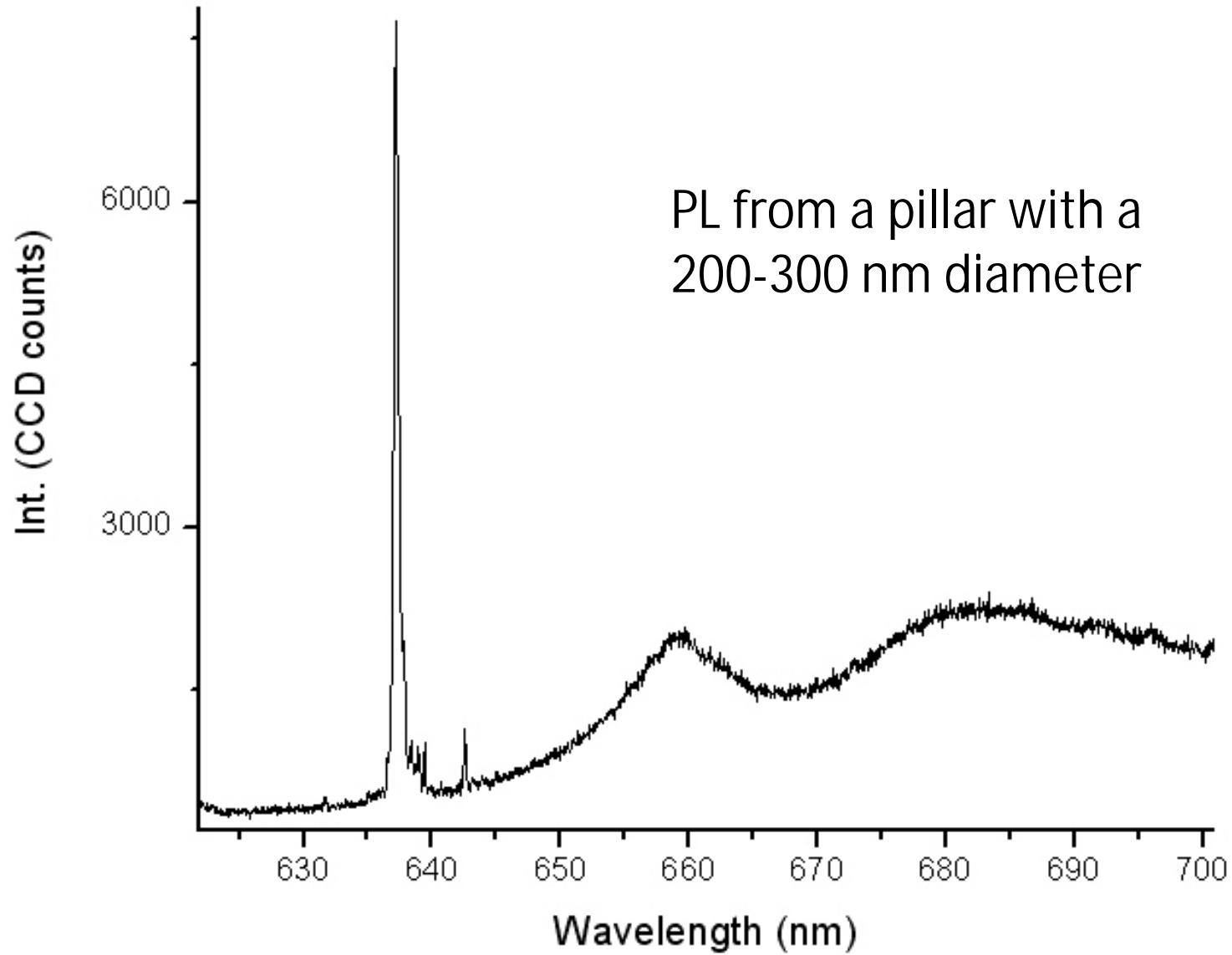


Preliminary Results



Successful at producing nanopillars with a diameter of approximately 140nm.

Preliminary Results



Conclusion

- We have successfully demonstrated an optical microcavity, in which nanometer sized diamond pillars containing NV centers are coupled to a silica microsphere.
- Created NVs near the diamond surface via N⁺ irradiation.
- Reduced the nanopillar size to approximately 140nm.