Quantum magnetometry with spins, mechanics and photons

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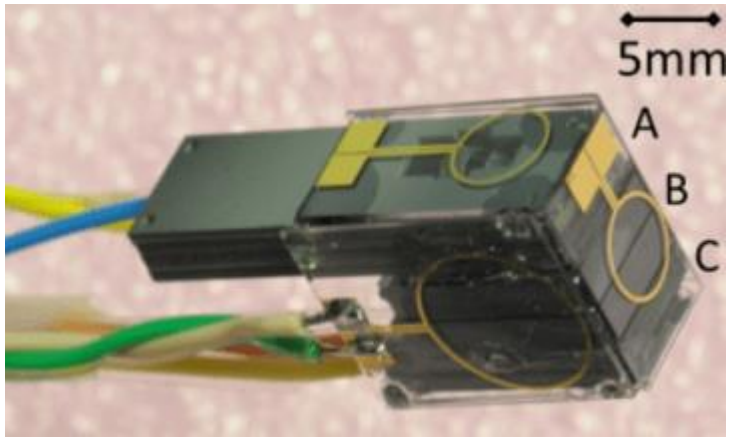
DTU Physics
Department of Physics

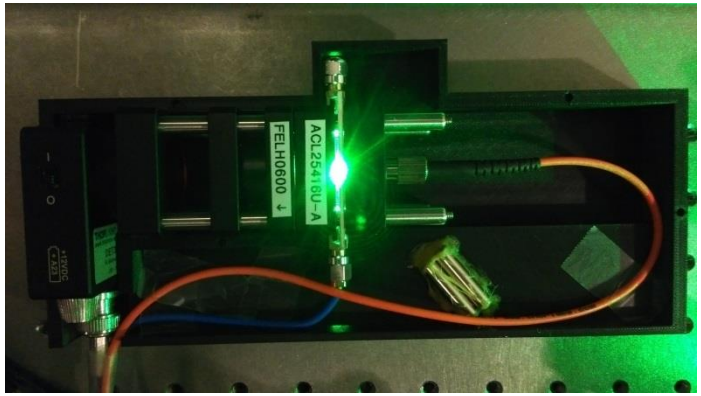
High-Sensitivity Magnetometers

SQUID

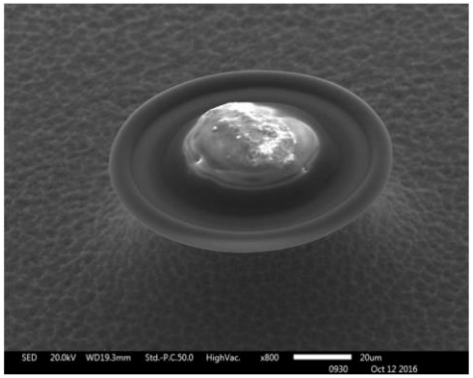
Atomic vapor



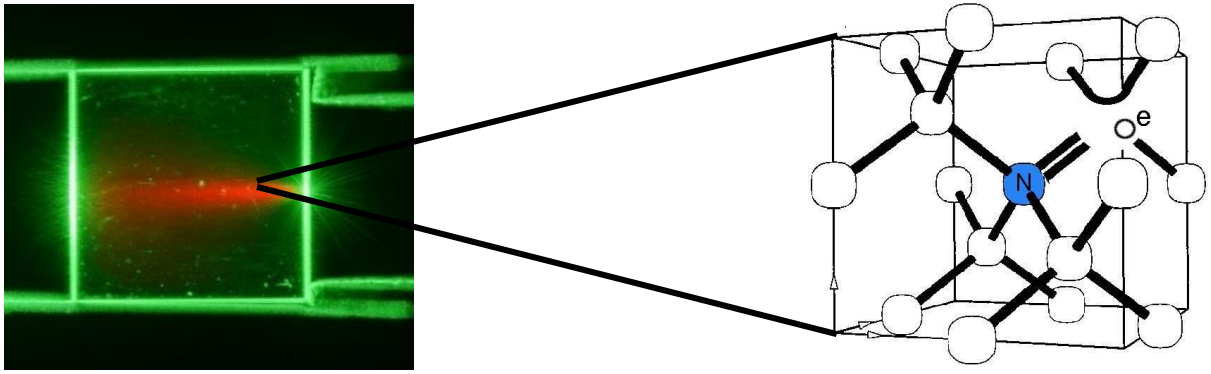
Diamond

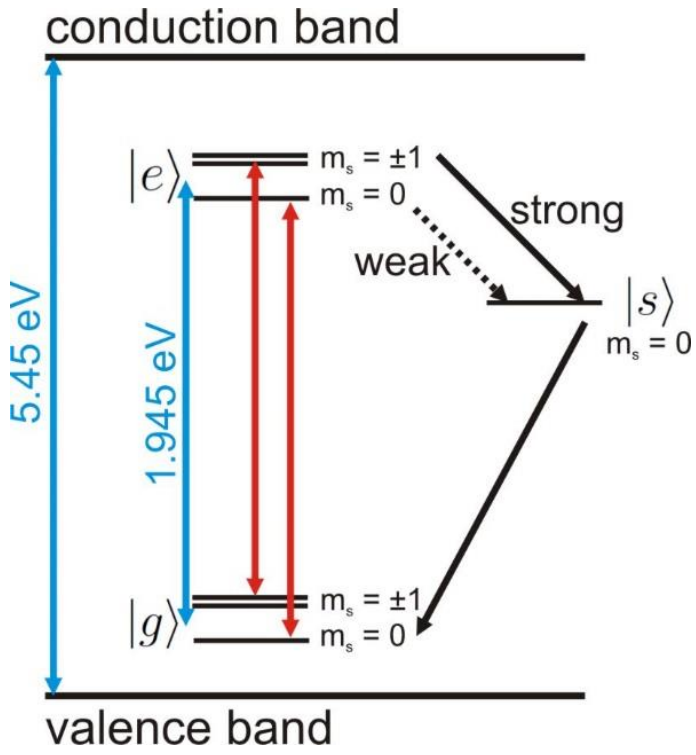


Opto-Mechanics

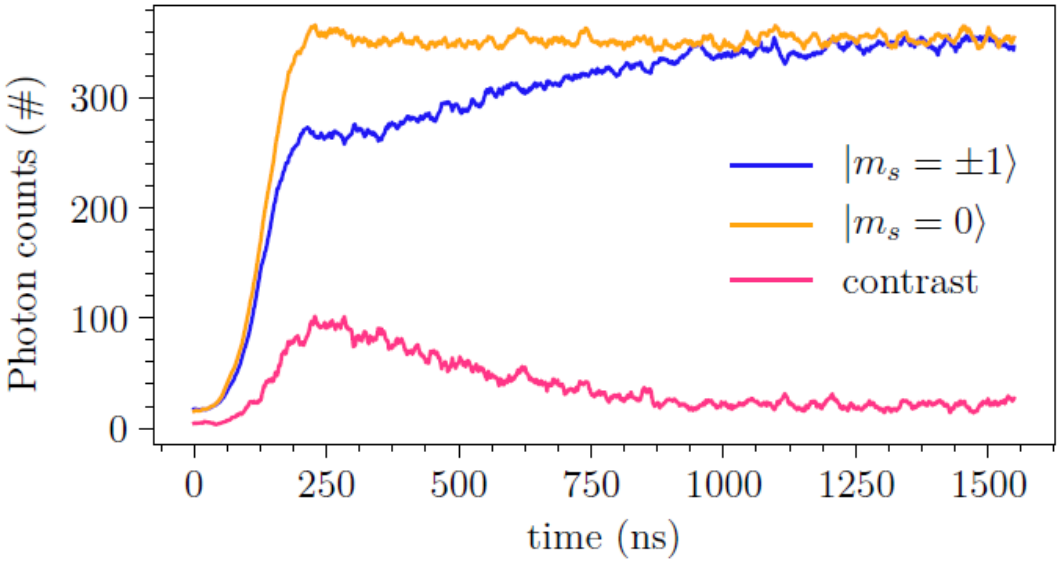


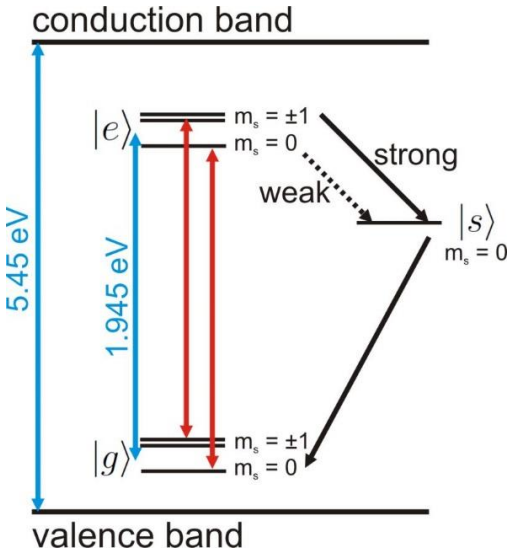
Physics of NV center



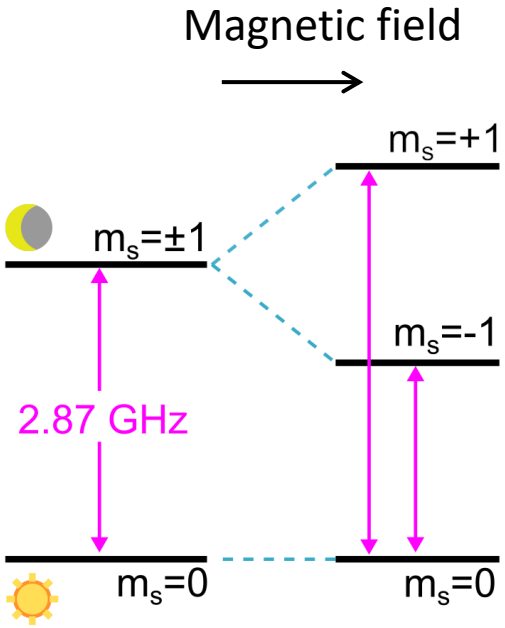


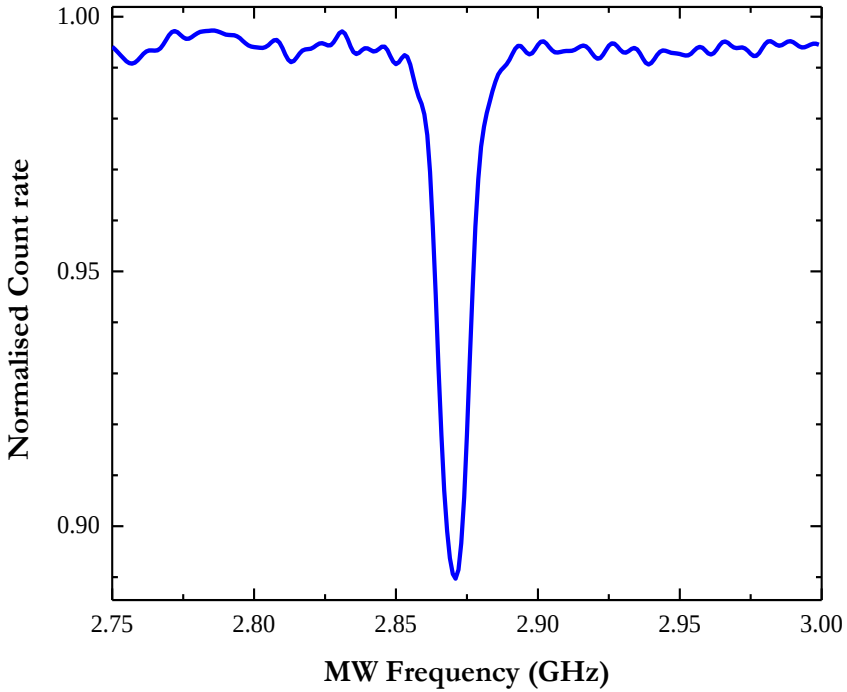
Optical pumping and read-out





Optical detected magnetic resonance





Diamond materials

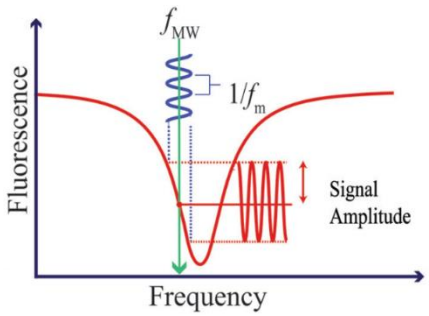
Structure:
NV ensemble; single NV; NV nanodiamond

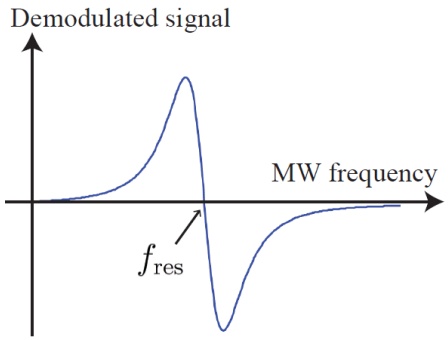
Growing diamond:
a) High-pressure high-temperature (N: ~100ppm)
b) Chemical vapor deposition (N: 1ppb-1ppm)

Forming NVs:
Bombardment and annealing
Delta doping

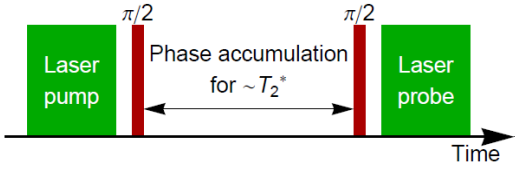
Measurement Strategies

1) Continuous wave detection

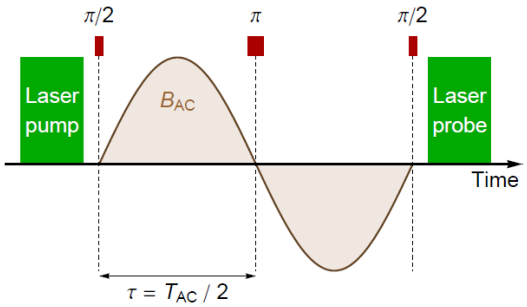




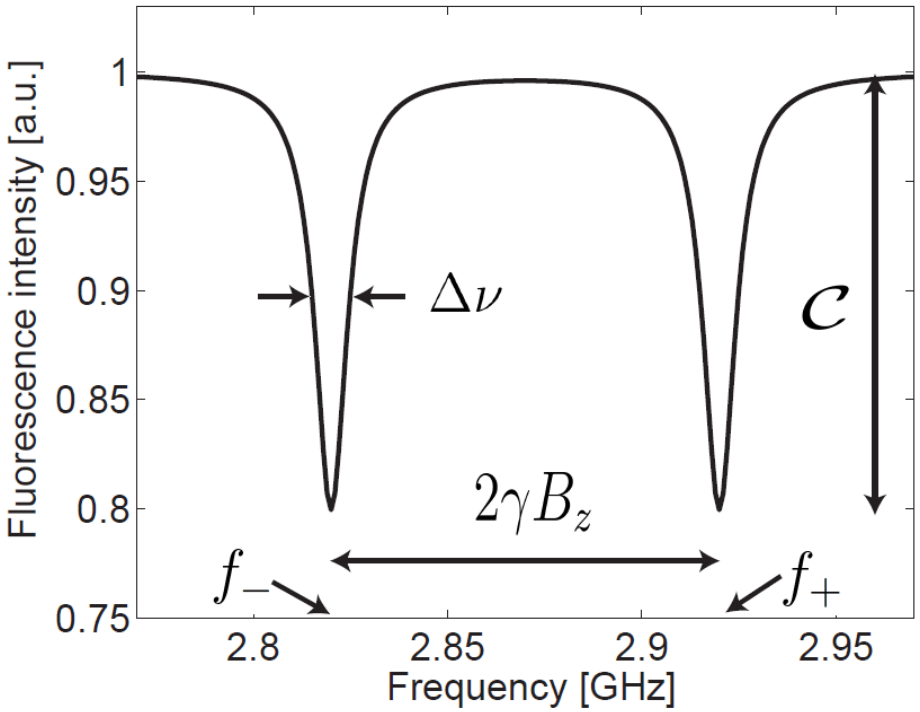
2) Ramsey sequence



3) Re-focussing sequences (Hanh, CPMG, XY-N)



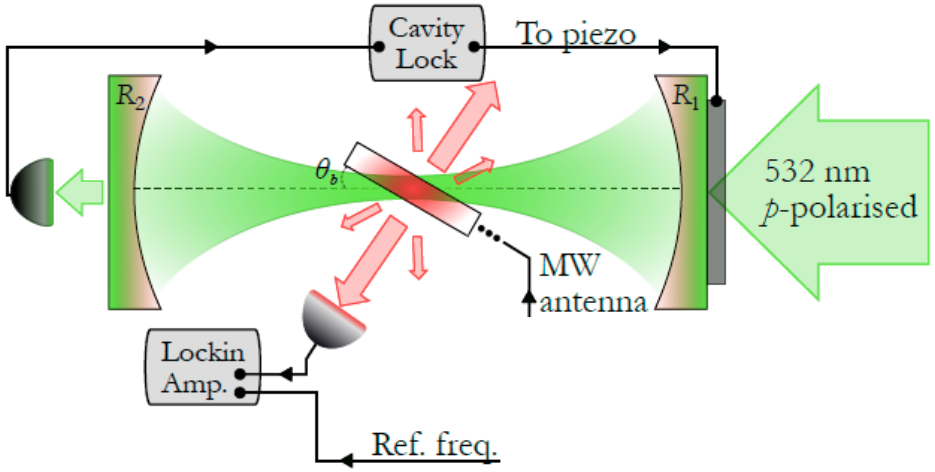
Sensitivity



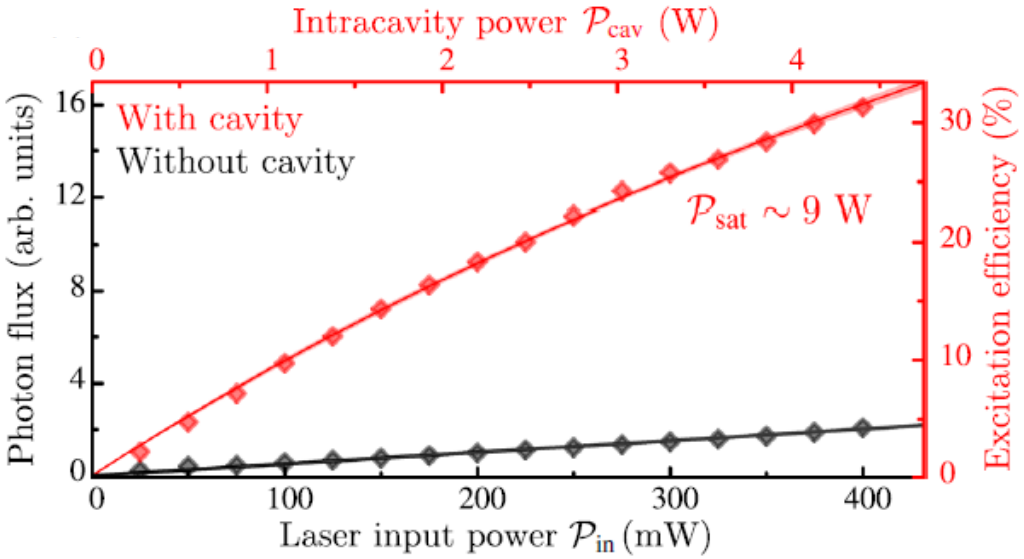
$$\delta B \simeq \frac{\hbar}{g\mu_B}\frac{\Gamma}{C\cdot \mathrm{SNR}} \simeq \frac{\hbar}{g\mu_B}\frac{\Gamma}{C\sqrt{\eta\mathcal{R}\tau}}$$

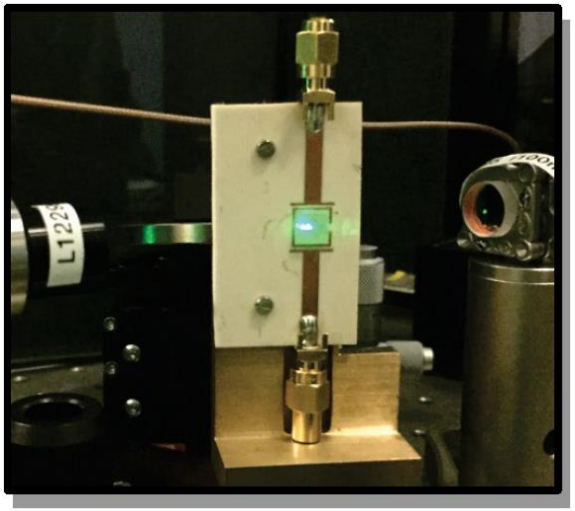
J. Taylor et al, Nat. Phys. 4, 810–816 (2008)

Cavity Enhanced Magnetometer



Efficiently address low density ensemble

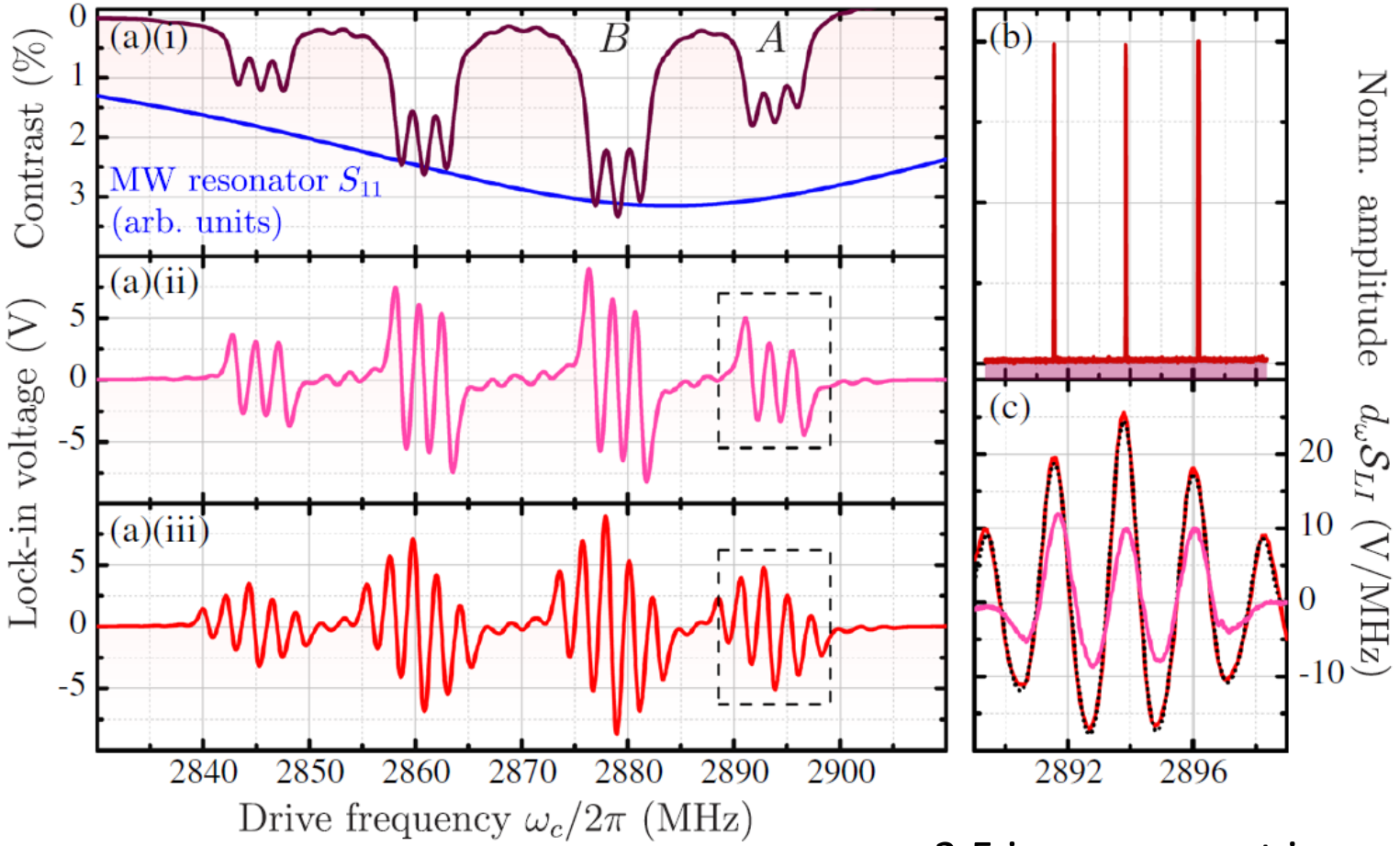




Microwave antenna
-> uniform field distribution
Bayat et al., Nano Lett. 14, 1208 (2014)

Hyperfine lines

Separated ^{14}N hyperfine spectrum (A_{hf} = 2.2MHz)

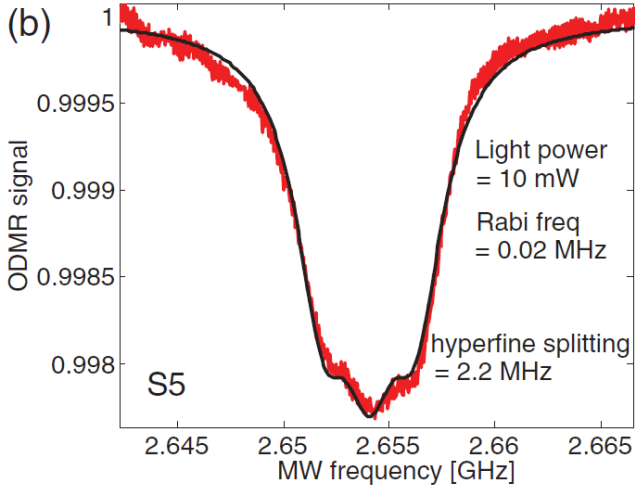


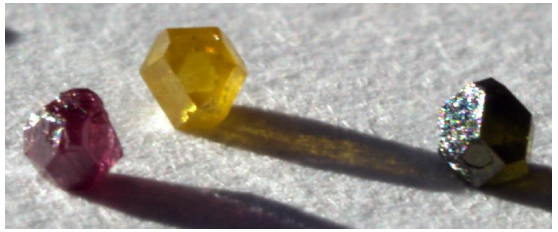
~2.5 improvement in contrast

S. Ahmadi et al., Phys. Rev. Applied 8, 034001 (2017)

Implantation vs. Native Defects

- Increase [NV] through radiation damage

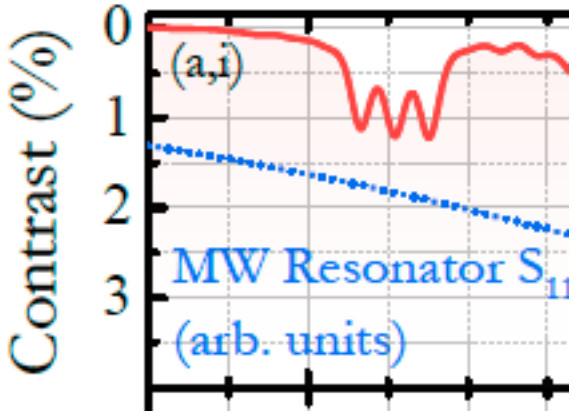




- [NV] ≈ ppm
- Γ ~ 5-10 MHz
- C < 0.1%

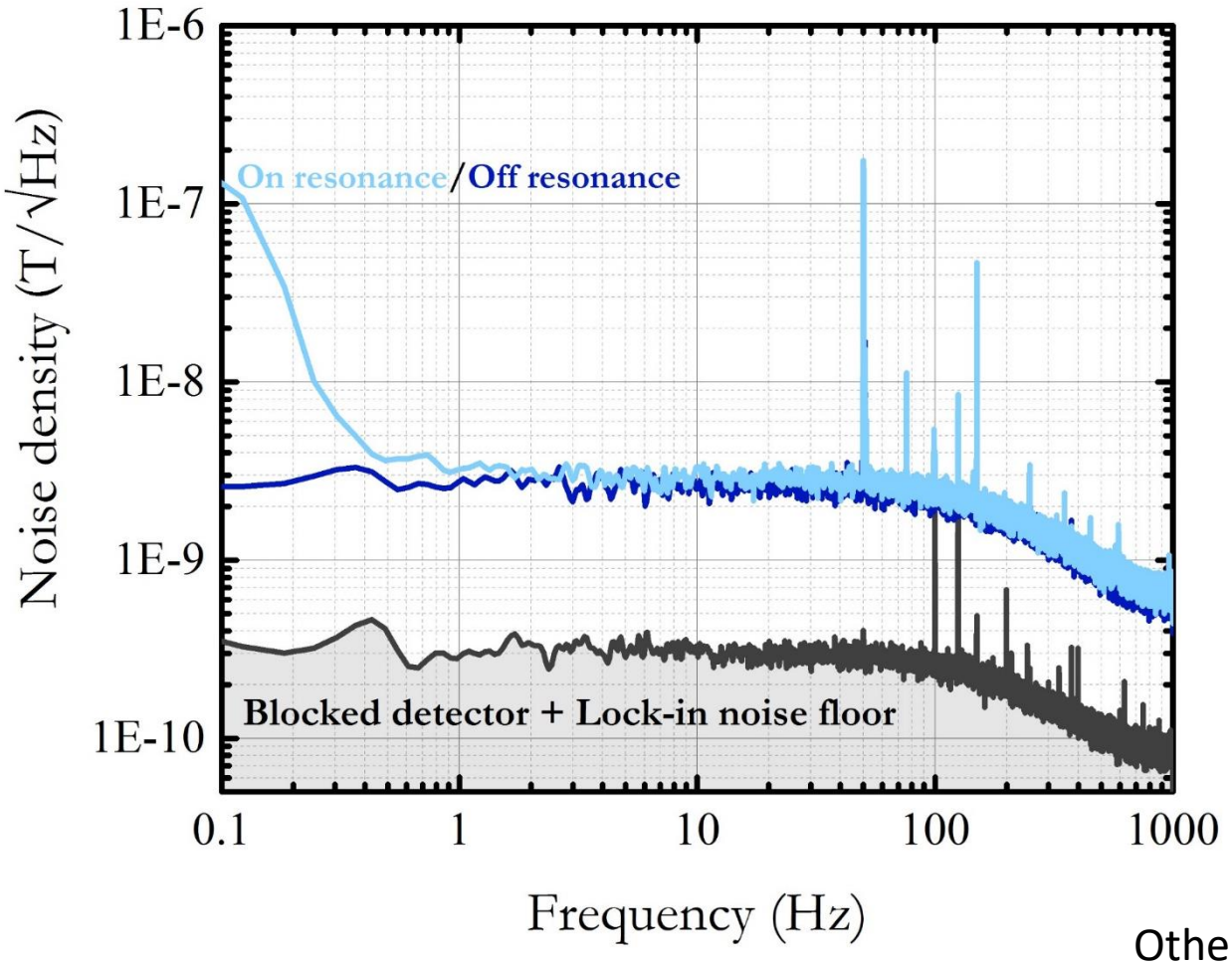
K. Jensen et al., PRB 87, 014115 (2013)

- CVD crystals – native defect density ρ ≈ 1 ppb



- [NV] ≈ 1 ppb
- Γ ~ 1-2 MHz
- C ~ 1-3%

Sensitivity



Limitations

- Technical noise
- Finite photon collection

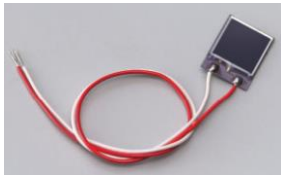
Shot noise limit: ~160 pT $Hz^{-1/2}$

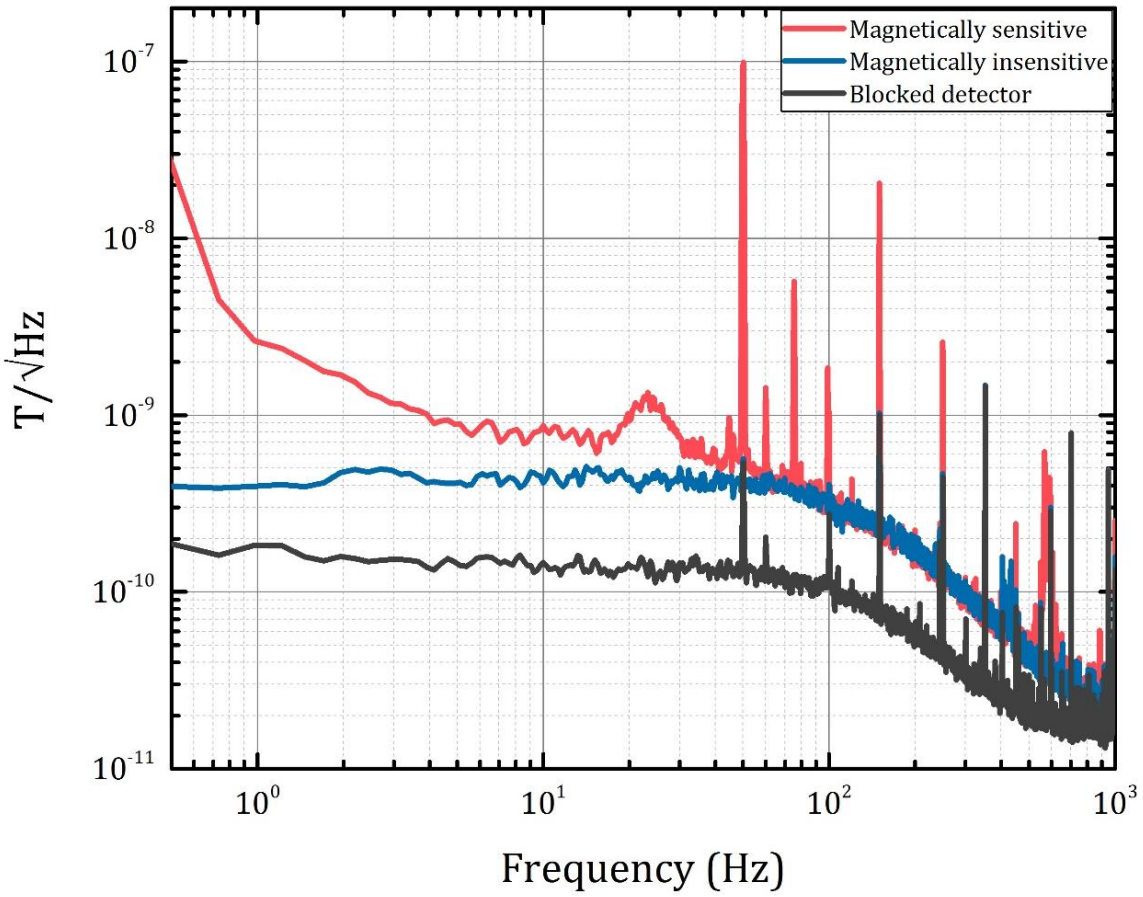
Other works:
PNAS 113, 14133 (2016): 15pT
Nat. Phys. 11393 (2015): 290pT
NV: 100ppb (and C12 purified)

S. Ahmadi et al., Phys. Rev. Applied 8, 034001 (2017)

Improved Sensitivity

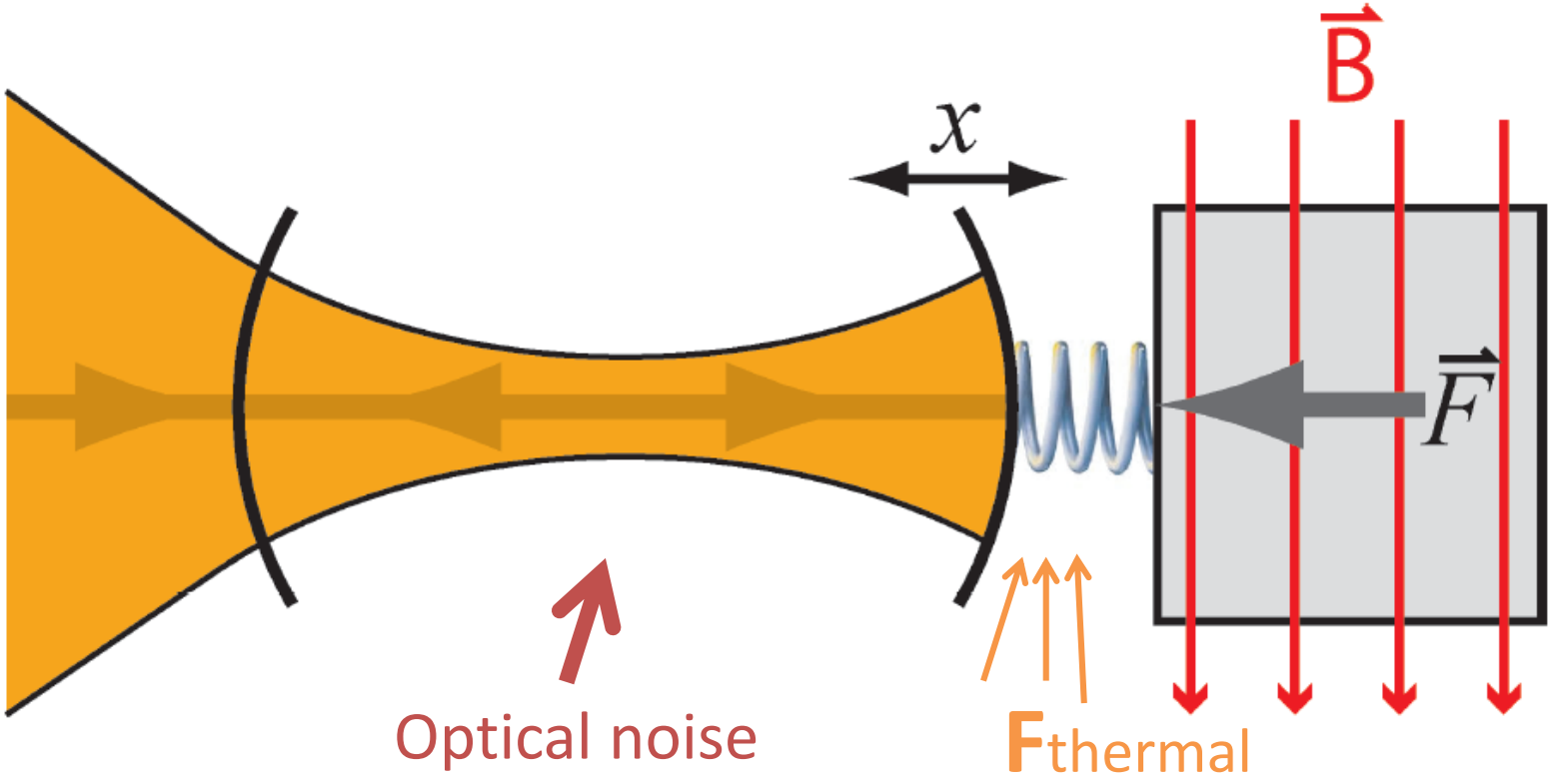
- larger diode (10x10 mm^2 vs. 3.6x3.6mm^2)
- noise cancellation





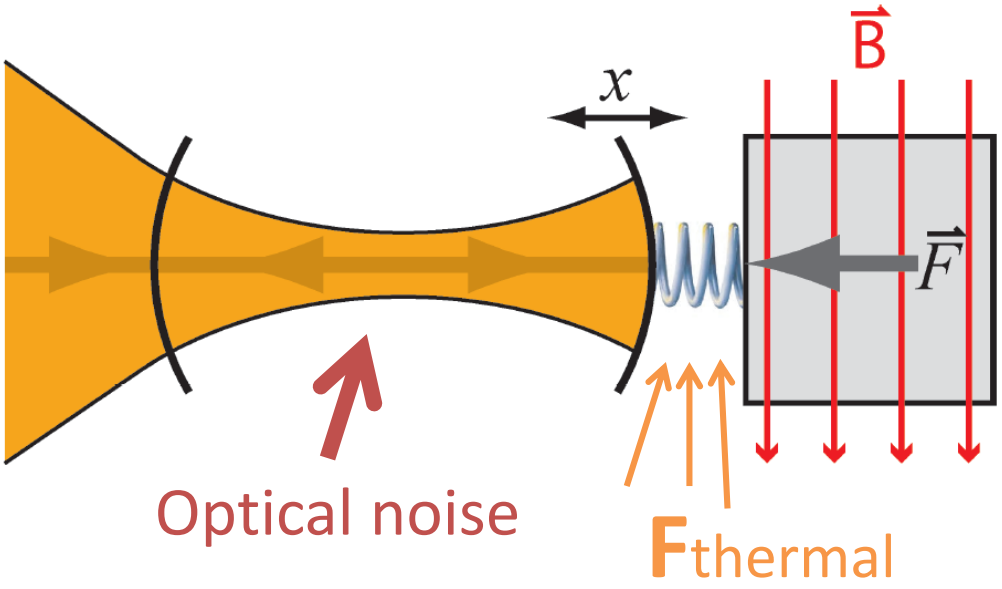
Shot noise limit: $\approx$ 120 pT $Hz^{-1/2}$

Cavity optomechanical magnetometry



S. Forstner et al, Phys. Rev. Lett. 108, 120801 (2012)

Noise sources



Thermomechanical noise (Fluctuation-dissipation theorem)

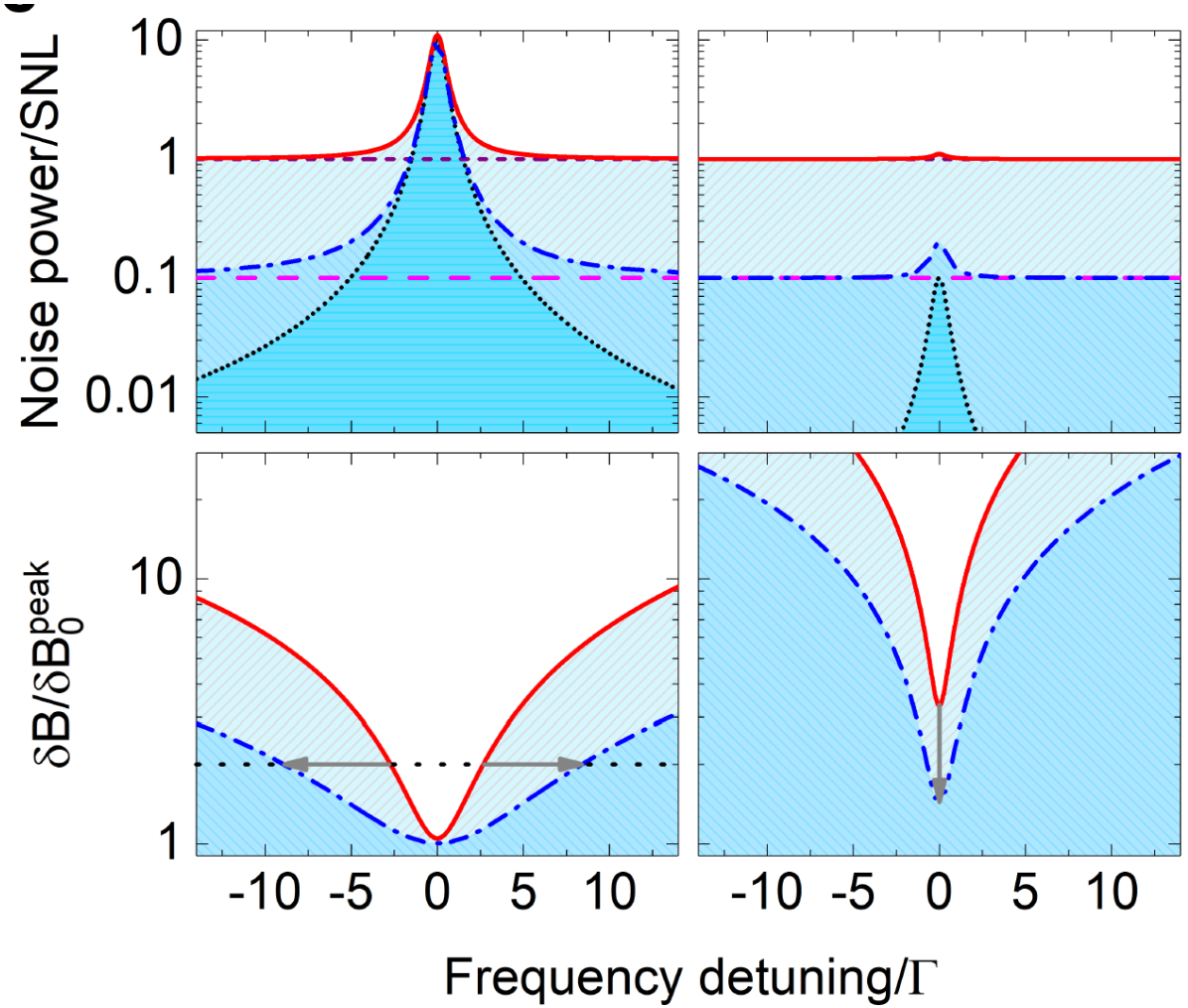
$$S_{th} = 2m\Gamma k_B T$$

Measurement noise from optical measurement

$$S_{mea} \propto \frac{V_{probe}}{G^2} + rad\,noise$$

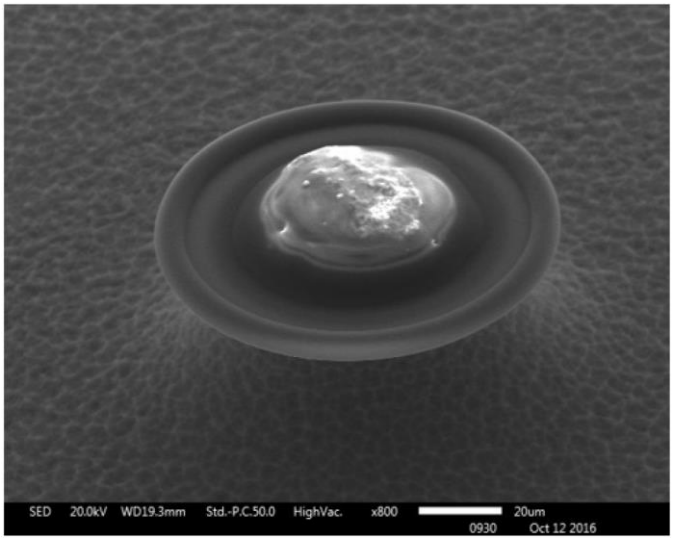
Quantum-enhanced performance

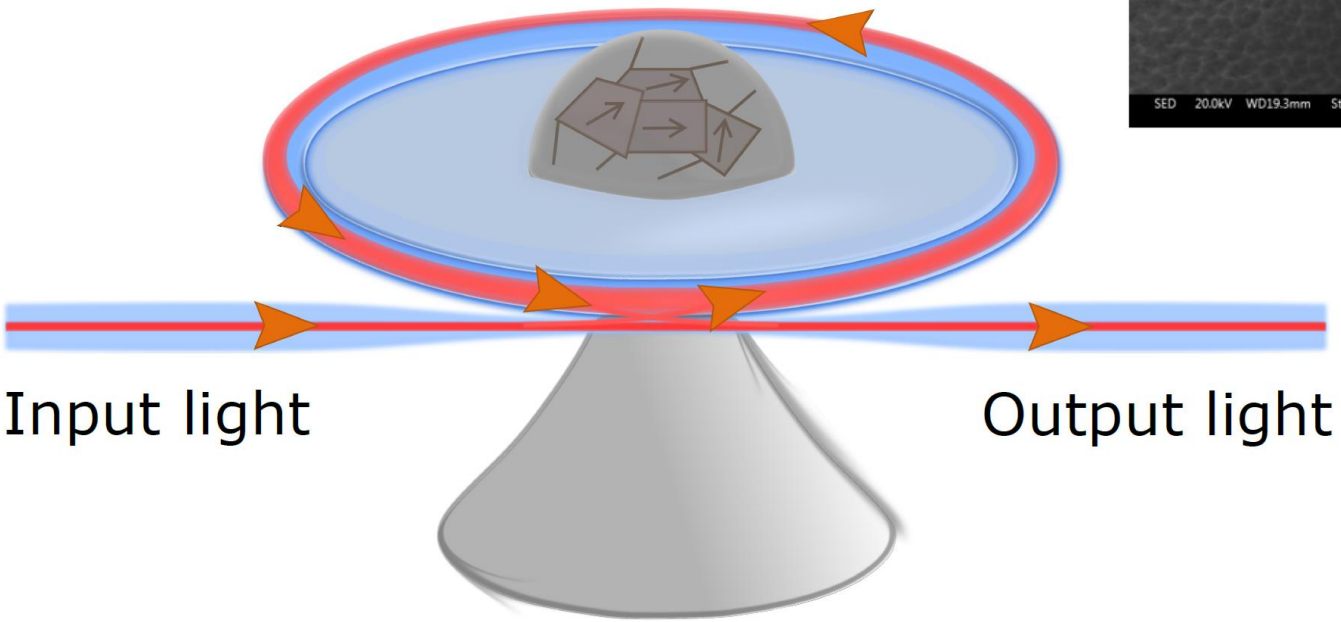
$$B_{\min} = c\sqrt{\frac{S_{imp}}{|\chi(\omega)|^2} + 2m\Gamma k_B T}$$



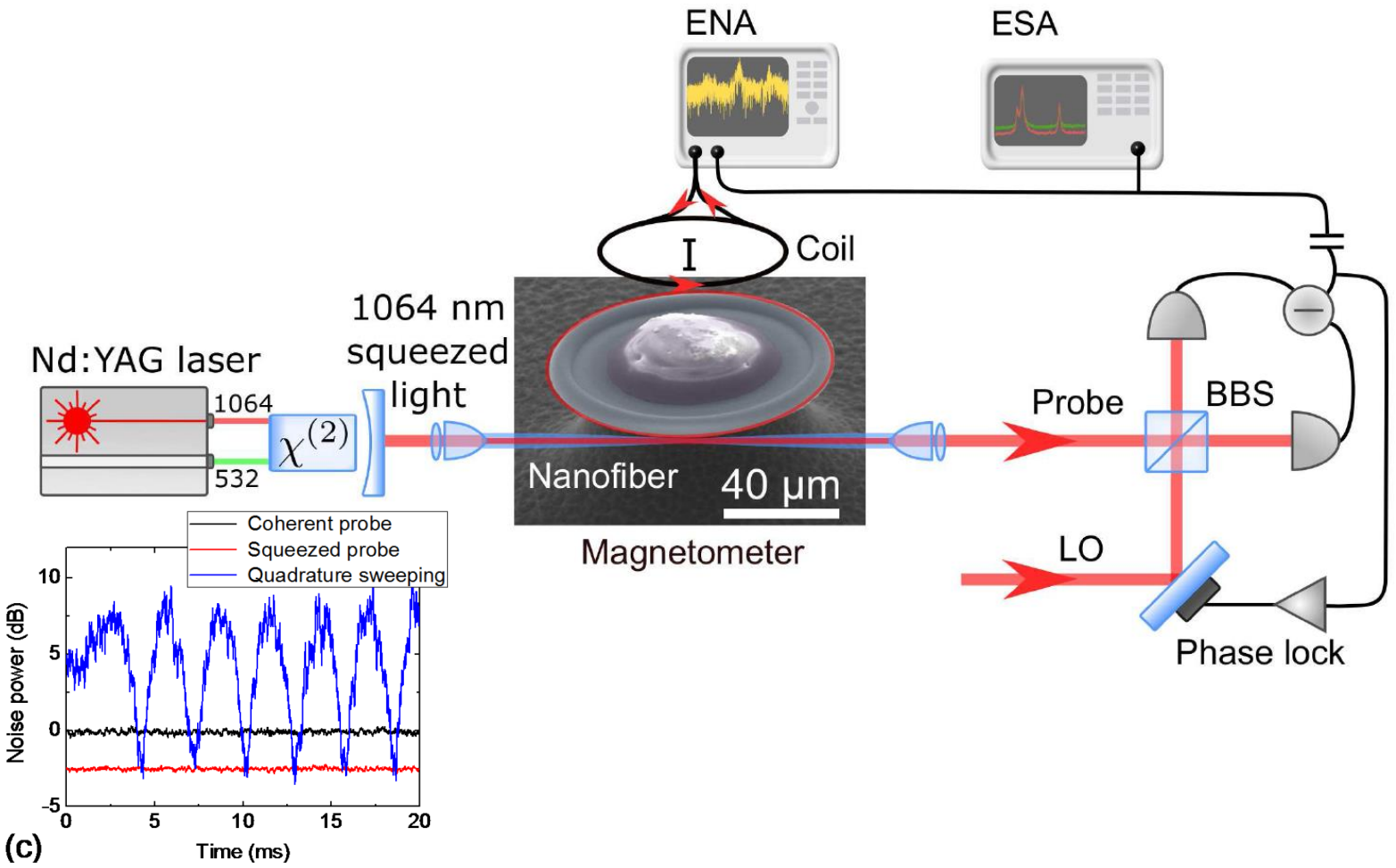
Beibei Li, Jan Bilek et al, arxiv:1802.09738

Silicon chip





Setup



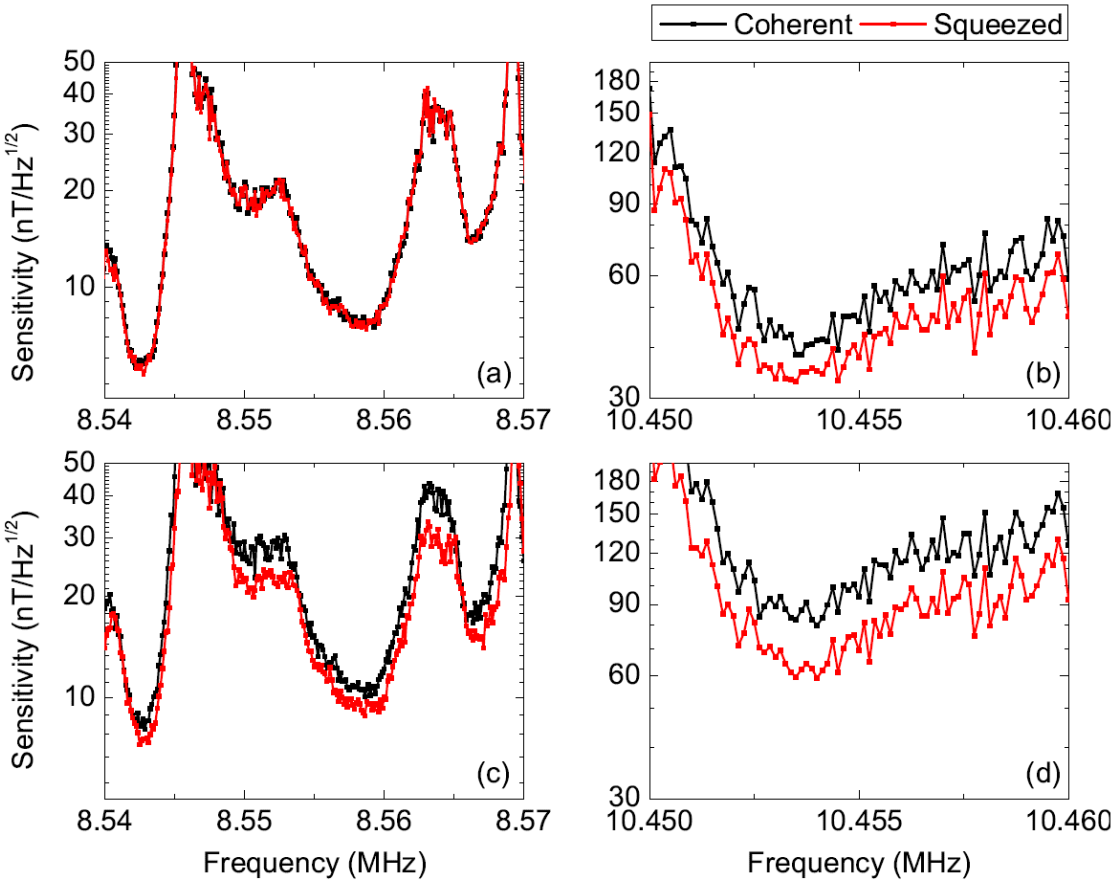
Beibei Li, Jan Bilek et al, arxiv:1802.09738

Thermomech. noise limited

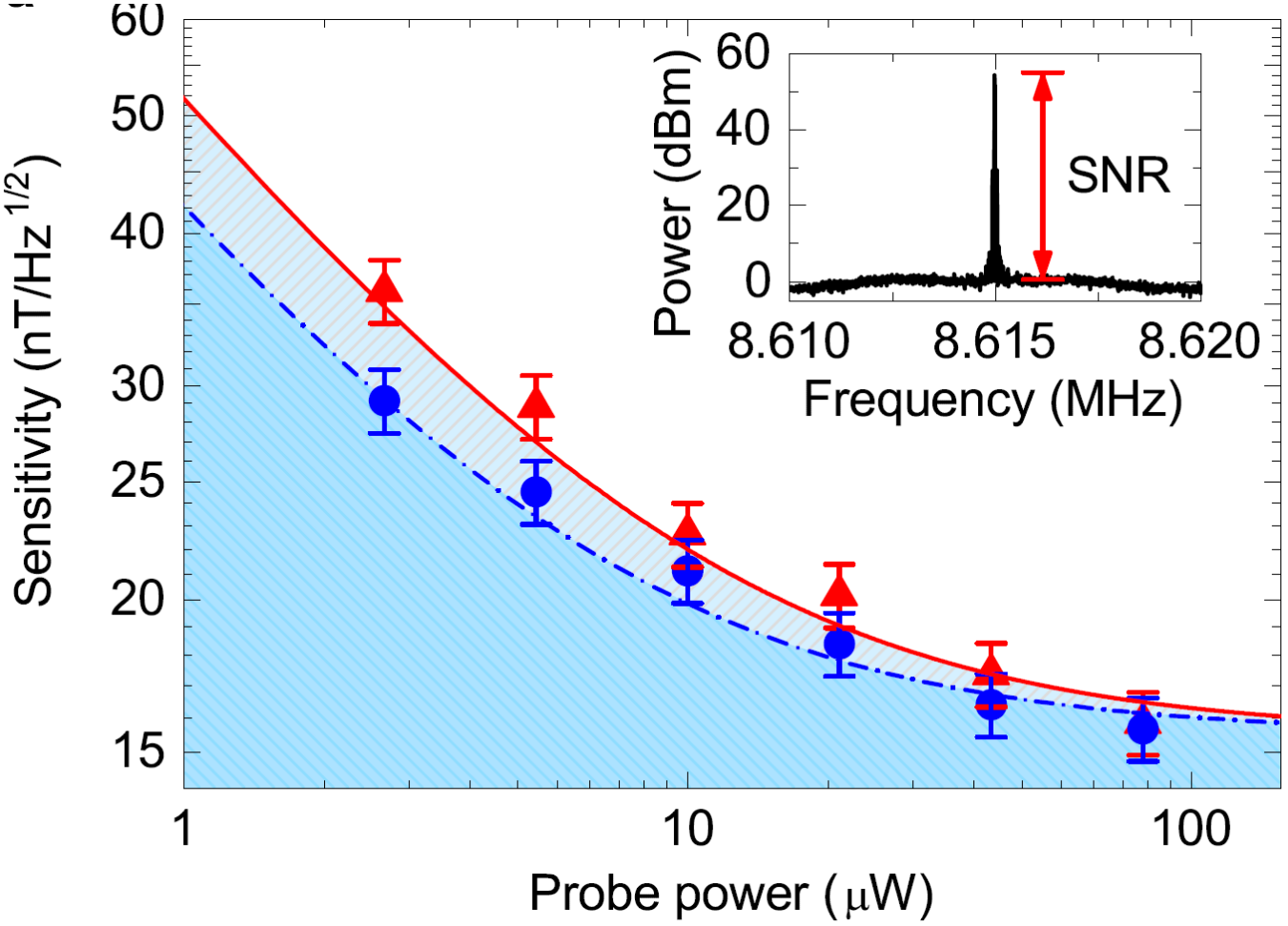
Probe noise limited

P = 80 muW

P = 20 muW



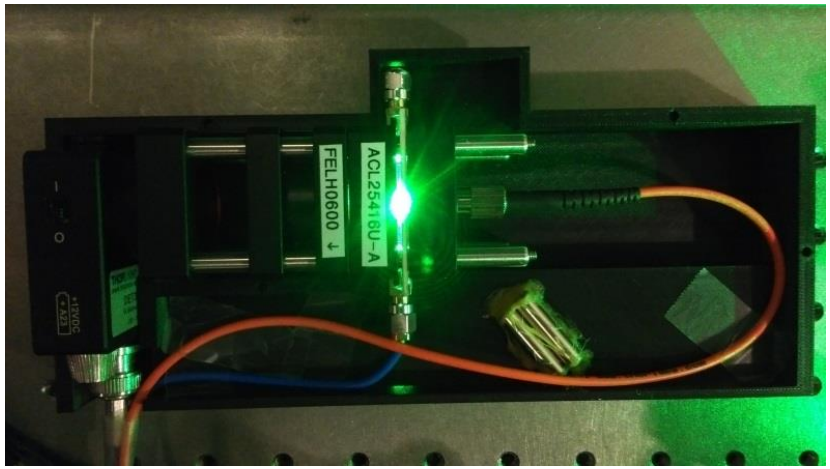
Results



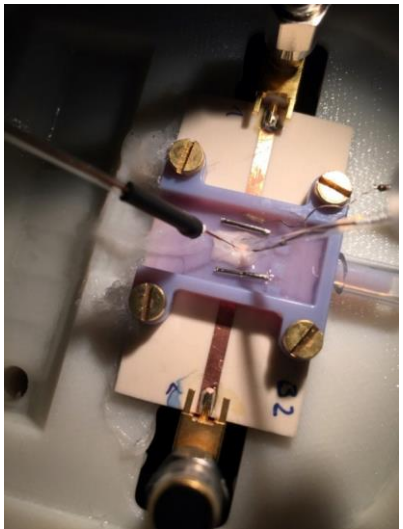
Beibei Li, Jan Bilek et al, arxiv:1802.09738

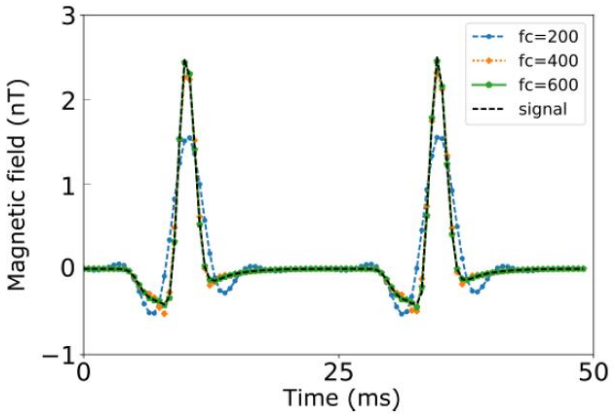
Summary

Diamond magnetometer



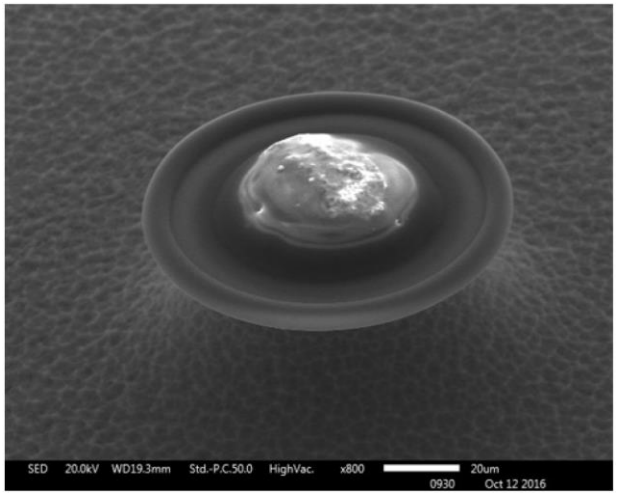
S. Ahmadi, H. El-Ella, J. Bindslev, A. Huck, U.L. Andersen, Phys. Rev. Applied 8, 034001 (2017)





M. Karadas et al., Scientific Report 2018

Optomechanical magnetometer



B. Li, J. Bilek, U. B. Hoff, L. S. Madsen, S. Forstner, V. Prakash, C. Schafermeier, T. Gehring, W. P. Bowen, U. L. Andersen arxiv:1802.09738