Room-Temperature Quantum Sensing in CMOS: On-Chip Detection of Electronic Spin States in Diamond Color Centers for Magnetometry

Mohamed I. Ibrahim*, Christopher Foy*, Donggyu Kim*, Dirk R. Englund, and Ruonan Han

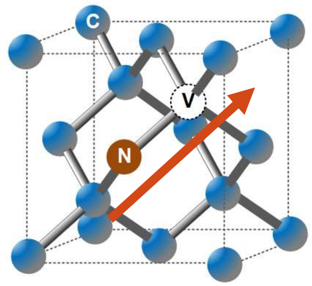
*Equal Contribution

Massachusetts Institute of Technology

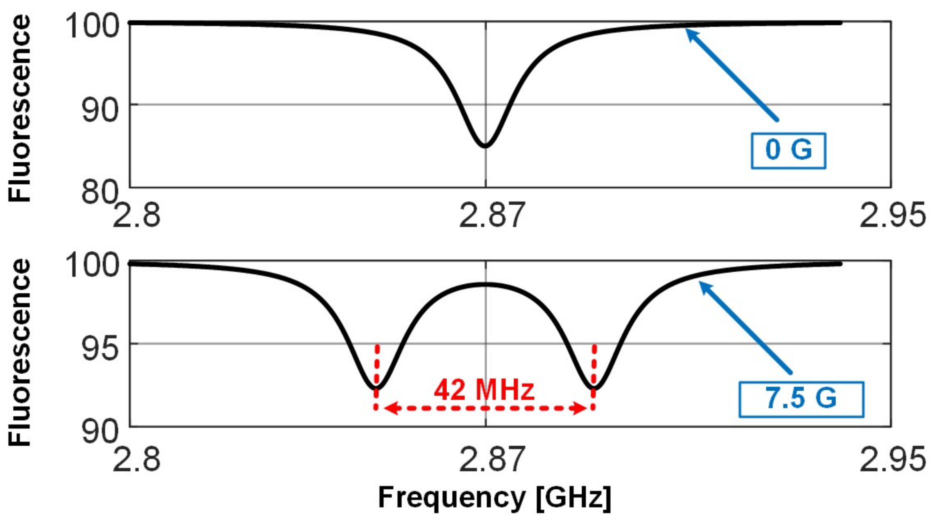
Outline

- Introduction
- CMOS-Based Quantum Magnetometer
  - System Architecture
  - Microwave Signal Generation
  - Optical Excitation Filtering
  - Optical Fluorescence Readout
- Experimental Data
  - Measurement Results Using Layer of Nano-Diamonds
  - Measurement Results Using Bulk Diamond
- Conclusion

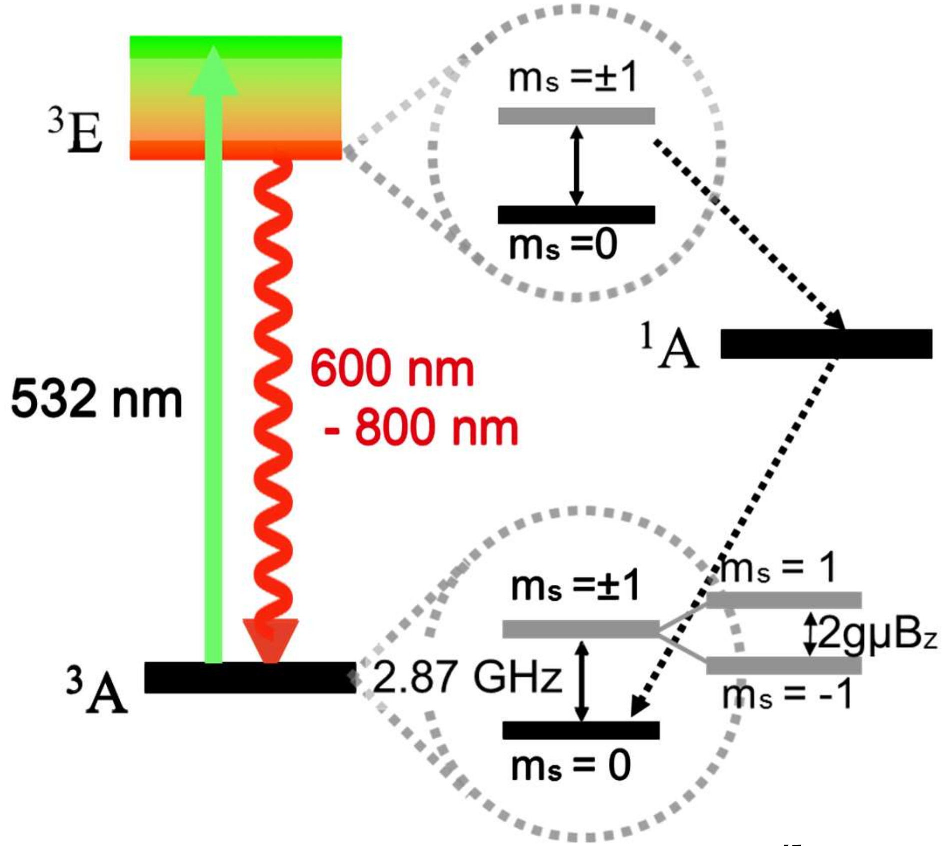
Nitrogen Vacancy (NV) in Diamond Magnetometer



Nitrogen vacancy center in diamond

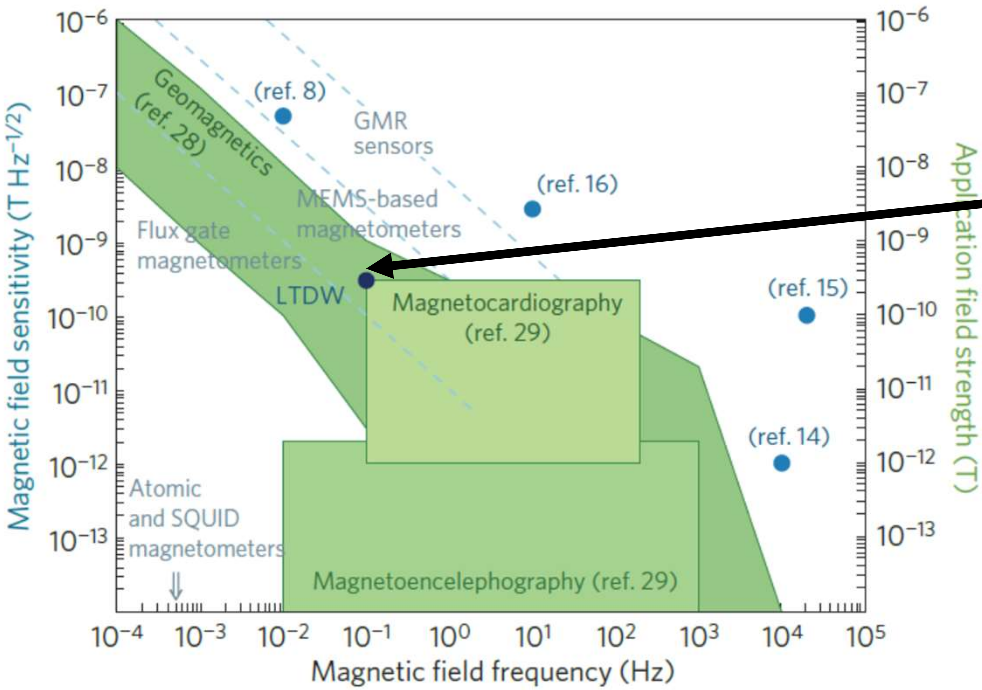


Optically detected magnetic resonance (ODMR)

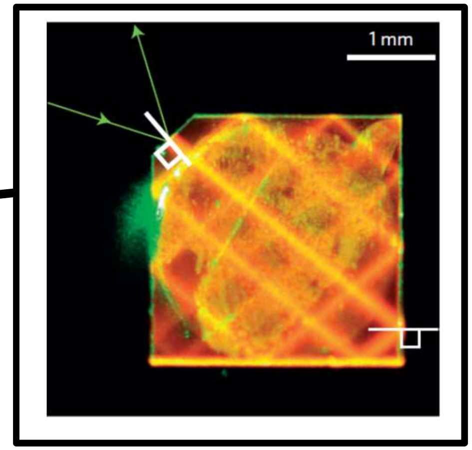


- Gyromagnetic ratio $\gamma = 2g\mu/h = 2.8\ \text{MHz/Gauss}$

Nitrogen Vacancy (NV) in Diamond Magnetometer



Clevenson, et al. Nature Physics 2015

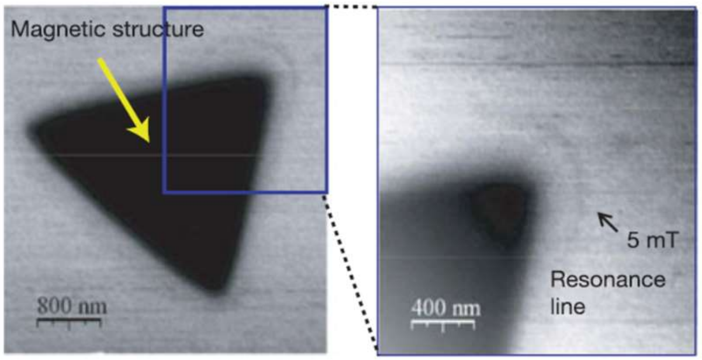


$0.29\ \mathrm{nT}/\sqrt{Hz}$

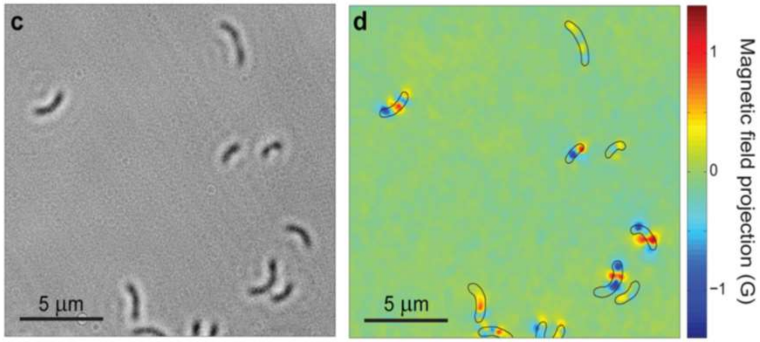
Ensemble of NVs
Clevenson, et al. Nature Physics 2015

- Sensitivity $\propto \frac{1}{\mathrm{SNR}} \propto \frac{1}{\sqrt{\mathrm{N}}}$
  - Where N is number of NVs

Nitrogen Vacancy (NV) in Diamond Magnetometer

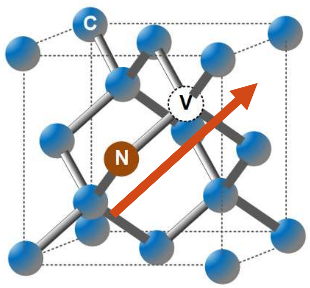


Magnetic structure imaging
Balasubramanian, et al. Nature (2008)



Bacteria magnetic imaging
Le Sage, et al. Nature 2013

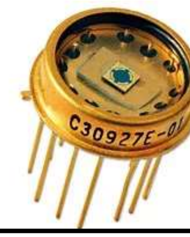
- Nano-tesla sensitivity
- Nanometer spatial resolution
- Vector field measurements
- Ambient conditions (room temperature)



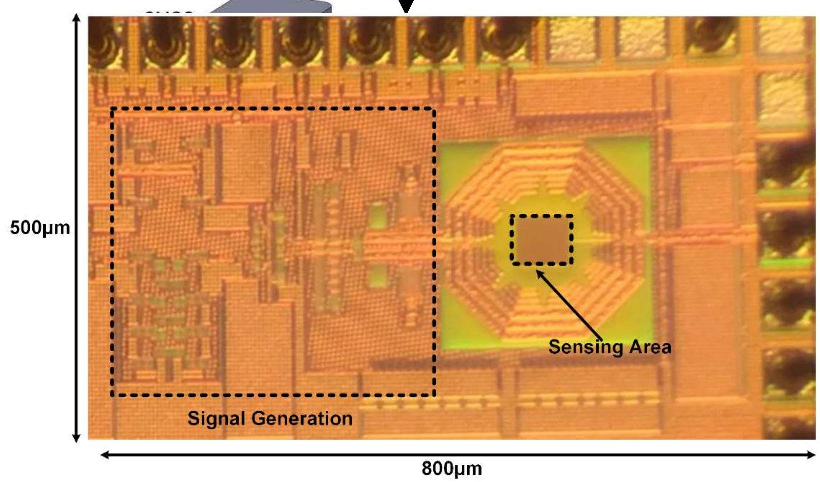
NV Magnetometer System Components

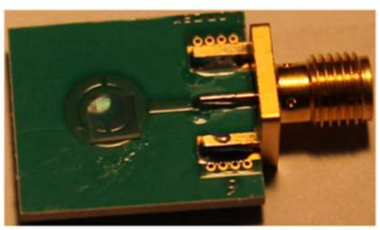
Green Laser

Signal generator



Photodetector





Microwave antenna

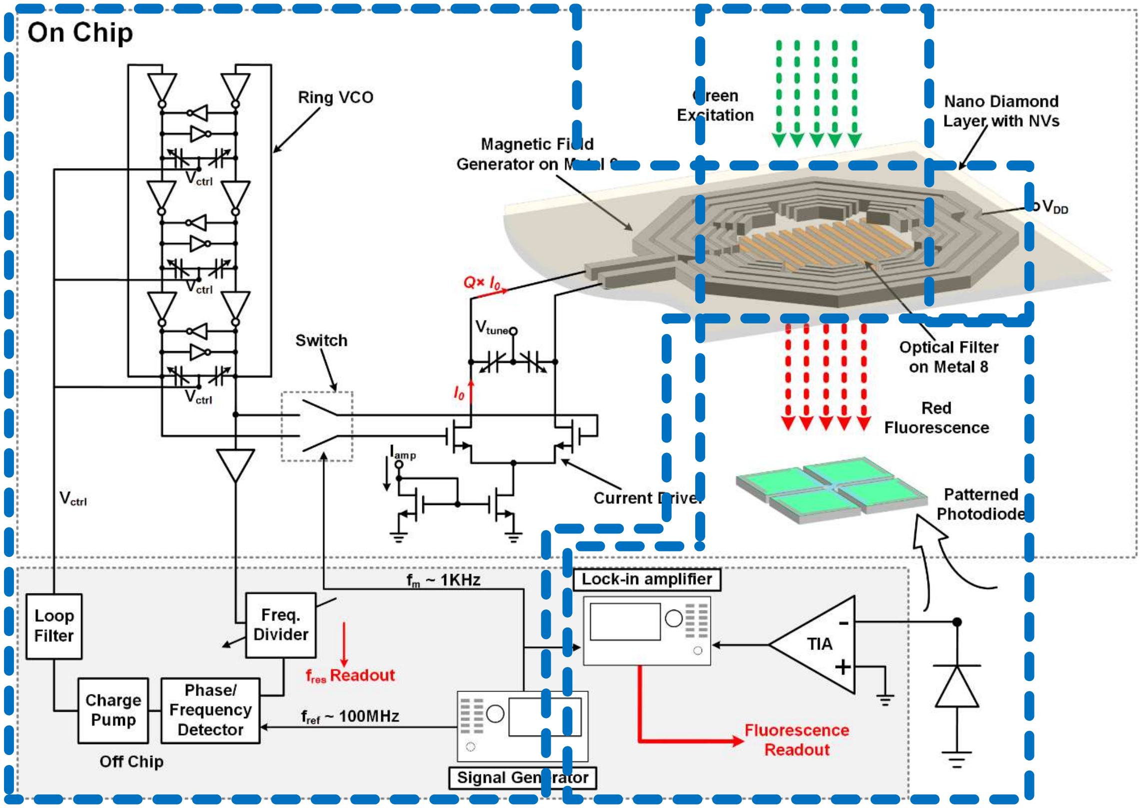
CMOS integrated NV magnetometer
(TSMC 65nm LP process)

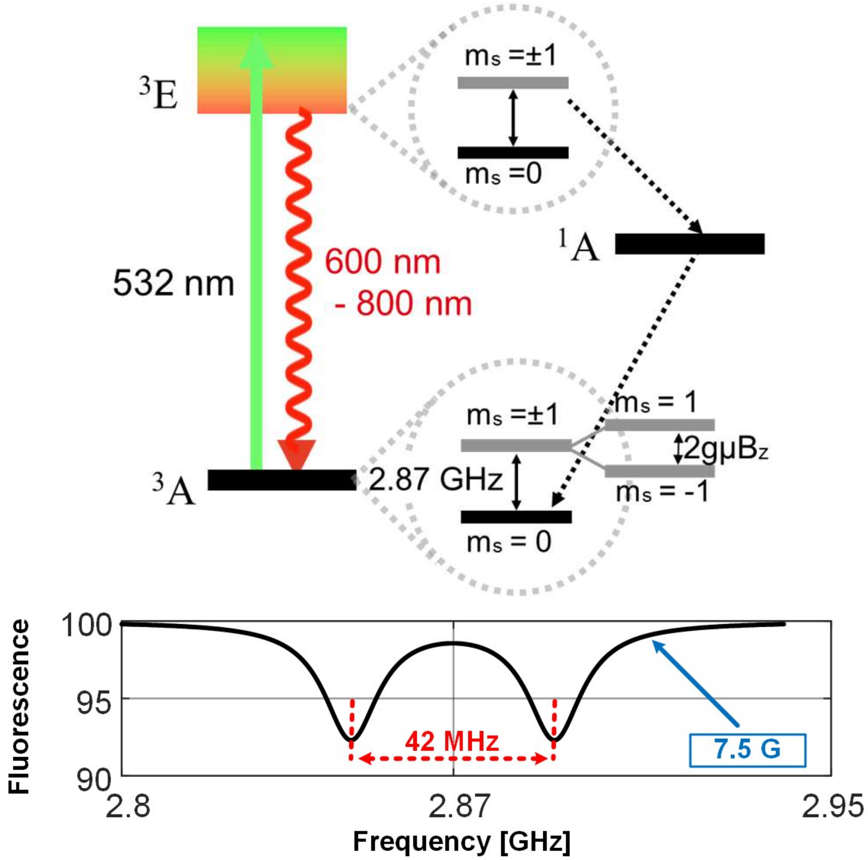
Optical filters

Outline

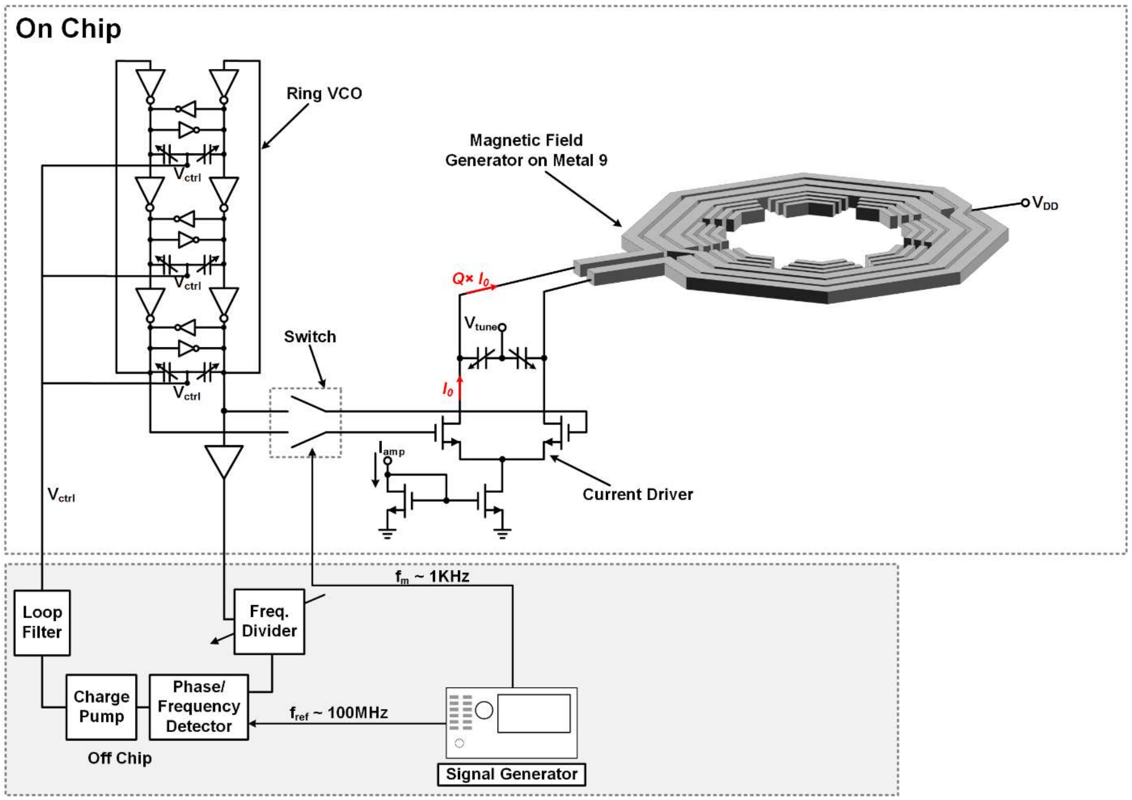
- Introduction
- CMOS Based Quantum Magnetometer
  - System Architecture
  - Microwave Signal Generation
  - Optical Excitation Filtering
  - Optical Fluorescence Readout
- Experimental Results
  - Measurement Results Using Layer of Nano-Diamonds
  - Measurement Results Using Bulk Diamond
- Conclusion

CMOS Based Quantum Magnetometer





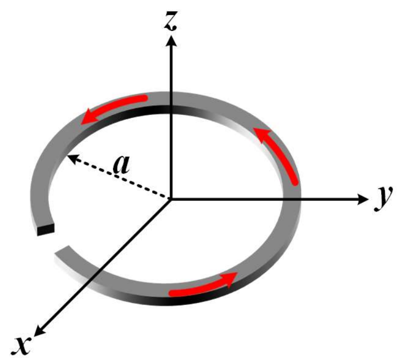
Microwave Signal Generation



- 2.87 GHz microwave signal generation
  - 2.6 GHz – 3.1 GHz for optically detected magnetic resonance (ODMR) measurements
- 10 Gauss field strength at 2.87 GHz with 95% homogeneity
  - To increase the contrast
  - To drive the NVs with equal strength for spin control pulsed sequences (Echo, Ramsey,..)

Microwave Signal Generation

Microwave Coil

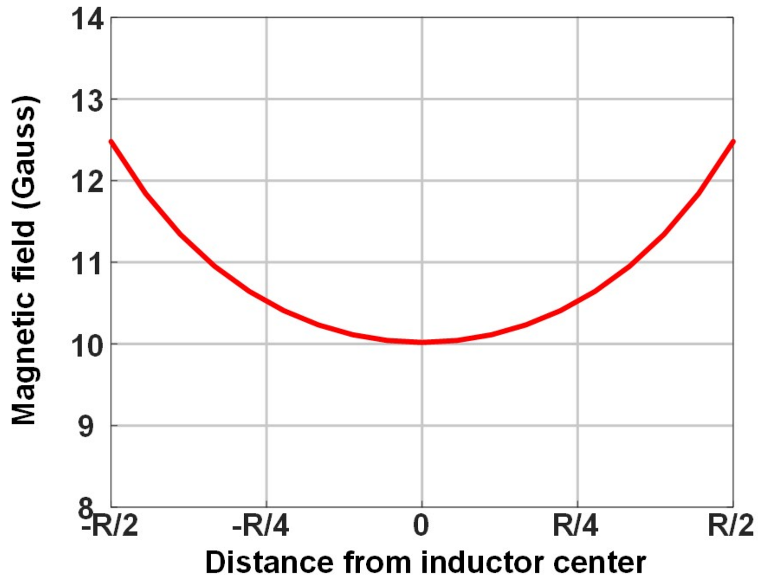


$$B_z = B_0 \frac{1}{\pi\sqrt{Q}}\left(E(k)\frac{1-\alpha^2-\beta^2}{Q-4\alpha}+K(k)\right)$$

$\alpha = \frac{r}{a}$, $\beta = \frac{z}{a}$, $k = \sqrt{\frac{4\alpha}{Q}}$, $r^2 = x^2 + y^2$ and $Q = (1+\alpha)^2 + \beta^2$

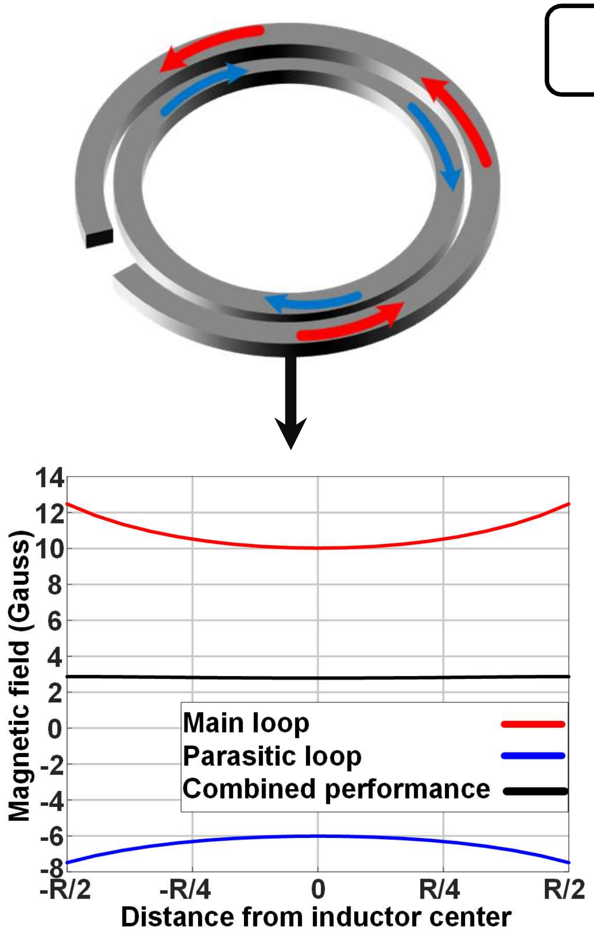
https://tiggerntatie.github.io/emagnet/offaxis/iloopoffaxis.htm

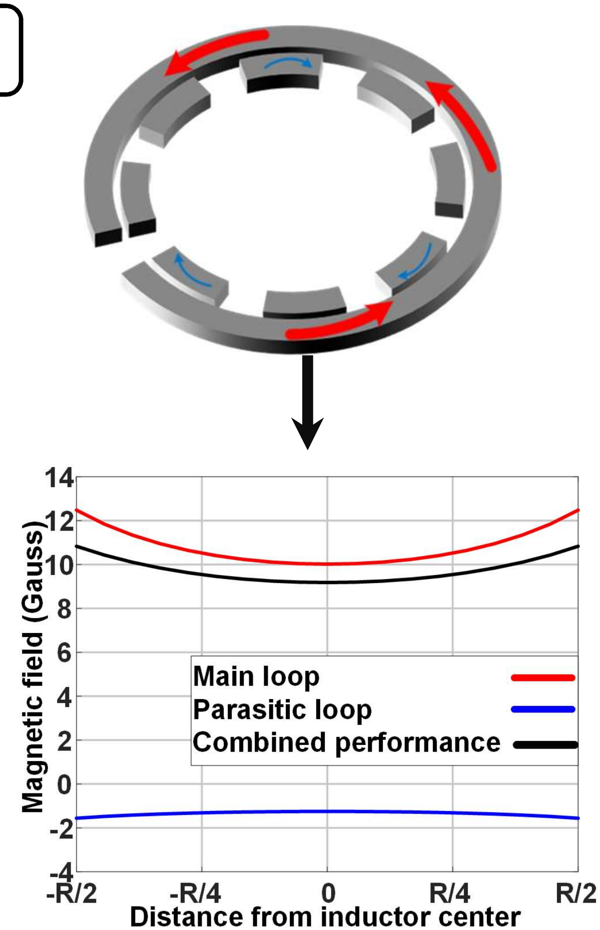
160 mA is required to get 10 Gauss for 200 μm diameter coil



Microwave Signal Generation

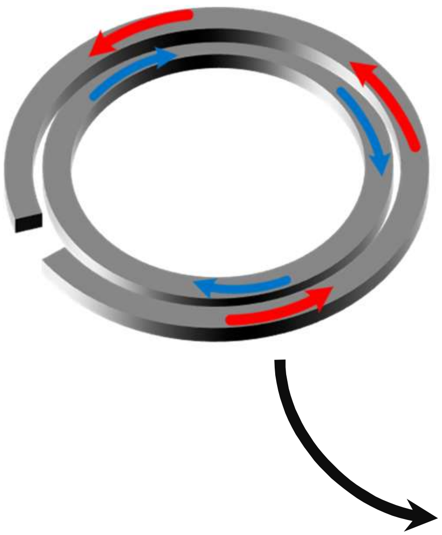
Microwave Coil

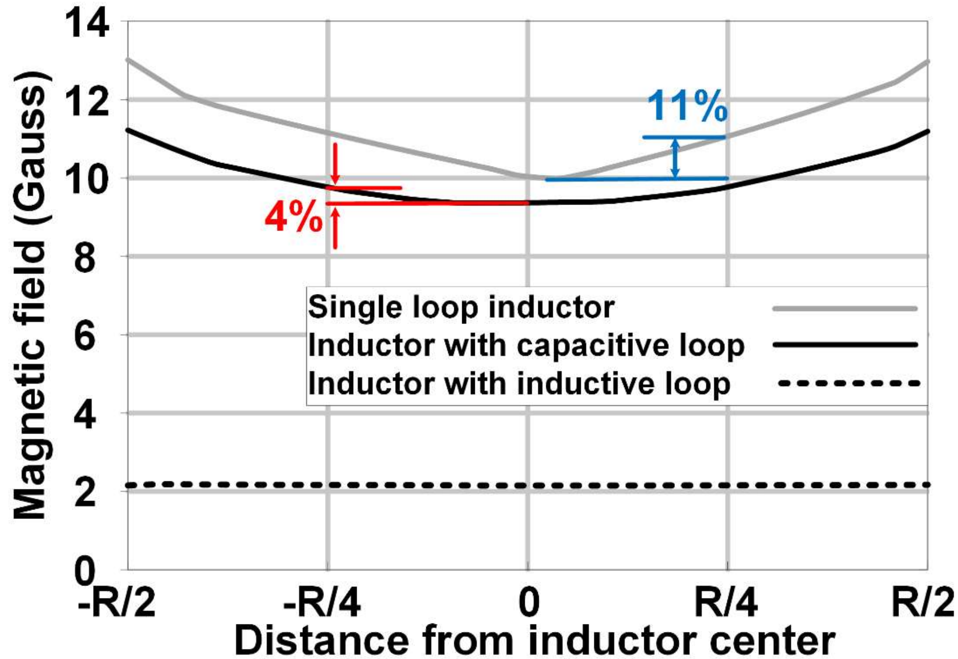


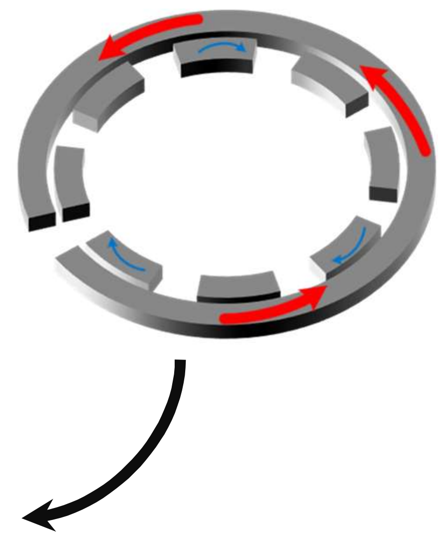


Microwave Signal Generation

Microwave Coil

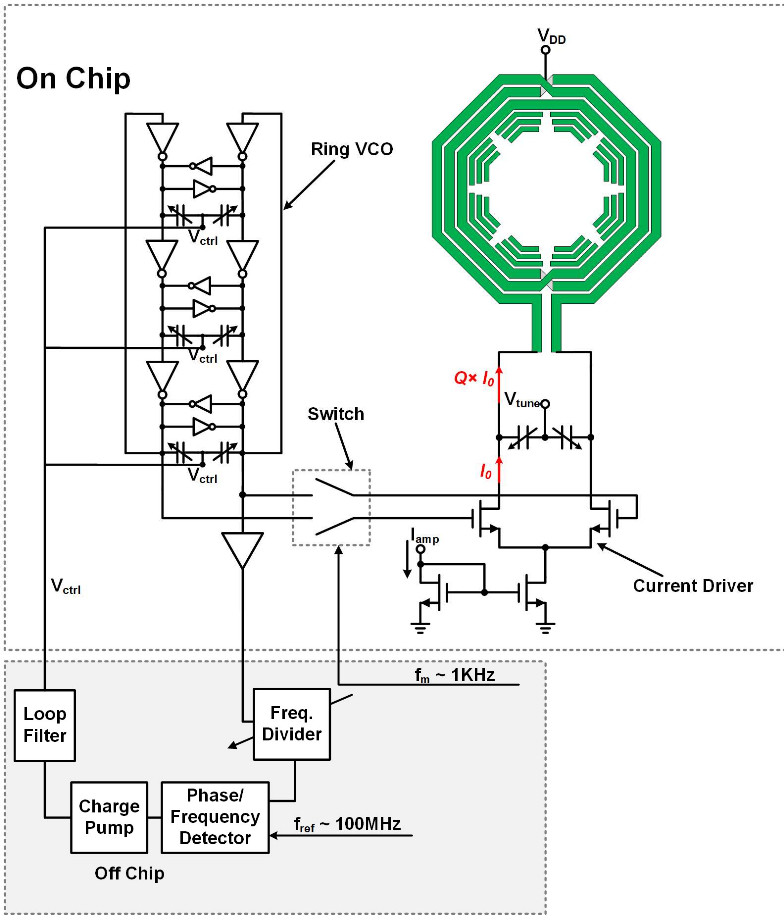




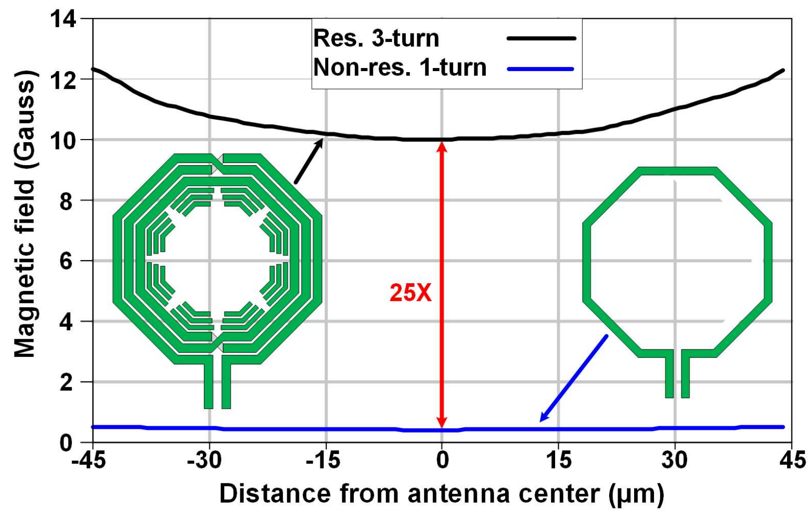


EM simulated performance

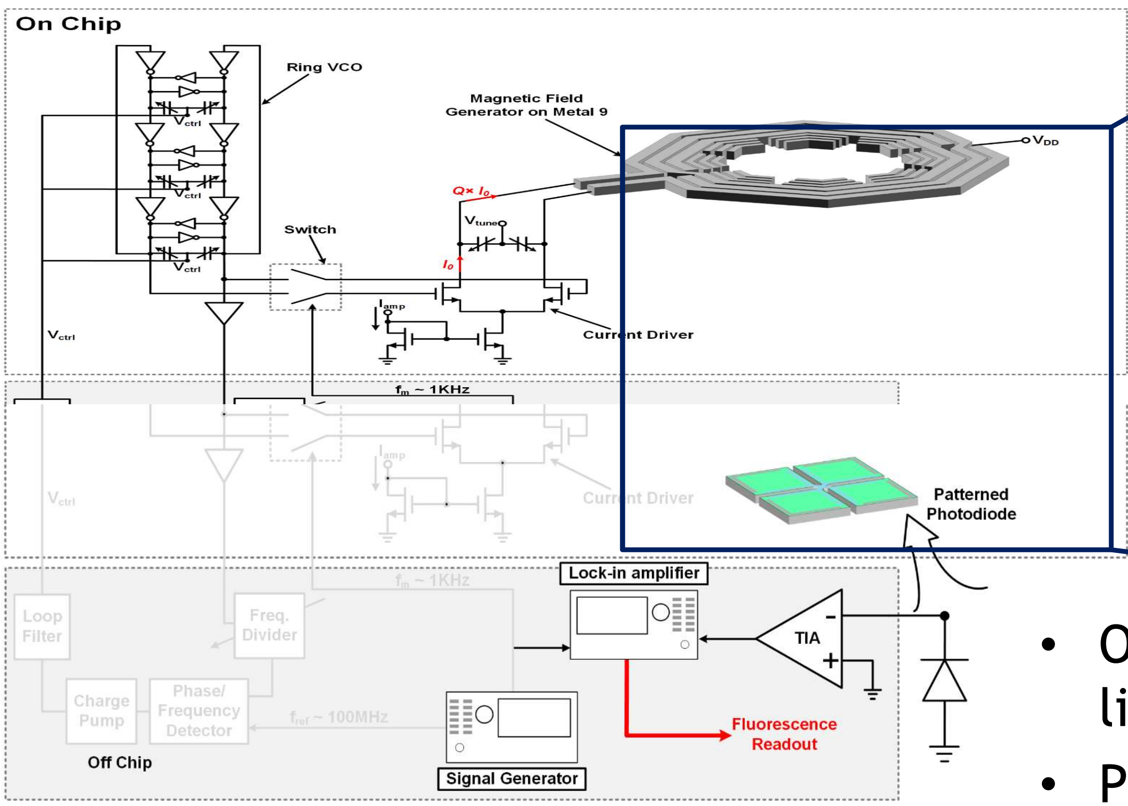
Microwave Signal Generation

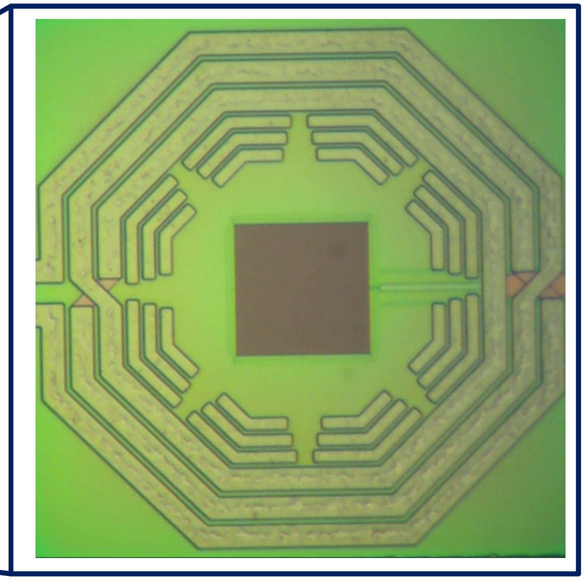


- **10 Gauss** with **95%** uniformity
  - **6 mA** DC current in the driver
  - **25x** field strength more than simple non-resonant loop
- **2.6 GHz-3.1 GHz** Microwave frequency sweep



Optical Spin Readout

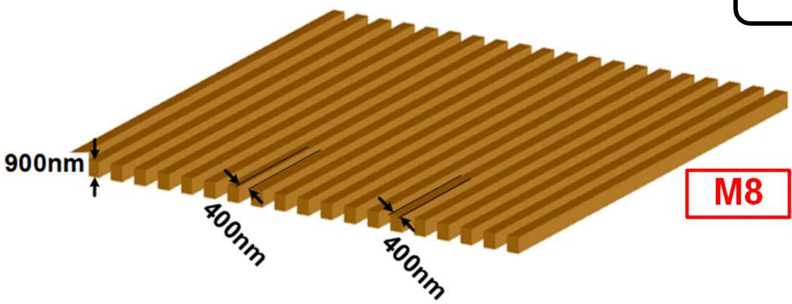




- Optical filter is required for green light rejection
- Photodiode is used to detect red fluorescence

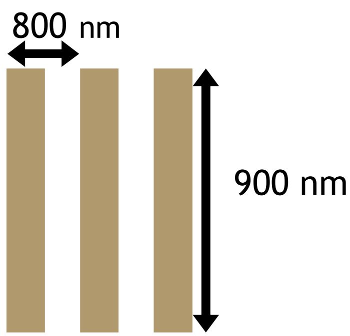
Optical Excitation Filtering

Plasmonic Filter



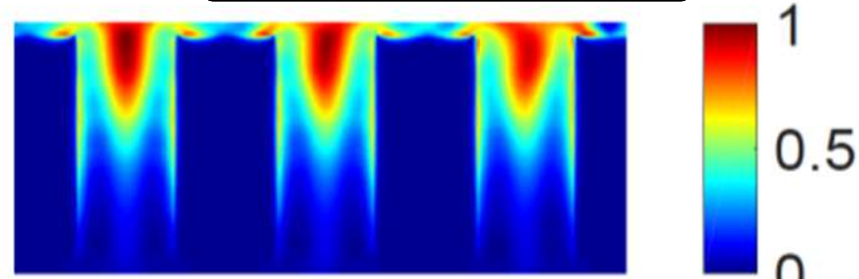
Filter 3D structure

Filter cross section

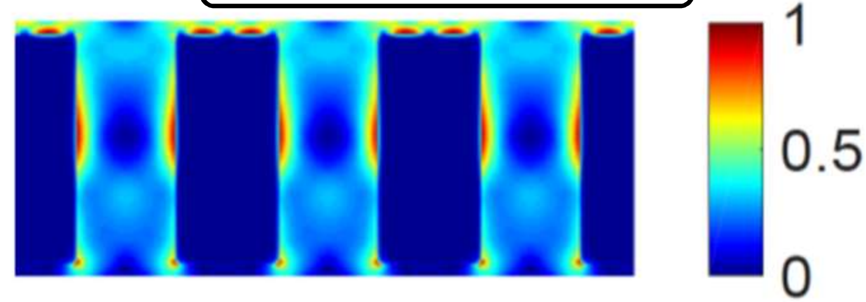


- Measured isolation is 10 dB

Green light (532 nm)



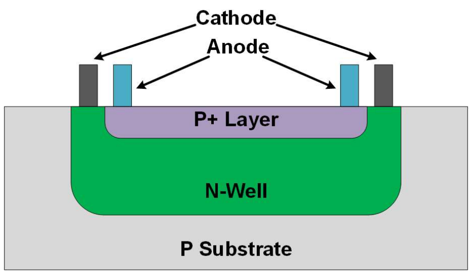
Red light (700 nm)

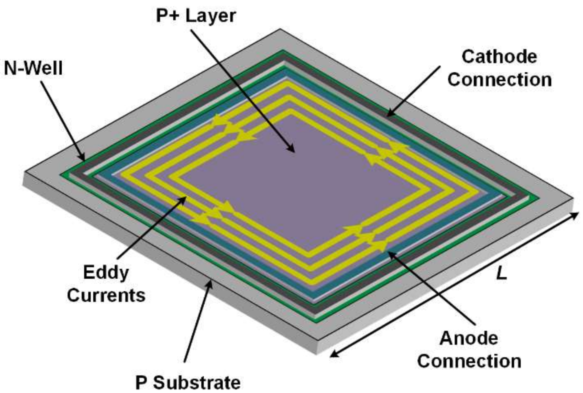


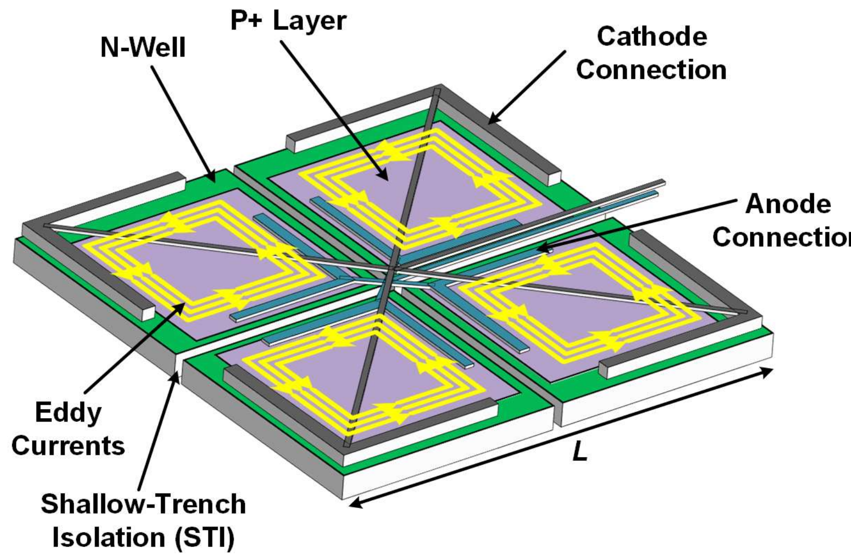
FDTD simulated performance

Optical Fluorescence Readout

P+ N-well Photo-diode







- $\mathbf{P_{Eddy}} \propto \frac{\mathrm{EMF}^2}{\mathrm{R}} \propto \frac{\left(\frac{d\phi}{dt}\right)^2}{\mathrm{R}} \propto \frac{\mathrm{L}^4\left(\frac{dB}{dt}\right)^2}{\mathrm{L}} \propto \mathrm{L}^3\left(\frac{dB}{dt}\right)^2 \propto \mathbf{L^3}$
- 2×2 diode $\rightarrow \mathbf{P_{Eddy}} \propto 4 \times \left(\frac{\mathrm{L}}{2}\right)^3\left(\frac{dB}{dt}\right)^2 \propto \frac{\mathbf{L^3}}{\mathbf{2}}$
- Cuts the losses in anode and cathode
- n×n diode $\rightarrow \mathbf{P_{Eddy}} \propto \frac{\mathbf{L^3}}{\mathbf{n}}$

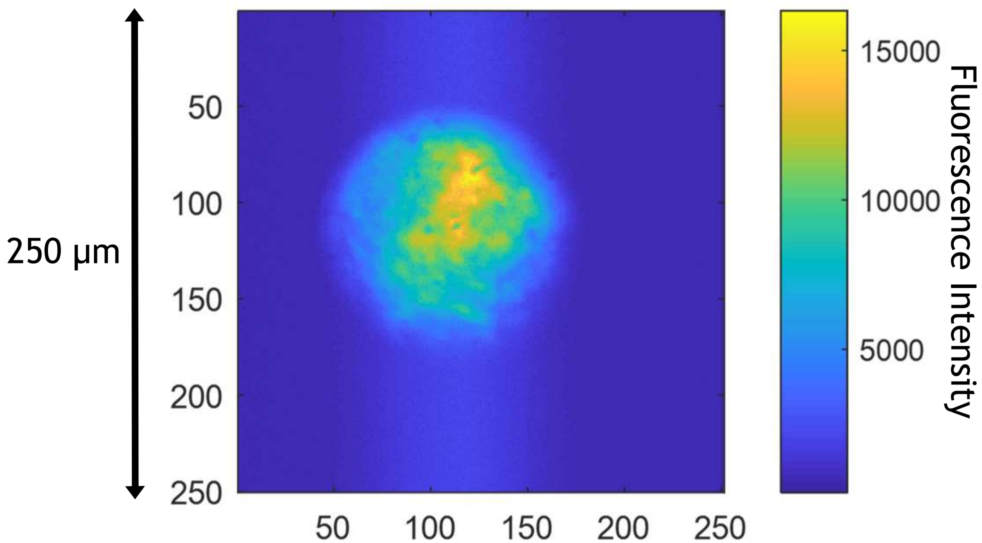
- Measured responsivity is 0.23 A/W

Outline

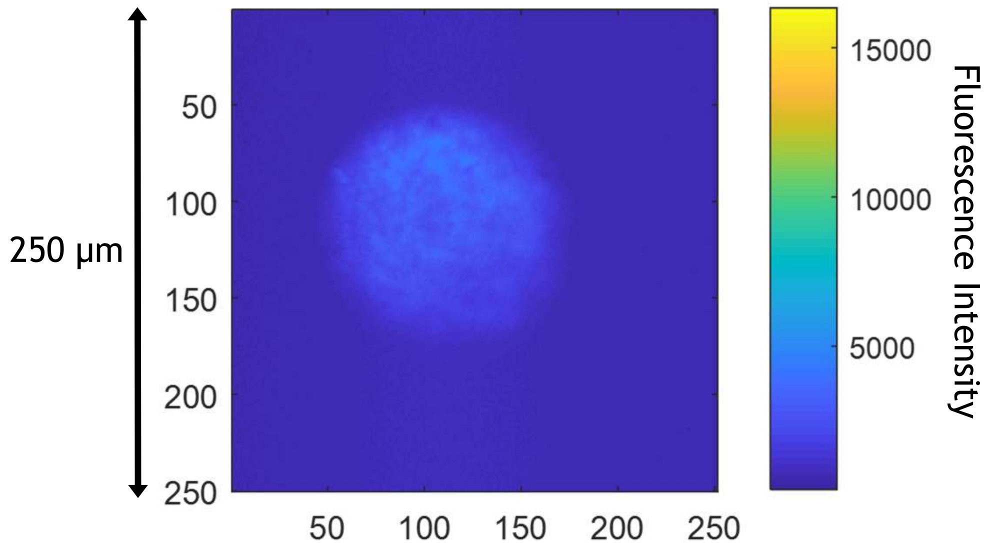
- Introduction
- CMOS Based Quantum Magnetometer
  - System Architecture
  - Microwave Signal Generation
  - Optical Excitation Filtering
  - Optical Fluorescence Readout
- Experimental Results
  - Measurement Results Using Layer of Nano-Diamonds
  - Measurement Results Using Bulk Diamond
- Conclusion

Passivation Layer Removal

- Background fluorescence is emitted from the passivation (silicon nitrite) layer
- Reactive ion etching (RIE) for passivation layer removal



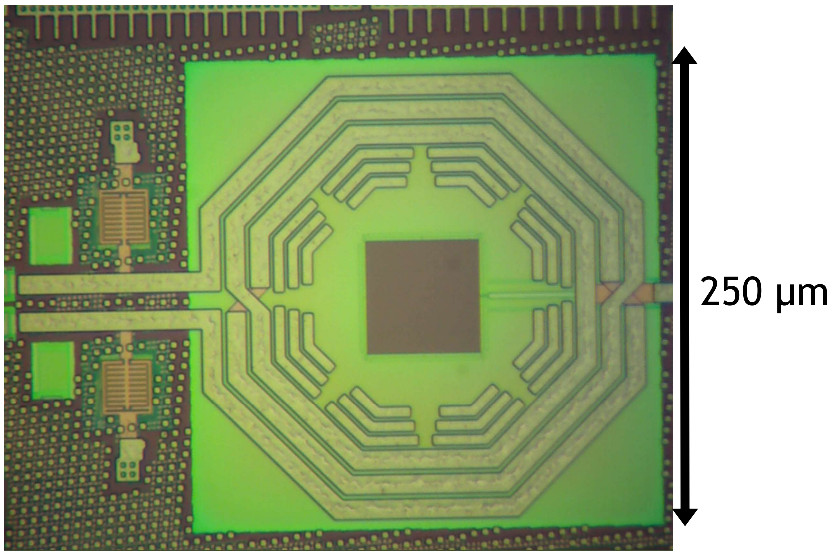
Before etching



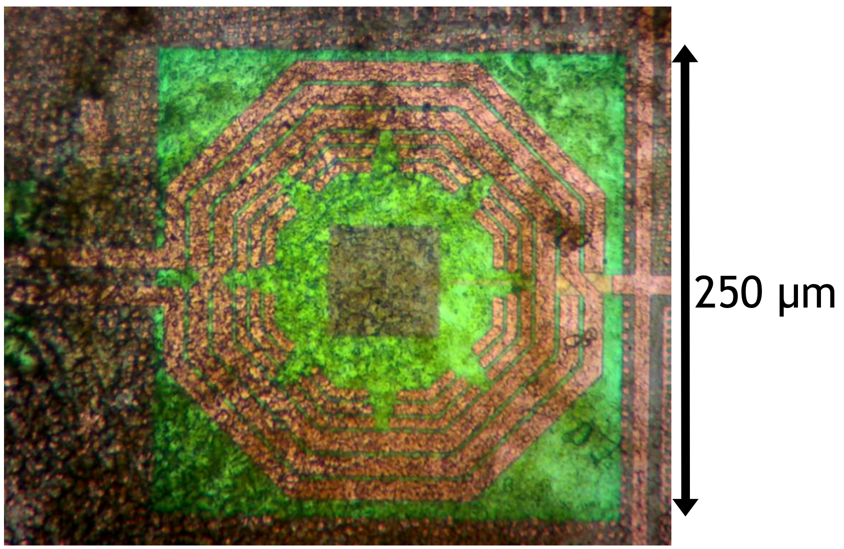
After etching

Nano-Diamonds Deposition

- Deposition of diamond nano-crystals solution

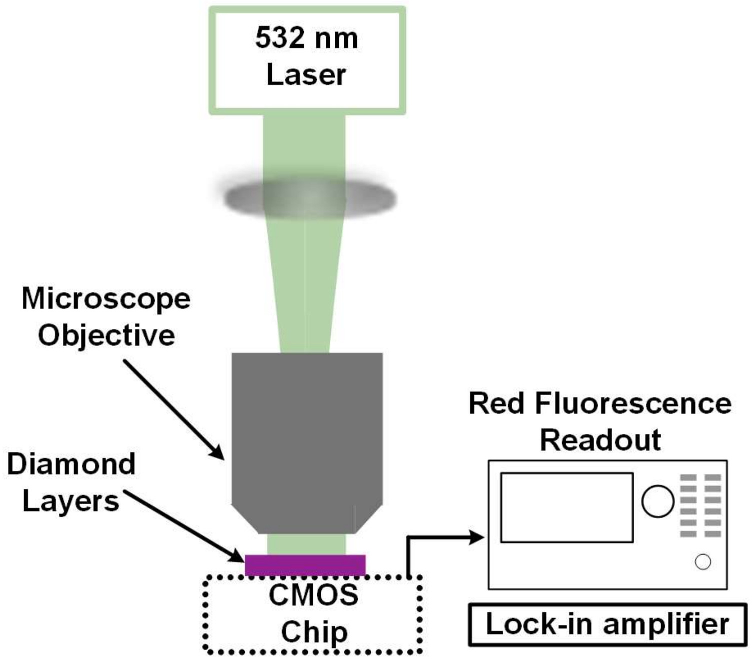


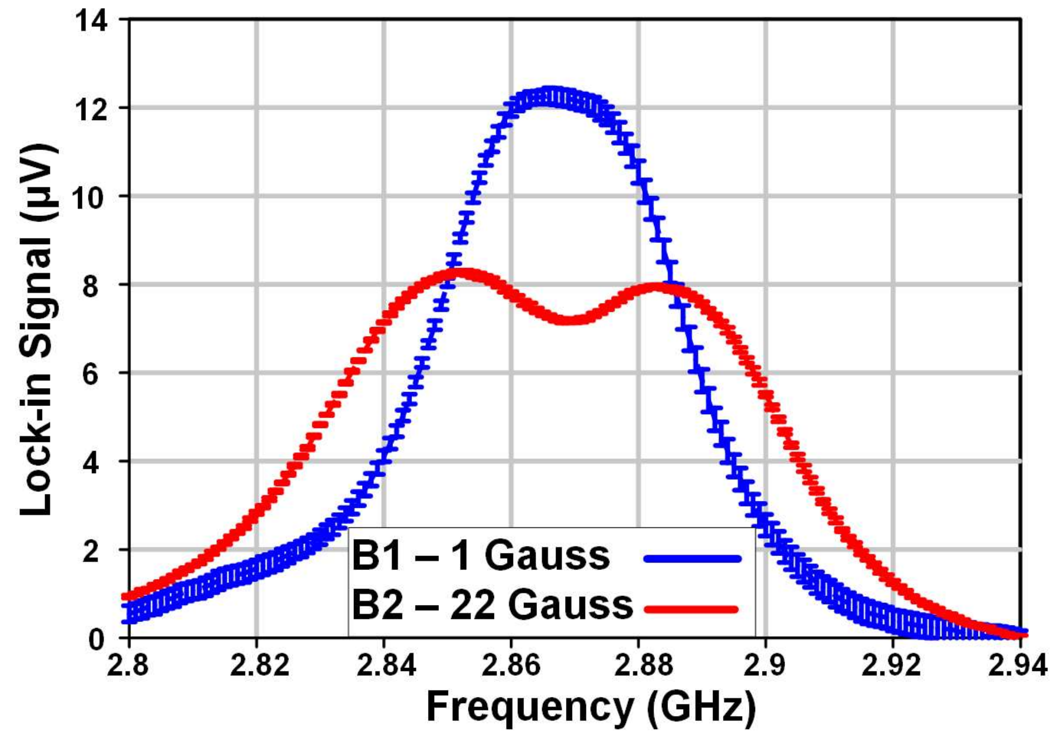
Before deposition



After deposition & evaporation

Nano-Diamonds Measurement Results

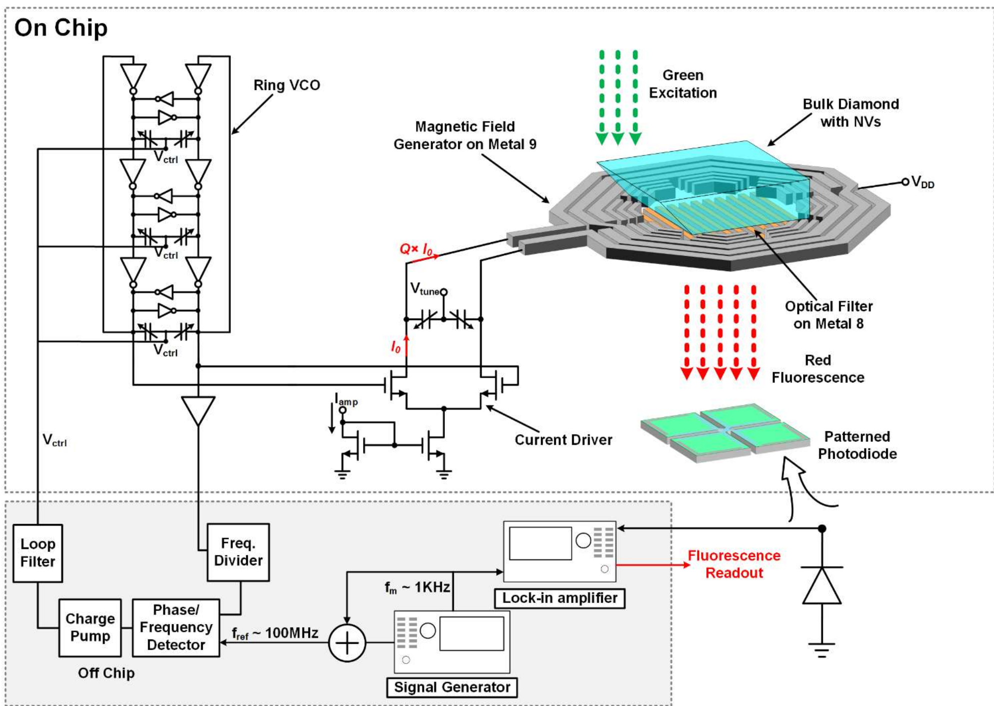


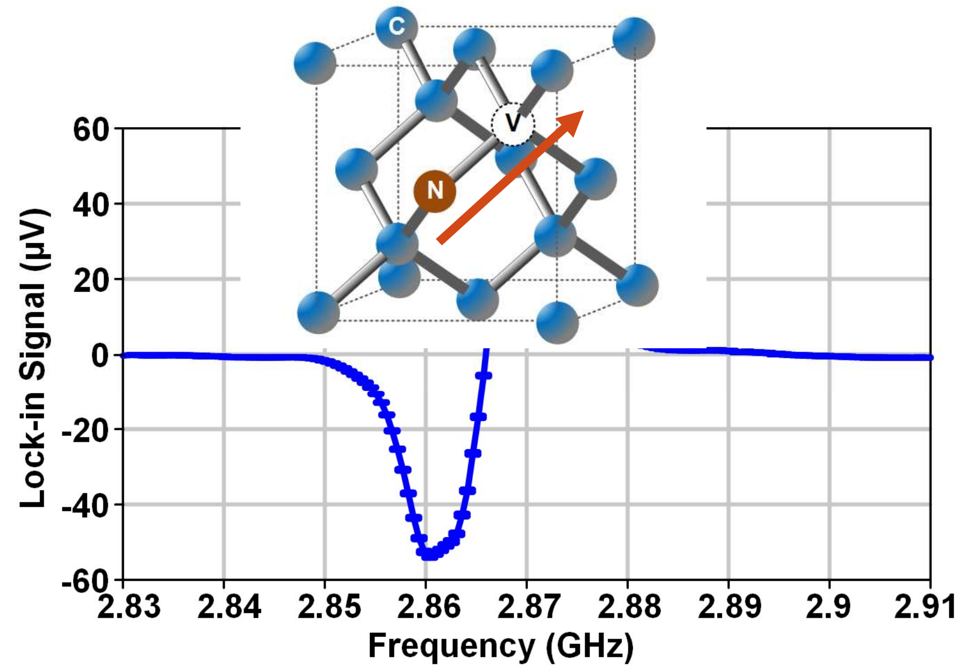


- **Sensitivity:** $\boldsymbol{\eta_{CW} = \frac{1}{\gamma}\frac{\sigma\Delta\nu}{C}\sqrt{t} = 74\mu T/\sqrt{Hz}}$

where $\gamma = \frac{g_e \mu_B}{h} = 2.8\ \text{MHz/Gauss}$, $\sigma \equiv \text{Std. dev.}$, $\Delta\nu \equiv \text{Linewidth}$, $C \equiv \text{Contrast}$, $t \equiv \text{Integration Time}$

Bulk Diamond Measurement Results

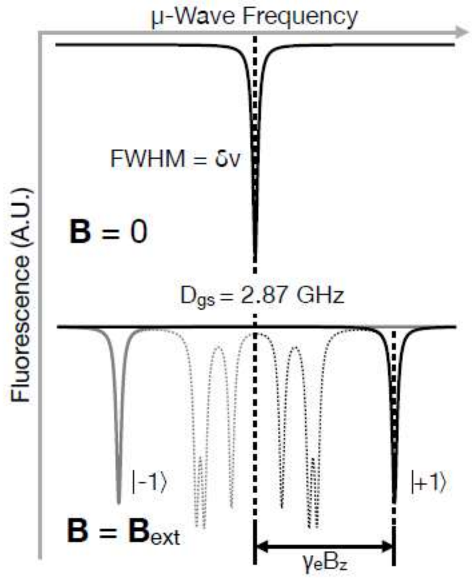


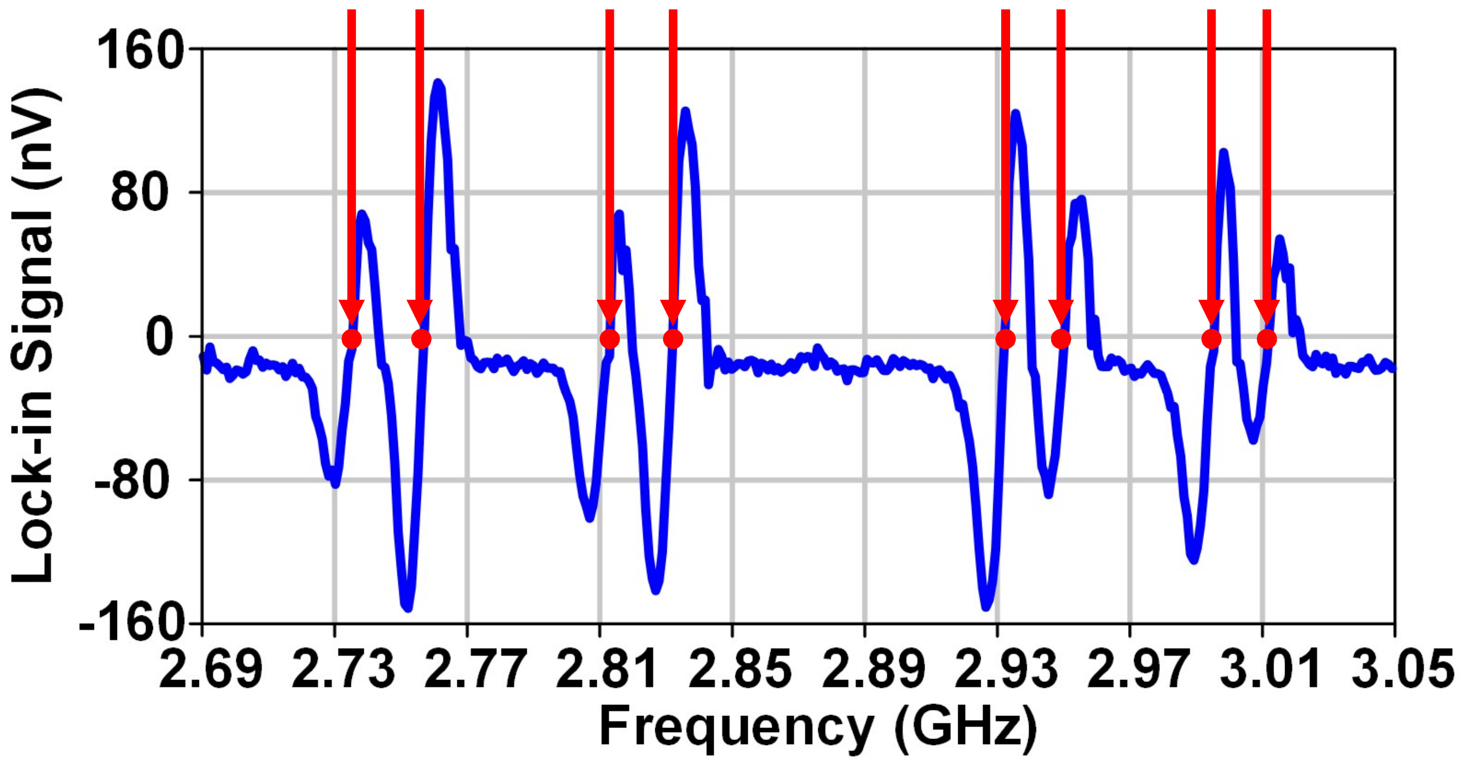


- **Sensitivity:** $\eta_{CW} = \frac{1}{\gamma}\frac{\sigma}{m}\sqrt{t} = 2.5\mu T/\sqrt{Hz}$

where $\gamma = \frac{g_e \mu_B}{h} = 2.8\ \mathrm{MHz/Gauss}$, $\sigma \equiv$ Std. dev., m $\equiv$ Slope of FM signal, t $\equiv$ Integration Time

Bulk Diamond Measurement Results





Outline

- Introduction
- CMOS Based Quantum Magnetometer
  - System Architecture
  - Microwave Signal Generation
  - Optical Excitation Filtering
  - Optical Fluorescence Readout
- Experimental Results
  - Measurement Results Using Layer of Nano-Diamonds
  - Measurement Results Using Bulk Diamond
- Conclusion

Performance Summary

	Technology	Vector meas.	Optical isolation	Sensing area	Form factor	Sensitivity
This work (Nano-diamonds)	65nm CMOS	No	10 dB	50 µm × 50 µm	~ 1 mm^3 **	73 $\frac{\mu T}{\sqrt{Hz}}$
This work (Bulk Diamond)	65nm CMOS	Yes	20 dB	50 µm × 50 µm	~ 1 mm^3 **	2.5 $\frac{\mu T}{\sqrt{Hz}}$
Nature physics (2015) *	Discrete devices	Yes	>60 dB	1 mm × 1mm	~ 1 m^3	0.29 $\frac{nT}{\sqrt{Hz}}$

*Clevenson, et al. Nature Physics 2015

** Does not include LASER

Conclusion

- Combines the advantages of CMOS and NV center in diamond in a small form factor
- Couples tightly the CMOS components with NV qubits
- Offers on-chip spin state readout
  - Easy integration of control logic
  - Less IOs
  - Closed-loop feedback between spin-manipulation and readout
- Enables compact and scalable advanced quantum systems.