National Aeronautics and Space Administration

Optically Pumped Solid State Quantum Magnetometers for Space Application

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Science Objectives

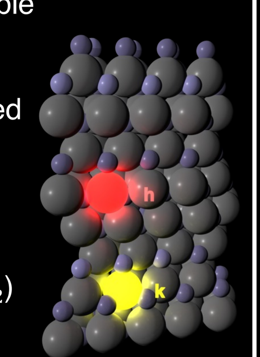
- detection of planetary and local magnetic fields
- information about existing, active or erstwhile geodynamos
- insights to inner structures
  - subsurface oceans
  - mining survey (ores)
- solar wind monitoring

scalar magnetometer (strength of field) & vector magnetometer (direction of field)

Quantum Centers in Solid State Systems

- diamond, silicon carbide (SiC) and hexagonal boron nitride (hBN) host a variety of optically accessible spin-active quantum centers
- comparable to trapped ions but instead of complex infrastructure the quantum centers are embedded in a crystal lattice
- excellent coherent properties at ambient conditions ("qubit at room temperature")
- promising system for quantum application: silicon vacancies (V_{Si}^-) in 4H SiC with spin quartet ($S=3/2$)

⇒ **widespread wafer-scale material with uniaxial quantum centers for a robust magnetometer**



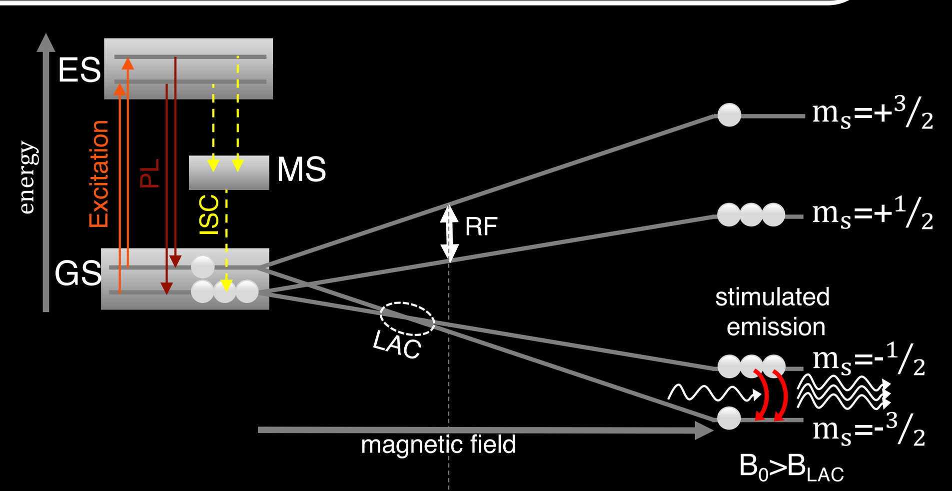
Advantages

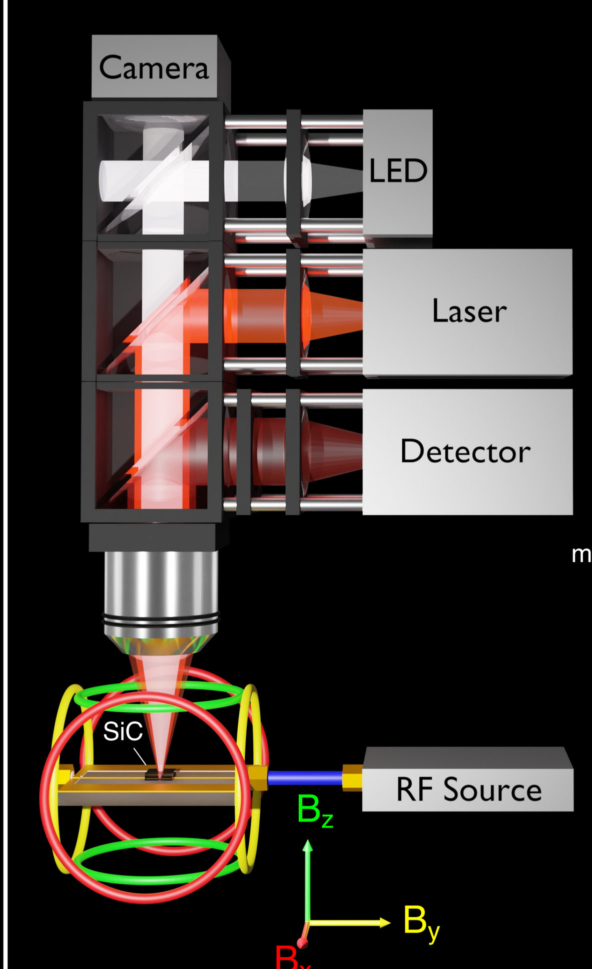
- ✓ extremely small (multiple sensors on spacecraft)
- ✓ rad-hard sensor
- ✓ lightweight
- ✓ optional self-calibration
- ✓ no gas leaking (⟷ optically pumped ^{4}He)
- ✓ only 1 coil per direction instead of 3 (⟷ fluxgate)

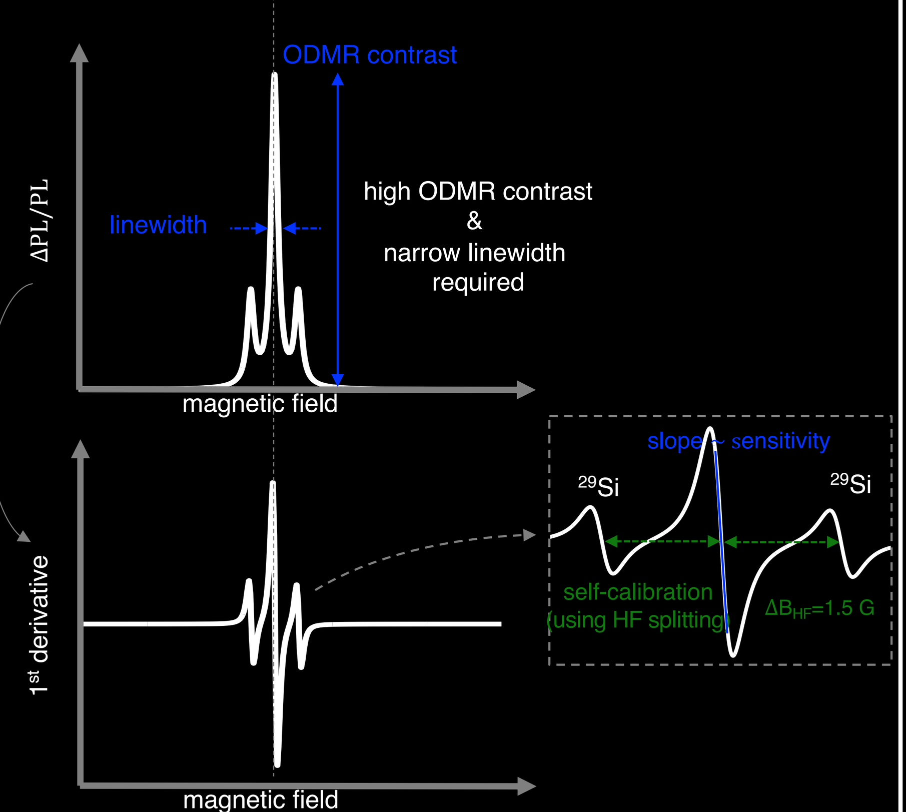
Optically Detected Magnetic Resonance

- optical spin polarization of V_{Si}^- in 4H SiC
- manipulation of spin state via radio frequencies
- readout via spin dependent photoluminescence

⇒ energy of spin state depends on magnetic field







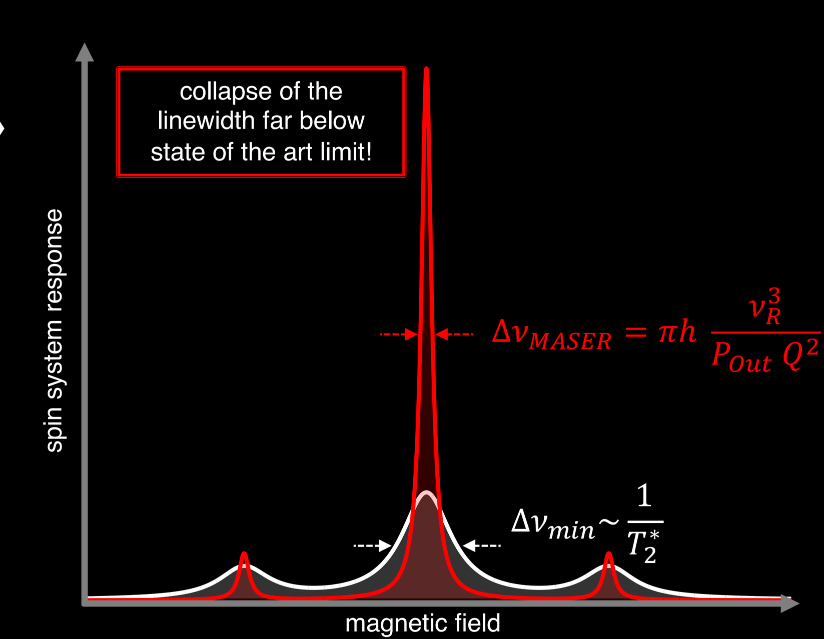
ODMR Device

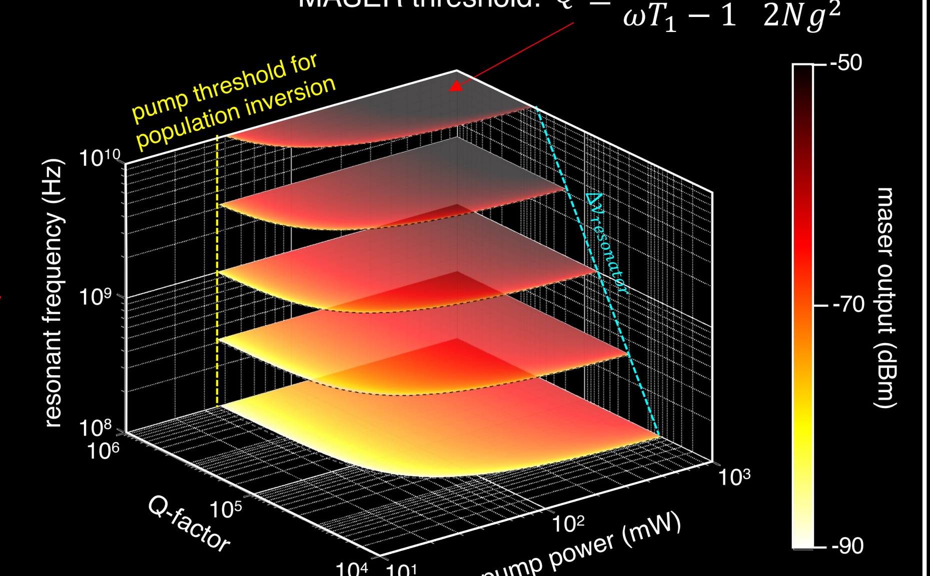
SiC based MASER

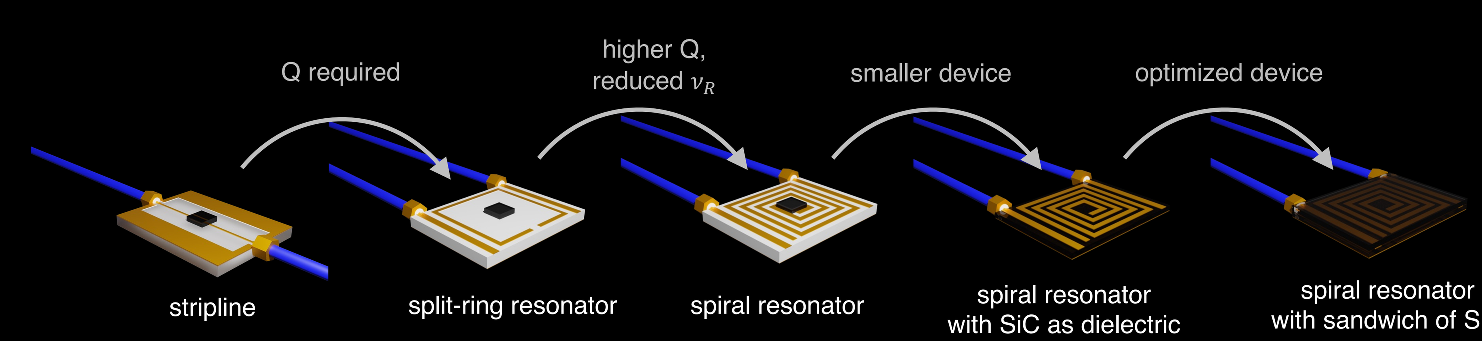
Microwave **A**mplification by **S**timulated **E**mission of **R**adiation:

- for V_{Si}^- in 4H SiC use stimulated emission of $m_s=-1/2 \leftrightarrow m_s=-3/2$ transition ($B_0>B_{LAC}$)
- place SiC into resonator with high Q-factor to reach masing regime

MASER threshold: $Q \overset{!}{\geq} \frac{\omega T_1 + 1}{\omega T_1 - 1} \frac{\pi \kappa_S \nu_R}{2Ng^2}$



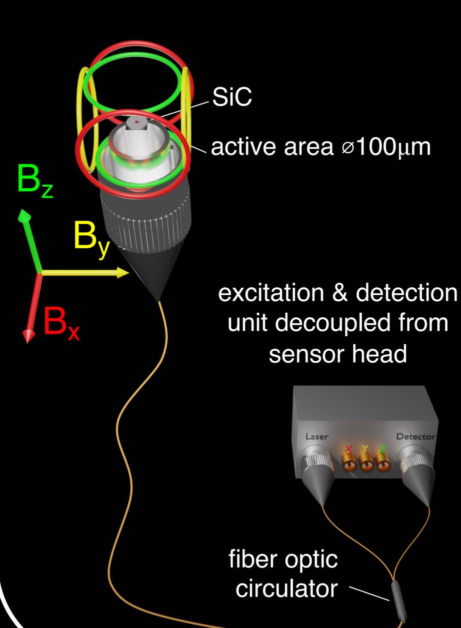


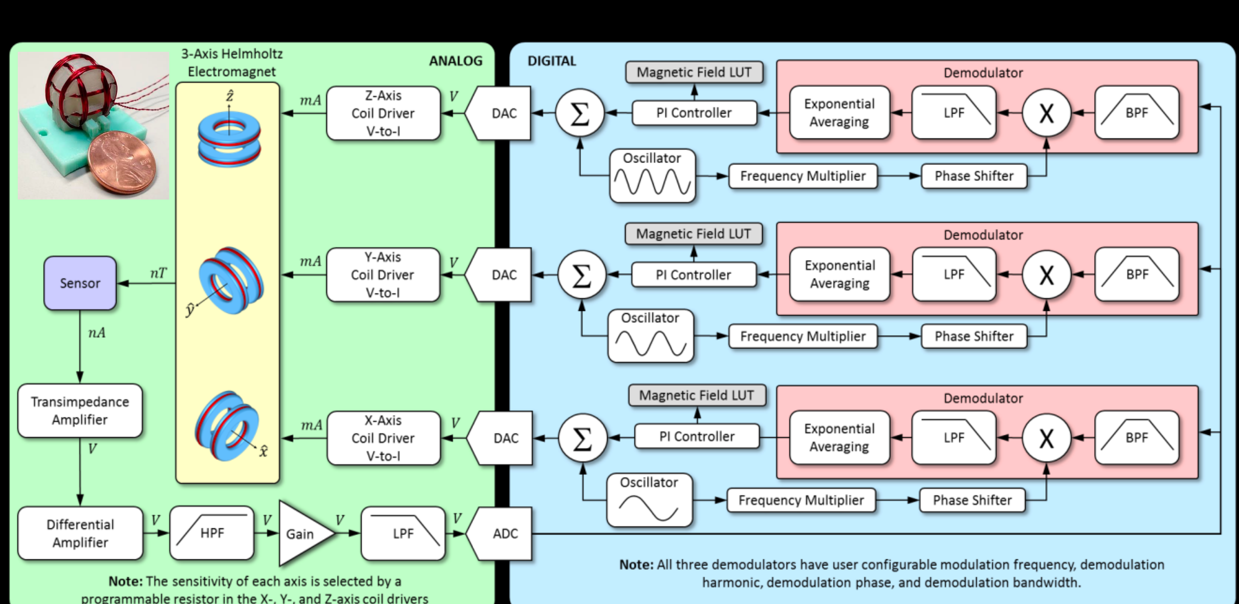


MASER Device

Miniaturized ODMR Magnetometer

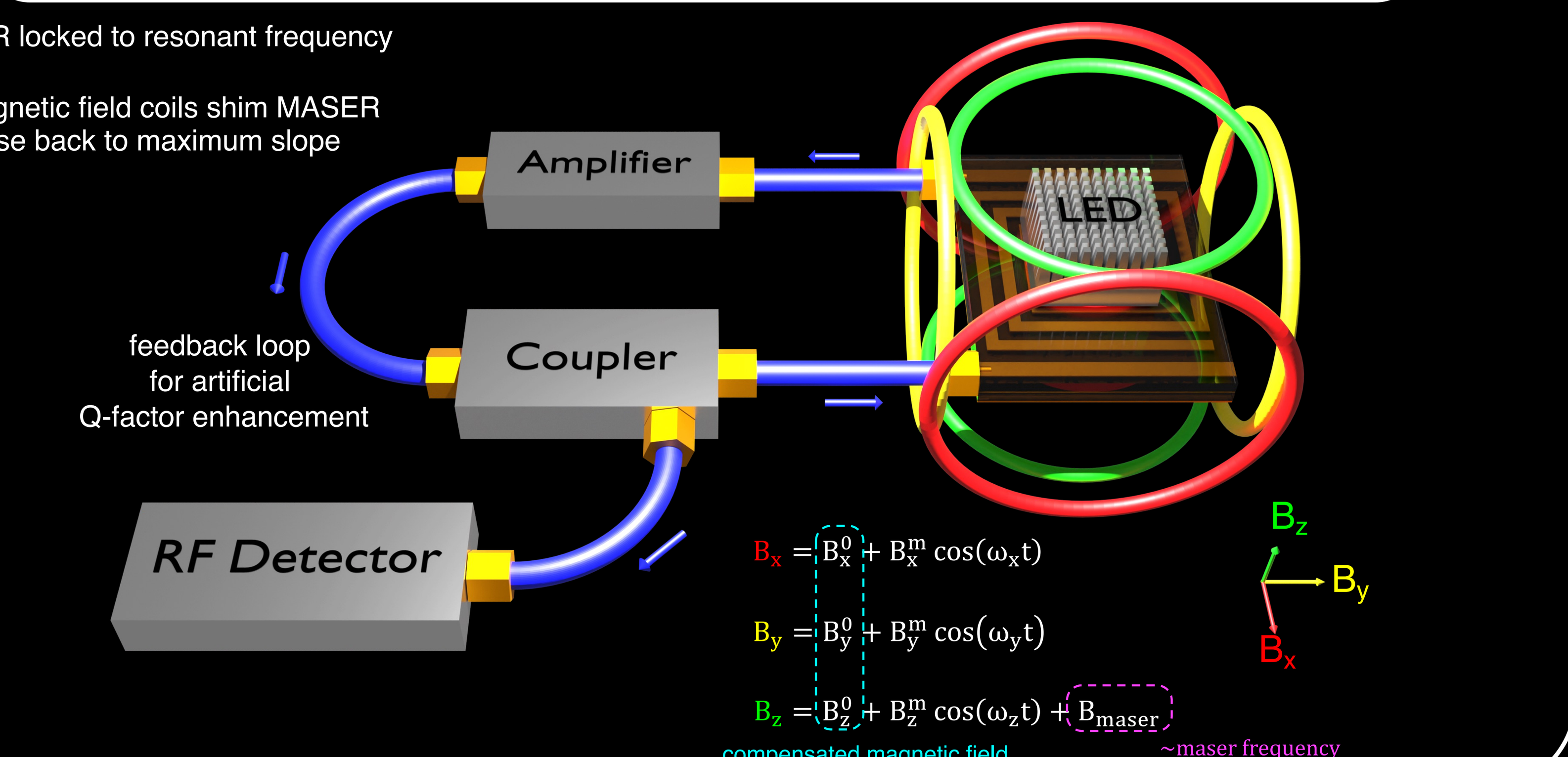
- attachment of SiC to end of a fiber and use optical circulator ⇒ small active area & simplified optics without adjustment
- compatible with heritage hardware (e.g. coil assembly and firmware) from SiC-MAG / Europa Clipper ICEMAG/ECM





MASER based Magnetometer

- MASER locked to resonant frequency
- 3D magnetic field coils shim MASER response back to maximum slope



Outlook: Seek the optimal Quantum System for Magnetometers

⇒ besides V_{Si}^- in 4H SiC: characterization of different quantum centers in other SiC polytypes but also in other materials to find the best system for magnetometer application

V_{Si}^- in 4H SiC	NV^- in diamond	V_B^- in hBN
✗ low ODMR contrast (≈ 0.1%)	✓ high ODMR contrast (≈10%)	✓ high ODMR contrast (≈10% with potential to >50%)
✓ narrow peaks	✓ narrow peaks	✗ broad peaks
✓ simple spectrum with only one defect orientation ($\vec{c}$-axis)	✗ complex spectrum due to different defect orientations	✓ simple spectrum with only one defect orientation ($\vec{c}$-axis)
✓ low frequencies required (70MHz)	✗ high frequencies required (2.9 GHz)	✗ high frequencies required (3.5GHz)

there is no perfect system, each has its advantages & disadvantages

⇓

study all of them to learn from each unique feature

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Publications:

H. Kraus et al. *Magnetic Field and Temperature Sensing with Atomic-Scale Spin Defects in Silicon Carbide* Sci. Rep. 4, 5303 (2014)

C. Cochrane et al. *Vectorized Magnetometer for Space Applications* Sci. Rep. 6, 37077 (2016)

A. Gottscholl et al. *Superradiance of Spin Defects in Silicon Carbide for Maser Applications* Front. Photon. 3, 886354 (2022)

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