Microwave-free vector magnetometry with nitrogen-vacancy centers along a single axis in diamond

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We propose and demonstrate a microwave-free vector magnetometer that simultaneously measures all Cartesian components of a magnetic field using nitrogen-vacancy (NV) ensembles in diamond. With fixed crystallographic axes inherent to the solid-state system, the present magnetometer leverages the level anticrossing in the triplet ground state at 102.4 mT, and is capable of measuring all three components of the magnetic field. Vector capability is proffered by modulating fields along the preferential NV axis and in the transverse plane and subsequent demodulation of the signal. This sensor exhibits a root mean square noise floor of \( \approx 300 \, \text{pT} / \sqrt{\text{Hz}} \) in all directions. The present technique is broadly applicable to both ensem-
ble sensors and potentially also single-NV sensors, extending the vector ability to nanoscale spatial resolution.

Sensitive vector magnetometers are exploited in applications including magnetic navigation\(^1\), magnetic anomaly detection\(^2\), current and position sensing, and measuring biological magnetic fields\(^3, 4\). For many such applications, measurement of magnetic-field vector components with high precision and high spatial resolution at ambient conditions is desirable. Although various approaches, such as Hall probes, flux-gate, tunneling-magnetoresistance\(^5\), superconducting quantum interference device (SQUID) based magnetometry\(^6\) and vapor cells based magnetometry\(^7, 8\), have been utilized, the sensor size, the extreme measurement conditions required, uncertainty or drifts in the relative orientations or the lack of vector measurement ability limit their applications. In contrast, spin-based solid-state sensors allow complete vector reconstruction while keeping systematic errors from sensor axis misalignment or sensitivity drifts under control.

In particular, negatively charged nitrogen-vacancy (NV) centers in single-crystal diamond provide high-sensitivity magnetic sensing and high-resolution imaging\(^9-11\). To date, diamond-based vector magnetometers have been based on using the optically detected magnetic resonance (ODMR) technique with the requirement of applying microwaves (MWs) sequentially or simultaneously\(^12-14\). In these existing implementations, at least three ODMR spectral features must be interrogated to determine the magnetic field vector, and actually four or more are often probed to mitigate systematic errors from strain, electric fields, or temperature variation. A multi-resonance interrogated vector magnetometer inherently exhibits sub-optimal sensitivity, because the sensor is temporarily insensitive to magnetic field components transverse to the chosen axis during the time another axis is measured in sequential read-out or it is subject to crosstalk between simultaneous interrogations. There can be also systematic errors during the vector-reconstruction procedure\(^14\).

To overcome these drawbacks, we propose and demonstrate a protocol that enables vectorial measurement of magnetic fields by interrogating an NV ensemble of only a single crystallographic axis (not a preferential-orientation NV diamond sample) at the ground-state level anti-
crossing (GSLAC). By applying two orthogonal alternating fields, along and perpendicular to the chosen axis, our technique offers direct and simultaneous readout of all the three magnetic components, free from systematic errors during reconstruction. In contrast to existing methods, our approach does not employ microwave fields. In particular, the method can be extended to single-NV probes. This will enable nanoscale full vector magnetic field sensing which is motivated by numerous applications, e.g. noninvasive tracking of particle motion in intracellular medium\textsuperscript{15,16}. This promising nanoscale vector magnetic-field sensing technique based on a single-NV probe can also address the under-constrained problem of microscopic characterization of novel spin textures\textsuperscript{17,18}, which would otherwise rely on system-dependent assumptions, artificially restricting the manifold of solutions compatible with experimental results.

\section{Results}

The microwave-free technique for magnetic sensing is based on detecting changes in NV-photoluminescence (PL) under optical pumping near the GSLAC\textsuperscript{19}. The change in the PL signal can be caused by both, longitudinal and transverse magnetic fields, lifting the degeneracy of or mixing the Zeeman sublevels\textsuperscript{20,21}. The resulting PL signal is simultaneously modulated by applying time-varying fields at two different frequencies, parallel and orthogonal to the static bias field. The resulting PL signal is demodulated with two lock-in amplifiers (LIAs). The first-harmonic outputs, amplitude and phase, contain vectorial information of the magnetic field to be measured, thus full knowledge of the vectorial components is obtained.

The NV center is an atomic-scale defect consisting of a substitutional nitrogen adjacent to a vacancy in the diamond lattice. It has a spin-triplet ground state ($S=1$), which can be optically polarized to $|m_s = 0\rangle$ and read out due to a spin dependent intersystem crossing into an intermediate singlet state. Without magnetic field the $|m_s = \pm 1\rangle$ states are degenerate; however, owing to spin-spin interaction, these states lie higher in energy than the $|m_s = 0\rangle$ state. This is the so-called zero-field splitting $D$ between the states corresponding to an energy of 2.87 GHz. Brought to degeneracy due to the Zeeman effect, the magnetic sublevels of NV centers experience a complex
GSLAC at an axial field \( B_z \approx 102.4 \text{ mT}^{19,22} \), in the presence of hyperfine coupling to nuclear spin of the intrinsic nitrogen (I=1), see Fig. 1 (a).

Figure 1 (b) shows PL the signal as a function of the axial magnetic field with zero transverse fields. A remarkably sharp feature around 102.4 mT, zoomed-in in the inset, reveals the GSLAC. In the inset, several additional features are visible which probably can be associated with cross-relaxation with the nearby spin bath\(^{19,23–25}\). A detailed study of these features is currently being conducted and will be presented in a separate manuscript. Transverse fields couple the \( |m_s = 0\rangle \) and \( |m_s = -1\rangle \) magnetic sublevel manifold and therefore affect contrast and amplitude of the GSLAC feature. Traces of the GSLAC feature for several transverse fields in the range of \( \pm 0.06 \text{ mT} \), are depicted in Fig. 1 (c). The amplitudes of the GSLAC feature as a function of transverse field is indicated by the trace-colored dots and connected with the black line. In summary, the GSLAC contrast exhibits a relatively narrow (\( \approx 38 \mu \text{T} \)) feature as a function of transverse magnetic field centered around zero field.

In order to describe the vector sensing mechanism, we first analyze the Hamiltonian of the triplet ground state around the GSLAC. The system can be modelled by only considering \( |m_s = 0\rangle \) and \( |m_s = -1\rangle \). The \( |m_s = +1\rangle \) is ignored because it is far separated in energy from the \( |m_s = 0\rangle \) state which is preferentially populated under optical excitation\(^{20}\). With the hyperfine interaction between the NV electron spin and the nuclear spin of the intrinsic nitrogen atom, the Hamiltonian is expressed in the basis of \( \{m_s,m_I\} \). Here we write a two-level Hamiltonian in the subspace \( \{|0, +1\rangle, |-1, +1\rangle\} \) since the spins are efficiently polarized to the \( |0, 1\rangle \) state for a \(^{14}\text{N}-\text{V}\) center\(^{22}\) under optical excitation. In the presence of an arbitrary magnetic field \( \mathbf{B} = (B_x, B_y, B_z) \) and neglecting the nuclear Zeeman shift, the reduced Hamiltonian is given by

\[
\mathcal{H}_r = \begin{pmatrix}
0 & \gamma_e B_{\perp} \frac{e^{-i\phi}}{\sqrt{2}} \\
\gamma_e B_{\perp} \frac{e^{+i\phi}}{\sqrt{2}} & D - \gamma_e B_z
\end{pmatrix},
\]

where \( B_{\perp} \) is the transverse magnetic field (\( |B_{\perp}| = \sqrt{B_x^2 + B_y^2} \)), \( \phi \) is the angle defined by \( \tan \phi = B_y/B_x \). In the absence of transverse fields, the \( |0, +1\rangle \) state does not mix with any other states [see Fig. 1 (a)]. Therefore, if the center is fully polarized to this state, the PL should not
depend on the exact value of the longitudinal magnetic field. However, in the presence of the spin bath producing randomly fluctuating magnetic fields, there arises an effective coupling between the eigenstates resulting in depolarization of the NV center and a corresponding drop in PL near the level crossings.

We introduce the axial field difference from the crossing, $\gamma_e \delta B_z = D - \gamma_e B_z$. If $|\delta B_z| \gg |B_\perp|$, far from the avoided crossing region, the PL is insensitive to the transverse field. Conversely, if $|B_\perp| \gg |\delta B_z|$, the signal becomes insensitive to small changes in the longitudinal field. In other words, near the GSLAC, the PL can be used to determine the transverse and longitudinal components of the magnetic field to be measured (TBM). This magnetic-vector sensing protocol can be extended to single-NV probes, and therefore, nanoscale sensing volume, since it just relies on intrinsic properties of the NV center and the presence of a spin bath.

For a given NV center, we define the $z$-axis along the symmetry axis of the center. A microwave-free magnetometer sensing the longitudinal component of a magnetic field is described in 19. Based on the Hamiltonian (Eq.1) and the assumption of an isotropic spin bath, we expect that the effect of a transverse magnetic field on the intensity of PL should not depend on the direction of the transverse field. In fact, we observe this experimentally, see Fig. 2 (b). The PL, however, does depend on the magnitude of the applied transverse field. Therefore, we have a sensor for the magnitude of the transverse field. Similar to how it is possible to measure the field vector with a scalar magnetometer by applying modulated fields in different directions, it is also possible, as we demonstrate here, to measure both Cartesian components of the transverse field with our sensor.

Typical methods to adapt a scalar magnetometer for vector measurement are to apply mutually orthogonal fields modulated at different frequencies. Thus it is possible to determine the components along each direction by individually demodulating the signal\textsuperscript{8}. In this work we propose a method to realize vector-field sensing in the $x$-$y$ plane using a transverse field rotating around the $z$-axis [Fig. 2 (a)] with just one frequency. To gain an intuitive understanding, we approximate the PL lineshape as a function of transverse magnetic field with a 2D Lorentzian centered around
Without an additional transverse field, the PL signal will be reduced but remains unmodulated. In the presence of an additional transverse field, the PL signal shows a modulation at the rotation frequency with a minimum when the rotating field points in the same direction as the field under interrogation and a maximum when both are antiparallel. For further analysis the PL signal is demodulated with a LIA. Amplitude and phase extracted from the demodulation correspond to magnitude and angle of the transverse field to be measured. Thus all Cartesian magnetic-field components can be directly read out in real time with equal sensitivity in all directions. Note here that the reference phase of the LIA for the transverse-field signal demodulation sets the coordinate axes in the $x$-$y$ plane while the phase for $z$-axis demodulation is tuned to maximize the amplitude of the signal in Fig. 3 (a). A more detailed description of the methodology can be found in section Supplementary Information A.

The Helmholtz coils, producing modulating fields, can be also used to provide calibrating magnetic fields, DC or time-varying, $\mathbf{B}_{\text{TBM}} = (B_x, B_y, B_z)$. The applied fields, in the range of 4 $\mu$T around zero along each direction, are calibrated by flux gate magnetometers and consistent with a priori calculations from the known coil geometry and applied currents. The single-frequency-modulation 2D vector magnetometry method was demonstrated by mapping the amplitudes and phase of the LIA output as a function of the applied fields in the $x$-$y$ plane, see Fig. 2 (b) and (c). A demonstration of the determination of the field direction in $x$-$z$ plane was also achieved by recording the measured ratio of $B_z/B_x$, see Supplementary Information section B.

Before the full vector-sensing protocol demonstration, the sensitivity along both the longitudinal and transverse directions ($z$ and $x$) as well as possible cross-talk effects were tested. Derivatives of the fluorescence signals in Fig. 1 (b), detected in the properly phased LIA X output while applying sinusoidally modulating fields along $z$-axis or $x$-axis in the presence of a static field along $z$-axis, are shown in Fig. 3 (a) and (b). The modulation frequencies were 3.7 kHz and 2.3 kHz, respectively, and the modulation depth $\approx 20 \mu$T. Pronounced magnetically dependent features around the GSLAC were detected. In the case of $z$-axis modulation, the resulting demodulated PL signal depends linearly on the magnetic field in the region near the GSLAC [Fig. 3 (a)], while it is
first-order insensitive to the $z$-axis magnetic field when applying modulation along the $x$-axis, [Fig. 3 (b)]. This demonstrates the absence of crosstalk between the different modulating fields in proximity of the GSLAC. At a longitudinal field corresponding to the GSLAC and with an applied $x$-axis modulation the demodulated PL signal shows a linear dependence on the $x$-axis magnetic field [see Fig. 3 (c)].

Figures 3 (d) and (e) show the single channel magnetic sensitivity along the $z$-axis and $x$-axis, respectively. These are calibrated by linearly fitting the data near the zero-crossing of the corresponding derivative curves [Fig. 3 (a) and (c)]. Despite the dominant 1/f noise (near an order of magnitude higher in the longitudinal direction due to the power supply of the electromagnet), we demonstrate a noise floor of around 300 pT/$\sqrt{\text{Hz}}$ in both the longitudinal direction and one transverse direction. The noise for the magnetically insensitive configuration in both cases was measured at magnetic fields of 0.2 mT off the GSLAC field. The electronic noise floor ($\approx 100$ pT/$\sqrt{\text{Hz}}$) was measured by turning off the green excitation light and acquiring the output of the LIA. The photon shot noise limit for the two measurements is 65 pT/$\sqrt{\text{Hz}}$ and 60 pT/$\sqrt{\text{Hz}}$, respectively. The overall noise is limited by the environmental noise. The noise can be further suppressed by differential detection schemes.

As a demonstration of the full vector capacity, a set of static magnetic field points designed along a 3D spiral curve was applied and measured. The trajectory of the vector fields is shown in Fig. 4 (a) and the corresponding amplitudes along each coordinate axis are displayed in Fig. 4 (b). The applied field in $z$ direction is $R \cos \theta$, where $R$ is the radius of the sphere and $\theta$ is the altitude angle (between the magnetic field to be measured and the $z$-axis). The applied $B_x$ and $B_y$ fields are $R \sin \theta \cos \phi$ and $R \sin \theta \sin \phi$, respectively, where $\phi$ is the azimuth angle (between the projection of $B$ in the $x$-$y$ plane and the $x$-axis). This corresponds to the values of $B_x$ and $B_y$ shown in Fig. 4 (b). The measured field components in $x$ and $y$ directions show good agreement with the amplitudes determined by a priori calculations. The scatter in the data can be attributed to environmental noise in the laboratory and the applied field. The latter is also the reason for the larger noise in the $z$ direction. The trajectory was measured multiple times and the angles were reconstructed.
every time. Figure 4 (c) shows the average angle with the statistical error. Note here that all the experiments were operated in the lab environment without magnetic shielding.

2 Conclusion

In summary, we have proposed and demonstrated a sensing method allowing simultaneous recording of all three Cartesian components of a vector magnetic field using a solid-state spin sensor. The method leverages the GSLAC of NV centers, and does not employ microwaves in the measurement. Further optimization of the apparatus will allow a compact vector magnetometer well suited for geophysical field measurement or biophysical imaging. The present method can be applied to the anticrossings in other color-center systems.

The GSLAC-based vector magnetometer using NV centers along a single axis exhibits a root mean square noise floor of \( \approx 300 \) pT in all three axes. More strategies are conceivable to further improve the magnetic sensitivity. While the technique was demonstrated without monitoring the intensity of the pump laser power, future experiments will utilize differential detection schemes and suppress laser-related noise. In addition, combination with infrared-absorption-based readout, or enhancement by optical cavities will allow for magnetic-field sensing with a sensitivity reaching or even exceeding the PL shot-noise limit.

This technique should be extendable to single NV sensors, in this case, it can be expected to advance nanoscale real-time magnetic sensing and imaging applications, such as single molecule imaging. With the ability to sense vector magnetic fields, this method could potentially enable real-time imaging of magnetic dipoles with arbitrary orientations.

Methods

Experimental setup. The experimental apparatus consists of a custom-built electromagnet and three pairs of orthogonal Helmholtz coils wound on a 3D printed mount. The electromagnet can
be moved with a computer-controlled 3D translation stage (Thorlabs PT3-Z8) and a rotation stage (Thorlabs NR360S, $x$-axis). The NV-diamond sensor is placed in the center of both the magnetic bore and the incorporated three pairs of orthogonal Helmholtz coils. The diamond can be rotated also around the $z$-axis. This enables all degrees of freedom for placing the diamond in the center of the magnet and aligning the NV axis parallel to the magnetic field.

A two-channel function generator (Tektronix AFG 3022A) provides sinusoidal signals for field modulations in the longitudinal and transverse directions and references for the demodulation by two LIAs. The signal from one of the channels is split in to two with one of them passing through a phase shifter. These two signals with the same frequency but 90-degree-shifted relative phase are applied to two pairs of the Helmholtz coils (along $x$ and $y$ axes). All three signals are amplified via a homemade 3-channel current amplifier before reaching the Helmholtz coils.

The light source is a solid-state laser emitting at a wavelength $\lambda=532$ nm (laser Quantum Gem 532). The PL emitted by the diamond sample is collected with a parabolic lens and detected with a photodetector (Thorlabs PDA 36A).

**Diamond sample.** The sensor incorporates a 99.97% $^{12}$C high-pressure, high-temperature (HPHT) synthesized, (111)-cut diamond single crystal, with dimensions 0.71 mm $\times$ 0.69 mm and a thickness 0.43 mm. It has 0.9 ppm NV$^-$ and 2 ppm P1 centers (substitutional nitrogen centers), measured by electron spin resonance. This diamond provides remarkable narrow GSLAC-features with small residual couplings to $^{13}$C nuclear spins which is essential for the sensitivity of the proposed method.

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Author contributions. HZ and AW conceived the initial idea for the experiment. HZ, ZS and AW designed the experiment with input from all authors. HZ and ZS and GC constructed the apparatus, performed the experiments, and analyzed the data with assistance from AW and DB. KN, HS, TO and JI fabricated the diamond sample. AW and DB oversaw and managed the project. HZ wrote the manuscript with contributions from ZS, GC, CZ, JI, JW, AW, DB. All authors discussed results and contributed to the writing of the manuscript.

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Figure 1:  (a) The ground-state energy level scheme of the NV center as a function of the applied axial field. The energy levels either cross or do not cross depending on the mixing between them, depicted in detail in the inset. (b) The PL signal as a function of the applied axial magnetic field, normalized to their respective signals at 80 mT. The inset shows a detailed view around the GSLAC trace. (c) Traces of the PL signal around the GSLAC under various transverse fields. The amplitude of the contrast extracted from the curves is shown as a two-dimensional plot in a plane, indicated by solid dots in corresponding trace colors.
Figure 2: (a) Experimental setup for the microwave-free magnetometer and the set Cartesian coordinate system. The diamond is placed in the center of a 3D Helmholtz coil. A static magnetic field \((B_s)\) is applied along a NV axis (noted as \(z\) direction) by a customized electromagnet. The static magnetic field, modulating fields and the axis of NV centers in the NV frame coordinate system are displayed. The measured magnitude (b) and the direction angle (c) as a function of the Cartesian components of the applied field. The reconstructed field vectors are also shown in (b), depicted by the red arrows.
Figure 3: (a) Demodulated PL signal, LIA output X, the measure of magnetic field sensitivity, as a function of axial field with a small added modulation (z-axis). (b) Demodulated PL signal as a function of axial field with an added transverse field modulation (x-axis). (c) Demodulated PL signal as a function of transverse field along the x-axis while modulating the magnetic field along the same direction. (d) Longitudinal (z-axis) magnetic field noise spectrum. The blue line indicates the noise in the magnetically sensitive configuration at a magnetic field of 102.4 mT, the red line indicates a noise in the magnetically insensitive configuration (average noise between 1−500 Hz is 300 pT/√Hz), and the amber line illustrates the electronic noise (average noise between 1−500 Hz is 100 pT/√Hz). The decrease in signal for frequencies above 1 kHz is due to the filtering of the LIA. Photon shot noise is estimated as 65 pT/√Hz. (e) Transverse magnetic field noise spectrum (x-axis). The blue line indicates the noise in the magnetically sensitive configuration measured at zero transverse field, the red line indicates the noise in the magnetically insensitive configuration at a transverse magnetic field of 0.2 mT (average noise between 1−500 Hz is 300 pT/√Hz), and amber line shows the electronic noise spectrum (average noise between 1−500 Hz is 100 pT/√Hz). Photon shot noise is estimated as 60 pT/√Hz.
Figure 4: Demonstration of full vector capability. (a) Trajectory of the detected magnetic fields using the microwave-free vector magnetometer. The green curve indicates the 3D applied field and the brown curve is the projection on $x$-$y$ plane. The red arrows represent the vectors of the measured fields. (b) The three Cartesian components of both the applied (green points) and measured (red circles) magnetic fields for each point. The applied field follows a parametric curve (black dashed lines) with $B_x = \sqrt{R^2 - B_z^2} \cos(2\pi t)$, $B_y = \sqrt{R^2 - B_z^2} \sin(2\pi t)$ and $B_z = 6.82t - 3.41$. (c) The altitude angle (between $\mathbf{B}$ and the $z$-axis) $\theta = \arccos(B_z/R)$ (yellow dots) and the azimuth angle (between the projection of $\mathbf{B}$ in the $x$-$y$ plane and the $x$-axis) $\phi = \arctan(B_y/B_x) = 2\pi t$ (blue dots) for each measured point. In the experiment, the altitude angle $\theta$ decreases in time from $180^\circ$ to $0^\circ$ and the azimuth angle $\phi$ increases from $0^\circ$ to $360^\circ$. 

"Angle φ [deg]   Angle θ [deg]"

-4
-4
-2
0
-2
2
4
0
2
4
2
4
0
-2
-4

Bx [uT] By [uT] Bz [uT]"
Microwave-free vector magnetometry with nitrogen-vacancy centers along a single axis in diamond

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1 Supplementary Information

Illustration of the working principle of the transverse field detection. The PL-GSLAC feature changes its shape according to the applied transverse field, which, however, does not depend on the direction of the field in the $x$-$y$ plane. We approximate the PL-GSLAC feature as a function of transverse field by a 2D Lorentzian function symmetric around the $z$-axis, indicated in Fig. S1 (a) (i). The maximum PL signal corresponds to zero transverse magnetic field and it decreases as
the magnitude of the transverse field increases. When applying a transverse magnetic field rotating around the $z$-axis, the PL signal is reduced but remains constant (no oscillating component) in the absence of a transverse DC field, indicated by the red curve in Fig. S1 (a) (ii). In the presence of a transverse field, the PL signal is off center from the coordinate origin and shows a minimum value when the rotating field reaches the same direction as the transverse field being interrogated, shown in Fig. S1 (a) (iii), (iv) and (v). The difference between the PL signals with (red curve) and without (blue curve) applied transverse field is shown in Fig. S1 (b). This is then demodulated by a LIA which delivers the information of both the amplitude and the angle of the magnetic field to be measured, as shown in Fig. S1 (c).

The $x$ and $y$ axes can be calibrated by tuning the reference phase of the modulation field. In our case, the measured $x$ and $y$ axes are set along the $x$- and $y$-modulating Helmholtz coils. The reference phase of the LIA was set so that a magnetic field along the $x$-axis corresponds to phase zero (and negative amplitude). The LIA output shows a maximum value at $0^\circ$ when applying a field along $x$-axis, shown in Fig. S1 (c). An applied field in any other direction leads to an oscillating PL signal with a corresponding phase. Therefore, the phase output of the LIA is the angle between the transverse field to be measured and the defined $x$ and $y$ axes.

The modulation field is generated with two Helmholtz coils excited by two sine waves with the same frequency but $90^\circ$-shifted phases, with an amplitude of $\approx 20 \mu T$. The phase between these two modulating fields as well as the amplitudes are adjusted to get minimal magnitude output of the LIA without transverse field.

**Demonstration of an $x$-$z$ measurement.** Full vector measurements of magnetic fields require a measurement in the $z$ direction. They are carried out by applying an additional modulated field along $z$ with a different frequency (than in the transverse direction) and demodulation of the PL signal. A matrix of 2D vector magnetic fields in $x$-$z$ plane was measured to demonstrate the method with various $B_x$ and $B_z$ in the range of $\pm 3 \mu T$. The angle of the field can be calculated as $\arctan(B_z/B_x)$ from the applied currents and calibration factors of the two coils. Figure S2
Figure S1: (a) Simulated PL signals as a function of transverse field. The red curves are the trajectories of PL signals superimposed on the 2D Lorentzian contrast function. Figures i) to v), correspond to different show cases: i) no modulated fields and no bias fields, ii) with modulated fields but no bias fields (the time-averaged PL drops), iii) with modulated fields and bias field along $y$, iv) with modulated fields and bias field along $x$, v) with modulated fields and bias field in $x$-$y$ plane, respectively. (b) The simulated PL signals with modulating magnetic field in the presence/absence (red curve/blue curve) of a bias field. (c) Simulated PL signals [in the same coordinate system as in column (a)] as a function of the angle of the modulated field referenced to the -$x$-axis for transverse fields corresponding to (a) and (b).
Figure S2: The ratios of measured fields $B_z/B_x$ corresponding to different angles are calculated from the applied fields in $x$-$z$ plane. The solid green line shows an arctangent dependence.

shows that the ratios of the measured fields $B_z$ and $B_x$ correspond to different angles following the expected arctangent curve. The comparison corroborates the method’s effectiveness.