

Miniaturized magnetic-field sensor based on nitrogen-vacancy centers

Stefan Johansson¹,* Dennis Lönard¹,* Isabel Cardoso Barbosa¹, Jonas Gutsche¹,
Jonas Witzernath, and Artur Widera¹†

Department of Physics and State Research Center OPTIMAS, RPTU University Kaiserslautern-Landau,
Erwin-Schroedinger-Str. 46, 67663 Kaiserslautern, Germany



(Received 4 February 2025; revised 23 July 2025; accepted 24 October 2025; published 26 November 2025)

The nitrogen-vacancy (NV) center in diamond is a prime candidate for quantum sensing technologies. Here, we present a fully integrated and mechanically robust fiber-based endoscopic sensor with a tip diameter of 1.25 mm. On its tip, a direct laser-writing process is used to secure a diamond containing NV centers above the fiber's core inside a polymer structure. Additionally, a metallic direct laser-written antenna structure next to the fiber facet allows efficient microwave manipulation of NV-center spins. The sensor achieves a shot-noise-limited magnetic-field sensitivity of $5.9 \text{ nT}/\sqrt{\text{Hz}}$ using a $15\text{-}\mu\text{m}$ -sized micro-diamond at a microwave power of 50 mW and an optical power of 2.15 mW. Using lock-in techniques, we measure a sensitivity of $51.8 \text{ nT}/\sqrt{\text{Hz}}$. Furthermore, we introduce a dual-fiber concept that enables, in combination with a direct laser-written structure, independent guiding of excitation and fluorescence light and thus reduces background autofluorescence. Moreover, controlled guiding of excitation light to the diamond while avoiding sample illumination may enable operation in light-sensitive environments such as biological tissue. While the demonstrated sensitivity is achieved using a single-fiber configuration, the dual-fiber approach provides a path toward integrating smaller diamonds, where autofluorescence would otherwise limit performance. We demonstrate the capability of vector magnetic-field measurements in the type of magnetic field used in state-of-the-art ultracold quantum gas experiments, opening a potential arena in which high resolution and high sensitivity are required.

DOI: [10.1103/lbqi-d5zv](https://doi.org/10.1103/lbqi-d5zv)

I. INTRODUCTION

The negatively charged nitrogen-vacancy (NV) center in diamond is an atomic-scale point defect in the diamond lattice consisting of a vacancy and a substitutional nitrogen atom next to it [1,2]. It provides optically addressable spin states and allows optical readout of the spin-state population [3]. When resonantly excited with a microwave (MW) field, it enables, due to spin-dependent intersystem crossing, optically detected magnetic resonance (ODMR) spectroscopy [4]. The inclusion of the defect in the diamond lattice results in a solid-state sensor with atom-like behavior [5], making it a leading candidate in research as a highly sensitive vectorial magnetic-field sensor with high spatial resolution [6] and the ability to measure temperature [7,8], pressure [9], and electrical fields [10–13].

Other magnetic-field sensors, such as superconducting quantum interference devices and optically pumped atomic magnetometers, have demonstrated sensitivities in the $\text{fT}/\sqrt{\text{Hz}}$ range [14,15]; however, they often require cryogenic temperatures or are not intrinsically capable of measuring vectorial magnetic fields with a single sensing element. Many applications, like measurements of electrical currents in coils or high-power electronics, paramagnetic materials, or permanent magnetic materials, need to be measured accurately with $\text{nT}/\sqrt{\text{Hz}}$ sensitivities [16–19]. Often, they require only moderate absolute sensitivities but strongly profit from an increased sensitivity per distance [20–22]. Diamonds containing NV centers provide high overall sensitivities, especially when combined with the use of flux concentrators [23], ^{12}C -enriched diamonds for longer coherence times [6], or by a large number of spins [24,25], and are usable from cryogenic temperatures up to hundreds of $^{\circ}\text{C}$ [26–28], promising to be the next generation of magnetic-field sensors. Moreover, single diamond-based sensors have demonstrated vector magnetometry with a wide dynamic range and high sensitivity [16]. Current state-of-the-art approaches to measuring magnetic fields are based on stationary setups such as wide-field microscopy using diamond plates [29], scanning diamond probes [30], or integrated portable devices [31].

*Both authors contributed equally.

†Contact author: widera@rptu.de

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

While stationary scanning probe and wide-field setups often provide very high magnetic-field sensitivities or high spatial resolution, these laboratory setups cannot be used as practical, portable sensors due to their size. Furthermore, most scanning-probe setups do not provide a vectorial field due to their use of a single NV center, and, just like confocal setups, stable environmental conditions are required for reliable results.

Thus, we focus on portable—especially fiber-based—approaches for NV sensors in this work. The reported portable devices can be split into two groups. Either they are fully integrated, consisting of necessary excitation and detection elements such as MW antennas, optical-excitation light sources, and detectors close by, or directly attached [32–34]. Integrating these elements, such as detectors and excitation sources, limits the possible miniaturization of the actual sensor. Alternatively, they consist of two parts where the sensor’s head, as well as the excitation and detection sections, are separated with optical fibers and electrical wires [35–39]. Therefore, miniaturization can be enhanced by only integrating the necessary elements on a sensor’s tip and connecting them to wires and optical fibers; however, combining an NV-doped diamond with optical and microwave access on a compact form factor leads to challenges in finding a robust platform. Usually, fiber-based sensors use light-curable adhesive to attach diamonds to a fiber, often with mismatching sizes between the diamond and optical fiber, sacrificing optical performance due to nonideal light-guiding efficiencies. Often, the integration of an antenna is realized by attaching an external antenna or a piece of wire using tape or glue, leading to a fragile sensor and poor MW efficiency [40–42]. Other publications use randomly oriented diamond ensembles, which only provide scalar field information and often have worse resolution than single diamond sensors or lack the integration of a microwave-emitting structure [43–45]. Previously reported results also suggest that positioning the microwave-emitting element near the diamond can provide good sensitivity even at low power settings [46].

In this context, a further limitation of miniaturized optical-fiber-based sensors is the so-called autofluorescence of optical fibers [47–49], especially when the diamond size is reduced below a few hundred nanometers. This autofluorescence arises from the excitation light required for NV centers, which also excites photoactive compounds within the fiber and typically overlays spectrally with the fluorescence of the NV center. When the diamond size and the number of NV centers are decreased, the total fluorescence from the actual sensor decreases, while the autofluorescence remains constant for the same laser power. This ratio leads to a worse signal-to-noise ratio (SNR) and, thereby, sensitivity, mainly when small sensing diamonds or diamonds with low NV-center dopings are used. Although bleaching strategies to temporarily

reduce the autofluorescence intensity have been suggested, it cannot be eliminated completely [50].

Here, we show a robust, miniaturized dual-fiber-based platform and sensor using standardized components and state-of-the-art additive manufacturing techniques. We use metallic direct laser writing of a silver resist to create an antenna structure next to a direct laser-written polymer structure. The polymer structure is used to guide excitation and fluorescence light and to secure a single deterministically positioned 15- μm -sized diamond to the tip of an optical fiber on a platform diameter of 270 μm . For our magnetic-field sensor, we find a shot-noise (SN)-limited sensitivity of 5.9 nT/ $\sqrt{\text{Hz}}$ in the single-fiber configuration with an intrinsic spatial resolution (based on the diamond size of 15 μm), at a microwave power as low as 50 mW and an optical laser power of 2.15 mW, with a total volume of our sensor head of 52.8 mm³. For better comparison across sensors with diamonds of different sizes, we calculate a volume normalized (volumetric) shot-noise-limited sensitivity related to the diamond size of 7.8 pT/ $\sqrt{\text{Hz}} \times \text{mm}^{3/2}$, assuming the microdiamond as a homogeneous 15- μm -sized sphere.

As a proof of principle, our dual-fiber-sensor approach paves the way toward the integration of smaller diamonds down to a size below 100 nm without being significantly affected by the autofluorescence in a detecting fiber. This is achieved by using different optical fibers guiding excitation or NV-fluorescence light in combination with a connecting waveguide structure. We measure a reduction of the amount of laser light guided in the detection fiber by 2 to 3 orders of magnitude, resulting in a significant reduction of autofluorescence; however, we note that a sensor using a 15- μm -sized diamond is not mainly limited by autofluorescence, and imperfections in the polymer structure significantly impact the reached sensitivity.

In Sec. II, we first describe the steps to build the platform and the process to create the antenna structure and polymer waveguide, which also fixes the diamond. In Sec. III, measurements characterize our sensor regarding autofluorescence, sensitivity, and noise, and we show a practical application. To better compare current sensor designs, we evaluate our approach against other fiber-based magnetic-field sensors in terms of size and sensitivity, normalizing the measured sensitivities by the diamond size used. Our results and limitations are summarized in Sec. IV, and further challenges for integrating nanometer-sized diamonds are discussed.

II. MATERIALS AND METHODS

Our sensor head is split into two components: the so-called sensor platform and the tip of the sensor. The sensor platform connects the MW guiding wires and light-guiding optical fibers together in an optical-fiber ferrule, as depicted in Fig. 1(a). After filling the remaining space

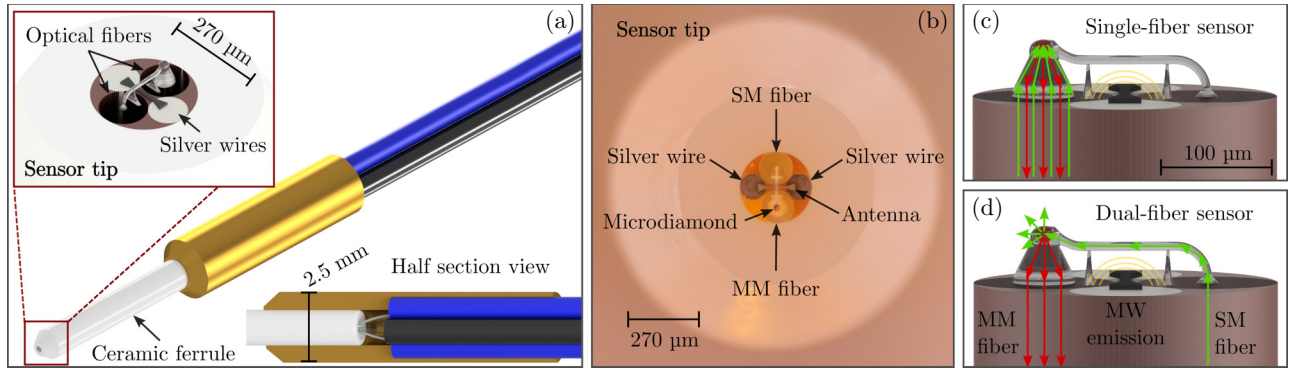


FIG. 1. (a) Rendered images of the assembled sensor platform. Two silver wires and two optical fibers are inserted into a ceramic ferrule. As a reinforcement between the ferrule and the protective tubing of the fibers, a mating sleeve is added. (b) Tip of a sensor after fabrication. (c),(d) Rendered images of the sensor tip with the antenna and a polymer waveguide structure and the light path for green excitation light and red fluorescence in single- and dual-fiber configurations.

using epoxy and subsequent polishing of the tip, the small tip diameter enables the use of microscopic additive technologies such as direct laser writing at the tip of the fibers and wires, as shown in Fig. 1(b).

The platform also enhances the mechanical stability of the whole sensor without significantly increasing the size of the necessary parts of the sensor. The silver antenna and polymer light-guiding structure at the sensor's tip are created using a direct laser-writing process based on a two-photon absorption process in a commercial lithography system (PPGT+, Nanoscribe). We modified the system with a positioning stage, which allows inserting and positioning of a sensor tip on five axes above an NV-doped (approximately 3.5 ppm) 15- μm -sized microdiamond (MDNV15umHi, Adamas Nanotechnologies) using the device's imaging system, as shown in Fig. 2. Using

this platform, the sensor can be used as a single-fiber or dual-fiber sensor, as depicted in Figs. 1(c) and 1(d), respectively. A detailed description of all steps of the fabrication is given in the next subsections.

A. Sensor platform

The sensor's fabrication starts with the platform, which consists of two optical fibers (FG050LGA and 460HP, Thorlabs) and two silver wires with a diameter of 100 μm . Fibers and wires are then inserted into a ceramic ferrule with an inner diameter of 270 μm and an outer diameter of 1.25 mm (CFX270-10, Thorlabs), as depicted in Fig. 1(a). The fibers, wires, and ferrule are chosen to fit tightly, ensuring a repeatable arrangement, as shown in Figs. 1(a) and 1(b). Protective tubing for optical fibers (FT900KB and FT900KK, Thorlabs) jackets the silver wires and optical fibers. The tubing is connected to the ceramic ferrule in a metal or polycarbonate sleeve, as shown in Fig. 1(a). The sensor platform's elements are then fixed in position using epoxy (353NDPK, Thorlabs) and polished after curing using optical-fiber polishing tools.

B. Sensor-tip fabrication

The fabrication of the sensor tip starts by creating a silver antenna structure using a photoactivated reduction process that has already been introduced in Ref. [46]. Therefore, the sensor platform is positioned as shown in Fig. 2. For the silver laser writing, additionally, a small reservoir filled with a silver resist encompasses the sensor's tip. Using a 2D silver resist [46,51] and a 20×0.5 NA objective (EC Epiplan-Neofluar, Zeiss), we directly write a silver microstrip-like antenna with a width of 10 μm and a thickness of 5 μm , as shown in Fig. 1(b). After rinsing the tip with water to remove unprocessed resist, the structure can already be used to excite the microwave transitions of

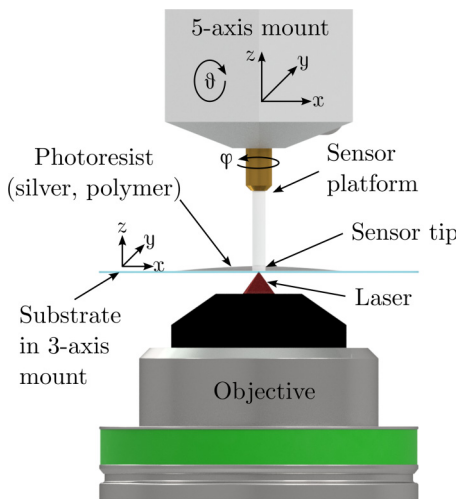


FIG. 2. Mounted sensor platform during the direct laser-writing process. The resist used is either a water-based silver solution or a polymer resist with suspended diamonds.

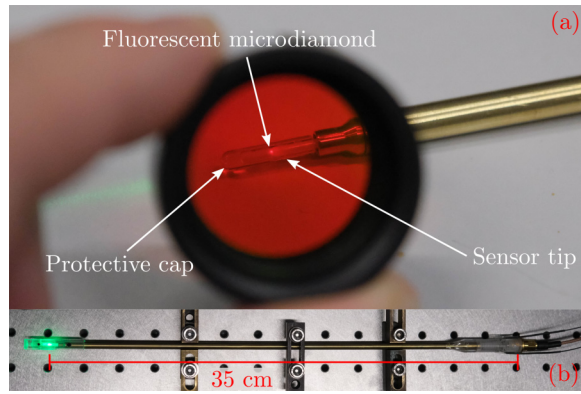


FIG. 3. Images of the assembled sensor with a total length of approximately 35 cm. (a) Close view of the sensor tip encased in a brass rod with an additional protective cap. The fluorescence of the diamond during excitation through the multimode fiber is shown through a long-pass filter (>600 nm). (b) Entire sensor, including the additional optional cap for a constant bias magnetic field, the optical fibers, and the SMA connector for the MW signal connection at the back of the sensor.

NV centers without further processing. Optionally, a subsequent galvanization step can be conducted after the silver direct laser-writing process, which increases the efficiency of the MW emission and lowers the ohmic resistance of the antenna by approximately 1 order of magnitude. For the sensor shown in Fig. 3 we galvanized the structure for 2 min at 0.7 V using a commercial silver solution, which reduced the ohmic resistance from approximately $35 \pm 0.5 \Omega$ to approximately $3.3 \pm 0.5 \Omega$ when measured at the SubMiniature version A (SMA) connector, which is soldered to the end of the silver wires.

To connect a diamond containing NV centers to an optical fiber, the tip of the multimode (MM) fiber is positioned $50 \mu\text{m}$ above the diamond using an external five-axis stage, along with the stages and imaging system of the Nanoscribe microscope, as depicted in Fig. 2. We use a polymer resist (IP Visio), which provides low fluorescence and high optical transparency in the visible spectrum [52]. As a connecting and light-guiding element, a cone structure is direct laser written between the core of the MM fiber and the diamond. The base of the cone is adapted to the size of the core of the MM fiber, and the tip of the cone is designed to be slightly larger than the diamond. Due to the scattering of the laser beam in the center of the cone caused by the microdiamond, the structure is written hollow using only contour lines. A second polymer structure is written between a single-mode (SM) fiber and the diamond to connect the SM fiber to the diamond for an additional optical-excitation beam path. It is shaped such that optical-excitation light hits the diamond from the side, reducing the overall excitation light in the MM fiber, as depicted in Figs. 1(c) and 1(d). The written structure is postcured

using an ultraviolet light-emitting diode after the chemical development. Further details can be found in Appendix A.

As a last step, the sensor is mounted in an optional metallic or plastic tube with a 5-mm outer diameter and a 3-mm inner diameter to enhance mechanical stability, as shown in Fig. 3(a). The antenna's resonance is tuned by measuring the S_{11} parameter and iterative shortening of the silver wires until a resonance of the S_{11} parameter is measured at 2.8 ± 0.2 GHz. An image of the assembled sensor is shown in Fig. 3(b). The distance between the MW connector and the tip is approximately 35 cm, while the optical fibers have a length of approximately 1.7 m, making the sensor easy to mount and hold but flexible.

III. RESULTS

The sensor's design is characterized by its potential to reduce autofluorescence in the detecting optical fiber and its sensitivity. The optics enclosure, depicted in Fig. 4, is used for all measurements. A detailed description of the optical setup is given in Appendix B.

A. Fluorescence measurements

Before characterizing the sensitivity of our sensor, we measure its relevant fluorescence properties and the reduction of the autofluorescence due to the use of the dual-fiber sensor, as depicted in Fig. 1(d). For this purpose, first, the transmitted laser power in the detecting MM fiber in the dual-fiber configuration with the attached structure and diamond is measured and compared to the laser power coupled into the SM fiber. Next, the autofluorescence intensity at a given laser power in an identical unprocessed MM fiber without an attached diamond and the sensor's fluorescence in the single-fiber configuration are measured. We then calculate the reduction in laser power by comparing the amount of laser power guided in the detecting MM fiber in both configurations. Assuming a linear scaling of the autofluorescence with the laser power, the potential reduction in autofluorescence arising from the transmitted light is estimated. From this ratio, we calculate the minimal possible diamond size in a dual- and single-fiber-based sensor, where the fluorescence of the diamond is not drowned out by the autofluorescence of the fiber.

For the first measurement, we detect a transmitted laser power through the detecting MM fiber in the dual-fiber configuration of $2.04 \mu\text{W}$ at a laser power transmitted through the SM fiber of 1.64 mW . Thus, we find a reduction of the laser light in the detection fiber by a factor of 804. Next, we measure the amount of autofluorescence and fluorescence transmitted through a long-pass filter with a cutoff wavelength of 650 nm and neutral-density (ND) filters using a single-photon counting module (SPCM). The absolute count rate is calculated by applying correction factors for each ND filter at the given transmission value at a wavelength of 685 nm, close to the NV center's

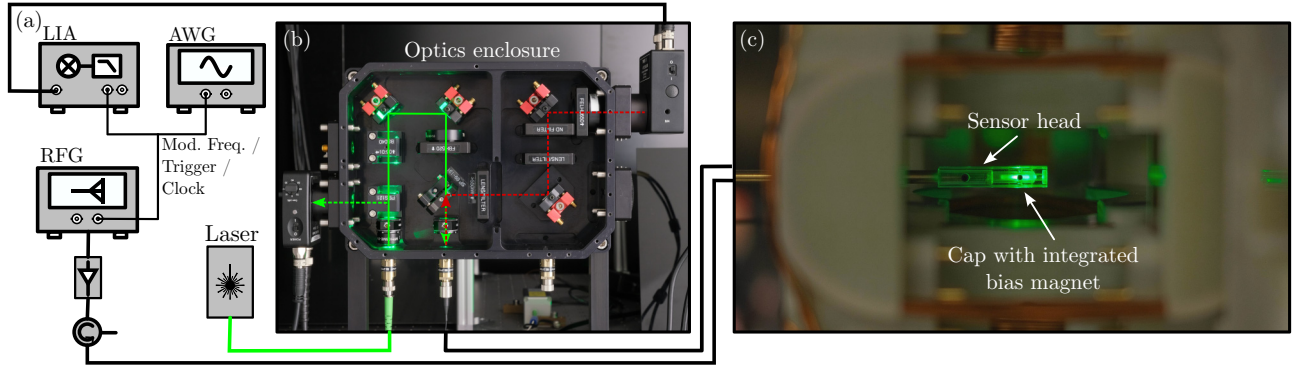


FIG. 4. Schematics of the electrical and optical setup, specifically in a configuration for lock-in amplifier (LIA) measurements. (a) The MW signal is frequency modulated and directly connected to the sensor. The fluorescence signal, measured either with a photodiode (PD) or an avalanche PD (APD), is demodulated and filtered by a LIA. (b) Optical-fiber coupling is conducted in a custom anodized enclosure, milled from aluminium. A first half-wave plate and a polarizing beam cube ensure a linear polarization of the in-coupled laser light and allow monitoring of changes in laser power caused by fluctuations in the polarization via a PD. A second nonpolarizing beam cube allows monitoring of the optical excitation power and can be used for further improvements using balanced detection schemes. Neutral-density (ND) and laser clean-up filters can be inserted, if needed, before the laser light is coupled into the sensor-head fiber. The collected fluorescence is either separated by a dichroic mirror for single-fiber measurements or, for dual-fiber measurements, fluorescence collected from the sensor head is guided back through the second fiber into the optical setup and then filtered with a long-pass filter. Finally, the fluorescence intensity is either measured by a PD or an APD or coupled to a MM fiber, which guides the fluorescence light to a single-photon counting module (SPCM). (c) The sensor head inside of the coil system. A bias magnetic field can be applied with a screw-on cap containing an integrated magnet.

maximum emission wavelength of 684 nm at room temperature [53]. We detect an autofluorescence intensity of 3.9×10^8 cps (counts per second) from the unprocessed MM fiber and 3.3×10^{12} cps of fluorescence light from the 15- μm -sized diamond at an excitation laser power of 2.2 mW in the single-fiber configuration. This yields a contrast ratio of approximately $\frac{8410}{1}$, from which we estimate the minimal diamond size necessary to have a contrast ratio $\text{SNR} = 1$. Hence, we find a minimum size of 740 nm when assuming a constant laser power and a constant NV doping in a single-fiber configuration. In comparison, integrating much smaller diamonds on the tip of a fiber down to a size of 79 nm and the same NV-doping of (approximately 3.5 ppm) is possible with a dual-fiber configuration, enabling even higher spatial resolution in the same sensor package; however, we also find a reduction in the fluorescence intensity by a factor of 9.9 in the dual-fiber configuration. We attribute this reduction to the worse coupling efficiency of the single-mode fiber and limitations in the fabrication process, where the used air objective provides an elongated focus shape, resulting in an imperfect, elongated waveguide structure.

In summary, the dual-fiber-based approach overcomes elementary issues associated with autofluorescence when using smaller diamond sizes, which can be realized using the same setup; however, the losses due to the imperfect waveguide structure significantly reduce the amount of fluorescence. Consequently, we achieve better sensitivities in the single-fiber configuration, knowing that the SNR is only moderately affected when using a 15- μm -sized

diamond, and the fluorescence, due to more efficient usage of laser power, is approximately 10 times higher. Therefore, if not stated otherwise, the subsequent measurements were conducted in a single-fiber configuration. For smaller diamonds, however, physical separation of the light path for excitation and detection yields significant advantages, and technical limitations can be overcome by using immersion objectives with higher numerical apertures. Results of a similar structure with a similar resist (OrmoComp, micro resist technology), a slightly modified design that compensates for the physical elongation, and a 25×0.8 NA immersion objective yield an identical efficiency in the optical excitation in both configurations. Therefore, we expect that the result is mainly limited by the imperfect structure.

B. Sensitivity characterization

Sweeping over a range of MW frequencies results in an ODMR spectrum of the NV resonances, as shown in Fig. 5. We track the X component of the lock-in amplifier (LIA) output over time, and the MW frequencies are calculated via the sweeping time.

An unconstrained nonlinear least-squares fit method (Levenberg-Marquardt) [54] is used to fit a model function of a sum of the derivatives of eight Lorentzian distributions

$$L(f) = \sum_{i=1}^8 -\frac{32\sqrt{3}}{9} \frac{C_i w_i^3 (f - f_i)}{(4(f - f_i)^2 + w_i^2)^2}, \quad (1)$$

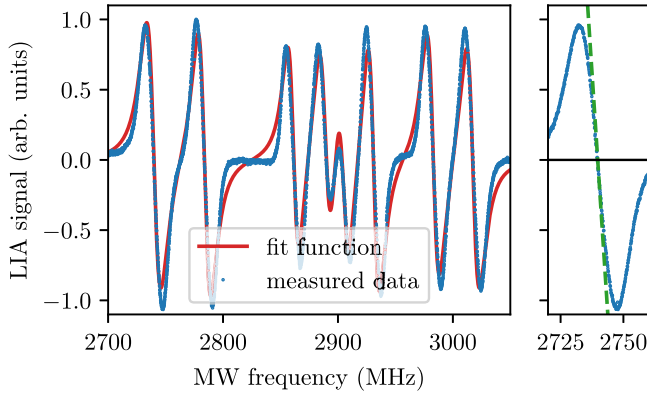


FIG. 5. Left: lock-in-amplified ODMR signal while a bias magnetic field is applied (solid blue). Resonances are fitted with derivatives of Lorentzian functions (red), where the zero-crossing marks the resonance frequency. Right: the magnetic-field sensitivity is dependent on the calculated slope at the zero-crossing point that is visualized as a dashed green line.

where for the i th resonance [$i \in (1, \dots, 8)$], C_i is the peak contrast, defined as the maximum value, f_i is the resonance frequency, and w_i is the FWHM linewidth. We found that to automate the selection of starting points for the fit model, using the mean abscissas between the peaks and valleys for each resonance frequency leads to reasonably stable fitting behavior.

The achieved magnetic-field sensitivity is highest at the zero-crossing point, where the fit function has a maximal slope $S_i = \frac{32\sqrt{3}}{9} \frac{C_i}{w_i}$. A small change in the external magnetic field along the NV axis will shift the resonances by the gyromagnetic ratio $\gamma = g_e \mu_B / h \approx 28.03 \text{ GHz T}^{-1}$ of the NV center [3]. The output of the LIA will then react with a change of output voltage at the previous resonance frequency of magnitude

$$R_i = \gamma S_i = \frac{32\sqrt{3}}{9} \frac{g_e \mu_B}{h} \frac{C_i}{w_i}, \quad (2)$$

where R is called the magnetometer response. The magnetic-field sensitivity, defined as the minimal change of magnetic field δB that can be resolved in a given time t , is related to the standard deviation of the LIA output σ , the magnetometer response R and the noise-equivalent power (NEP) bandwidth of the LIA's low-pass filter f_{NEP} [55]

$$\eta_{\text{LIA}} = \delta B \sqrt{t} = \frac{\sigma}{R \sqrt{2f_{\text{NEP}}}} \left[\text{T}/\sqrt{\text{Hz}} \right]. \quad (3)$$

We reach an optimal sensitivity of $51.8 \text{ nT}/\sqrt{\text{Hz}}$ for one continuous ODMR sweep for a MW power of 50 mW and laser power of 2.15 mW. A more detailed discussion about optimizing measurement parameters can be found in Appendix C.

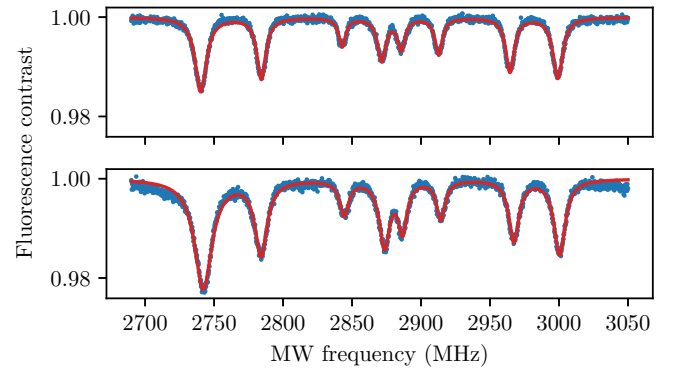


FIG. 6. The upper graph shows the ODMR spectrum when exciting and detecting via the MM fiber of the sensor. The lower graph shows the ODMR spectrum when exciting via the SM fiber and detecting through the MM fiber. Resonances are fitted with Lorentzian functions (red) to obtain contrast and linewidth.

To estimate the photon shot-noise limit, we average over multiple ODMR measurements with an SPCM at the same MW and laser powers and calculate the shot-noise-limited sensitivity for each axis according to [56]

$$\eta_{\text{SN}} = \frac{4}{3\sqrt{3}} \frac{h}{g_e \mu_B} \frac{w}{C \sqrt{I_0}} \left[\text{T}/\sqrt{\text{Hz}} \right], \quad (4)$$

where I_0 is the photon collection rate, corrected for optical losses due to the filters and the detector efficiency. The optimal shot-noise-limited sensitivity for one resonance is $5.9 \text{ nT}/\sqrt{\text{Hz}}$. To test our two-fiber scheme for reducing the impact of fiber autofluorescence, we compare the sensitivity to an otherwise identical measurement but excite the NV centers via the SM fiber and still detect the signal using the MM fiber. The ODMR spectra, in which we optically excite the NV centers via the MM and SM fiber, are shown in Fig. 6. The sensitivity of all NV axes is listed in Table I. The best shot-noise-limited sensitivity of our sensor is achieved when exciting and detecting through the MM fiber ($5.9 \text{ nT}/\sqrt{\text{Hz}}$) compared to the identical measurement with excitation through the SM fiber ($27.7 \text{ nT}/\sqrt{\text{Hz}}$). We attribute this decrease in sensitivity to a reduced fluorescence due to a lack of optical excitation power from the SM fiber and MW-induced power broadening of the linewidth. Normalizing the sensitivity with respect to the volume of the diamond enables comparability with other sensors and, thus, the characterization of the efficiency of the sensor platform independent of the size of the diamond. Therefore, we multiply the sensitivity by the square root of the diamond size or the sensor volume, as the sensitivity increases with the square root of the number of emitting spins. The volumetric SN-limited sensitivity related to our total sensor head size is $42.9 \text{ mm}^{3/2} \times \text{nT}/\sqrt{\text{Hz}}$ and to the diamond size is $7.8 \text{ mm}^{3/2} \times \text{pT}/\sqrt{\text{Hz}}$ assuming a homogeneous $15\text{-}\mu\text{m}$ -sized sphere for the diamond.

C. Noise floor

Next, we characterize the noise floor of our sensor by keeping the MW excitation frequency fixed to one resonance and evaluating the amplitude spectral noise density (SND) [31,57,58] and the overlapping Allan deviation [59].

For the SND, the resulting signal is binned into windows of 1-s duration. We then calculate the absolute value of the averaged single-sided discrete Fourier transform $|\mathcal{F}|$ of the signal. The SND follows from the relation [35,60]

$$\text{SND} = \frac{|\mathcal{F}|}{R} \sqrt{\tau} \left[T/\sqrt{\text{Hz}} \right], \quad (5)$$

where the Fourier transform is scaled by the magnetometer response R and the single-sided bandwidth $1/\tau$ of the rectangle window function, which results from the binning of the discrete Fourier transform. The bandwidth scaling is proportional to $\sqrt{\tau}$, because we consider the amplitude SND, which is the square root of the power SND. We note that in some reports, the amplitude is defined as the root-mean-squared amplitude [60,61], leading to a scaling difference of $1/\sqrt{2}$ in SND. When recording the X component of the LIA output signal, the signal is said to be magnetically sensitive, while recording the Y component, which is not dependent on magnetic field changes, denotes the magnetically insensitive case. Additionally, we measure the noise without laser excitation, resulting in only electrical noise from the PD and the LIA [35]. Figure 7 shows the SND for all three cases. We notice uncanceled noise peaks at multiples of approximately 300 Hz. Because these peaks appear in both the magnetically sensitive and insensitive cases, we attribute this noise to our laser. In the future, we plan to employ balanced photodetection schemes [55] to further mitigate laser noise.

The bandwidth of our sensor is limited by the 3-dB bandwidth of the low-pass filter of our LIA to 80.9 Hz, as indicated by the inset in Fig. 7(a). We reach a mean SND of $74.6 \text{ nT}/\sqrt{\text{Hz}}$ in this bandwidth. When ac magnetic fields with higher bandwidths are to be recorded, the bandwidth of our sensor can be extended up to the modulation frequency of the LIA. The modulation frequency can then also be further extended to higher frequencies [55]; however, a trade-off between modulation frequency and sensitivity is then necessary, as discussed in Appendix C.

To characterize the long-term stability of our sensor, we record a dataset for a longer time of approximately 15 h and calculate its overlapping Allan deviation. We reach a minimal sensitivity of 21.3 nT for an integration time of 41 s, as shown in Fig. 7(b). We conclude that the integration of optical fibers, a MW antenna, and the NV-doped diamond in a fixed package on our sensor head results in a highly stable sensor platform that is capable of resolving magnetic fields down to the nT range.

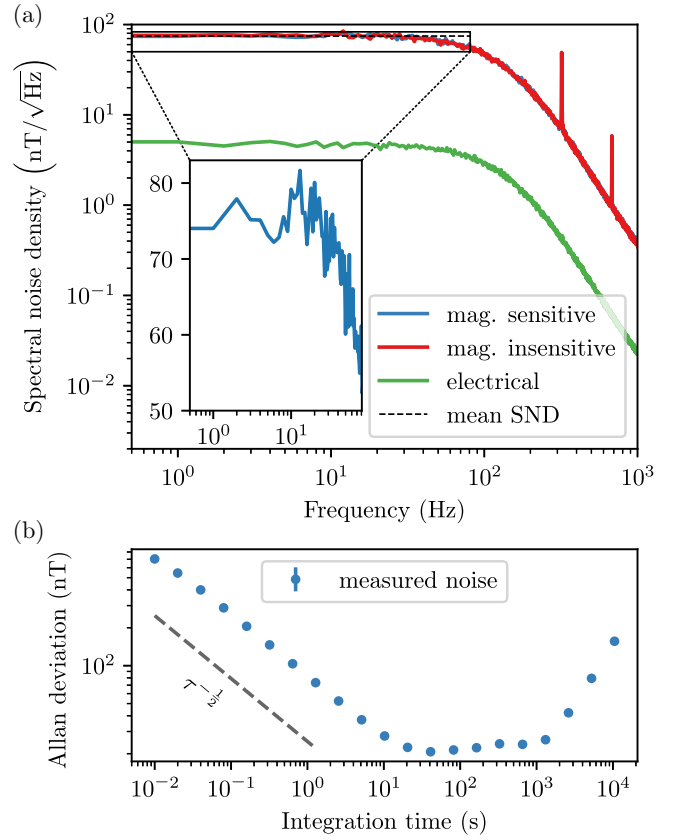


FIG. 7. (a) Amplitude spectral noise density of our sensor for magnetically sensitive (blue), magnetically insensitive (red), and electrical (green) noise measurements. We reach a mean spectral noise density of $74.6 \text{ nT}/\sqrt{\text{Hz}}$ (dashed black) in a 3-dB bandwidth of 80.9 Hz. (b) Overlapping Allan deviation of our sensor. Error bars for the Allan deviation are too small to be visible.

D. Magnetic field measurements

We demonstrate a magnetic-field measurement of a complex 3D anti-Helmholtz coil system to illustrate the real-world benefits that NV-based sensors bring over conventional solutions like Hall sensors.

The vectorial sensing capability of our sensor allows us to measure the direction of the magnetic field directly in a single measurement without the need to measure in multiple directions, in contrast to a Hall sensor with a single Hall element. In our implementation, the resolution is given by the sensing volume of the NV diamond, which has a size of $15 \mu\text{m}$. Here, we use spatial resolution in the intrinsic sense, i.e., the smallest spatial variation of the magnetic field that can be resolved at the sensor location. While the effective resolution in planar magnetic structures also depends on sensor-sample distance, for volumetric fields, the intrinsic limit set by the diamond size is dominant. For this, our sensor is fastened to a stage and moved in three dimensions through the magnetic field, and a screw-on cap with integrated permanent magnets is fixed to the tip of our sensor to apply

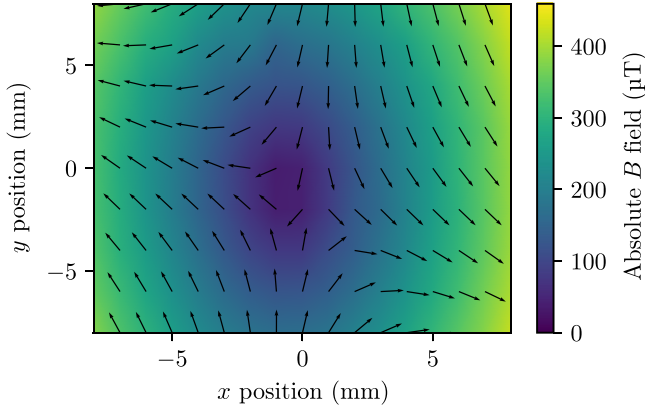


FIG. 8. Contour plot of the interpolated measured Helmholtz-coil magnetic field in an anti-Helmholtz configuration. Absolute field values are shown as a color bar. The x and y components of the field vector are shown as black arrows, and the base of each arrow represents the measured position.

a bias magnetic field of 10.3 mT, as depicted in Fig. 4. Triangle-shaped sweeps of the microwave frequency at each position of the translation stages were performed to mitigate the influence of delays between the sweep and data recording, and the following resonance frequency calculations are always averaged between one up-scan and one down-scan. We then calculate the absolute value of the magnetic-field vector B for each NV axis j from its upper and lower resonance frequencies $f_{u,j}$ and $f_{l,j}$, according to Appendix D. To calibrate the sensor with the applied bias field, we calculate one magnetic-field vector without a coil magnetic field. This bias field is then subtracted from subsequent measured field vectors. Figure 8 shows one scan

of magnetic-field vectors in one xy plane of many slices in the z direction inside the 3D coil system. In conclusion, the experiment demonstrates the necessity of a robust sensor that is capable of three-dimensional movement with vectorial-field sensing in a volumetric field. This approach benefits from the small size of the sensing NV-diamond and thus achieves high spatial resolution.

E. Comparison of sensor designs

To provide a better overview, we compare other fiber-based sensors in the field to our approach in Fig. 9(a) in terms of sensitivity and effective diamond size l_{eff} , which we calculate as the cube root of the given diamond volume. In what follows, we use l_{eff} as a measure of the intrinsic spatial resolution of the sensing element. Alternatively, one could consider the excited volume of the diamond, often referred to as the effective sensing volume, since the full diamond volume is not always excited. We also note that the effective resolution in a given experiment additionally depends on the type of sample. For example, when planar quasi-2D magnetic surfaces need to be mapped, the sample-sensor distance needs to be taken into account; however, for volumetric magnetic fields inside three-dimensional coil systems, the effective resolution is limited by the size of the sensing element. This effective volume is not always given, and technological advantages also lie in efficiently attaching a diamond to a fiber. Therefore, we compare the sensitivity to the diamond size in Fig. 9 and, for completeness, include the comparison for the given effective sensing volume in Appendix E. For our sensor, we consider the diamond to be fully illuminated.

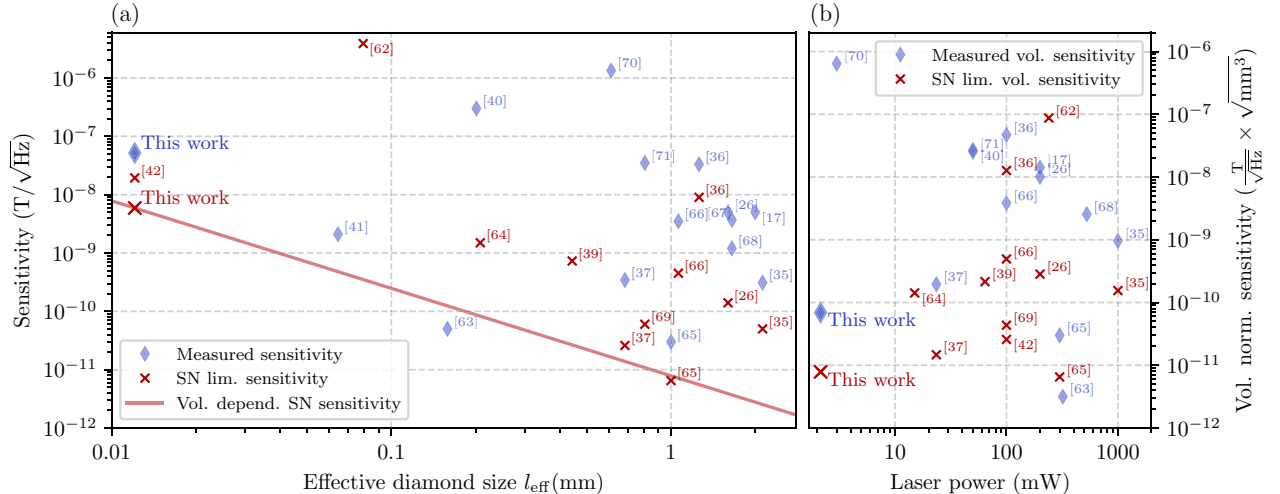


FIG. 9. (a) Measured and shot-noise-limited calculated sensitivities of the present work and other publications [62–71] for different effective diamond sizes. The values for measured sensitivities represent retrieved values from noise and time-trace measurements, compared to shot-noise-limited sensitivities, which are calculated from the measured contrast, linewidth of fit data, and photon count rate. (b) Normalized sensitivity of the presented sensors with respect to the individual diamond volume at the given laser power. The bandwidth of the presented sensors is set differently in most cited publications and is therefore not compared.

In Fig. 9 and in Appendix E, we plot the values for shot-noise-limited and measured sensitivities that are obtained using lock-in techniques and noise and time-trace measurements. Both values—the SN-limited and measured sensitivities—are important metrics. The SN-limited sensitivity has the advantage of being independent of noise sources, e.g., electronic or magnetic field background noise. Therefore, the SN-limited sensitivity specifies the sensor’s capabilities independent of the environment. In contrast, the measured sensitivity is the value that represents the capabilities in a given technical setup and environment, including the existing background. Furthermore, many publications provide only shot-noise-limited sensitivity values, while others present only the measured sensitivity. Assuming that the sensitivity scales in proportion to $1/\sqrt{N}$, where N is the number of spins and N scales in proportion to the diamond volume, we include a line that shows the expected sensitivity if one could increase the diamond size, ignoring other effects such as coupling efficiency, field and diamond inhomogeneities, collective NV effects, and scattering.

In Fig. 9(a), a sensor with a sensitivity below the red line could be achieved by more efficient collection of fluorescence light, a brighter diamond, a higher fluorescence contrast, or a smaller linewidth. As shown, only a few publications reach this line, yet the presented ones use externally attached MW antennas or ^{12}C -enriched diamonds, tracking pulse techniques, and use larger diamonds. Furthermore, in Fig. 9(b), we plot the normalized sensitivities of the presented sensors by the respective diamond volume for the given laser powers. Here, our sensor provides one of the best volume-normalized sensitivities at the lowest laser power, making it especially suitable for light-sensitive applications.

IV. CONCLUSION AND OUTLOOK

The miniaturized fiber-based sensor we present here provides a small sensor platform capable of measuring magnetic fields in full vectorial resolution. The direct laser writing of polymer and silver structures onto the sensor’s tip enables us to fully integrate the diamond and a microwave antenna onto the sensor head. Together with a diamond size (and thus spatial resolution) of $15\ \mu\text{m}$, we have demonstrated a highly sensitive, small, and robust sensor platform, and we show an integrated fiberized NV-based sensor with a single diamond with the smallest diamond size published to date. In the single-fiber configuration, we achieve a shot-noise-limited sensitivity of $5.9\ \text{nT}/\sqrt{\text{Hz}}$ while only using $2.15\ \text{mW}$ of laser power and $50\ \text{mW}$ of microwave power. The sensitivity of the sensor using lock-in-amplification techniques is $51.8\ \text{nT}/\sqrt{\text{Hz}}$ at the same powers and configuration.

When analyzing the fluorescence properties of our sensor, we find that with our approach, we can reduce the

amount of autofluorescence in the detecting fiber by a factor of approximately 800, thus enabling the integration of even smaller diamonds with only a small impact on the SNR. We emphasize that losses in laser light and slightly reduced sensitivity in the dual-fiber configuration result from an imperfect waveguide structure. The air objective used provides an elongated voxel shape, and thus an elongated structure, significantly affecting light-guiding properties. Sensors with an optimized structure using an immersion medium-matched objective with a higher NA exhibit identical excitation efficiency, independent of the fiber used for excitation. Using our sensor, we show, as a practical use case, the measurement of vectorial magnetic fields of a coil system. Furthermore, we emphasize that our approach shows that reducing the total sensor size can achieve high sensitivities at low laser and microwave powers, enabling light- and microwave-sensitive measurements.

The presented platform provides a physically robust solution for the sensor head with flexible cables and fibers, allowing the integration of diamonds of varying sizes and achieving high sensitivity. The dual-fiber configuration, while critical to manufacture precisely, allows the integration of diamonds of varying sizes and can overcome the autofluorescence limitations of single-fiber sensors down to a diamond size below $100\ \text{nm}$. Integration of diamonds below the optical resolution of the microscope system is possible; however, further techniques are needed to identify single diamonds, e.g., by ODMR measurements of a sample with a magnetic field applied just before attaching a diamond to the sensor tip.

In addition to the CW ODMR measurements shown here, our sensor platform is compatible with the full range of pulsed magnetometry schemes. The technical capability to pulse the laser and MW excitation can be added independently of the sensor platform, for example, by switching the laser diode current and the MW signal with a PIN diode. Pulsing laser and MW excitation would allow the implementation of all known coherent spin control sequences like Rabi, Ramsey, or spin-echo measurements. Such pulsed measurements then allow for the measurement of not only dc magnetic fields but also ac magnetic-field measurements. Pulsed measurement sequences can further improve the magnetic-field sensitivity by suppressing specific noise sources.

In conclusion, we present a reliable, reproducible sensor platform for fiberized fluorescent particle sensors at small scales with high volume-normalized sensitivity. We use functional photonic waveguide polymer and silver-antenna structures on the tips of optical fibers and electrical wires and show an approach to overcome existing limitations of autofluorescence. The presented sensor platform and techniques also pave the way for future developments of advanced fiber-based sensors that could potentially integrate multiple diamonds of varying

sizes and networks, combined with advanced photonic structures.

V. DATA AND CODE AVAILABILITY

All data shown in the images and plots, along with data supporting the findings in this publication, are available on Zenodo [72]. The code library used to control the devices for all measurements can be found in Ref. [73].

ACKNOWLEDGMENTS

We acknowledge support by the Nano Structuring Center (NSC). This project was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Project No. 454931666, the German Federal Ministry of Education and Research (BMBF) as part of the QuanTEAM project (FKZ13N16467), and the Quanten-Initiative Rheinland-Pfalz (QUIP). Furthermore, we thank Dr. Erik Hagen Waller for providing the silver resist as well as Professor Dr. Georg v. Freymann, Professor Dr. Elke Neu-Ruffing, Alexander Bukschat, Nimba Pandey, Oliver Opaluch, and Tobias Pätkau from the RPTU University Kaiserslautern-Landau for helpful discussions and experimental support. We also thank Dr. Gesa Welker and Dr. Samer Kurdi from the van der Sar Lab at TU Delft for their support on technical questions.

DATA AVAILABILITY

The data that support the findings of this article are openly available [72].

APPENDIX A: GEOMETRICAL DESIGN OF THE POLYMER STRUCTURE

A schematic image of the designed polymer waveguide structure is shown in Fig. 10.

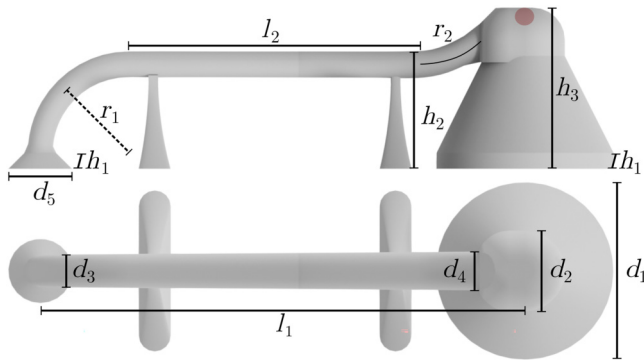


FIG. 10. Schematic rendering of the designed polymer structure and given geometries. The red dot indicates the intended position of the microdiamond.

The geometrical shape of the polymer structure is motivated by a set of functional and fabrication-related constraints. The primary objective is to fix a diamond above the core of a multimode fiber while ensuring efficient light guidance between the fiber and the diamond. Additionally, the structure must facilitate efficient coupling between a single-mode fiber and the diamond while minimizing coupling into the multimode fiber core. The width and shape of the polymer structure at the connection between the fiber core and the polymer structures need to be matched in diameter such that most light is guided from the fiber to the diamond. Furthermore, the structure has to be optimized for strength without interfering with the antenna or waveguide. To ensure structural integrity during the undocking process after direct laser writing, adhesion should be strong at the fiber tip and weak at the glass substrate. Therefore, the contact area between the fiber tip and the polymer structure must be maximized without affecting the light-guiding properties, which directly impacts d_1 , d_5 , and the geometry of the supporting structure. In contrast, the contact area between the glass substrate and the polymer structure must be minimized, which is achieved by different heights ($h_2 = 37 \mu\text{m}$) of the light-guiding waveguide structure and the attached diamond at the very tip h_3 , as well as by the diameter of the polymer material surrounding the diamond d_2 .

The base of the cone has a diameter of $d_1 = 55 \mu\text{m}$ and is slightly larger than the $50\text{-}\mu\text{m}$ -sized core of the MM fiber, having $5 \mu\text{m}$ of positional tolerance and slightly increasing the adhesion between the polymer structure and the optical fiber. Furthermore, the cone stands on top of an $h_1 = 5\text{-}\mu\text{m}$ -tall cylinder to compensate any tilts and focus mismatching and improve adhesion. The tip of the cone is designed to be slightly larger ($d_2 = 30 \mu\text{m}$) than the diameter of the $15\text{-}\mu\text{m}$ -sized diamond. The edges of the tip of the cone are also rounded to reduce physical contact with the glass substrate below. The total height h_3 is $50 \mu\text{m}$.

Due to scattering of the laser beam in the center of the cone caused by the microdiamond during the direct laser-writing process, the structure is written in 12 contour lines, with $0.4\text{-}\mu\text{m}$ spacing between them and a top-layer thickness below and around the diamond of only $12 \mu\text{m}$. Furthermore, a structure connecting an SM fiber to the diamond, providing an additional optical excitation-light-guiding beam path, is added. This waveguide structure consists of a small cone with a base diameter of $d_5 = 20 \mu\text{m}$ and height of $5 \mu\text{m}$, at which the cone diameter is $d_3 = 10 \mu\text{m}$. This cone has no effect on the optical properties but increases contact area, and the diameters d_3 and d_4 were set to be wide enough to fully illuminate the diamond as well as to have minimal impact on the light-collection efficiency of the cone above the MM fiber.

The radii of the curved waveguide structure are designed to be as large as possible, considering other boundary conditions. The initial $10\text{-}\mu\text{m}$ -wide waveguide follows a

90° curve with a radius of $r_1 = 28 \mu\text{m}$, continues as a straight line with a length of $l_2 = 88 \mu\text{m}$ and is then guided slightly upwards at a radius of $r_2 = 30 \mu\text{m}$, which directs light centrally to the designed diamond center position. At this position, the waveguide has a width of $d_4 = 12 \mu\text{m}$, which is increased gradually. For the chosen radii r_1 and r_2 , no significant change is expected based on previous work [74]. The waveguide structure is supported via two small towers and intentionally designed such that it does not bond to the glass substrate, which is at the same height as the diamond. Furthermore, the geometrical value of $l_1 = 150 \mu\text{m}$ is given by design from the diameters of the fibers $d_{\text{fiber}} = 125 \mu\text{m}$, wires $d_{\text{wire}} = 100 \mu\text{m}$, and inner ferrule $d_{\text{ferrule}} = 270 \mu\text{m}$. Further details of all direct laser-written structures can be retrieved from the computer-aided design models in the Supplemental Material.

APPENDIX B: MEASUREMENT SETUP

Our optical setup consists of a modular compact enclosure with a size of $215 \times 150 \times 58 \text{ mm}^3$, which contains all necessary optical elements as well as some optional elements to connect an excitation laser, fiber sensor, and various detectors. A fiber-coupled laser (Cobolt 06-MLD, Hübner Photonics) with a wavelength of 520 nm is used to excite the NV centers optically. To avoid damaging the sensor head through excessive heating, we limit the laser power to 2.2 mW in the subsequent measurements.

The laser light is directly coupled into the enclosure, where first, a half-wave plate (WPH05ME-514, Thorlabs) and a polarizing beam cube (PBS121, Thorlabs) ensure a linear polarization of the in-coupled laser light. The reflected part of the beam can be monitored by a PD, enabling the measurement of changes in power caused by fluctuations in polarization. A second nonpolarizing beam cube (BS040, Thorlabs) allows monitoring of the optical excitation power and can be used for further improvements using balanced detection schemes. ND filters and laser clean-up filters can be inserted if needed before the laser light is coupled into the sensor head fiber. The collected fluorescence is either separated by a dichroic mirror (SP 69-191, Edmund Optics) for single-fiber measurements or, for dual-fiber measurements, fluorescence collected from the sensor head is guided back through the second fiber into the optical setup and then filtered with a long-pass filter (FELH650, Thorlabs) and further optional ND filters. Finally, the fluorescence intensity is either measured by a photodiode (SM05PD3A, Thorlabs) or an APD (APD130A, Thorlabs) or coupled to a multimode fiber (M43L05, Thorlabs), which guides the fluorescence light to an SPCM (COUNT-T-100-FC, LaserComponents).

The MW signal used is first generated by a radio-frequency generator (SMB100A, Rohde&Schwarz) and then further amplified by an amplifier (ZHL-16W-43-S+, Mini-Circuits) by 46 dBm. We limit the MW power in

the subsequent measurements to approximately 50 mW to avoid thermally damaging the sensor head; however, we see significant broadening of the ODMR linewidths, indicating that our sensitivity is not limited by the MW power. A coaxial isolator (JIC2700T3500S2, JQL Technologies) is inserted to avoid back reflections before the MW signal is guided via the SMA connector to the fiber-head antenna. To determine the actual microwave power at the sensor, we measure the absolute gain between the MW signal generator and the SMA connector of the sensor with a vector network analyzer (MS2038C, Anritsu). We obtain an absolute amplification of the signal in combination with all loss elements (circulator, amplifier, connectors, and connecting cable) of 38 dB.

To perform lock-in amplification of the measured PD/APD signal, we sine-wave modulate the MW frequency. The required reference signal is generated by an arbitrary waveform generator (33622A, Keysight). The PD/APD signal is ac coupled, using a 100-nF capacitance in series, to an LIA (MFLI 500 kHz, Zurich Instruments), which demodulates and filters the signal. We apply a third-order low-pass filter with a 1-ms time constant (equivalent to a 3-dB bandwidth of 80.9 Hz or a noise-equivalent power bandwidth of 93.5 Hz) with the LIA. The phase shift between the reference signal and the measured fluorescence signal is always chosen to maximize the signal of the X component.

All devices are connected to the same 10-MHz clock reference signal. Appendix C contains a more detailed discussion about optimizing individual measurement parameters.

APPENDIX C: SENSITIVITY OPTIMIZATIONS

Optimizing all eight ODMR resonances for their best sensitivity simultaneously is generally not possible. Due to imperfect optical and MW addressing, each resonance

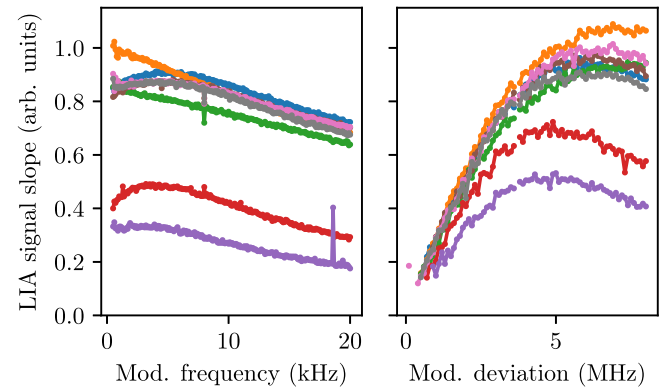


FIG. 11. Zero-crossing slope of the LIA output for all eight resonances as a function of MW modulation frequency (left) and modulation deviation (right), with each color representing one resonance. Each resonance generally has a different set of parameters where the zero-crossing slope, and therefore the magnetic-field sensitivity, is maximized.

TABLE I. Magnetic-field sensitivities for each resonance.

No.	η_{LIA}	$\eta_{SN,MM}$	$\eta_{SN,SM,MM}$
1	60.0 nT/ $\sqrt{\text{Hz}}$	6.14 nT/ $\sqrt{\text{Hz}}$	30.0 nT/ $\sqrt{\text{Hz}}$
2	53.8 nT/ $\sqrt{\text{Hz}}$	5.90 nT/ $\sqrt{\text{Hz}}$	30.5 nT/ $\sqrt{\text{Hz}}$
3	60.9 nT/ $\sqrt{\text{Hz}}$	9.89 nT/ $\sqrt{\text{Hz}}$	48.2 nT/ $\sqrt{\text{Hz}}$
4	70.4 nT/ $\sqrt{\text{Hz}}$	7.95 nT/ $\sqrt{\text{Hz}}$	29.7 nT/ $\sqrt{\text{Hz}}$
5	77.2 nT/ $\sqrt{\text{Hz}}$	9.70 nT/ $\sqrt{\text{Hz}}$	33.9 nT/ $\sqrt{\text{Hz}}$
6	51.8 nT/ $\sqrt{\text{Hz}}$	8.17 nT/ $\sqrt{\text{Hz}}$	40.9 nT/ $\sqrt{\text{Hz}}$
7	57.5 nT/ $\sqrt{\text{Hz}}$	6.34 nT/ $\sqrt{\text{Hz}}$	30.1 nT/ $\sqrt{\text{Hz}}$
8	59.2 nT/ $\sqrt{\text{Hz}}$	6.50 nT/ $\sqrt{\text{Hz}}$	27.7 nT/ $\sqrt{\text{Hz}}$

will have a slightly different contrast and linewidth and, therefore, a different set of optimal measurement parameters, especially when one changes laser power, MW power, MW modulation frequency, or MW modulation deviation. Figure 11 shows, as an example, the dependence of the LIA signal slope on the MW modulation frequency and deviation.

This leads to the fact that each resonance has its own sensitivity. Table I lists our achieved sensitivities for each resonance of the ODMR spectrum shown in Figs. 5 and 6.

APPENDIX D: MAGNETIC-FIELD CALCULATION

To calculate the magnetic field from measured resonances, we solve the NV Hamiltonian analytically, following Ref. [75]. Consider the shifted Hamiltonian for one NV center [3] with $\text{Tr}(H) = 0$,

$$H = DS_z^2 + E(S_x^2 - S_y^2) + \frac{\vec{B}}{\gamma} \cdot \vec{S} - \frac{2}{3}DI, \quad (\text{D1})$$

where $D = 2.87 \text{ GHz}$ is the zero-field splitting, $E \approx 5 \text{ MHz}$ is the diamond-dependent stress splitting, $\vec{B}$ is the magnetic-field vector, $S_{x,y,z}$ are the 3×3 Pauli matrices, and I is the unit matrix. Without loss of generality, the magnetic field $\vec{B} = \gamma B(\sin \theta \hat{x} + \cos \theta \hat{z})$ can always be rotated around the NV axis to remove the B_y component, where θ is the angle between the magnetic-field vector and the NV axis. The roots of the characteristic polynomial are then given by

$$0 = \lambda^3 - \left(\frac{1}{3}D^2 + E^2 + B^2 \right) \lambda - \frac{1}{2}DB^2 \cos(2\theta) - EB^2 \sin^2 \theta - \frac{1}{6}DB^2 + \frac{2}{27}D^3 - \frac{2}{3}DE^2. \quad (\text{D2})$$

This polynomial has three real roots λ_1 , λ_2 , and λ_3

$$(\lambda - \lambda_1)(\lambda - \lambda_2)(\lambda - \lambda_3) = \lambda^3 - (\lambda_1 + \lambda_2 + \lambda_3)\lambda^2 + (\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_1\lambda_3)\lambda - \lambda_1\lambda_2\lambda_3. \quad (\text{D3})$$

When defining upper and lower resonance frequencies as $f_u = \lambda_3 - \lambda_1$ and $f_l = \lambda_2 - \lambda_1$, these roots can be expressed as $\lambda_1 = (-f_u - f_l)/3$, $\lambda_2 = (2f_l - f_u)/3$, and $\lambda_3 = (2f_u - f_l)/3$, respectively.

We compare the individual terms of Eqs. (D2) and (D3) to derive formulas for B^2 and $\cos^2 \theta$. Comparing linear terms leads to

$$B^2 = \frac{1}{3} (f_u^2 + f_l^2 - f_u f_l - D^2 - 3E^2), \quad (\text{D4})$$

while comparing constant terms leads to

$$\cos^2 \theta = \frac{2f_l^3 - 3f_l^2 f_u - 3f_l f_u^2 + 2f_u^3}{27(D - E)B^2} + \frac{2D^3 - 18DE^2}{27(D - E)B^2} + \frac{D - 3E}{3(D - E)}. \quad (\text{D5})$$

After measuring both resonance frequencies $f_{u,j}$ and $f_{l,j}$ for all four NV orientations j , Eq. (D4) gives us four independent measurements of the absolute value of the magnetic field. We can simply take the mean value of all four B_j as our final result B .

We now only know the angles θ_j between the magnetic-field vector and the NV axis j . This is akin to four cones in three-dimensional space, where we want to find the vector that best overlaps all four cones [76]. The magnetic-field direction can be obtained by considering the scalar product $\hat{n} \cdot \hat{b} = \cos \theta$ between the NV-axis unit vector $\hat{n}$ and the magnetic-field unit vector $\hat{b}$. This gives us a linear overdetermined system $Nb = c$ of four equations with three unknowns that can be written in matrix form as

$$\frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & -1 & -1 \\ -1 & 1 & -1 \\ -1 & -1 & 1 \end{pmatrix} \cdot \begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix} = \begin{pmatrix} \cos \theta_1 \\ \cos \theta_2 \\ \cos \theta_3 \\ \cos \theta_4 \end{pmatrix}, \quad (\text{D6})$$

where the matrix N is constituted of the unit vectors along the NV axes, which are parallel to $[111]$, $[1\bar{1}\bar{1}]$, $[\bar{1}1\bar{1}]$, and $[\bar{1}\bar{1}1]$, respectively [55].

The solution to this kind of linear least-squares problem is known to be $\hat{b} = (N^T N)^{-1} N^T c$ [77], which gives us our final magnetic-field vector $\vec{B} = \gamma \hat{B} \hat{b}$ as

$$\vec{B} = \gamma B \frac{\sqrt{3}}{4} \begin{pmatrix} 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \end{pmatrix} \cdot \begin{pmatrix} \pm \cos \theta_1 \\ \pm \cos \theta_2 \\ \pm \cos \theta_3 \\ \pm \cos \theta_4 \end{pmatrix}. \quad (\text{D7})$$

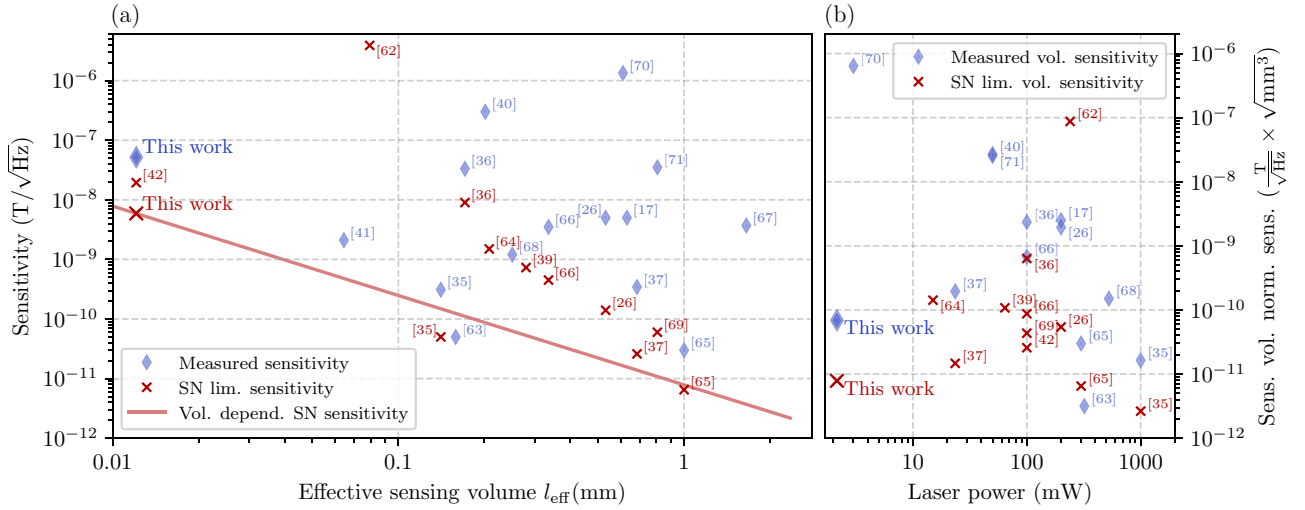


FIG. 12. (a) Measured and shot-noise-limited calculated sensitivities of the present work and other publications [62–71] for different effective diamond sizes with respect to the diamond or, if defined, sensing volume. The values for measured sensitivities represent retrieved values from noise and time-trace measurements, compared to shot-noise-limited sensitivities, which are calculated from the measured contrast, linewidth of fit data, and photon count rate. (b) Normalized sensitivity of the presented sensors with respect to the individual diamond or, if given, the sensing volume at the specified laser power. The bandwidth of the presented sensors is set differently in most cited publications and is therefore not compared.

Because of the ambiguity in $\pm \cos \theta$, we have 2^4 possible solutions $\hat{b}$; however, most of these solutions represent four cones that are not oriented correctly. Unwanted solutions will have a large sum of squared residuals [77]

$$S(\hat{b}) = (c - N\hat{b})^T(c - N\hat{b}), \quad (\text{D8})$$

meaning we can compute $S(\hat{b})$ and choose the vector $\hat{b}$ that minimizes S .

Finally, the resulting vector $\vec{B}$ can only be determined up to a symmetry of T_d , stemming from the tetrahedral structure of the diamond lattice. One can circumvent this restriction with a known bias field, which breaks the symmetry of the problem. After determining the direction of the bias field using a known external magnetic field, changes in the magnetic field that are small compared to the bias field can be vectorially resolved without ambiguities. The resulting magnetic-field vector still has to be transferred from NV coordinates to outer laboratory coordinates. This can also be accomplished with a known bias field because the unknown orientation of the diamond on the fiber tip can be obtained from one calibration measurement of the known bias field.

APPENDIX E: COMPARISON OF SENSORS IN TERMS OF SENSING VOLUME

In addition to Fig. 9, we plot in Fig. 12 the sensitivity versus the effective sensing volume, which we either retrieved directly or calculated based on the dimensions provided in the cited publications. If only the diamond

volume was specified, we used this value instead as an approximation.

- [1] J. H. N. Loubser, and J. A. V. Wyk, Electron spin resonance in the study of diamond, *Rep. Prog. Phys.* **41**, 1201 (1978).
- [2] M. W. Doherty, N. B. Manson, P. Delaney, F. Jelezko, J. Wrachtrup, and L. C. Hollenberg, The nitrogen-vacancy colour centre in diamond, *Phys. Rep.* **528**, 1 (2013).
- [3] L. Rondin, J.-P. Tetienne, T. Hingant, J.-F. Roch, P. Maletinsky, and V. Jacques, Magnetometry with nitrogen-vacancy defects in diamond, *Rep. Prog. Phys.* **77**, 056503 (2014).
- [4] E. V. Levine, M. J. Turner, P. Kehayias, C. A. Hart, N. Langellier, R. Trubko, D. R. Glenn, R. R. Fu, and R. L. Walsworth, Principles and techniques of the quantum diamond microscope, *Nanophotonics* **8**, 1945 (2019).
- [5] A. Haque, and S. Sumaiya, An overview on the formation and processing of nitrogen-vacancy photonic centers in diamond by ion implantation, *J. Manuf. Mater. Process.* **1**, 6 (2017).
- [6] J. F. Barry, M. H. Steinecker, S. T. Alsied, J. Majumder, L. M. Pham, M. F. O’Keeffe, and D. A. Braje, Sensitive ac and dc magnetometry with nitrogen-vacancy-center ensembles in diamond, *Phys. Rev. Appl.* **22**, 044069 (2024).
- [7] 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).
- [8] S. Choe, J. Yoon, M. Lee, J. Oh, D. Lee, H. Kang, C.-H. Lee, and D. Lee, Precise temperature sensing with

- nanoscale thermal sensors based on diamond NV centers, *Curr. Appl. Phys.* **18**, 1066 (2018).
- [9] P. Kehayias, M. J. Turner, R. Trubko, J. M. Schloss, C. A. Hart, M. Wesson, D. R. Glenn, and R. L. Walsworth, Imaging crystal stress in diamond using ensembles of nitrogen-vacancy centers, *Phys. Rev. B* **100**, 174103 (2019).
- [10] F. Dolde, H. Fedder, M. W. Doherty, T. Nöbauer, F. Rempp, G. Balasubramanian, T. Wolf, F. Reinhard, L. C. L. Hollenberg, F. Jelezko, and J. Wrachtrup, Electric-field sensing using single diamond spins, *Nat. Phys.* **7**, 459 (2011).
- [11] E. Van Oort, and M. Glasbeek, Electric-field-induced modulation of spin echoes of N-V centers in diamond, *Chem. Phys. Lett.* **168**, 529 (1990).
- [12] P. Tamarat, T. Gaebel, J. R. Rabeau, M. Khan, A. D. Greentree, H. Wilson, L. C. L. Hollenberg, S. Prawer, P. Hemmer, F. Jelezko, and J. Wrachtrup, Stark shift control of single optical centers in diamond, *Phys. Rev. Lett.* **97**, 083002 (2006).
- [13] J.-P. Tetienne, N. Donschuk, D. A. Broadway, A. Stacey, D. A. Simpson, and L. C. L. Hollenberg, Quantum imaging of current flow in graphene, *Sci. Adv.* **3**, e1602429 (2017).
- [14] J.-H. Storm, P. Hömmen, D. Drung, and R. Körber, An ultra-sensitive and wideband magnetometer based on a superconducting quantum interference device, *Appl. Phys. Lett.* **110**, 072603 (2017).
- [15] W. C. Griffith, S. Knappe, and J. Kitching, Femtotesla atomic magnetometry in a microfabricated vapor cell, *Opt. Express* **18**, 27167 (2010).
- [16] S. C. Scholten, A. J. Healey, I. O. Robertson, G. J. Abrahams, D. A. Broadway, and J.-P. Tetienne, Widefield quantum microscopy with nitrogen-vacancy centers in diamond: Strengths, limitations, and prospects, *J. Appl. Phys.* **130**, 150902 (2021).
- [17] Y. Hatano, J. Shin, J. Tanigawa, Y. Shigenobu, A. Nakazono, T. Sekiguchi, S. Onoda, T. Ohshima, K. Arai, T. Iwasaki, and M. Hatano, High-precision robust monitoring of charge/discharge current over a wide dynamic range for electric vehicle batteries using diamond quantum sensors, *Sci. Rep.* **12**, 13991 (2022).
- [18] D. A. Broadway, S. C. Scholten, C. Tan, N. Donschuk, S. E. Lillie, B. C. Johnson, G. Zheng, Z. Wang, A. R. Oganov, S. Tian, C. Li, H. Lei, L. Wang, L. C. L. Hollenberg, and J. Tetienne, Imaging domain reversal in an ultrathin van der Waals ferromagnet, *Adv. Mater.* **32**, 2003314 (2020).
- [19] S. Steinert, F. Ziem, L. T. Hall, A. Zappe, M. Schweikert, N. Götz, A. Aird, G. Balasubramanian, L. Hollenberg, and J. Wrachtrup, Magnetic spin imaging under ambient conditions with sub-cellular resolution, *Nat. Commun.* **4**, 1607 (2013).
- [20] C. Degen, Microscopy with single spins, *Nat. Nanotechnol.* **3**, 643 (2008).
- [21] P. Rembold, N. Oshnik, M. M. Müller, S. Montangero, T. Calarco, and E. Neu, Introduction to quantum optimal control for quantum sensing with nitrogen-vacancy centers in diamond, *AVS Quantum Sci.* **2**, 024701 (2020).
- [22] E. O. Schäfer-Nolte, *Development of a diamond-based scanning probe spin sensor operating at low temperature in ultra high vacuum*, Ph.D. thesis, Universität Stuttgart, 2014.
- [23] I. Fescenko, A. Jarmola, I. Savukov, P. Kehayias, J. Smits, J. Damron, N. Ristoff, N. Mosavian, and V. M. Acosta, Diamond magnetometer enhanced by ferrite flux concentrators, *Phys. Rev. Res.* **2**, 023394 (2020).
- [24] T. Wolf, P. Neumann, K. Nakamura, H. Sumiya, T. Ohshima, J. Isoya, and J. Wrachtrup, Subpicotesla diamond magnetometry, *Phys. Rev. X* **5**, 041001 (2015).
- [25] J. H. Shim, S.-J. Lee, S. Ghimire, J. I. Hwang, K.-G. Lee, K. Kim, M. J. Turner, C. A. Hart, R. L. Walsworth, and S. Oh, Multiplexed sensing of magnetic field and temperature in real time using a nitrogen-vacancy ensemble in diamond, *Phys. Rev. Appl.* **17**, 014009 (2022).
- [26] K. Kubota, Y. Hatano, Y. Kainuma, J. Shin, D. Nishitani, C. Shinei, T. Taniguchi, T. Teraji, S. Onoda, T. Ohshima, T. Iwasaki, and M. Hatano, Wide temperature operation of diamond quantum sensor for electric vehicle battery monitoring, *Diam. Relat. Mater.* **135**, 109853 (2023).
- [27] P. J. Scheidegger, S. Diesch, M. L. Palm, and C. L. Degen, Scanning nitrogen-vacancy magnetometry down to 350 mK, *Appl. Phys. Lett.* **120**, 224001 (2022).
- [28] G.-Q. Liu, X. Feng, N. Wang, Q. Li, and R.-B. Liu, Coherent quantum control of nitrogen-vacancy center spins near 1000 kelvin, *Nat. Commun.* **10**, 1344 (2019).
- [29] G. J. Abrahams, S. C. Scholten, A. J. Healey, I. O. Robertson, N. Donschuk, S. Q. Lim, B. C. Johnson, D. A. Simpson, L. C. L. Hollenberg, and J.-P. Tetienne, An integrated widefield probe for practical diamond nitrogen-vacancy microscopy, *Appl. Phys. Lett.* **119**, 254002 (2021).
- [30] P. Appel, E. Neu, M. Ganzhorn, A. Barfuss, M. Batzer, M. Gratz, A. Tschöpe, and P. Maletinsky, Fabrication of all diamond scanning probes for nanoscale magnetometry, *Rev. Sci. Instrum.* **87**, 063703 (2016).
- [31] J. L. Webb, J. D. Clement, L. Troise, S. Ahmadi, G. J. Johansen, A. Huck, and U. L. Andersen, Nanotesla sensitivity magnetic field sensing using a compact diamond nitrogen-vacancy magnetometer, *Appl. Phys. Lett.* **114**, 231103 (2019).
- [32] D. Zheng, Z. Ma, W. Guo, L. Niu, J. Wang, X. Chai, Y. Li, Y. Sugawara, C. Yu, Y. Shi, X. Zhang, J. Tang, H. Guo, and J. Liu, A hand-held magnetometer based on an ensemble of nitrogen-vacancy centers in diamond, *J. Phys. D: Appl. Phys.* **53**, 155004 (2020).
- [33] F. M. Stürner, A. Brenneis, J. Kassel, U. Wostradowski, R. Rölver, T. Fuchs, K. Nakamura, H. Sumiya, S. Onoda, J. Isoya, and F. Jelezko, Compact integrated magnetometer based on nitrogen-vacancy centres in diamond, *Diam. Relat. Mater.* **93**, 59 (2019).
- [34] J. Pogorzelski, L. Horsthemke, J. Homrighausen, D. Stiegeköter, M. Gregor, and P. Glösekötter, Compact and fully integrated LED quantum sensor based on NV centers in diamond, *Sensors* **24**, 743 (2024).
- [35] R. L. Patel, L. Q. Zhou, A. C. Frangoskou, G. A. Stimpson, B. G. Breeze, A. Nikitin, M. W. Dale, E. C. Nichols, W. Thornley, B. L. Green, M. E. Newton, A. M. Edmonds, M. L. Markham, D. J. Twitchen, and G. W. Morley, Subnanotesla magnetometry with a fiber-coupled diamond sensor, *Phys. Rev. Appl.* **14**, 044058 (2020).
- [36] A. Kuwahata, T. Kitaizumi, K. Saichi, T. Sato, R. Igarashi, T. Ohshima, Y. Masuyama, T. Iwasaki, M. Hatano, F. Jelezko, M. Kusakabe, T. Yatsui, and M. Sekino, Magnetometer with nitrogen-vacancy center in a bulk diamond for detecting magnetic nanoparticles in biomedical applications, *Sci. Rep.* **10**, 2483 (2020).

- [37] F. M. Stürner, A. Brenneis, T. Buck, J. Kassel, R. Rölver, 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).
- [38] D. Kim, M. I. Ibrahim, C. Foy, M. E. Trusheim, R. Han, and D. R. Englund, A CMOS-integrated quantum sensor based on nitrogen-vacancy centres, *Nat. Electron.* **2**, 284 (2019).
- [39] M. Zhao, Q. Lin, Q. Meng, W. Shan, L. Zhu, Y. Chen, T. Liu, L. Zhao, and Z. Jiang, All fiber vector magnetometer based on nitrogen-vacancy center, *Nanomaterials* **13**, 949 (2023).
- [40] I. V. Fedotov, L. V. Doronina-Amitonova, D. A. Sidorov-Biryukov, N. A. Safronov, S. Blakley, A. O. Levchenko, S. A. Zibrov, A. B. Fedotov, S. Y. Kilin, M. O. Scully, V. L. Velichansky, and A. M. Zheltikov, Fiber-optic magnetic-field imaging, *Opt. Lett.* **39**, 6954 (2014).
- [41] M. Zhao, Q. Lin, Q. Meng, W. Shan, L. Zhu, Y. Chen, L. Zhao, and Z. Jiang, Efficient fluorescence coupling microlens integrated fiber magnetometer probe based on nitrogen vacancy centers, *Opt. Lett.* **48**, 4045 (2023).
- [42] J. Homrighausen, F. Hoffmann, J. Pogorzelski, P. Glösekötter, and M. Gregor, Microscale fiber-integrated vector magnetometer with on-tip field biasing using N-V ensembles in diamond microcrystals, *Phys. Rev. Appl.* **22**, 034029 (2024).
- [43] M. M. Dong, Z. Z. Hu, Y. Liu, B. Yang, Y. J. Wang, and G. X. Du, A fiber based diamond RF B-field sensor and characterization of a small helical antenna, *Appl. Phys. Lett.* **113**, 131105 (2018).
- [44] A. Filipkowski, M. Mrózek, G. Stępniewski, M. Głowacki, D. Pysz, W. Gawlik, R. Buczyński, M. Klimczak, and A. Wojciechowski, Magnetically sensitive fiber probe with nitrogen-vacancy center nanodiamonds integrated in a suspended core, *Opt. Express* **30**, 19573 (2022).
- [45] Y. Chen, Q. Lin, H. Cheng, H. Huang, J. Shao, Y. Ye, G.-S. Liu, L. Chen, Y. Luo, and Z. Chen, Nanodiamond-based optical-fiber quantum probe for magnetic field and biological sensing, *ACS Sens.* **7**, 3660 (2022).
- [46] S. Dix, J. Gutsche, E. Waller, G. Von Freymann, and A. Widera, Fiber-tip endoscope for optical and microwave control, *Rev. Sci. Instrum.* **93**, 095104 (2022).
- [47] M. Bianco, A. Balena, M. Pisanello, F. Pisano, L. Sileo, B. Spagnolo, C. Montinaro, B. L. Sabatini, M. D. Vittorio, and F. Pisanello, Comparative study of autofluorescence in flat and tapered optical fibers towards application in depth-resolved fluorescence lifetime photometry in brain tissue, *Biomed. Opt. Express* **12**, 993 (2021).
- [48] J. A. Udovich, N. D. Kirkpatrick, A. Kano, A. West Rynes, U. Utzinger, and A. F. Gmitro, Spectral background and transmission characteristics of fiber optic imaging bundles, *Appl. Opt.* **47**, 4560 (2008).
- [49] Y. Li, F. A. Gerritsma, S. Kurdi, N. Codreanu, S. Gröblacher, R. Hanson, R. Norte, and T. van der Sar, A fiber-coupled scanning magnetometer with nitrogen-vacancy spins in a diamond nanobeam, *ACS Photonics* **10**, 1671 (2023).
- [50] H. Patrick, S. L. Gilbert, and A. Lidgard, Decrease of fluorescence in optical fiber during exposure to pulsed or continuous-wave ultraviolet light, *Opt. Mater.* **3**, 209 (1994).
- [51] E. H. Waller, S. Dix, J. Gutsche, A. Widera, and G. V. Freymann, Functional metallic microcomponents via liquid-phase multiphoton direct laser writing: A review, *Micromachines* **10**, 827 (2019).
- [52] M. Schmid, D. Ludescher, and H. Giessen, Optical properties of photoresists for femtosecond 3D printing: Refractive index, extinction, luminescence-dose dependence, aging, heat treatment and comparison between 1-photon and 2-photon exposure, *Opt. Mater. Express* **9**, 4564 (2019).
- [53] J. L. Sánchez Toural, V. Marzoa, R. Bernardo-Gavito, J. L. Pau, and D. Granados, Hands-on quantum sensing with NV-centers in diamonds, *C* **9**, 16 (2023).
- [54] J. J. Moré, in *Numerical Analysis*, Vol. 630, edited by G. A. Watson (Springer Berlin Heidelberg, Berlin, Heidelberg, 1978), p. 105, series Title: Lecture Notes in Mathematics.
- [55] J. M. Schloss, J. F. Barry, M. J. Turner, and R. L. Walsworth, Simultaneous broadband vector magnetometry using solid-state spins, *Phys. Rev. Appl.* **10**, 034044 (2018).
- [56] A. Dréau, M. Lesik, L. Rondin, P. Spinicelli, O. Arcizet, J.-F. Roch, and V. Jacques, Avoiding power broadening in optically detected magnetic resonance of single NV defects for enhanced dc magnetic field sensitivity, *Phys. Rev. B* **84**, 195204 (2011).
- [57] 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^{-1/2} toward measurement of biomagnetic field, *Phys. Rev. Appl.* **21**, 064010 (2024).
- [58] S. Ahmadi, H. A. R. El-Ella, J. O. B. Hansen, A. Huck, and U. L. Andersen, Pump-enhanced continuous-wave magnetometry using nitrogen-vacancy ensembles, *Phys. Rev. Appl.* **8**, 034001 (2017).
- [59] D. Allan, Statistics of atomic frequency standards, *Proc. IEEE* **54**, 221 (1966).
- [60] D. A. Van Baak, and G. Herold, Response of a lock-in amplifier to noise, *Am. J. Phys.* **82**, 785 (2014).
- [61] J. Zhang, T. Liu, L. Xu, G. Bian, P. Fan, M. Li, C. Xu, and H. Yuan, A pulsed lock-in method for DC ensemble nitrogen-vacancy center magnetometry, *Diam. Relat. Mater.* **125**, 109035 (2022).
- [62] W.-K. Quan, L. Liu, Q.-Y. Luo, X.-D. Liu, and J.-F. Wang, Fiber-coupled silicon carbide divacancy magnetometer and thermometer, *Opt. Express* **31**, 15592 (2023).
- [63] S.-C. Zhang, H.-B. Lin, Y. Dong, B. Du, X.-D. Gao, C. Yu, Z.-H. Feng, X.-D. Chen, G.-C. Guo, and F.-W. Sun, High-sensitivity and wide-bandwidth fiber-coupled diamond magnetometer with surface coating, *Photonics Res.* **10**, 2191 (2022).
- [64] A. K. Dmitriev, and A. K. Vershovskii, Concept of a microscale vector magnetic field sensor based on nitrogen-vacancy centers in diamond, *J. Opt. Soc. Am. B* **33**, B1 (2016).
- [65] S. M. Graham, A. T. M. A. Rahman, L. Munn, R. L. Patel, A. J. Newnman, C. J. Stephen, G. Colston, A. Nikitin, A. M. Edmonds, D. J. Twitchen, M. L. Markham, and G. W. Morley, Fiber-coupled diamond magnetometry with an unshielded sensitivity of 30 pT/√Hz, *Phys. Rev. Appl.* **19**, 044042 (2023).

- [66] Y. Hatano, J. Shin, D. Nishitani, H. Iwatsuka, Y. Masuyama, H. Sugiyama, M. Ishii, S. Onoda, T. Ohshima, K. Arai, T. Iwasaki, and M. Hatano, Simultaneous thermometry and magnetometry using a fiber-coupled quantum diamond sensor, *Appl. Phys. Lett.* **118**, 034001 (2021).
- [67] Q. Liu, F. Xie, X. Peng, Y. Zhang, N. Wang, Y. Hu, L. Wang, Y. Liu, Y. Wang, S. Nie, H. Chen, J. Cheng, and Z. Wu, Closed-loop diamond quantum sensor for large range and high precision current measurement, *IEEE Sens. J.* **24**, 4356 (2024).
- [68] Q. Liu, F. Xie, X. Peng, Y. Hu, N. Wang, Y. Zhang, Y. Wang, L. Li, H. Chen, J. Cheng, and Z. Wu, Millimeter-scale temperature self-calibrated diamond-based quantum sensor for high-precision current sensing, *Adv. Quantum Technol.* **6**, 2300210 (2023).
- [69] S. M. Blakley, I. V. Fedotov, S. Y. Kilin, and A. M. Zheltikov, Room-temperature magnetic gradiometry with fiber-coupled nitrogen-vacancy centers in diamond, *Opt. Lett.* **40**, 3727 (2015).
- [70] H. Deguchi, T. Hayashi, H. Saito, Y. Nishibayashi, M. Teramoto, M. Fujiwara, H. Morishita, N. Mizuochi, and N. Tatum, Compact and portable quantum sensor module using diamond NV centers, *Appl. Phys. Express* **16**, 062004 (2023).
- [71] S. M. Blakley, I. V. Fedotov, L. V. Amitonova, E. E. Serebryannikov, E. Perez, S. Y. Kilin, and A. M. Zheltikov, Fiber-optic vectorial magnetic-field gradiometry by a spatiotemporal differential optical detection of magnetic resonance in nitrogen-vacancy centers in diamond, *Opt. Lett.* **41**, 2057 (2016).
- [72] S. Johansson, D. Lönard, I. Cardoso Barbosa, J. Gutsche, J. Witzernath, and A. Widera, Data for: “Miniaturized magnetic-field sensor based on nitrogen-vacancy centers”, 2025, <https://doi.org/10.5281/zenodo.16410952>
- [73] D. Lönard, Microscope Experiment Control Application, 2025, <https://gitlab.rlp.net/agwidera/public/waveguide-control-python>
- [74] A. Landowski, D. Zepp, S. Wingerter, G. von Freymann, and A. Widera, Direct laser written polymer waveguides with out of plane couplers for optical chips, *APL Photonics* **2**, 106102 (2017).
- [75] G. Balasubramanian, I. Y. Chan, R. Kolesov, M. Al-Hmoud, J. Tisler, C. Shin, C. Kim, A. Wojcik, P. R. Hemmer, A. Krueger, T. Hanke, A. Leitenstorfer, R. Bratschkitsch, F. Jelezko, and J. Wrachtrup, Nanoscale imaging magnetometry with diamond spins under ambient conditions, *Nature* **455**, 648 (2008).
- [76] Y. Wang, R. Zhang, Y. Yang, Q. Wu, Z. Yu, and B. Chen, Orientation determination of nitrogen-vacancy center in diamond using a static magnetic field, *Chin. Phys. B* **32**, 070301 (2023).
- [77] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes - The Art of Scientific Computing - 3rd Edition* (Cambridge University Press, Cambridge, 2007).