

# Integration architecture for a pocket-sized quantum vector magnetometer using spin defects in silicon carbide

Andreas Gottscholl,<sup>\*</sup> Corey J. Cochrane<sup>✉</sup>, and Hannes Kraus<sup>✉<sup>†</sup></sup>

*NASA Jet Propulsion Laboratory, California Institute of Technology,  
4800 Oak Grove Drive, Pasadena, California 91104, USA*



(Received 9 December 2025; revised 30 June 2026; accepted 21 July 2026; published 22 September 2026)

We present a miniaturized, modular vector magnetometer based on silicon vacancy ( $V_{Si}^-$ ) centers in 4H-SiC. While N-V-diamond magnetometers can offer high sensitivity, spacecraft integration is often complicated by their requirement for disruptive, mT-scale bias fields. Our silicon carbide (SiC) architecture instead enables a net-zero dc magnetic footprint suitable for magnetically clean payloads, in an integrated demonstrator with a credit-card-scale footprint and a total mass of 185 g. A transmission-geometry SiC-GaAs wafer stack with quartz-rod coupling enables efficient photoluminescence collection while suppressing residual pump light. Resonant rf excitation near 70 MHz is provided by a detuned commercial-off-the-shelf (COTS) NFC coil with tunable capacitance and impedance matching. Modulating the spin energy levels in all three orientations using orthogonal Helmholtz coil pairs enables spin-dependent photoluminescence detection and confirms vector operation. The fully integrated instrument achieves a sensitivity of  $4 \mu\text{T}/\sqrt{\text{Hz}}$ . A detailed noise budget attributes the performance gap primarily to a 225-fold reduction in optically detected magnetic resonance (ODMR) contrast (1.8% to 0.008%) caused by the poor rf  $B_1$  filling factor of the unoptimized COTS coil. With benchtop laser and readout systems, the instrument head reaches  $1 \mu\text{T}/\sqrt{\text{Hz}}$ , identifying laser and electronic-driver noise as the dominant remaining instrument-level contribution. The modular architecture enables independent subsystem optimization and provides a roadmap toward the single-digit nT/ $\sqrt{\text{Hz}}$  benchtop limit.

DOI: [10.1103/51zn-q6t6](https://doi.org/10.1103/51zn-q6t6)

## I. INTRODUCTION

Magnetometers have number of applications in science and engineering [1,2]. Applications include space weather analysis, heliophysics, probing planetary interiors, and GPS-denied guidance, navigation and control (GN&C). [3–5]. In planetary science, magnetometers probe the interior of planets and moons, e.g., leading to the discovery of subsurface oceans within icy worlds [6,7]. These applications require the use of high-sensitivity magnetometers in the  $< \text{nT}/\sqrt{\text{Hz}}$  range. Recent analyses have shown that a higher number of small and inexpensive, but less sensitive, magnetometers could augment full science-grade instruments by characterizing and real-time canceling the spacecraft distortion field [8,9].

In GN&C, inertial measurement units are critical for autonomous navigation in GPS-denied environments but

are fundamentally limited by their tendency to accumulate drift over time, leading to position errors [10]. To address this, magnetometers can be paired with detailed magnetic anomaly maps to recalibrate position estimates and mitigate these drift errors [11]. Leading technologies like SQUIDS (superconducting quantum-interference device) and OPMs (optically pumped Magnetometer), while offering high performance, have practical challenges such as requiring gas cells or specific cryogenic refrigeration requirements, making them unsuitable for compact and mobile navigation systems [12].

Spin-defect-based magnetometers offer an attractive alternative due to their high sensitivity and room-temperature operation. Among these, the nitrogen-vacancy (N-V) center in diamond has demonstrated record sensitivities in the  $\text{pT}/\sqrt{\text{Hz}}$  range [13]. This remarkable performance comes at the price of anisotropy of the field response due to crystallographic orientation and strain [14], necessitating deconvolving bias fields in the mT range, even larger than Earth's  $\approx 30\text{--}50 \mu\text{T}$  field.

A multiple-sensor gradiometry system for the aforementioned distortion field cancellation would suffer from a large number of sensors emitting mT-range bias fields, as would the magnetic cleanliness required for other sensitive

<sup>\*</sup>Contact author: [gottscholl.andreas@gmail.com](mailto:gottscholl.andreas@gmail.com)

<sup>†</sup>Contact author: [hannes.kraus@jpl.nasa.gov](mailto:hannes.kraus@jpl.nasa.gov)

*Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.*

payloads. As more magnetic sources are added to a spacecraft, especially ones positioned close to the magnetometer sensors, the inferred magnetic model becomes increasingly complex due to the higher number of parameters required to accurately model the field using an appropriate multipolar expansion [8]. Recent magnetic testing associated with NASA's Europa Clipper mission revealed that a suite of sixteen 3-axis magnetometers (yielding 48 independent measurements) positioned in the near-field of a mock-up spacecraft consisting of six calibrated coils representing offset-dipole sources was sufficient to accurately recover the spacecraft magnetic moment to within 3% [15].

There are some approaches to mitigate the bias field challenge, such as isolating specific spin responses with circular rf polarization [16] or rapidly alternating bias fields yielding an effective zero field [17].

Rather than engineering complex workarounds for inherent defect anisotropy, our architectural path employs the silicon vacancy ( $V_{Si}^-$ ) in silicon carbide (SiC), an alternative defect systems that inherently lack an off-axis zero-field splitting component, thus bypassing the bias field requirement entirely [18–20].

Unlike the N-V center, the ( $V_{Si}^-$ ) features a single orientation and no  $E$ -value, yielding a simpler energy structure and a truly linear Zeeman response at low magnetic fields and at room temperature [21,22]. It also lends itself to well-controlled quantum center implantation through electron or ion irradiation [23,24]. Despite these advantages,  $V_{Si}^-$  centers face challenges such as low photoluminescence yield, reduced optically detected magnetic resonance (ODMR) contrast, and broad linewidths, all of which limit sensitivity. Nevertheless, the ground state  $V_{Si}^-$  resonances exhibit remarkable thermal stability, shifting only in response to magnetic fields rather than temperature fluctuations [19,25]. For comparison, N-V centers typically require stringent thermal stabilization (sub-mK) to maintain 1 nT sensitivity, due to their  $-74$  kHz/K temperature dependence [26].

Recent progress in SiC material engineering has begun to overcome many of its limitations. Advances such as optimized thermal treatments (e.g., quenching) and isotopic purification have demonstrated order-of-magnitude improvements in ODMR contrast and linewidth reduction by up to two orders of magnitude [27,28]. Furthermore, SiC offers advantages in terms of fabrication scalability, defect engineering, and compatibility with semiconductor industry processes. Laboratory-scale demonstrations have already achieved sensitivities in the single-digit nT/ $\sqrt{\text{Hz}}$  range using commercially available SiC, even without advanced material optimization [22,29]. These developments suggest that SiC-based spin-defect magnetometers are approaching practical viability; however, miniaturization of this technology has proven challenging, with first steps in the literature showing 12300 nT/ $\sqrt{\text{Hz}}$  performance metrics [30].

In this work, we present the first miniaturized vector magnetometer modular architecture based on SiC spin defects, with a footprint of 86 mm  $\times$  54 mm, comparable to that of a credit card. This instrument prototype is mostly made out of commercial off-the-shelf (COTS) and 3D-printed parts, in an attempt to minimize the utilization of expensive, specialized engineering.

While the demonstrated sensitivity falls significantly short of the 1 nT/ $\sqrt{\text{Hz}}$  target required for operational GPS-denied navigation or planetary science targets, the system serves as a proof-of-concept and a modular engineering blueprint for modular, scalable magnetometer design. It shows that integrated sensors suffer from sensitivity penalties, but improves upon previous state-of-the-art of integrated SiC magnetometers [30], inching closer to benchtop performance metrics. The modularity of our approach enables independent optimization of individual subsystems, paving the way toward future performance improvements. In the following sections, we describe the operational principles of the device, its design architecture, and the integration of its key subcomponents. We also delineate differences from our benchtop system—yielding a sensitivity of 6 nT/ $\sqrt{\text{Hz}}$  and identify, module-by-module, reasons for performance reduction in the integrated systems and corresponding mitigation plans.

## II. OVERVIEW OF THE MAGNETOMETER

The heart of the magnetometer presented here is the quantum center hosting semiconductor SiC. After electron irradiation of a commercial wafer, negatively charged silicon vacancies ( $V_{Si}^-$ ) are created that can be addressed and read out optically. Figure 1(a) shows a simplified model of the quantum centers' energetic structure and relaxation paths (energy gaps not to scale). The optical cycle begins with laser excitation at 830 nm, promoting electrons from the ground state (GS) to an excited state (ES). The relaxation pathways include both radiative photoluminescence (PL) and nonradiative decay through a metastable state (MS) via intersystem crossing (ISC). Crucially, the ISC rate is spin-dependent, resulting in preferential population of specific ground-state spin sub-levels and enabling spin polarization. The resulting PL intensity thus encodes information about the spin-state population. To probe the spin states, a radio frequency (rf) field is applied in resonance with the ground-state spin transitions between the  $|m_s| = 3/2$  and  $|m_s| = 1/2$  levels. When the rf frequency matches the spin resonance condition, the equilibrium spin population is perturbed, producing a measurable change in PL intensity, also referred to as ODMR. A magnetic field in any orientation will detune the energy levels and thus push the system out of resonance with the rf  $B_1$  field, observable in a modulation of the PL. A simulation of the energy levels using EasySpin [31,32] is shown below with an approximation

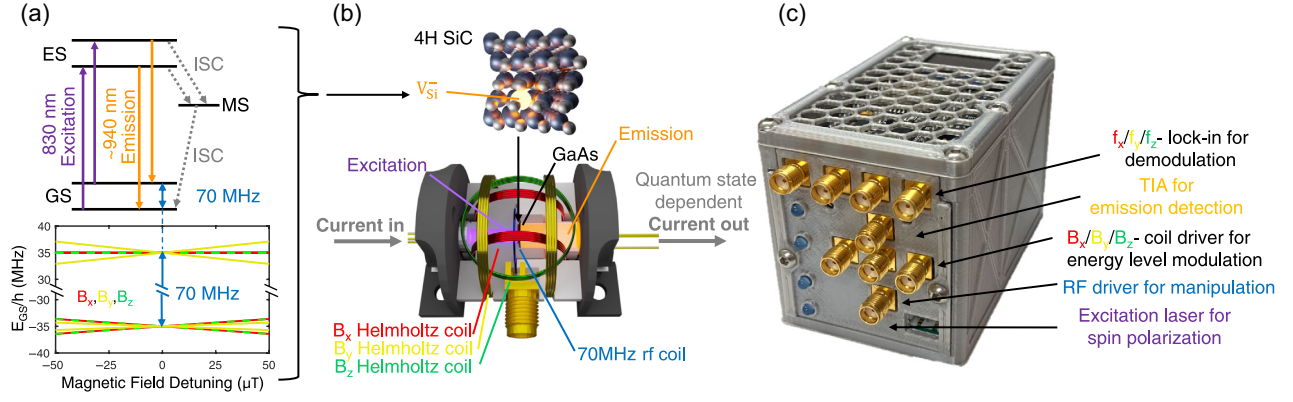


FIG. 1. Overview of the compact magnetometer. (a) Energy diagram of the quantum center ( $V_{Si}^-$  in SiC) with the pump scheme on the top and the simulated magnetic field dependency in the bottom. (b) Transmission geometry of the magnetometer. (c) Photo of the entire magnetometer in drawer configuration with each PCBA representing a subsystem.

linear shifts for small detuning within  $\pm 50 \mu\text{T}$  (crystal axis in  $y$ -direction). The optically readout of these states typically requires sophisticated optics (lenses, mirrors, fibers, dichroic mirrors) mounted on a square-meter-sized optical table. Here, we created a new design to accommodate compact packaging, resulting in a transmission geometry with excitation source, sample, and detector placed in line and locked against each other avoiding mirrors and adjustment. The CAD model with a half-open Helmholtz-coil system is shown in subpanel of Fig. 1(b). This configuration allows a very simple current-in (laser), current-out (photo-current of detector) approach with the quantum state information being encoded in the intensity of the photocurrent. The required rf and magnetic fields for manipulating the quantum state are realized by seven coils:  $1 \times \text{rf}$  (blue),  $2 \times B_x$  (red),  $2 \times B_y$  (yellow), and  $2 \times B_z$  (green). Details regarding the optics and the homogeneity of the coils will be discussed in each of the sections of the subsystems. A photograph of the entire magnetometer including its driver electronics is shown in Fig. 1 subpanel (c). The complete system weighs 185 g (including the sensor head with quartz rod, excitation and detection at 22 g) and has the footprint of a credit card ( $86 \text{ mm} \times 54 \text{ mm}$ ) with a height of  $\approx 60 \text{ mm}$ . The height primarily arises from the modular architecture of the device, which is designed as a stackable “drawer” system: individual printed circuit board assemblies (PCBAs) can be pulled out, modified, and replaced independently. This modularity enables iterative optimization of subsystems without redesigning the entire instrument. Once the optimal circuitry and components are identified for achieving the target sensitivity, the separate PCBAs can be integrated into a single compact board, significantly reducing the device volume.

The prototype magnetometer operates as a fully self-contained unit, powered by 5 and 12 V supply lines. Measurement results can be displayed locally on a 0.96” display, allowing standalone operation without additional

readout electronics, although we used external components (see below) to characterize the subsystems in detail and deal with the large amounts of data. For this reason, a set of external SMA connectors provides direct access to individual subsystems for characterization, calibration, and performance benchmarking, thereby facilitating a systematic evaluation of their contributions to overall sensitivity.

In the following sections, we describe each subsystem of the magnetometer in detail. For each component, we discuss the design considerations, operational parameters, and their influence on the overall sensitivity of the device.

### A. Optical excitation and readout

Excitation and readout of the spin-dependent photoluminescence are performed in a transmission geometry. The most compact implementation would place the pump source (laser), SiC sample, and detector in a direct vertical stack. However, during initial tests we observed that the magnetic field modulation coils (discussed in a later section) induced parasitic currents in the photodetector, producing unwanted background signals. To mitigate this effect, we spatially separated both the laser and detector from the sample. An alternative is to employ a tandem demodulation technique, which separates these parasitic currents as demonstrated for electrically detected magnetic resonance (EDMR) [33].

To achieve stable optical alignment in a compact form factor, two polished quartz rods were positioned on either side of the sample. These rods act as optical waveguides, ensuring efficient collection of the photoluminescence (PL) while simultaneously providing mechanical stability by locking the sample in place. Due to the total internal reflection angle of  $43.3^\circ$  between quartz and air, a fraction of  $\approx 13\%$  (see Fig. 6 in Appendix B) of the PL could already be captured. This provides sufficient photon collection efficiency while eliminating the need for additional optics.

A challenge specific to this fiber-based approach is the random propagation angle of transmitted laser photons. Conventional long-pass filters, which rely on orthogonal incident light, are therefore unsuitable. To address this, we developed a novel filtering approach: the SiC wafer is stacked directly onto a gallium arsenide (GaAs) wafer, which has an absorption edge at approximately 873 nm, corresponding to its 1.42 eV band gap. This configuration ensures strong absorption of the residual 830 nm pump light, while transmitting the longer-wavelength  $V_{\text{Si}}^-$  emission encoding the spin-state response.

The silicon photo diode used for detection provides an integrated current signal, proportional to the total incoming light intensity, without spectral discrimination. Consequently, it cannot directly distinguish between residual laser photons and spin-dependent PL. Leveraging the modularity of the system, we performed verification measurements by replacing the detector module with a spectrometer (see methods). The resulting wavelength-resolved spectrum is shown in Fig. 2. The characteristic  $V_{\text{Si}}^-$  emission (orange) is clearly observed, and no 830 nm laser line is present, confirming the filtering efficacy of the SiC-GaAs stack in transmission geometry. A small residual background (purple) remains, originating from the finite linewidth of the pump laser.

This leakage is only significant when the  $V_{\text{Si}}^-$  emission is weak, as illustrated in the brown and red curves of Fig. 2(b). By increasing the defect density, the integrated PL signal increases accordingly. The  $V_{\text{Si}}^-$  density was calibrated using electron paramagnetic resonance (EPR), and we systematically measured the integrated PL across more than two orders of magnitude in density. The results, plotted in the inset of Fig. 2(b), show that densities below  $1 \times 10^{14} \text{ cm}^{-3}$  are unusable due to insufficient signal, whereas densities approaching  $10^{18}/\text{cm}^3$  yield signals

approximately  $20\times$  above the noise floor. At this density, the residual laser leakage reduces sensitivity by less than 5%. Future improvements could target reduction of laser leakage through the use of pump lasers with narrower linewidths or shorter excitation wavelengths that are further removed from the  $V_{\text{Si}}^-$  emission band. Increasing defect density will also improve the PL-to-background ratio, although this is fundamentally limited by self-absorption effects, as indicated by the sublinear scaling exponent ( $n < 1$ ) in the power law fit of integrated PL versus density. Achieving ratios of 100 (corresponding to only  $\approx 1\%$  sensitivity reduction) would require significantly higher densities, which are not technically feasible due to cumulative lattice damage during prolonged electron irradiation.

An alternative strategy is to employ multilayer SiC structures to increase the effective number of  $V_{\text{Si}}^-$  centers. However, preliminary experiments (not shown) revealed a reduction in PL efficiency due to poor optical coupling in extended SiC crystals. Considering the scope of this work, which is focused primarily on demonstrating the modular geometry, we accept the  $\approx 5\%$  sensitivity reduction caused by residual laser leakage. In the following section, we turn to the methods used for spin-state manipulation.

## B. Resonant spin manipulation via rf

To render the spin system (and therefore the spin-dependent photoluminescence) sensitive to external magnetic fields, radio frequencies resonant with the zero-field spin transition must be applied. As described previously, resonant excitation perturbs the spin equilibrium and generates a brighter PL signal. Any relative change in brightness encodes detuning of the energy levels caused by external magnetic fields.

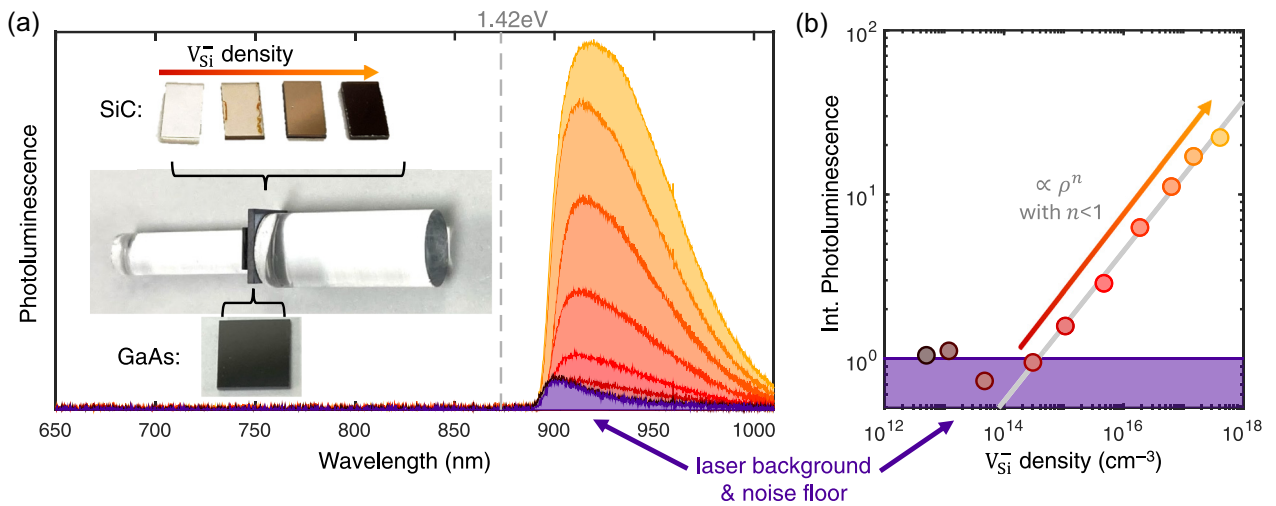


FIG. 2. Optimization of the quantum centers' emission. (a) Photoluminescence spectra of various SiC wafer with different quantum center density with GaAs as long-pass filter. (b) Integrated PL from subpanel (a) showing a monotonic but sublinear increase due to self-absorption.

In conventional ODMR experiments, microstriplines are commonly used for inducing spin flips with rf, providing a broadband response across a swept frequency range. This approach is well suited for confocal microscopy, where only a micrometer-scale voxel is excited. In our case, however, the excitation volume extends to the millimeter-scale, making the microstripline approach impractical due to strong spatial inhomogeneities of the rf magnetic field ( $B_1$ ). Since we require uniform excitation over a large volume but only at a single frequency (the zero-field resonance near 70 MHz), a frequency-independent broadband design is unnecessary.

After evaluating several geometries, we selected a commercial NFC coil (see methods for details) with a radius large enough to ensure  $B_1$  uniformity across the excitation region. This choice also offers the advantage of reproducibility and scalability: identical, cheap COTS coils can be used across multiple prototypes, ensuring comparable rf performance for different magnetometer configurations. Being a near-field-communication COTS parts, the coil's nominal operating frequency (13.56 MHz) is far from the 70 MHz spin resonance. This was compensated by integrating a tunable capacitor to adjust the resonant frequency [see Fig. 3(a)]. Additional impedance-matching circuitry was included to maintain a 50  $\Omega$  load.

Sweeping the rf frequency around resonance revealed ODMR-like spectra even for arbitrary capacitor values (green curve, Fig. 3). The strongest ODMR contrast, corresponding to the expected ground-state transition at 70 MHz, was observed when the resonator was tuned close to resonance. By varying the capacitor, we could further resolve hyperfine features near the expected positions. Interestingly, we found that even when the resonator was significantly detuned, off-resonant driving still produced

measurable ODMR contrast in  $V_{Si}^-$ . This allowed us to tune the resonator without relying on an external vector network analyzer: the spin system itself can serve as the tuning reference, simply by monitoring the ODMR contrast at 70 MHz [see Fig. 3 subpanel (b)].

In the current prototype, the tuning capacitor must be adjusted manually. For future designs, replacing it with a voltage-controlled capacitor would allow for automatic compensation of temperature-dependent drifts in the resonator. Since the ground-state splitting of  $V_{Si}^-$  is intrinsically temperature-independent, maintaining the rf frequency at 70 MHz is sufficient once tuning is achieved.

The measured resonator linewidth is approximately 2.8 MHz [see inset, Fig. 3(c)], well within the intrinsic linewidth of the spin transition at practical rf powers. This opens the possibility of implementing automatic frequency control (AFC) schemes similar to those used in EPR, by applying small frequency modulations ( $\Delta f < \text{linewidth}$ ) around 70 MHz, either at frequencies much higher or much lower than the magnetic modulation frequency. Such an approach would enable closed-loop stabilization of the resonator without manual adjustment.

To investigate the effect of rf power on the ODMR response, we recorded spectra for input powers between approximately 20  $\mu\text{W}$  and 200 mW [see Fig. 3 subpanel (e)]. The extracted signal amplitude follows the expected  $C \propto B_1 \propto \sqrt{P_{\text{rf}}}$ .

### C. Magnetic field modulation and vector mode

While the current device already enables scalar magnetic field measurements by projecting onto the defect axis of the  $V_{Si}^-$  centers, our goal is to extend the system into a true vector magnetometer. As outlined previously,

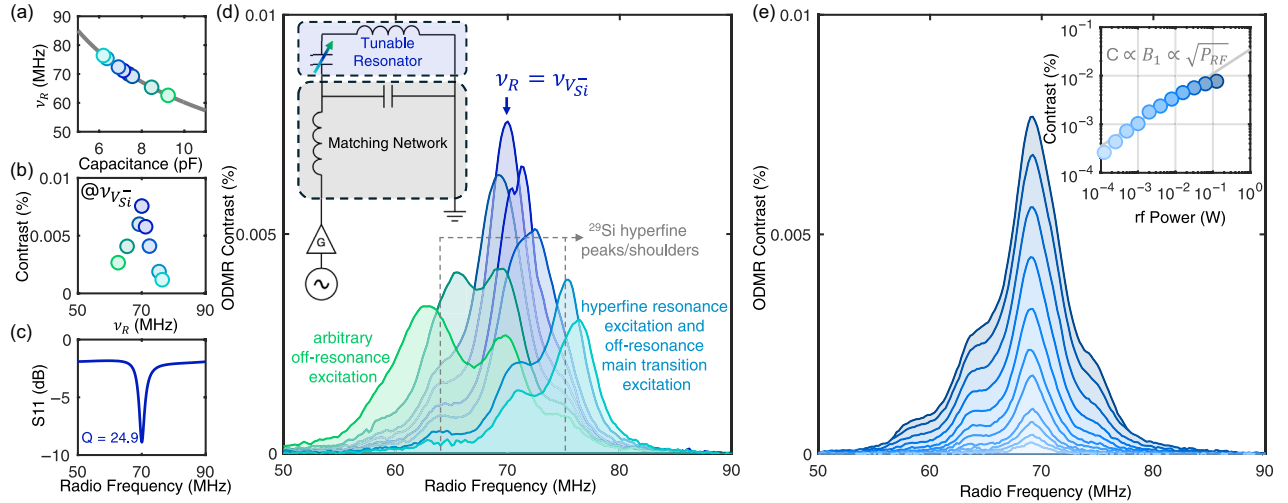


FIG. 3. Radio frequency (rf) manipulation of the quantum state. (a) Resonance frequency of the tunable resonator for various capacitor values. (b) ODMR contrast at spin transition for various resonator frequencies. (c)  $Q$ -factor measurement of in resonance condition. (d) Various ODMR spectra for resonator tuning. (e) Power dependence of ODMR spectra. Inset indicates that the system is only barely saturating.

detuning of the spin resonance by an external magnetic field reduces the PL intensity as the system is driven out of resonance. By applying a sinusoidal magnetic field modulation, the derivative of the ODMR signal can be obtained—analogueous to EPR—yielding a linear response in the vicinity of the resonance condition right at the zero crossing. This provides a direct conversion from magnetic field variation to output voltage using simply the demodulated photodetector output [32].

By applying independent modulation frequencies along three orthogonal axes, the contributions from each orientation can be frequency division multiplexed, enabling full vector reconstruction of the external magnetic field. The method is valid as long as the measured field remains within the linear Zeeman regime [32]. For larger external fields, cancellation techniques can be used to restore operation, although in this work we focus on achieving a magnetometer design with zero net dc magnetic footprint—a requirement for operation in magnetically noisy vehicular environments [34].

Although the strongest response arises along the defect axis due to the symmetry of the  $V_{Si}^-$  system, both simulations and initial measurements confirmed that a measurable linear response can also be extracted along all three orthogonal orientations. To achieve this, we implemented three orthogonal pairs of Helmholtz coils, enabling modulation of the magnetic field along the  $x$ ,  $y$ , and  $z$  axes [shown in Fig. 4(a) in red, yellow, and green, respectively].

The coil geometry was carefully optimized to balance compactness with field homogeneity. Smaller coils reduce

power consumption, as lower currents are sufficient to achieve the required modulation amplitude, but excessively small coils introduce strong field gradients across the sample. We therefore identified coil dimensions that ensure minimal nonlinearity while preserving a compact form factor. Figure 4(b) shows the calculated deviation of the magnetic field magnitude across the thickness of the active sample volume, with the circle indicating the optically addressed region containing the spin defects. The maximum deviation was found to be  $< 0.05\%$ , corresponding to negligible additional broadening of the ODMR line.

#### D. Linearity of the magnetometer

To evaluate the linear response of the system for different orientations, each coil was modulated at a distinct frequency ( $f_x = 1009$  Hz,  $f_y = 1091$  Hz, and  $f_z = 1201$  Hz). Demodulation at the corresponding frequency yields a voltage proportional to the external magnetic field. To demonstrate the vector operation mode of the compact system, we applied a sequence of test fields along each axis, as illustrated in Fig. 4(c). Specifically, the following field sequence was applied, for 10 s each along all three orientations:  $[50, 0, 40, 0, 30, 0, 20, 0, 10]$   $\mu$ T. This procedure serves two purposes: (i) to verify the linearity of the magnetometer response and (ii) to assess potential cross-talk of the axis, as the three coils cannot be expected to be perfectly orthogonal.

Figure 4 Subpanel (d) displays the raw lock-in amplifier data, including both in-phase (IP) and out-of-phase (OP)

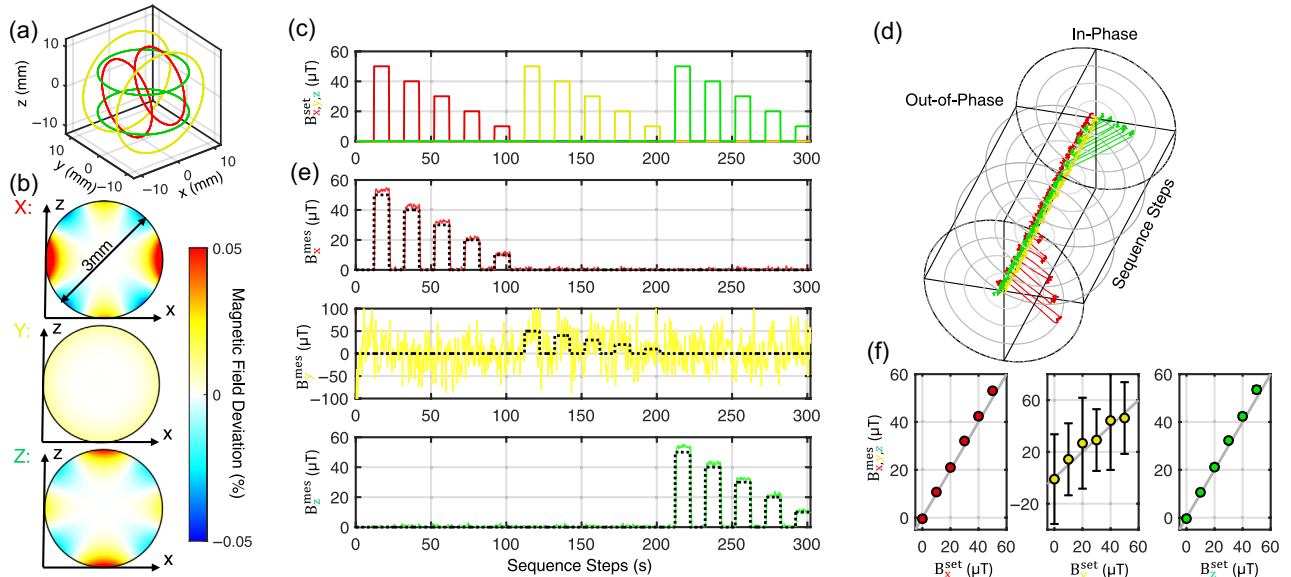


FIG. 4. Magnetic field coils of the magnetometer. (a) orientation and size of the used coils. (b) Calculated homogeneity across the active area of the sample based on coil diameters. (c) Magnetic field sequence to test the different axes. (d) Time-dependent polar plot of the three-frequency lock-in amplifier. The  $x$ - and  $z$ - contribution can clearly be seen in the raw data. (e) Calibrated measured values. While  $x$ - and  $z$ - are reproducing the applied sequence,  $y$ - suffers from a weak magnetic field response. (f) Extracted values correspond to applied values, but with large error-bars for  $y$ -orientation.

components. The applied test fields are clearly visible for the  $x$  and  $z$  directions, while the  $y$  axis response remains indistinct at this stage. Only minor offsets are observed, indicating sufficient spatial separation between the detector and the modulation coils.

For calibration, we adopted the calibration matrix methodology developed for the fluxgate magnetometers of the *Europa Clipper* spacecraft [9,35]. To avoid explicit phase correction of the raw lock-in data, we extended the calibration matrix  $\mathbf{M}$  to include both IP and OP components. The magnetic field  $\vec{B}$  is extracted by measuring the lock-in voltages  $U_i^{\text{IP}}$  and  $U_i^{\text{OP}}$  simultaneously for each channel  $i = x, y, z$ :

$$\vec{B} = \mathbf{M}^{\text{IP}} \vec{U}^{\text{IP}} + \mathbf{M}^{\text{OP}} \vec{U}^{\text{OP}} + \vec{c},$$

with the vectors

$$\vec{B} = \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix}, \quad \vec{U}^{\text{IP}} = \begin{bmatrix} U_x^{\text{IP}} \\ U_y^{\text{IP}} \\ U_z^{\text{IP}} \end{bmatrix}, \quad \vec{U}^{\text{OP}} = \begin{bmatrix} U_x^{\text{OP}} \\ U_y^{\text{OP}} \\ U_z^{\text{OP}} \end{bmatrix}, \quad \vec{c} = \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix},$$

and the calibration matrix

$$\mathbf{M}^{\text{IP}} = \begin{bmatrix} m_{11}^{\text{IP}} & m_{12}^{\text{IP}} & m_{13}^{\text{IP}} \\ m_{21}^{\text{IP}} & m_{22}^{\text{IP}} & m_{23}^{\text{IP}} \\ m_{31}^{\text{IP}} & m_{32}^{\text{IP}} & m_{33}^{\text{IP}} \end{bmatrix}, \quad \mathbf{M}^{\text{OP}} = \begin{bmatrix} m_{11}^{\text{OP}} & m_{12}^{\text{OP}} & m_{13}^{\text{OP}} \\ m_{21}^{\text{OP}} & m_{22}^{\text{OP}} & m_{23}^{\text{OP}} \\ m_{31}^{\text{OP}} & m_{32}^{\text{OP}} & m_{33}^{\text{OP}} \end{bmatrix}.$$

We deliberately refrained from enforcing orthogonality between the IP and OP contributions, since, depending on the relaxation dynamics and modulation frequencies, the signal can appear in both channels due to fast-passage effects (spin-lattice relaxation rate  $\frac{1}{T_1} \approx 3.3$  kHz [36], see Fig. 8 in Appendix B). This approach allows for a comprehensive calibration without the need for explicit phase adjustments.

Figure 4 Subpanel (e) shows the successful reconstruction of the applied test fields (dashed black lines) for  $x$  (red) and  $z$  (green). The  $y$ -orientation (yellow) remains barely discernible within the noise, primarily due to current limitations in the design of the corresponding Helmholtz coil pair. The coil performance is governed by a trade-off: increasing the number of turns reduces the required current, but also raises the inductance, which in turn lowers the performance of the coil driver and thus the achievable modulation depth. This limitation can be mitigated by adding a capacitor to form an LC circuit with a resonance frequency matched to the optimal demodulation frequency, which will be determined later in the manuscript (see Fig. 5). Because the  $y$ -coil has the largest diameter, it requires the greatest number of turns, resulting in a higher inductance and consequently reduced performance. In addition, a poor calibration can be excluded, as

the baselines of  $B_x$  and  $B_z$  remain flat during intervals where  $B_y$  is applied (around 110 s and 200 s). Likewise, a lack of responsivity of the quantum centers along this axis can be ruled out, since the  $c$ -axis corresponds to the standard quantization direction for scalar-based magnetometry typically reported in the literature. A more balanced, though not yet optimized, coil design already shows a similar response across all three orientations and can be found in the Appendix B (see Fig. 9).

Figure 4 Subpanel (f) summarizes the measured field amplitudes for each 10 s step of the applied sequence. The measured values closely match the set values ( $B^{\text{set}} = B^{\text{mes}}$ , solid gray line), confirming the linearity of the magnetometer response up to 50  $\mu\text{T}$ . Even for the  $y$  axis (which qualitatively exhibited weaker performance due to sub-optimal coil geometry), the applied fields can still be extracted, albeit with larger standard deviations. In contrast, the error bars for the  $x$  and  $z$  orientations lie within the marker size, further confirming the linearity of the magnetometer within the tested range.

### E. Isotropy and sensitivity of the magnetometer

It is important to emphasize that this test sequence evaluates the magnetometer's performance only for magnetic fields aligned along specific orientations. To verify isotropy more comprehensively, we apply arbitrary test fields. This is achieved by generating test fields within one octant of an equipotential sphere with a maximum field strength of 50  $\mu\text{T}$ . The resulting magnetic field values are shown in Fig. 5, where the color code indicates the deviation from the applied magnitude of 50  $\mu\text{T}$ .

Figure 5 Subpanel (a) shows the deviation of the absolute magnetic field value. The markers on the sphere are mostly white, with some light blue and yellow regions ( $\pm 5$   $\mu\text{T}$ ), corresponding to deviations within a 10% range (measured values are slightly too large in the corners and too low for magnetic fields between the three main axes). To understand the origin of these deviations, we now analyze each contribution individually.

Figure 5 Subpanel (b) shows the deviation between the set and measured magnetic field component  $B_x$  for all combinations across the entire octant (the full sphere corresponds to a mirrored behavior of each octant). Notably, the deviation for the  $x$ -orientation is mostly negligible, with the only relevant deviation occurring at the bottom of the octant (blue belt). This deviation does not arise from poor performance but from the applied test sequence, which changes the magnetic field too quickly within the expected bandwidth. Each magnetic field position is held for 2 s before stepping to the next one. The test sequence starts in the  $xy$ -plane and increases the  $z$  value while decreasing the  $x$  and  $y$  values, respectively, to remain within the 50  $\mu\text{T}$  sphere. This means that the  $x$ -value for  $B_z^{\text{set}} = 0$  is still affected by the previous (lower)

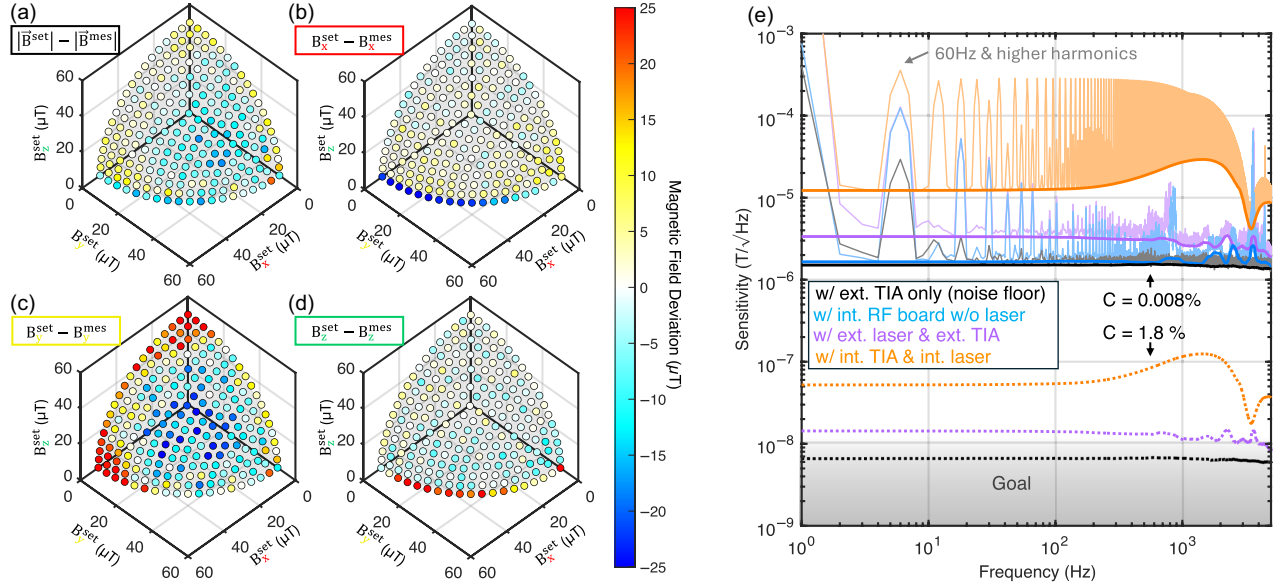


FIG. 5. Crosstalk and isotropy of the magnetometer. (a)–(d) 50  $\mu\text{T}$  sphere plots. The magnetic field vector is varied in  $\approx 5$  degree steps to cover one octant. The different plots show the deviation of the absolute value and the individual components, respectively. (e) Measured sensitivity across various frequencies for various subsystems being activated/deactivated. The best sensitivity for the fully integrated magnetometer (orange) is 4  $\mu\text{T}/\sqrt{\text{Hz}}$ . Further optimization steps promise sensitivities for this configuration down to 10's of  $\text{nT}/\sqrt{\text{Hz}}$ , projected with the dashed lines, assuming benchtop  $B_1$  filling leading to contrast  $C = 1.8\%$  instead of the current  $C = 0.008\%$ .

value due to the lock-in amplifier's time constant of 0.15 s for the anticipated 1 Hz bandwidth. Thus, this deviation can clearly be attributed to the test sequence and not to poor magnetometer performance.

The deviation in the y-direction, on the other hand, can be attributed to imperfect coil design. Similar to the previously shown linearity results, the values here are very noisy, leading to large fluctuations in the extracted magnetic field. The z direction, however, again confirms the overall isotropy of the sensor [see Fig. 5 subpanel (d)]. As in Fig. 5 subpanel (b), the only notable deviation is the red belt, which results from the previously larger  $B_z$  value stepping down within a fraction of a second for each  $B_z^{\text{set}} = 0$ , while the bandwidth remains 1 Hz. Overall, no evidence of nonisotropic behavior is observed; the magnetometer exhibits a uniform response to arbitrary applied magnetic fields within the tested range of  $< 50 \mu\text{T}$ .

We next evaluate the overall sensitivity of the magnetometer and quantify the noise contributions of the individual subsystems. To identify the dominant noise source, we measured the electronic noise under various configurations—selectively enabling or disabling subsystems and external components (e.g., the temperature-stabilized laser)—to determine the ultimate performance attainable with a more mature laser platform. This approach provides an estimate of the fundamental sensitivity limit achievable for the transmission geometry with quartz-fiber coupling reported here.

## F. Quantitative analysis of sensitivity shortfall and long-term stability

Figure 5(e) summarizes the relevant noise sources, displaying the frequency-resolved sensitivity without demodulation and thus highlighting suitable modulation frequencies for optimal magnetometer operation. The solid black line in the upper panel, slightly above 1  $\mu\text{T}/\sqrt{\text{Hz}}$ , represents the *intrinsic electronic noise floor* of the external transimpedance amplifier (TIA) used for benchmarking, with all other subsystems inactive. Among the tested boards, the rf board (shown in blue) exhibits the lowest intrinsic noise, though it introduces distinct features at 60 Hz (power-line frequency) and its harmonics due to the linear power supply.

The most significant increase in noise occurs once the laser is activated (purple trace), corresponding to a sensitivity of approximately 2  $\mu\text{T}/\sqrt{\text{Hz}}$  at modulation frequencies above 1 kHz. Replacing the high-end external laser and TIA with the integrated onboard laser driver and TIA introduces numerous higher harmonics and intensifies the 60 Hz component (orange trace). The solid orange line represents the noise floor of the fully integrated system, yielding a best sensitivity of 4  $\mu\text{T}/\sqrt{\text{Hz}}$  near a 3 kHz modulation frequency. Notably, this frequency range remains approximately one order of magnitude below the onset of fast-passage effects, allowing operation in a regime with reduced flicker noise while still maintaining the full spin response (see Fig. 8).

The ultimate sensitivity ( $\eta$ ) of a spin-defect magnetometer is governed by the relation  $\eta \propto \Delta\nu/(C\sqrt{R})$ , where  $\Delta\nu$  is the linewidth,  $C$  is the ODMR contrast, and  $R$  is the detected photon count rate. The  $B_1$ -field deficiency from the off-the-shelf NFC coil is the most significant performance inhibitor, suppressing the measurable contrast from a benchmark value of  $C_{\text{bench}} = 1.8\%$  reported in the literature for  $V_{\text{Si}}^-$  centers [27] to  $C_{\text{integrated}} = 0.008\%$  in our integrated system [Fig. 5(e)]. This contrast reduction corresponds to a degradation factor of:

$$\frac{C_{\text{benchtop}}}{C_{\text{integrated}}} = \frac{1.8\%}{0.008\%} = 225.$$

This demonstrates that the  $B_1$  field deficiency is responsible for a  $225\times$  performance degradation. Scaling our measured values of the integrated system by this factor yields a sensitivity of  $\approx 20 \text{ nT}/\sqrt{\text{Hz}}$ , with an electronic noise floor of  $< 10 \text{ nT}/\sqrt{\text{Hz}}$ , as indicated by the dashed lines in Fig. 5(e). Notably, this would surpass the sensitivity reported in Ref. [27]. The primary reason is the high photon count achieved using the chosen transmission geometry with quartz rod coupling. While this geometry does not support the use of an efficient microstrip coupling of the rf field, it provides the advantage of addressing orders of magnitude more  $V_{\text{Si}}^-$  centers compared with a confocal benchtop readout. In this configuration, the effective “voxel” corresponds to a macroscopic cylinder of  $300 \mu\text{m} \times (15 \text{ mm})^2 \times \pi$ , resulting in an ensemble of approximately  $10^{15}$   $V_{\text{Si}}^-$  centers, whereas a typical confocal microscope interrogates only a few thousands/millions. This, in turn, substantially increases the photon count rate  $R$ , thereby improving the shot-noise limit by a factor of  $\sqrt{R}$ .

Although the onboard drivers introduce a measurable  $4\times$  noise penalty [the orange trace in Fig. 5(e)] being  $4\times$  higher than the black trace), the analysis shows that *improving the  $B_1$ -field efficiency* to achieve the full  $1.8\%$  contrast reported in the literature remains the most critical engineering challenge [27]. Achieving this contrast would place the instrument firmly in the low-two-digit  $\text{nT}/\sqrt{\text{Hz}}$  regime, and removing the additional  $4\times$  electronic noise penalty would allow performance to approach the single-digit target. Reaching the single-digit  $\text{nT}/\sqrt{\text{Hz}}$  regime would place our device in the performance range of N-V-based magnetometers with similarly sized sensor heads. For example, sensitivities of  $31 \text{ nT}/\sqrt{\text{Hz}}$  [37],  $344 \text{ pT}/\sqrt{\text{Hz}}$  [38], and  $57.6 \text{ nT}/\sqrt{\text{Hz}}$  for ac fields [39] have been reported. While these systems achieve higher sensitivities, we emphasize that our device already constitutes a fully integrated and compact system (including the laser driver, rf oscillator, as well as modulation and demodulation electronics) and operates directly in vector mode without requiring a bias field, which is particularly

advantageous for applications involving multiple sensors. In addition, the magnetometer turns out to be very stable over time, mainly due to the robustness of the quartz rod approach, which keeps all components well aligned. Figure 7 (Appendix B) shows the Allan deviation of the system, indicating predominantly white-noise behavior with additional contributions from pink (flicker) noise, likely originating from the electronics.

These results confirm the viability of the system concept, and we identify several clear pathways for standard engineering improvement, in order of importance:

- (1) Sample quenching to increase the ODMR contrast [27].
- (2) Enhancement of the  $B_1$ -field efficiency of the rf coil. The current COTS part, chosen for repeatability and scalability, yields insufficient  $B_1$  filling. A research-grade stopgap will be to fabricate a one-off custom 70 MHz coil; scaling up for larger batch production will require collaborating with industry for professional fabrication of coils outside of the usual 14 MHz range.
- (3) Stabilized low-noise laser
- (4) Dedicated line-frequency suppression or battery operation to eliminate harmonics that constrain available modulation/demodulation frequencies and induce cross-talk.

### III. CONCLUSION

In this work, we have presented the first realization of a fully modular, miniaturized vector magnetometer based on silicon vacancy centers in 4H-SiC. The system achieves a credit-card-sized footprint with a mass of only 185 g, enabled by a highly modular design philosophy in which individual subsystems can be independently optimized and iterated. While the current prototype does not yet reach the target sensitivity of  $1 \text{ nT}/\sqrt{\text{Hz}}$  required for GPS-denied navigation, it provides a comprehensive engineering blueprint toward that goal. It also demonstrates a pathway to inexpensive, low-complexity instruments allowing distributed sensor systems, allowing modeling and canceling the vehicle’s distortion field. The choice of the net-zero bias field silicon carbide architecture plays toward that goal, making further research to improve the sensor performance worthwhile.

Several pathways offer promising opportunities for improvement: Several pathways offer promising opportunities for improvement. *Material advances*, including optimized postirradiation treatments and the use of isotopically purified SiC, could yield order-of-magnitude enhancements in ODMR contrast and linewidth. *Optical readout* performance could be improved through the use of narrower-linewidth or shorter-wavelength excitation sources to reduce residual pump leakage, while advanced waveguide structures could be integrated directly into the SiC chip. In addition, *rf optimization* through the

replacement of manually tuned capacitors with voltage-controlled elements would enable closed-loop stabilization against environmental fluctuations, and further refinement of coil geometries could enhance isotropic sensitivity.

Beyond these incremental improvements, the modular architecture demonstrated here opens the door to broader applications. By enabling independent optimization of subsystems, the design can be tailored not only for navigation in GPS-denied environments, but also for compact and portable sensing in geophysics, biomedical imaging, and nondestructive testing. While the silicon carbide architecture is our first choice for its waiving of heavy bias-field requirements, the overall instrument architecture is material agnostic and can readily be used with other sensor materials such as N-V-diamond or hBN.

### ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (Contract No. 80NM0018D0004) and funded by the Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) program. The samples were provided by Dr. Takeshi Ohshima of QST Japan; the irradiation process was funded by 3rd SIP, Promoting application of advanced quantum technologies to social challenges (Funding agency: QST) and JST FOREST Program (Grant No. JPMJFR203G, Japan). ©2026. California Institute of Technology. Government sponsorship acknowledged.

### DATA AVAILABILITY

The data that support the findings of this article are not publicly available because of legal restrictions preventing unrestricted public distribution. The data are available from the authors upon reasonable request.

### APPENDIX A: METHODS

The devices used to build and characterize the magnetometer presented here can be divided into two categories: internal components and external components used to test the subsystems.

As mentioned in the main text, the heart of the magnetometer consists of a stack of electron-irradiated SiC wafer and GaAs, mounted between two quartz rods. The whole system is aligned and fixed in place by screwing the pump source, a Thorlabs TO-Can laser diode (200 mW, 830 nm), from one side, and the detector, a Si photodiode (FDS100), from the other side. To supply the laser diode with a low-noise constant current, we use a commercially available Coheron DRV100-A-200 laser driver, with approximately  $250 \text{ pA}/\sqrt{\text{Hz}}$  of current noise in the frequency regime where the system is modulated/demodulated. To read out the emission, we use a precision

operational amplifier (OP27G) in a custom transimpedance amplifier configuration. To drive the spin system into resonance, we use a voltage-controlled oscillator (Mini-Circuits, POS-100+) in combination with an rf amplifier (Mini-Circuits, PHA-102+). The rf signals are coupled to the spin system using a detuned NFC coil (Taoglas Limited, FXC.16.A). Notably, to mount the NFC coil around the sample, the 3-axis Helmholtz coil system consists of two cylindrical halves [see Fig. 1(b), gray half on the left and white half on the right], which can be locked together with the NFC coil in between. This barrel configuration provides three pairs of Helmholtz coils, with the sample centered at the intersection of their axes. To drive the magnetic field in the coils, we use two audio amplifiers (Texas Instruments, TPA1517NE). The reference frequencies are generated by two DACs of a system-on-chip type microcontroller ( $\mu\text{C}$ , Espressif Systems, ESP32), with an additional DAC (Microchip Technology, MCP4728) used for the third frequency.

We characterized the subsystems using the following external devices: To measure the photoluminescence wavelength resolved in Fig. 2, we replaced the photodiode and the quartz rod with an extended quartz rod that enabled coupling into a fiber-coupled USB spectrometer (custom calibrated OceanOptics). In order to obtain a more stable laser with easily controlled output power, we used a temperature-compensated external laser (Lumics, LU0808M250-1C06F10A) driven by an external laser controller (Thorlabs, ITC4001). Later, we set the internal laser diode to the same power, confirmed using both a laser power meter and the measured PL level. To perform cw-ODMR measurements (Fig. 3) with variable power and a defined frequency sweep, we used an external rf generator (Stanford Research Systems, SG382) together with an external rf amplifier (Mini-Circuits, ZHL-1A) coupled into the SMA port of the rf board. Once the required power and frequency were confirmed, we set the internal VCO to the corresponding values. Since the rf signals are modulated for cw-ODMR measurements, we used an external lock-in amplifier (Stanford Research Systems, SR850) for demodulating the signal. To verify the required V/A gain, an external low-noise current amplifier (Stanford Research Systems, SR570) was used. These components were later replaced by the self-built versions mentioned above. To test the performance of the magnetometer, we used a three-channel power supply (Keithley, 2230-20-1) in combination with a  $\mu$ -metal chamber (Twinleaf, MS-1L) which provides both shielding from parasitic external magnetic fields (e.g., the Earth's magnetic field) and the ability to apply test fields in different directions via the built-in coils. An 18-bit ADC from a National Instruments device (NI USB-6289) was used to characterize the magnetometer noise by recording the raw output of the TIA for different subsystem combinations, as described in Fig. 5. Notably, the 12-bit ADC of the current ESP32 is sufficient for this

proof-of-concept magnetometer; however, once the noise floor is further reduced, upgrading the ADC (e.g., to an 18-bit MCP3421) will be crucial to fully exploit the available dynamic range.

## APPENDIX B: SUPPLEMENTARY FIGURES

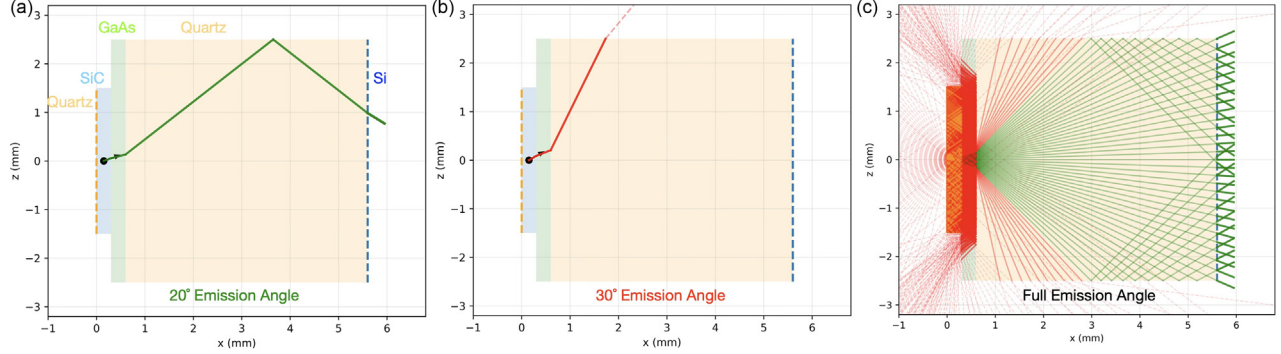


FIG. 6. Collection efficiency of the quartz rod geometry. (a) Ray trace for a  $20^\circ$  emission angle from a defect located at the center of the SiC sample. The photon reaches the Si detector (dashed blue line) via total internal reflection within the quartz rod walls (yellow). (b) Ray trace for the same defect at a  $30^\circ$  emission angle, where the photon leaks out of the quartz rod. (c) Full emission profile of a defect located at the center. Assuming isotropic emission, a uniformly distributed defect density across the SiC sample, and extrapolation from 2D to 3D, this leads to a collection efficiency of  $\approx 13\%$ .

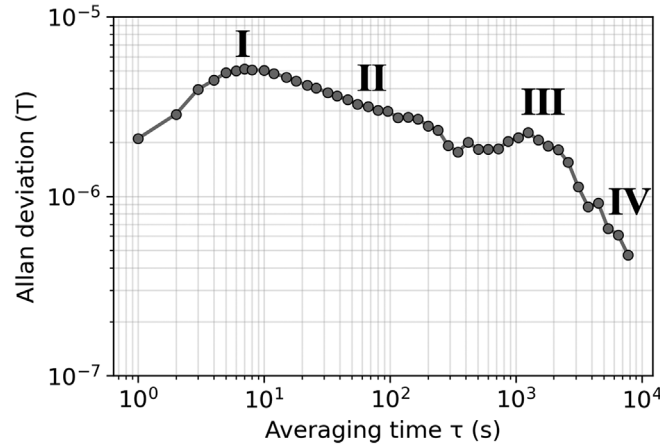


FIG. 7. Allan deviation of the magnetometer. The deviation is evaluated under realistic operating conditions using the isotropy measurement shown in Fig. 5. Since the magnetic field is changed every 2 s, the Allan deviation initially rises at short averaging times (region I), reflecting the applied test field rather than intrinsic sensor noise. At longer averaging times, the deviation decreases with a slope of approximately  $-0.3$  (II), indicating that the sensor is not purely white-noise limited, but still shows contributions from technical noise, such as electronic flicker noise. No characteristic upturn is visible at long averaging times, apart from a small feature around  $10^3$  s (III). Overall, the magnetometer does not show significant drift and appears very stable. This stability is attributed to the fact that the optical setup is not based on free-space optics, but instead uses a compact, integrated stack of laser, fiber, sample, filter, fiber, and detector. As these components are mechanically fixed together, the system is robust against long-term misalignment and environmental perturbations. The faster decay (IV) at the longest averaging times can be attributed to a statistical artifact of the finite dataset.

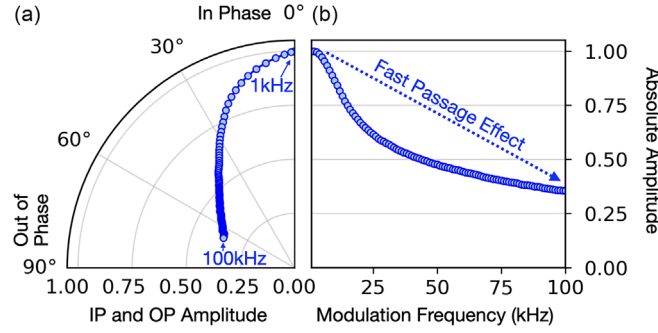


FIG. 8. Impact of fast-passage effects on the ODMR response. (a) Normalized demodulated signal from the lock-in amplifier visualized in a polar plot. Each circle represents the measured spin response under resonance conditions with rf amplitude modulation (see Fig. 3) for various modulation frequencies ranging from 1 to 100 kHz, measured using an external lock-in amplifier. Notably, this measurement was conducted under similar conditions as in the miniaturized magnetometer, but in a benchtop setup to characterize the sample. Since fast-passage effects originate from the longitudinal relaxation time  $T_1$ , they are not limited by the experimental setup but rather by the sample itself. While the signal is IP for small modulation frequencies, it shifts OP at higher modulation frequencies. As mentioned in the main text, the phase of the lock-in amplifier can be chosen arbitrarily to maximize the response; however, the absolute amplitude decreases rapidly at higher modulation frequencies. (b) Absolute amplitude for various modulation frequencies. The signal decreases once the modulation frequency exceeds the spin-lattice relaxation rate ( $\frac{1}{T_1} \approx 3.3$  kHz [36]), as the spin system reacts too slowly to changes in the resonance condition. This effect deteriorates the performance of the lock-in amplifier at higher frequencies (e.g., 50% signal reduction at  $\approx 40$  kHz), despite the benefit of flicker-noise reduction. As shown in subpanel (e) of Fig. 5, the optimal modulation frequency is around  $\approx 4$  kHz, where fast-passage effects can be neglected, as observed here.

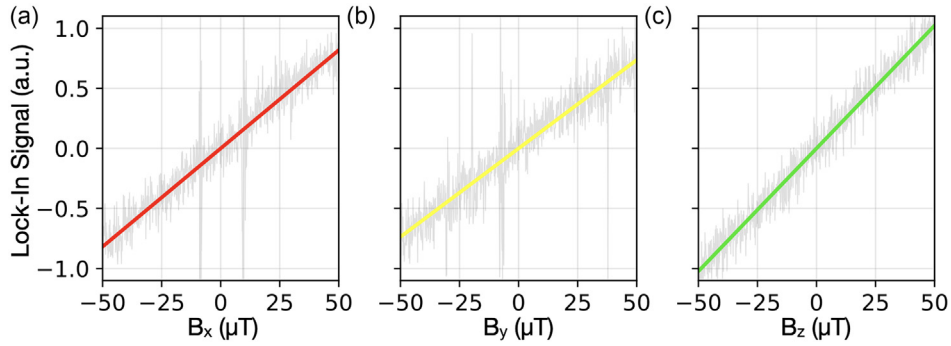


FIG. 9. Updated coil system demonstrating that all orientations are functional for the sensor when the coils are properly balanced. (a)  $\pm 50$   $\mu\text{T}$  sweep along  $x$  with fit in red, (b) sweep along  $y$  with fit in yellow, and (c) sweep along  $z$  with fit in green.

- [1] X. Wang, W. Li, B. Moran, B. C. Gibson, L. T. Hall, D. A. Simpson, A. N. Kealy, and A. D. Greentree, Quantum diamond magnetometry for navigation in GNSS denied environments, *Gravity, Positioning and Reference Frames*, edited by J. T. Freymueller and L. Sánchez (Springer Nature Switzerland, Cham, 2024), pp. 87–92.
- [2] M. W. Dunlop, M. K. Dougherty, S. Kellock, and D. J. Southwood, Operation of the dual magnetometer on Cassini: Science performance, *Planet Space Sci.* **47**, 1389 (1999).
- [3] K. W. Behannon, M. H. Acuna, L. F. Burlaga, R. P. Lepping, N. F. Ness, and F. M. Neubauer, Magnetic field experiment for Voyagers 1 and 2, *Space Sci. Rev.* **21**, 235 (1977).
- [4] E. Smith, B. Connor, and G. Foster, Measuring the magnetic fields of jupiter and the outer solar system, *IEEE Trans. Magn.* **11**, 962 (1975).
- [5] N. El-Sheimy and A. Youssef, Inertial sensors technologies for navigation applications: State of the art and future trends, *Satell. Navig.* **1**, 2 (2020).
- [6] M. G. Kivelson, K. K. Khurana, C. T. Russell, M. Volwerk, R. J. Walker, and C. Zimmer, Galileo magnetometer measurements: A stronger case for a subsurface ocean at Europa, *Science* **289**, 1340 (2000).
- [7] M. K. Dougherty, K. K. Khurana, F. M. Neubauer, C. T. Russell, J. Saur, J. S. Leisner, and M. E. Burton, Identification of a dynamic atmosphere at enceladus with the Cassini magnetometer, *Science* **311**, 1406 (2006).

- [8] C.J. Cochrane, N. Murphy, C.A. Raymond, J.B. Biersteker, K. Dang, X. Jia, H. Korth, P. Narvaez, J.B. Ream, and B.P. Weiss, Magnetic field Modeling and visualization of the Europa Clipper spacecraft, *Space Sci. Rev.* **219**, 34 (2023).
- [9] C.J. Cochrane, S.P. Joy, H. Korth, J.B. Biersteker, J. Blacksberg, M. Bouchard, J. Contreras, O.R. Dawson, K.K. Khurana, N. Murphy, D. Palm, M.O. Perley, D.R. Pierce, I. Richter, C.T. Russell, S. Sherman, R.J. Strangeway, B.P. Weiss, L. Wigglesworth, M.G. Kivelson, X. Jia, and C. A. Raymond, Europa Clipper magnetometer boom deployment: A first look at the magnetometer observations of the spacecraft and the interplanetary magnetic field, *Space Sci. Rev.* **221**, 115 (2025).
- [10] J. Lee, J. Lim, and J. Lee, Compensated heading angles for outdoor mobile robots in magnetically disturbed environment, *IEEE Trans. Ind. Electron.* **65**, 1408 (2018).
- [11] A. R. Gnad, J. Belarge, A. Canciani, G. Carl, L. Conger, J. Curro, A. Edelman, P. Morales, A.P. Nielsen, M.F. O’Keeffe *et al.*, Signal enhancement for magnetic navigation challenge problem, [arXiv:2007.12158](https://arxiv.org/abs/2007.12158).
- [12] Use of 6 K ACTDP cryocoolers for the MIRI instrument on JWST, *Cryocoolers 13, SpringerLink Bücher*, edited by R. G. Ross and Ronald G. Ross (Springer US, Boston, MA, 2006).
- [13] N. Sekiguchi, M. Fushimi, A. Yoshimura, C. Shinei, M. Miyakawa, T. Taniguchi, T. Teraji, H. Abe, S. Onoda, T. Ohshima, M. Hatano, M. Sekino, and T. Iwasaki, Diamond quantum magnetometer with dc sensitivity of sub-10 pT/Hz<sup>-1/2</sup> toward measurement of biomagnetic field, *Phys. Rev. Appl.* **21**, 064010 (2024).
- [14] V.M. Acosta, E. Bauch, M.P. Ledbetter, C. Santori, K.-M. C. Fu, P.E. Barclay, R. G. Beausoleil, H. Linget, J. F. Roch, F. Treussart, S. Chemerisov, W. Gawlik, and D. Budker, Diamonds with a high density of nitrogen-vacancy centers for magnetometry applications, *Phys. Rev. B* **80**, 115202 (2009).
- [15] K. Dang, P. Narvaez, K. Mehlem, J. Trinh, C. J. Cochrane, M. M. Soriano, and J. Ream, Novel approach to spacecraft system level magnetic test at NASA jet propulsion laboratory, in *2025 IEEE International Symposium on Electromagnetic Compatibility, Signal & Power Integrity (EMC+SIPI)*, Raleigh, NC, USA (2025), pp. 190–197, [10.1109/EMCSIP152291.2025.11169792](https://doi.org/10.1109/EMCSIP152291.2025.11169792).
- [16] T. P. M. Alegre, C. Santori, G. Medeiros-Ribeiro, and R. G. Beausoleil, Polarization-selective excitation of nitrogen vacancy centers in diamond, *Phys. Rev. B* **76**, 165205 (2007).
- [17] L. M. Pham, E. M. Thompson, J. F. Barry, K. A. Johnson, and D. A. Braje, Chopped bias magnetic field solid state spin sensor for low frequency measurements of physical quantities, U.S. Patent US11041916B2 (2021).
- [18] D. Riedel, F. Fuchs, H. Kraus, S. V  th, A. Sperlich, V. Dyakonov, A. A. Soltamov, P. G. Baranov, V. A. Ilyin, and G. V. Astakhov, Resonant addressing and manipulation of silicon vacancy qubits in silicon carbide, *Phys. Rev. Lett.* **109**, 226402 (2012).
- [19] H. Kraus, V. A. Soltamov, F. Fuchs, D. Simin, A. Sperlich, P. G. Baranov, G. V. Astakhov, and V. Dyakonov, Magnetic field and temperature sensing with atomic-scale spin defects in silicon carbide, *Sci. Rep.* **4**, 5303 (2014).
- [20] A. Abragam and M.H.L. Pryce, Theory of the nuclear hyperfine structure of paramagnetic resonance spectra in crystals, *Proc. R. Soc. A* **205**, 135 (1951).
- [21] H. Kraus, V. A. Soltamov, D. Riedel, S. V  th, F. Fuchs, A. Sperlich, P. G. Baranov, V. Dyakonov, and G. V. Astakhov, Room-temperature quantum microwave emitters based on spin defects in silicon carbide, *Nat. Phys.* **10**, 157 (2013).
- [22] D. Simin, F. Fuchs, H. Kraus, A. Sperlich, P. G. Baranov, G. V. Astakhov, and V. Dyakonov, High-precision angle-resolved magnetometry with uniaxial quantum centers in silicon carbide, *Phys. Rev. Appl.* **4**, 014009 (2015).
- [23] H. Kraus, D. Simin, C. Kasper, Y. Suda, S. Kawabata, W. Kada, T. Honda, Y. Hijikata, T. Ohshima, V. Dyakonov, and G. V. Astakhov, Three-dimensional proton beam writing of optically active coherent vacancy spins in silicon carbide, *Nano Lett.* **17**, 2865 (2017).
- [24] T. Ohshima, T. Satoh, H. Kraus, G. V. Astakhov, V. Dyakonov, and P. G. Baranov, Creation of silicon vacancy in silicon carbide by proton beam writing toward quantum sensing applications, *J. Phys. D* **51**, 333002 (2018).
- [25] H. B. Banks,   ney O. Soykal, R. L. Myers-Ward, D. K. Gaskill, T. L. Reinecke, and S. G. Carter, Resonant optical spin initialization and readout of single silicon vacancies in 4 H-Si C, *Phys. Rev. Appl.* **11**, 024013 (2019).
- [26] V. M. Acosta, E. Bauch, M. P. Ledbetter, A. Waxman, L.-S. Bouchard, and D. Budker, Temperature dependence of the nitrogen-vacancy magnetic resonance in diamond, *Phys. Rev. Lett.* **104**, 070801 (2010).
- [27] J. B. Abraham, C. Gutzwiller, D. Todorovski, S. Sperling, J. E. Epstein, B. S. Tien-Street, T. M. Sweeney, J. J. Wathen, E. A. Pogue, P. G. Brereton *et al.*, Nanotesla magnetometry with the silicon vacancy in silicon carbide, *Phys. Rev. Appl.* **15**, 064022 (2021).
- [28] I. Lekavicius, S. G. Carter, D. J. Pennachio, S. White, J. R. Hajzus, A. P. Purdy, D. K. Gaskill, A. L. Yeats, and R. L. Myers-Ward, Magnetometry based on silicon-vacancy centers in isotopically purified 4 H - SiC, *Phys. Rev. Appl.* **19**, 044086 (2023).
- [29] D. Simin, V. A. Soltamov, A. V. Poshakinskiy, A. N. Anisimov, R. A. Babunts, D. O. Tolmachev, E. N. Mokhov, M. Trupke, S. A. Tarasenko, A. Sperlich, P. G. Baranov, V. Dyakonov, and G. V. Astakhov, All-optical dc nanotesla magnetometry using silicon vacancy fine structure in isotopically purified silicon carbide, *Phys. Rev. X* **6**, 031014 (2016).
- [30] W.-K. Quan, L. Liu, Q.-Y. Luo, X.-D. Liu, and J.-F. Wang, Fiber-integrated silicon carbide silicon-vacancy-based magnetometer, *Opt. Lett.* **48**, 1423 (2023).
- [31] S. Stoll and A. Schweiger, EasySpin, a comprehensive software package for spectral simulation and analysis in EPR, *J. Magn. Reson.* **178**, 42 (2006).
- [32] A. Gottscholl, C. J. Cochrane, and H. Kraus, Operation modes of an optically pumped 6H SiC quantum/solid-state magnetometer, *IEEE Sens. J.* **24**, 17596 (2024).
- [33] A. Gottscholl, H. Kraus, T. Aichinger, and C. J. Cochrane, Enhancing the electrical readout of the spin-dependent recombination current in SiC JFETs for EDMR based

- magnetometry using a tandem (de-) modulation technique, [Sci. Rep. \*\*14\*\*, 14283 \(2024\)](#).
- [34] C. J. Cochrane, J. Blacksberg, M. A. Anders, and P. M. Lenahan, Vectorized magnetometer for space applications using electrical readout of atomic scale defects in silicon carbide, [Sci. Rep. \*\*6\*\*, 1239 \(2016\)](#).
- [35] M. G. Kivelson, X. Jia, K. A. Lee, C. A. Raymond, K. K. Khurana, M. O. Perley, J. B. Biersteker, J. Blacksberg, R. Caron, C. J. Cochrane *et al.*, The Europa Clipper magnetometer, [Space Sci. Rev. \*\*219\*\*, 48 \(2023\)](#).
- [36] C. Kasper, D. Klenkert, Z. Shang, D. Simin, A. Gottscholl, A. Sperlich, H. Kraus, C. Schneider, S. Zhou, M. Trupke, W. Kada, T. Ohshima, V. Dyakonov, and G. V. Astakhov, Influence of irradiation on defect spin coherence in silicon carbide, [Phys. Rev. Appl. \*\*13\*\*, 044054 \(2020\)](#).
- [37] F. M. Stürner, A. Brenneis, J. Kassel, U. Wostradowski, R. Röhlver, T. Fuchs, K. Nakamura, H. Sumiya, S. Onoda, J. Isoya *et al.*, Compact integrated magnetometer based on nitrogen-vacancy centres in diamond, [Diam. Relat. Mater. \*\*93\*\*, 59 \(2019\)](#).
- [38] F. M. Stürner, A. Brenneis, T. Buck, J. Kassel, R. Röhlver, T. Fuchs, A. Savitsky, D. Suter, J. Grimm, S. Hengesbach, M. Förtsch, K. Nakamura, H. Sumiya, S. Onoda, J. Isoya, and F. Jelezko, Integrated and portable magnetometer based on nitrogen-vacancy ensembles in diamond, [Adv. Quantum Technol. \*\*4\*\*, 2000111 \(2021\)](#).
- [39] A. Kuwahata, T. Kitaizumi, K. Saichi, T. Sato, R. Igarashi, T. Ohshima, Y. Masuyama, T. Iwasaki, M. Hatano, F. Jelezko *et al.*, Magnetometer with nitrogen-vacancy center in a bulk diamond for detecting magnetic nanoparticles in biomedical applications, [Sci. Rep. \*\*10\*\*, 2483 \(2020\)](#).