

Fiber-integrated N-*V* diamond magnetometer compatible with commercial endoscopic systems

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The nitrogen-vacancy (N-*V*) center in diamond provides a robust, solid-state platform for magnetic field measurements at room temperature. To harness its potential in inspecting inaccessible regions, here we present a compact endoscopic configuration of a N-*V* diamond-based magnetometer. The endoscopic magnetometer was developed by integration of a large-core optical fiber with a bulk N-*V* diamond for laser excitation and photoluminescence (PL) collection. The diamond and fiber were specially shaped to enhance PL collection through the fiber. Additionally, a three-dimensionally-printed endoscope head was used to facilitate alignment of the bias magnetic field along the N-*V* axis. A magnetic field sensitivity of approximately 3 nT/√Hz at 20 Hz was achieved by continuous-wave magnetometry measurements. The endoscope diameter was restricted to 10 mm to match the dimensions of most commercial endoscopes. The magnetic field nonuniformity caused by the small separation between the diamond and the magnet in the endoscope head limited the overall sensitivity. It could be further improved to 0.85 nT/√Hz at 20 Hz by use of a magnet placed at a sufficient distance outside the endoscope head. Our endoscopic design is mechanically stable and provides additional opportunities for integrating other functionalities into the probe head as needed.

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I. INTRODUCTION

The negatively charged nitrogen-vacancy (N-*V*[−]) center in diamond has been extensively investigated for high-sensitivity sensing of magnetic fields [1–4], temperature [5–7], and electric fields [8,9], as well as for use in gyroscopes [10], and quantum information processing [11–13]. In magnetic field sensing, extensive work has been conducted to improve detection sensitivity and spatial resolution. To achieve higher sensitivity, various measurement configurations based on pulse sequences [14–17] have been developed. A magnetic field sensitivity of 0.5 pT/√Hz has been achieved with an ensemble of N-*V* centers [18]. For spatial resolution, single N-*V*

center-based sensing techniques have led to nanoscale resolution [19–21]. However, most of these high-sensitivity or high-resolution designs are often realized with the use of high-end instrumentation and are thus better suited to benchtop operation in isolated environments [14–21]. This may limit the applicability of N-*V* centers to sensing magnetic fields from sources in spatially confined or inaccessible environments. For such purposes, a portable magnetometer with a mobile probe head is highly desirable.

For the realization of portable N-*V* diamond-based magnetometers, fiber-integrated configurations have been developed [22–33]. In these configurations, the N-*V* diamond is generally integrated on the apex of an optical fiber, and microwaves are delivered via a nearby attached loop or wire. Multiple approaches, such as the use of a cuboctahedral microdiamond [22], the incorporation of a parabolic condenser lens and fiber collimator [23], and the use of photonic crystal fiber [25], have been considered in previous work. Magnetic field sensitivity in the subnanotesla range has been reported for such fiber-integrated magnetometer configurations [22,23]. Optical

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fiber tapering [27,28], microlens fabrication on the fiber facet [29], and reflective coatings [30] have been demonstrated as effective approaches to improve fluorescence collection in fiber-coupled N- V sensors. Compact probes that integrate optical delivery and microwave control at the fiber tip have also been demonstrated [31]. A fiber-coupled ensemble N- V magnetometer using a compact sensor head has achieved an unshielded sensitivity of approximately 30 pT/ $\sqrt{\text{Hz}}$ [32]. While a fully integrated, portable configuration with subnanotesla magnetic field sensitivity has also been developed [33], its use in typical endoscopic applications may be limited due to its design constraints.

A compact endoscopic configuration having all the essential components fully integrated into a probe head is desirable for practical applications ranging from the clinical sector to the industrial sector. In the present study, a simple and mechanically robust endoscopic magnetometer is developed for applications in difficult-to-access regions. The endoscopic configuration is based on the integration of a bulk ensemble N- V diamond and a large-core (diameter 1.5 mm) optical fiber. Both the diamond and the fiber were shaped to improve photoluminescence (PL) collection through the fiber. A three-dimensionally (3D)-printed endoscope head was used to integrate a permanent magnet to apply a bias field and a microwave delivery coil in the endoscopic probe. The details of the endoscopic design are presented in Sec. II. A magnetic field sensitivity of around 3 nT/ $\sqrt{\text{Hz}}$ at 20 Hz was obtained by continuous-wave (cw) magnetometry measurements. Although the sensitivity obtained is lower than that for some previously reported fiber-based systems, the primary objective of this study is to explore the feasibility of a compact and simple endoscopic configuration.

II. METHODS

A. Construction of the endoscope

The endoscopic magnetic sensor developed in this study uses a (100)-cut single-crystal diamond (DNV-B14, Element Six) with a N- V center concentration of approximately 4.5 ppm. The N- V diamond was attached to a multimode optical fiber (FP1500ERT, Thorlabs) with a 1.5 mm core diameter and a numerical aperture (NA) of 0.50. This fiber serves as the main body of the endoscope for excitation of N- V centers and collection of PL. The magnetic field sensitivity of the N- V diamond magnetometer fundamentally depends on the collected PL intensity [1–4]; therefore, both the diamond and the optical fiber were specifically shaped to improve PL collection through the fiber. The refractive indices of the core and cladding of the large-core fiber are specified to be 1.458 and 1.365, respectively. This corresponds to critical angles of 69.5° for the core/cladding interface and 43.3° for the core/air interface. After attachment of N- V diamond to the apex of the fiber, the emission angle of the PL signal from the

diamond ($n \sim 2.42$ at 640 nm) into the fiber core ranges from 0° to 90°. Thus, inefficient total internal reflection at certain angles in the fiber section can lead to a certain amount of PL signal loss. This problem can be remedied by shaping the fiber facet into a curved geometry with an angle gradually varying from 0° to 43.3°, as shown in Fig. 1(a). A combination of diamond lapping/polishing sheets (Thorlabs) and a rotational grinding machine was used for precisely curving the bare optical fiber at the desired angle. The thin cladding layer was removed during the process, allowing a lower critical angle condition at the core/air interface. The fiber apex diameter was reduced from 1.5 to 1.0 mm. In addition, the diamond slab ($1.5 \times 1.5 \times 0.5 \text{ mm}^3$) was polished into a truncated cone geometry with 1.0 mm base diameter, 0.5 mm height, and 0.5 mm top diameter. The semivertical angle was approximately 25° (the critical angle for total internal reflection at the diamond/air interface is 24.6°), as shown in Fig. 1(b). This design aims to reduce the trapping of the PL signal inside the high-refractive-index diamond and to efficiently direct the PL into the fiber. This shaping work was outsourced to Almax easyLab, Belgium. The truncated cone N- V diamond was affixed to the apex with Norland optical adhesive NOA 146H. A nonmagnetic coaxial cable (UT-047C-TP-LL, Amphenol CIT) was used to deliver microwave excitation to the N- V diamond for transitions between the $m_s = 0$ and $m_s = \pm 1$ spin states.

The diamond-fiber assembly was inserted into an endoscopic instrument channel tube with external and internal diameters of approximately 4 mm and approximately 3 mm, respectively. For demonstration purposes, a commercially available endoscopic clamp tube for the FUJINON EG-590WR gastroscope was used as the instrument channel. Note that conventional endoscopes commonly have an instrument channel with a diameter of approximately 3 mm (outer diameter of approximately 4 mm). The fiber was secured inside the tube with the use of heat-shrink tubing, which was tightened sufficiently to prevent unintentional movement, while still allowing manual rotation and repositioning. The inner conductor of a semirigid coaxial cable was wrapped around the instrument channel tube precisely at the N- V diamond position. The other end of the inner conductor was grounded by connecting it to the outer conductor. In this configuration, the instrument channel tube protects the microwave wire from accidental contact with the diamond, providing a stable configuration.

The alignment of a bias magnetic field along one of the four N- V axes is a typical way of isolating a single N- V orientation [2–4]. The component of the measured magnetic field along this axis can be extracted from the shifts in the optically detected magnetic resonance (ODMR) frequency. For this purpose, a custom endoscope head was specially designed and fabricated by in-house three-dimensional printing, as shown in Fig. 1(c). The endoscope head has a channel for placing the instrument channel tube. In the

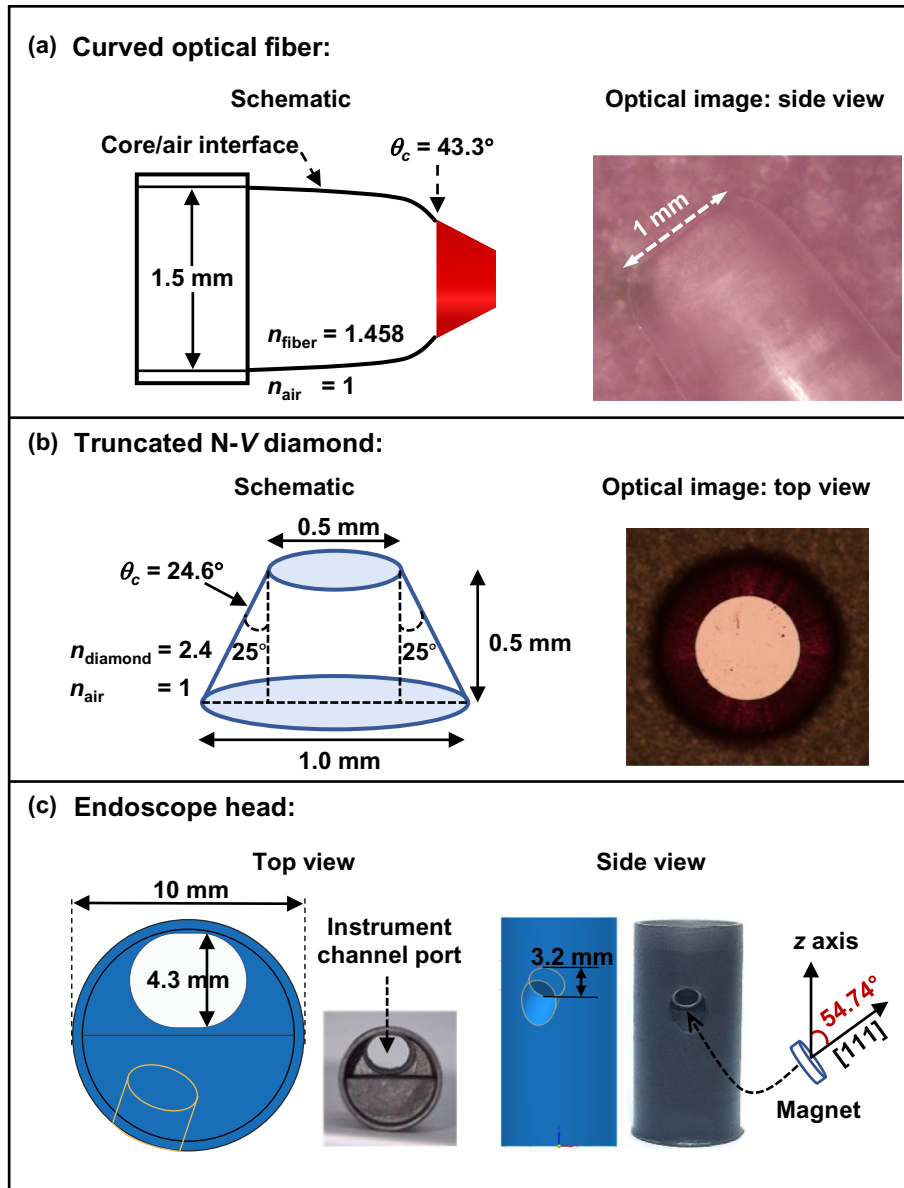


FIG. 1. (a) Schematic (left) and optical microscope image (right) of the shaped large-core fiber. The fiber core has a refractive index of 1.458, with a critical angle of 43.3° at the core/air interface. The fiber apex was polished in-house with use of a grinding rotator motor, gradually varying the angle from 0° to 43.3° near the tip to minimize PL loss. The surface was then finished with a polishing film. (b) Bulk N-V diamond polished into a truncated cone by Almax easyLab, Belgium. (c) Design of the custom 3D-printed endoscope head (top and side views), showing dimensions and the magnet configuration for the bias field, along with corresponding photographs. A magnet placed at its position in the endoscope head can be seen in (c).

head, there is provision for placing a permanent magnet (3 mm diameter, 1 mm width, N50 neodymium magnet) aligned toward a preselected N-V diamond position. The diameter of the endoscope head was deliberately restricted to 10 mm, which is the typical size of clinically used endoscopes, for instance, the Endoeye HD II 10 mm from Olympus. This enables the design's applicability across a wide range of applications. The vacant space in the endoscope head can be further used to incorporate additional channels for monitoring, cleaning, etc.

As the endoscopic design demands a narrower diameter (approximately 10 mm), the distance between the N-V diamond and a permanent magnet is constrained. Alternative approaches, such as attaching a combination of small magnets directly to the fiber near the diamond, were also explored to isolate the N-V axis. These methods proved to be technically challenging and less effective for achieving precise control of the bias magnetic field alignment. However, this approach was recently investigated in another study, showing the growing interest in the

development of a N- V diamond-based endoscopic magnetometer [34]. In contrast, our 3D-printed endoscope head allows a ring-shaped permanent magnet to be positioned in a dedicated slot angled at 54.74° to the vertical axis, corresponding to the N- V orientation in the diamond lattice. The fiber fitted comfortably within the endoscope, enabling precise rotation and axial translation for fine alignment of the magnetic field along the N- V axis. The diamond-fiber assembly was also carefully positioned and rotated inside the instrument channel tube to align the N- V axis with the magnetic field. This controllable rotation and translation of the fiber-integrated diamond provides flexibility in selecting the N- V axis, in addition to the mechanical stability provided by the heat-shrink tubing around the fiber.

The back end of the optical fiber was used to deliver 532 nm cw excitation laser light to the N- V diamond and to collect the PL signal, unless otherwise mentioned. All other optical components, except the excitation laser, were integrated into a portable setup ($30 \times 30 \text{ cm}^2$), as depicted in Fig. 2. The excitation laser was coupled into the setup through a fiber-coupling arrangement. The 532 nm excitation and the PL signal were separated with the use of a dichroic mirror, and a 650 nm long-pass filter was used for selection of the PL of N- V^- centers. The microwave signal was delivered by connecting the amplified output to the semirigid coaxial cable through an SMA connector (not shown). This configuration allows the optical setup to be moved to remote locations.

B. Instrumentation

A continuous-wave 532 nm laser (CNI-MGL-III-532 nm) was used to excite the N- V diamond. The laser power at the portable optical setup was 300 mW. Two identical photodetectors (PDA100A, Thorlabs) operated at the

same gain settings were used to detect the PL and reference laser signals for balanced measurement. Microwaves were generated with a Hewlett-Packard E4421B signal generator and amplified by a Mini-Circuits ZHL-16W-43-S+ power amplifier. To protect the microwave source, the line included a microwave circulator/isolator and 50 Ω terminations. The internal low-frequency function generator built into the microwave signal generator provided the low-frequency signal for frequency modulation. A digital lock-in amplifier (SR850, Stanford Research Systems) was used for lock-in detection of the frequency-modulated signal. The balanced configuration of the lock-in amplifier was used to suppress laser source-induced noise. The time constant of lock-in amplifier was set to 1 ms, corresponding to a bandwidth of 125 Hz at a filter setting of 12 dB/octave. The signal was maximized using the in-phase output (X) of the lock-in amplifier and digitized using an NI USB-6363 BNC data-acquisition device. A homemade LabVIEW (National Instruments) program was used for synchronization and measurement control.

III. RESULTS AND DISCUSSION

The optical response of the shaped diamond-fiber assembly was evaluated with a homebuilt confocal microscope. For this, as shown in Fig. S1 in Supplemental Material [35], the N- V diamond attached to the fiber was directly excited with an air objective lens (0.6 NA), and the PL signal collected at the fiber end was approximately 12 times stronger than that detected through the same objective. This demonstrates efficient PL coupling from the truncated-cone diamond into the curved fiber. Ray-tracing simulations (see Fig. S2 in Supplemental Material [35]) were performed for both the shaped fiber-diamond geometry and the unshaped diamond slab-fiber geometry [36]. The simulations show a PL collection

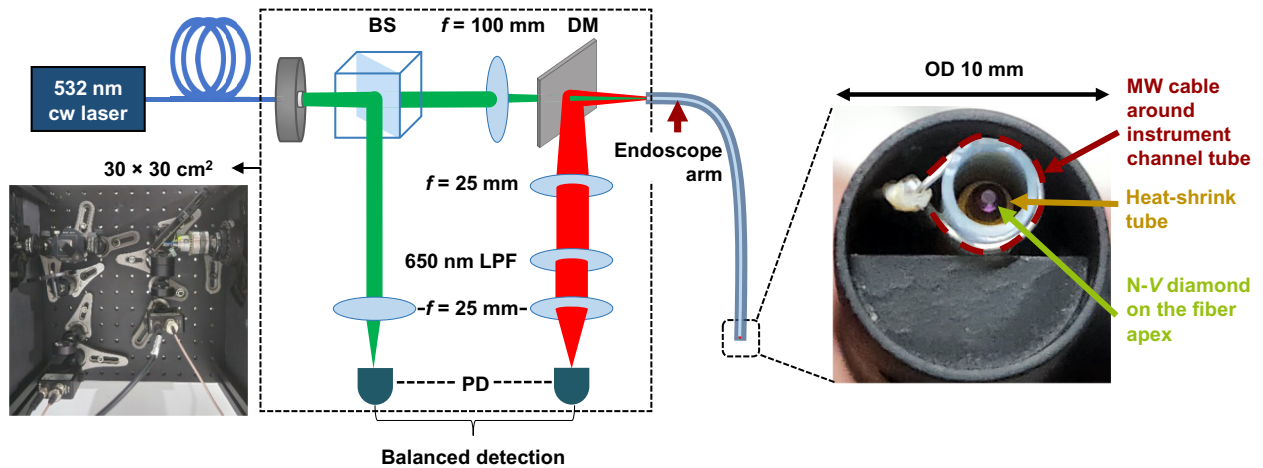


FIG. 2. System configuration of the developed N- V diamond-based endoscopic magnetometer, showing the optical measurement setup and the endoscope head. BS, beam splitter; DM, dichroic mirror; LPF, long-pass filter; MW, microwave; OD, outer diameter; PD, photodiode.

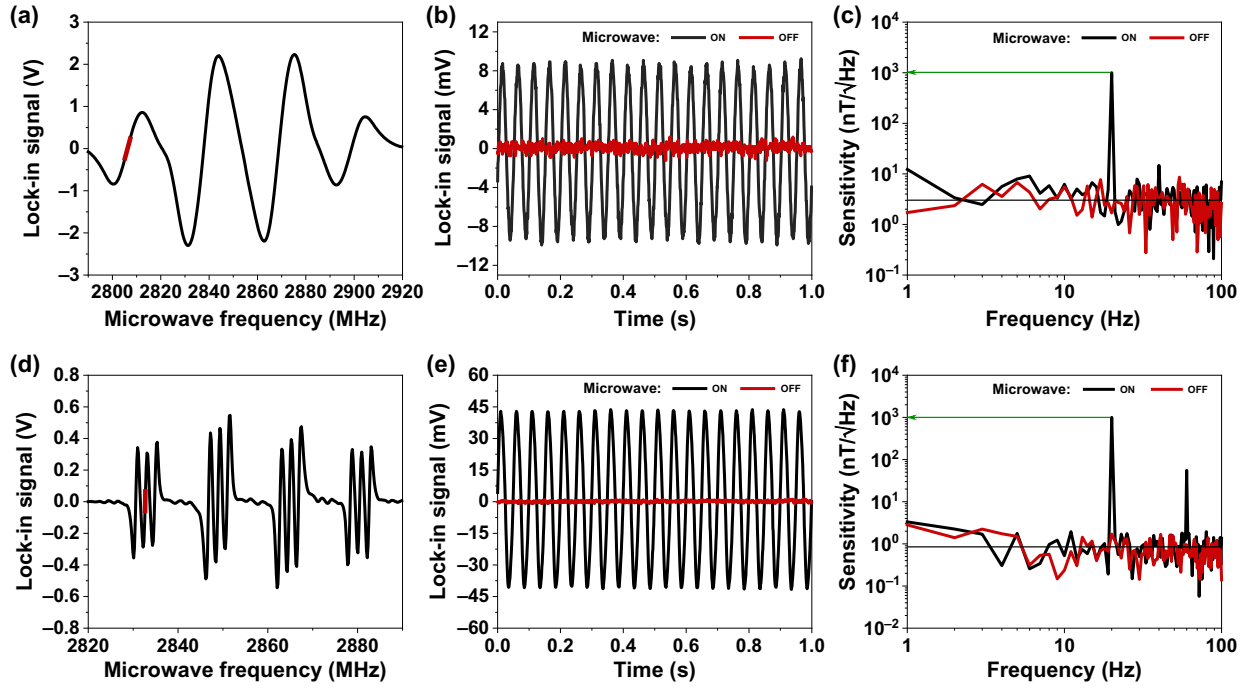


FIG. 3. (a),(d) ODMR spectrum obtained with a bias magnetic field aligned along the N-V axis with a permanent magnet placed (a) in the endoscope head and (d) at a sufficient distance to provide a uniform field at the N-V diamond. (b),(e) Time trace recorded in the linear region of the lock-in spectrum [red in (a), (d)] under an applied test magnetic field with a projection strength of $1 \mu\text{T}$ rms at 20 Hz along the N-V axis. (c),(f) Magnetic field sensitivity derived from FFT analysis of the time traces in (b),(e), showing an average noise floor of approximately $3 \text{ nT}/\sqrt{\text{Hz}}$ and approximately $0.85 \text{ nT}/\sqrt{\text{Hz}}$ at 20 Hz, respectively. Black and red curves correspond to the cases with microwave excitation turned on and off, respectively.

efficiency of approximately 30% for our shaped geometry, compared with approximately 2.8% for the unshaped diamond slab-fiber geometry, confirming the significance of geometry optimization. For reference, the reported PL collection efficiency is approximately 2% for a diamond slab with a 0.6 NA air objective and 10% or less with a 1.45 NA oil-immersion objective [37]. The enhanced collection achieved with the shaped diamond-fiber assembly highlights the advantage of our design. Moreover, the optical fiber provides a flexible and portable medium for both excitation and collection, paving the way for compact endoscopic N-V diamond magnetometers.

To test the performance of the endoscopic magnetometer, the cw-ODMR spectrum for the magnetic field aligned along the N-V axis was measured by the lock-in detection method. The microwaves were frequency modulated for the lock-in detection with the use of a sine wave low-frequency reference signal. The frequency modulation depth was optimized to maximize the slope in the lock-in signal corresponding to the [111] axis. A representative ODMR spectrum, measured at a modulation frequency of 5 kHz and a modulation depth of 8.5 MHz, is shown in Fig. 3(a). The spectrum shows a clear ODMR signal for a well-isolated [111] axis. The linear region with maximum slope for the $m_s = 0$ to $m_s = -1$ resonance is marked in red.

The magnetic field sensitivity of the developed endoscope was evaluated by application of a known ac test magnetic field. A homebuilt Helmholtz coil was used to generate a magnetic field of $1.73 \mu\text{T}$ rms at a frequency of 20 Hz along the [100] crystallographic direction at the N-V diamond position. The component of this field projected onto the [111] axis was $1 \mu\text{T}$ rms. Before these measurements, the Helmholtz coil was calibrated by comparing the theoretically calculated magnetic field, based on the Helmholtz coil configuration, with the magnetic field values inferred from shifts in the ODMR resonance frequencies. As shown in Fig. 3(b), a time trace was recorded at a sampling rate of 1000 samples/s over 1 s, within the linear region of the lock-in signal highlighted in red in Fig. 3(a). The time-domain signal was analyzed with use of a fast Fourier transformation (FFT) to obtain the rms amplitude spectral density. A distinct spectral peak at 20 Hz, corresponding to the applied test field of $1 \mu\text{T}$ rms, was observed, as shown in Fig. 3(c). This analysis indicates an average magnetic field noise floor of approximately $3 \text{ nT}/\sqrt{\text{Hz}}$ at 20 Hz. For comparison, the magnetic field sensitivity with a diamond slab with the same specification (DNV-B14) was measured with a homebuilt confocal configuration, yielding a noise floor of approximately $1 \text{ nT}/\sqrt{\text{Hz}}$. The lower sensitivity in the endoscope case,

compared with the confocal measurements, is attributed to broadening of the ODMR linewidth due to the magnetic field nonuniformity over the illuminated area of the diamond. This suggests that sensitivity could be improved by optimizing the configuration of the permanent magnet within the endoscope head, an approach that will be explored in future work.

The effect of magnetic field nonuniformity in the diameter-constrained endoscopic magnetometer was further evaluated. For this, a bias magnetic field along the N- V axis was applied by means of a larger-diameter permanent magnet placed at a sufficiently large distance, instead of the closely placed endoscopic magnet. This configuration was assumed to provide a uniform magnetic field at the N- V diamond. In the following discussion, this configuration is referred to as “configuration B,” while the original design with the magnet integrated into the endoscope head is referred to as “configuration A.” The ODMR spectrum measured with configuration B using the lock-in detection method is shown in Fig. 3(d). Hyperfine splitting was clearly observed, which was absent in the ODMR spectrum for configuration A. The optimized modulation depth was approximately 0.6 MHz. This suggests that the nonuniform magnetic field at the N- V diamond in configuration A of the endoscope causes linewidth broadening, thereby limiting the sensitivity.

Further, the same test field at 20 Hz frequency with 1 μ T rms projected along the [111] axis was applied. As shown in Fig. 3(e), a time trace was recorded at a sampling rate of 1000 samples/s over 1 s, within the linear region of the lock-in signal for the $m_s = 0$ to $m_s = -1$ transition. From the FFT analysis of the time trace in Fig. 3(e), an average magnetic field noise floor of approximately 0.85 nT/ $\sqrt{\text{Hz}}$ at 20 Hz was obtained, as shown in Fig. 3(f).

These results show a significant improvement in the sensitivity compared with configuration A. It is worth noting that for configuration B further improvement in the sensitivity (approximately 4 times) can be expected through simultaneous driving of hyperfine transitions and double resonance excitation [38]. Configuration B is suitable for test environments that allow the use of an externally applied bias field. However, configuration A remains advantageous in scenarios where the use of an external magnet is restricted, as is typically the case in endoscopic applications.

IV. CONCLUSIONS

An endoscopic configuration of a N- V diamond-based magnetometer was developed. A bulk diamond with a N- V concentration of approximately 4.5 ppm was attached to the apex of a large-core optical fiber, which served for both excitation and PL collection. To maximize PL collection, the diamond was polished into a truncated-cone geometry with a semivertical angle corresponding to the

critical angle (24.6°) of the diamond/air interface, and the fiber facet was shaped into a curved geometry based on the core/air critical angle (43.3°). The diamond-fiber assembly was inserted into a commercially available endoscopic clamp tube (4 mm outer diameter), occupying the instrument channel of conventional endoscopes. A custom 3D-printed head was designed to accommodate the channel tube and to include a slot for a permanent magnet, enabling application of a bias magnetic field. Manual control of the fiber-diamond assembly allowed rotation and translation for alignment of the N- V axis with the magnetic field. The total diameter of the endoscope head was restricted to 10 mm, ensuring compatibility with clinically used endoscopes. A magnetic field sensitivity of approximately 3 nT/ $\sqrt{\text{Hz}}$ at 20 Hz was achieved by cw magnetometry. When the bias field was applied with a magnet placed externally to the endoscope, the sensitivity improved to approximately 0.85 nT/ $\sqrt{\text{Hz}}$ at 20 Hz. Both configurations demonstrated here provide practical utility for magnetic field measurements in otherwise inaccessible regions.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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