

Dead-zone-free orientation-based pulsed atomic magnetometer

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The dead zones of atomic magnetometers bring great challenges for the mobile applications in high-sensitivity magnetic field measurement. To solve this fundamental problem, we present a dead-zone-free orientation-based atomic magnetometer employing free-induction-decay (FID) scheme. A modulation scheme combining synchronous optical pumping and radio frequency pulse manipulation is utilized to achieve the free precession of spin polarization in all magnetic field orientations, and the FID signals are detected in two directions with an orthogonal pump-probe light configuration. We perform a comprehensive theoretical analysis of spin polarization evolution for arbitrary magnetic field orientations, and both simulation and experimental results demonstrate that the fusion of information from the pump and probe beams enables the dead-zone-free measurement of the magnetometer, with the sensor exhibiting a sensitivity in the range of 0.6–1.4 pT/Hz^{1/2} across all directions. The proposed scheme is of great significance for the advancement of pulsed atomic magnetometers and their various applications in mobile platforms.

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I. INTRODUCTION

The past few decades have witnessed remarkable breakthroughs in sensor performance and applications of optically pumped magnetometers (OPMs). Zero-field OPMs exploiting the spin-exchange relaxation-free mechanism have reached excellent sensitivity comparable to that of superconducting quantum interference devices [1–4]. Such highly sensitive devices can provide the spatial information of the weak magnetic field in near-zero field environments, making them well suited for biomedical imaging applications such as magnetocardiography [5–7] and magnetoencephalography [8–10]. Total-field OPMs combine high sensitivity with a large dynamic range that extends to Earth’s magnetic field magnitudes [11,12]. Consequently, they can be widely used for high-sensitivity magnetic field sensing applications in geomagnetic environments, such as mineral exploration [13], geomagnetic navigation [14], space science [15], unshielded biomagnetism detection [16–18], and magnetic anomaly detection [19].

Total-field OPMs measure the magnetic field magnitude by detecting the Larmor frequency of polarized atoms [20–22]. Traditionally, they extract magnetic field information by inducing atomic magnetic resonance with a continuous radio

frequency (RF) field [23,24] or modulated pump light [25,26], but their accuracy suffers from phase errors in lock-in detection and light shifts caused by intense pump light. In contrast, the pulsed OPMs employing free-induction-decay (FID) scheme directly measure the magnetic field by resolving the time-domain FID signal without lock-in detection [27–29]. Besides, the optical pumping and detection are separated in FID magnetometers, thereby reducing the influence of light shifts [30,31]. Thus, FID magnetometers exhibit superior accuracy to continuous-wave magnetometers and have attracted intense research interest.

Among various uses of total-field OPMs, mobile applications account for a large proportion, such as the magnetic field measurement in satellites and unmanned aerial vehicles. However, these applications face an unavoidable issue owing to the inherent limitation of OPMs, known as “dead zone.” Dead zone refers to certain orientations of the magnetic field relative to the sensor, where the response signal vanishes and the magnetometer fails to work [32]. Due to the uncertainty and temporal variability of the relative orientation between the ambient magnetic field and the sensor in mobile platforms, the dead zone brings critical challenges to mobile magnetic field sensing applications. Over the years, a variety of methods have been proposed to suppress the dead zones of the atomic magnetometers. Multiple sensors or cells can be used to compensate each other for the dead zone [33–36], but the magnetic gradient and occupied volume may limit their further applications. Controlling the linear polarization and the RF field perpendicular to the external field can achieve isotropic measurement in helium atomic magnetometers [37–39], but such methods are not suitable for alkali metal atomic magnetometer. Other solutions for the

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dead-zone suppression include adding signals of two beams with orthogonal linear polarization [40], simultaneously detecting orientation and alignment polarization [41,42], modulating the polarization of the light beam [43,44], utilizing the coherent population trapping effect [45], changing the optical path in the vapor cell [46,47], and employing a hybrid Poincaré beam [48]. However, these techniques are mainly applied in continuous-wave atomic magnetometers. Although the dead zones of FID magnetometers can be eliminated by creating atomic orientation and alignment [49,50], the presence of two different frequencies complicates the extraction of magnetic field information from time-domain signals. Therefore, using single atomic polarization to achieve dead-zone-free measurement in FID magnetometers remains worthy of exploration.

In this paper, we propose a dead-zone-free orientation-based atomic magnetometer employing FID scheme. The sensor uses an orthogonal pump-probe light configuration to detect the polarization evolution in two perpendicular directions. Synchronous optical pumping is utilized to build up the atomic spin coherence, and then a transverse RF pulse is applied to manipulate the entire spin polarization into free precession. The theoretical model of the dead-zone-free FID magnetometer is derived in detail, followed by the simulation and experiment to validate the performance of the magnetometer. The pulsed modulation scheme enables the free precession of spin polarization in all magnetic field orientations, and the fusion of information from the pump and probe beams successfully achieves all-space dead-zone-free measurement based on atomic orientation polarization. This work provides an important development scheme for high-sensitivity atomic magnetometers and will greatly advance their applications in mobile platforms.

The article is organized as follows. Section II describes the modulation scheme and derives the theoretical model of the dead-zone-free FID magnetometer in detail, followed by the presentation of simulation results. Section III introduces the experimental setup and presents the experimental results for characterizing the sensor performance of the dead-zone-free FID magnetometer. Finally, the article is concluded in Sec. IV.

II. THEORETICAL MODEL

The geometry of our dead-zone-free FID magnetometer is shown in Fig. 1(a). A circularly polarized pump light aligned along the z axis at resonant wavelength interacts with the atoms to create a population imbalance and generate atomic orientation, thereby establishing the spin polarization. To manipulate the entire spin polarization into free precession, a transverse pulsed RF field with magnetic component oriented along the y axis is applied, oscillating at the Larmor frequency. Furthermore, an orthogonally linearly polarized probe light propagates along the x axis, and the laboratory frame $Oxyz$ is thereby established based on the configuration of the magnetometer. The bias magnetic field $\mathbf{B}_0$ to be measured induces Zeeman splitting of the hyperfine level, causing the spin polarization to precess at the Larmor frequency $\omega_L = \gamma B_0$, where γ is the gyromagnetic ratio and B_0 is the magnitude of the magnetic field [51]. Its orientation is defined by θ and

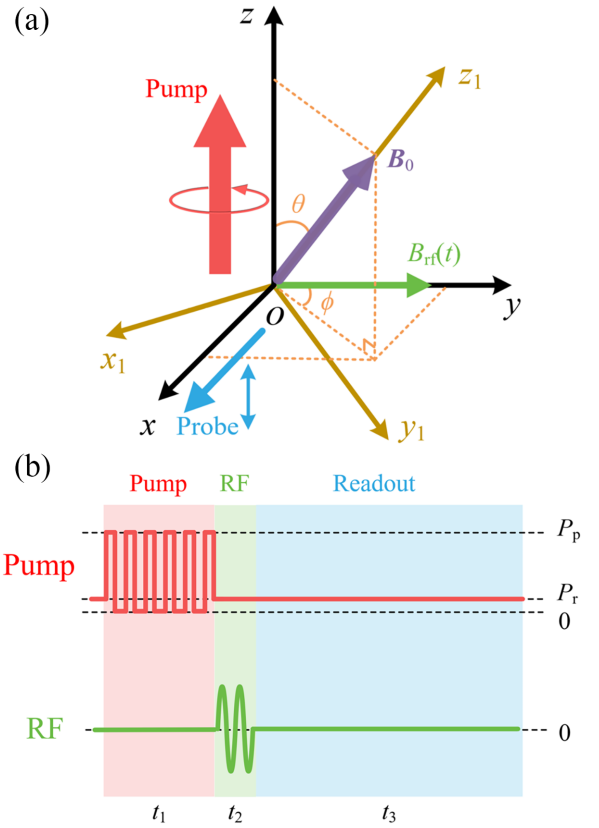


FIG. 1. (a) Geometry of the dead-zone-free FID magnetometer. The laboratory frame $Oxyz$ is established based on the orthogonal pump-RF-probe configuration, and it can be rotated into the field frame $Ox_1y_1z_1$ where the z_1 axis aligns with the bias field $\mathbf{B}_0$. Here, θ is the angle between the pump beam and $\mathbf{B}_0$, and ϕ is the angle between the RF pulse and the projection of $\mathbf{B}_0$ onto the xy plane. (b) Timing pulse sequence of the modulation scheme. In a single measurement period, synchronous optical pumping is employed to create the spin polarization, followed by an RF pulse that manipulates the spin polarization into free precession, and then the FID signal is recorded by both the pump and probe beams in the readout stage.

ϕ in the laboratory frame, where θ is the angle between the pump beam and $\mathbf{B}_0$, and ϕ denotes the angle between the RF pulse and the projection of $\mathbf{B}_0$ onto the xy plane. Then, the laboratory frame $Oxyz$ can be rotated into the field frame $Ox_1y_1z_1$ via coordinate transformation, where the z_1 axis is defined along the $\mathbf{B}_0$.

In an FID magnetometer, pulsed modulation scheme is employed to induce free precession of the spin polarization, and the timing pulse sequence of our magnetometer is shown in Fig. 1(b). Each measurement period can be divided into three stages: pump, RF, and readout. During the pump stage, synchronous optical pumping is used to build up spin polarization for a duration t_1 , where the light intensity of pump beam is modulated at the Larmor frequency, with a peak power P_p and a 50% duty cycle. In real-world applications, the modulation frequency required for synchronous optical pumping can first be approximated in an FID setting by scanning the modulation frequency of the pump beam and maximizing the time-domain signal amplitude. Then, a feedback program can be used to

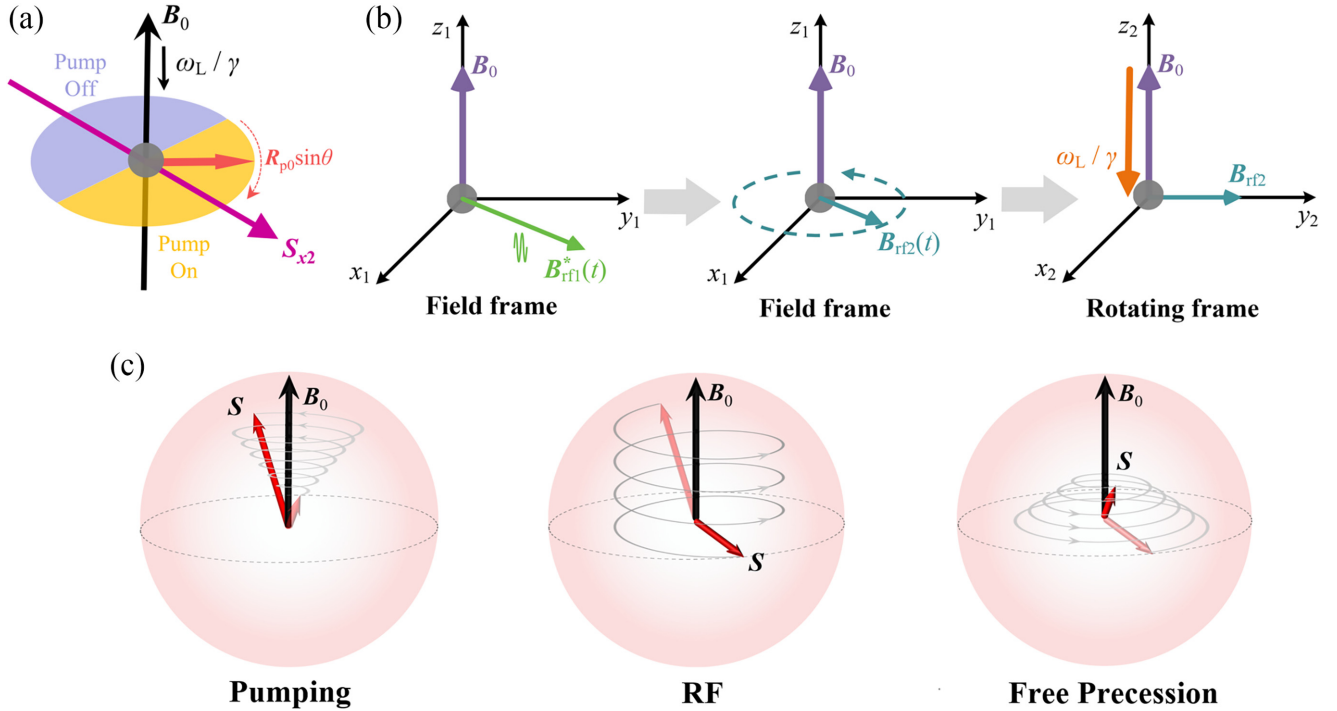


FIG. 2. (a) Principle of polarization buildup with amplitude-modulated light. During the first half-period (yellow-shaded region), the pump light is on and the spin polarization is enhanced by optical pumping, and during the second half-period (purple-shaded region), the pump light is off with no pumping occurring. (b) Rotating wave approximation. Only the effective RF pulse $B_{rf1}^*(t)$ perpendicular to B_0 drives atomic magnetic resonance. It can be decomposed into two parts: $B_{rf2}(t)$, which corotates with the spin polarization, and a counterrotating component, which is neglected. Then, in the rotating frame, the effective rotating component becomes a static field B_{rf2} in the $x_2 y_2$ plane. (c) Evolution of spin polarization in three stages. The initial polarization gets enhanced by synchronous optical pumping during the pump stage, and then it is manipulated into the plane orthogonal to B_0 by the RF pulse. After the RF stage, the spin polarization undergoes free precession, with a small component building up along B_0 due to residual optical pumping.

dynamically adjust the modulation frequency according to the Larmor frequency derived from the FID signal in the preceding measurement cycle. Immediately following the pump stage, the RF pulse oscillating at the Larmor frequency is applied with an extremely short duration t_2 that is far shorter than the atomic relaxation time to reduce spin polarization decay in this stage. It manipulates the spin polarization into the plane orthogonal to B_0 , and then the spin polarization undergoes free precession after the RF stage. During the readout stage, the pump light power is reduced to P_r to monitor the FID signal along the z axis while decreasing perturbations from residual optical pumping. Besides, the FID signal along the x axis is detected by the linearly polarized probe light that undergoes paramagnetic Faraday rotation, enabling the fusion detection of the atomic precession in two orthogonal directions. The FID signal is recorded for a duration t_3 , after which the pump light is modulated again to enter the next period.

The dynamics of the spin polarization in the orientation-based atomic magnetometer can be described by the Bloch equation [52,53]:

$$\frac{d}{dt} \mathbf{S} = \gamma \mathbf{B} \times \mathbf{S} + R_p \hat{z} - R_{rel} \mathbf{S}, \quad (1)$$

where $\mathbf{S}$ is the spin polarization vector, $\mathbf{B}$ is the magnetic field vector, R_p is the optical pumping rate, and R_{rel} is the relaxation rate.

During the pump stage, the spin coherence is created by synchronous optical pumping, and by rotating the field frame counterclockwise around the z_1 axis at the Larmor frequency, a rotating frame $Ox_2 y_2 z_2$ can be established, where B_0 is canceled by a fictitious magnetic field of equal magnitude but opposite direction due to the frame rotation. The optical pumping of amplitude-modulated pump light contributes $R_{p0} \cos \theta / 2$ to the polarization component along B_0 , where R_{p0} denotes the optical pumping rate corresponding to the peak light power. For the spin polarization component orthogonal to B_0 , the principle of polarization buildup using amplitude-modulated light is illustrated in Fig. 2(a). The spin polarization is enhanced by optical pumping when the pump light is on during the first half-period, while no pumping occurs during the second half-period. The pump light contributes $R_{p0} \sin \theta$ to the transverse component, resulting in the transverse optical pumping rate of $R_{p0} \sin \theta / \pi$ along the x_2 axis over one period [54]. Then, the optical pumping rate in the rotating frame during the pump stage can be written as $(R_{p0} \sin \theta / \pi, 0, R_{p0} \cos \theta / 2)^T$, and the evolution of spin polarization with time t can be derived from the Bloch equation:

$$S_{x2}(t) = A_s e^{-R_2 t} + \frac{R_{p0} \sin \theta (1 - e^{-R_2 t})}{\pi R_2}, \quad (2a)$$

$$S_{y2}(t) = 0, \quad (2b)$$

$$S_{z2}(t) = A_p e^{-R_1 t} + \frac{R_{p0} \cos \theta (1 - e^{-R_1 t})}{2R_1}, \quad (2c)$$

where $S_{x2}(t)$, $S_{y2}(t)$, and $S_{z2}(t)$ are the three-axis components of spin polarization in the rotating frame, A_s and A_p are the transverse and longitudinal initial polarization components at the start of the period, and R_1 and R_2 are the longitudinal and transverse relaxation rates during the pump stage, respectively. Both the longitudinal and transverse polarization are enhanced by synchronous optical pumping in the rotating frame, so the spin polarization is strengthened and rotates around $\mathbf{B}_0$ in the field frame, as shown in the first picture of Fig. 2(c).

After the buildup of spin polarization, the pulsed RF field $\mathbf{B}_{rf}(t) = (0, 2B_1 \cos \omega_L t, 0)^T$ with short duration is immediately applied along the y axis. Only the component of $\mathbf{B}_{rf}(t)$ perpendicular to $\mathbf{B}_0$ induces atomic magnetic resonance. Accordingly, with the parallel component neglected, the effective RF pulse can be written as $\mathbf{B}_{rf1}^*(t) = (-2B_1 \cos(\omega_L t) \sin \phi, 2B_1 \cos(\omega_L t) \cos \theta \cos \phi, 0)^T$ in the field frame. To derive the algebraic solution describing spin polarization evolution, the rotating wave approximation is further employed, as shown in Fig. 2(b). $\mathbf{B}_{rf1}^*(t)$ can be decomposed into two rotating components with equal amplitude: One is $\mathbf{B}_{rf2}(t)$, which corotates with the spin polarization around $\mathbf{B}_0$ at frequency ω_L , and the other is a counterrotating component, which is neglected [55]. Then, in the rotating frame $Ox_2y_2z_2$, the effective rotating component transforms into a static field, which can be expressed as $\mathbf{B}_{rf2} = (0, B_1 \sqrt{(\cos \theta \cos \phi)^2 + \sin^2 \phi}, 0)^T$. With the relaxation term neglected due to extremely short pulse duration, the evolution of spin polarization during the RF stage can be derived from the Bloch equation:

$$S_{x2}(t) = K_{xy} \cos \delta \cos(\gamma B_1 \alpha t) + K_z \sin(\gamma B_1 \alpha t), \quad (3a)$$

$$S_{y2}(t) = K_{xy} \sin \delta, \quad (3b)$$

$$S_{z2}(t) = -K_{xy} \cos \delta \sin(\gamma B_1 \alpha t) + K_z \cos(\gamma B_1 \alpha t), \quad (3c)$$

where K_{xy} and K_z are the transverse and longitudinal polarization components at the start of RF stage, $\alpha = \sqrt{(\cos \theta \cos \phi)^2 + \sin^2 \phi}$, and δ is the angle between transverse initial polarization and $\mathbf{B}_{rf2}$. K_{xy} and K_z are given by

$$K_{xy} = A_s e^{-R_2 t_1} + \frac{R_{p0} \sin \theta (1 - e^{-R_2 t_1})}{\pi R_2}, \quad (4a)$$

$$K_z = A_p e^{-R_1 t_1} + \frac{R_{p0} \cos \theta (1 - e^{-R_1 t_1})}{2R_1}. \quad (4b)$$

It can be seen from Eq. (3) that the spin polarization component parallel to the static field $\mathbf{B}_{rf2}$ remains still, while the orthogonal component rotates around $\mathbf{B}_{rf2}$ in the rotating frame. By adjusting the amplitude and duration of the RF pulse, the spin polarization can be fully rotated into the plane orthogonal to $\mathbf{B}_0$ to maximize the FID signal, and the evolution of spin polarization in the field frame is shown in the second picture of Fig. 2(c). In the real-world applications, full polarization rotation can be achieved by optimizing the RF pulse amplitude dynamically via the bisection method at a constant pulse duration.

By directly solving the Bloch equation in the field frame, the evolution of spin polarization during the readout stage can be derived as follows:

$$S_{x1}(t) = P_{\text{tot}} \cos(\gamma B_0 t + \varphi) e^{-R_{r2} t}, \quad (5a)$$

$$S_{y1}(t) = P_{\text{tot}} \sin(\gamma B_0 t + \varphi) e^{-R_{r2} t}, \quad (5b)$$

$$S_{z1}(t) = \frac{R_{pr} \cos \theta (1 - e^{-R_{r1} t})}{R_{r1}}, \quad (5c)$$

where $S_{x1}(t)$, $S_{y1}(t)$, and $S_{z1}(t)$ are the three-axis components of spin polarization in the field frame; $P_{\text{tot}} = \sqrt{K_{xy}^2 + K_z^2}$ denotes the amplitude of spin polarization undergoing free precession; φ is the angle between spin polarization and x_1 axis at the start of the readout stage; and R_{pr} , R_{r1} , and R_{r2} are the optical pumping rate, longitudinal relaxation rate, and transverse relaxation rate during the readout stage, respectively. The spin polarization freely precesses in the plane orthogonal to $\mathbf{B}_0$, and a small polarization component builds up along $\mathbf{B}_0$ due to residual optical pumping, which is shown in the third picture of Fig. 2(c).

After the readout stage, synchronous optical pumping is employed again and the spin polarization continues to evolve in the next period. The amplitudes of initial polarization components A_s and A_p can be derived according to the periodical evolution:

$$A_s = \frac{P_2 e^{-R_2 t_1} + \sqrt{P_1^2 (e^{2R_2 t_3} - e^{-2R_2 t_1}) + P_2^2 e^{2R_2 t_3}}}{e^{2R_2 t_3} - e^{-2R_2 t_1}}, \quad (6a)$$

$$A_p = \frac{R_{pr} \cos \theta (1 - e^{-R_{r1} t_3})}{R_{r1}}, \quad (6b)$$

where P_1 and P_2 are expressed as

$$P_1 = \frac{R_{p0} \cos \theta (1 - e^{-R_1 t_1})}{2R_1} + \frac{R_{pr} \cos \theta e^{-R_1 t_1} (1 - e^{-R_{r1} t_3})}{R_{r1}}, \quad (7a)$$

$$P_2 = \frac{R_{p0} \sin \theta (1 - e^{-R_2 t_1})}{\pi R_1}. \quad (7b)$$

Inserting Eqs. (6) and (7) into Eq. (4), the amplitude of spin polarization undergoing free precession can be written as

$$P_{\text{tot}} = \sqrt{P_1^2 + (A_s e^{-R_2 t_1} + P_2)^2}. \quad (8)$$

Then, through coordinate transformation, the evolution of spin polarization detected by the probe and pump beams during the readout stage can be derived from Eq. (5):

$$S_x(t) = \frac{R_{pr} \cos \theta \sin \phi \sin \theta (1 - e^{-R_{r1} t})}{R_{r1}} + P_{\text{tot}} [\cos(\gamma B_0 t + \varphi) \cos \phi + \cos \theta \sin \phi \sin(\gamma B_0 t + \varphi)] e^{-R_{r2} t}, \quad (9a)$$

$$S_z(t) = \frac{R_{pr} \cos^2 \theta (1 - e^{-R_{r1} t})}{R_{r1}} - P_{\text{tot}} \sin \theta \sin(\gamma B_0 t + \varphi) e^{-R_{r2} t}, \quad (9b)$$

where $S_x(t)$ and $S_z(t)$ are the spin polarization components along the probe beam and the pump beam in the laboratory

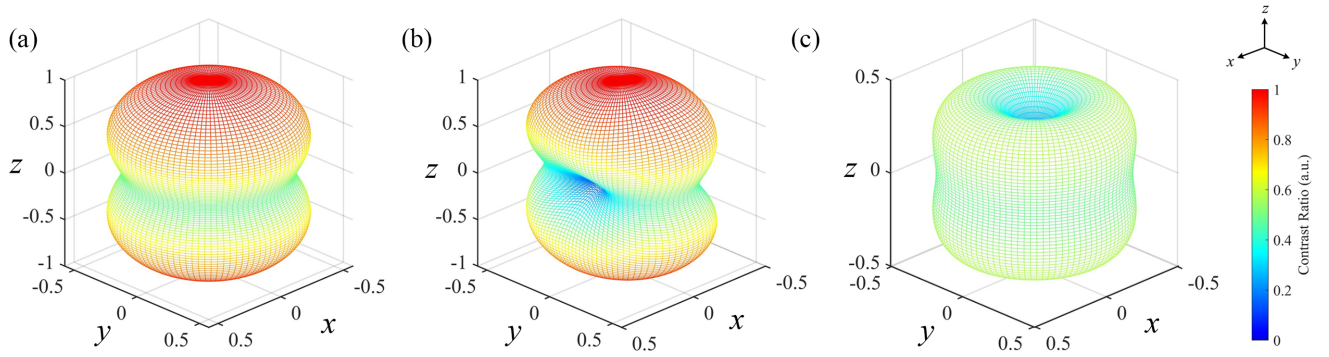


FIG. 3. Simulation results for (a) the amplitude of spin polarization undergoing free precession, and the responses of (b) the probe beam and (c) the pump beam across all magnetic field orientations, expressed in normalized FID amplitude. The probe beam output exhibits a dead zone when $\mathbf{B}_0$ is parallel to the propagation direction of the probe beam, whereas the pump beam output exhibits a dead zone when $\mathbf{B}_0$ is parallel to the propagation direction of the pump beam.

frame, respectively. The first term in each polarization expression is the slowly varying component that arises from residual optical pumping, and the second term corresponds to the FID signal.

The probe beam reads out the polarization component $S_x(t)$ via the paramagnetic Faraday rotation of linearly polarized light, and the polarization rotation angle θ_{rad} is given by [56]

$$\theta_{\text{rad}} = \frac{\pi}{2} l c n r_e S_x(t) (-f_{D1} \text{Im}[L(\nu - \nu_{D1})] + \frac{1}{2} f_{D2} \text{Im}[L(\nu - \nu_{D2})]), \quad (10)$$

where l is the length of the beam passing through the atomic ensemble, $c = 3 \times 10^8$ m/s is the speed of light, n is the number density of the measured alkali metal atoms, $r_e = 2.82 \times 10^{-15}$ m is the classical electron radius, f_{D1} and f_{D2} are the oscillator strengths corresponding to the D1 and D2 transitions, ν is the light frequency, $L(\nu - \nu_0)$ represents the Lorentzian profile in complex form, and ν_{D1} and ν_{D2} are the resonance frequencies of the D1 and D2 transitions, respectively. The polarization component $S_z(t)$ is read out by the pump beam via the absorption of circularly polarized light, and the pump light intensity I transmitting through the vapor cell is given by [57]

$$I = I_0[1 - n\sigma(\nu)l] + I_0 n\sigma(\nu)IS_z(t), \quad (11)$$

where I_0 is the incident pump light intensity and $\sigma(\nu)$ is the photon absorption cross section at light frequency ν .

Figure 3(a) shows the simulation results for the amplitude of spin polarization undergoing free precession across all magnetic field orientations, based on Eq. (8). The 3D plot is constructed using the normalized FID amplitude, where the directions from the frame origin to the surface points represent the magnetic field orientations. It can be seen that the pulsed modulation scheme enables the free precession of spin polarization in arbitrary magnetic field orientations. The atomic ensemble exhibits the largest FID amplitude when $\mathbf{B}_0$ is aligned with the pump beam, and as θ increases, the FID amplitude gets smaller due to the reduced degree of spin polarization established by optical pumping. Using the same method, the simulation results for the responses of probe and pump beams across all magnetic field orientations are shown in Figs. 3(b) and 3(c), respectively, according to Eq. (9). It can

be seen that the probe beam output has the similar variation trend as Fig. 3(a), but there is no FID signal output when $\mathbf{B}_0$ is aligned with the probe beam, resulting in a dead zone of the magnetometer. The pump beam output achieves the largest FID amplitude in specific tilted magnetic field orientations, which arises from the trade-off between the degree of spin polarization and the precession projection along the beam, and it exhibits a dead zone when $\mathbf{B}_0$ is parallel to the propagation direction of the pump beam. The failure to detect the FID signal causes the dead zone for both the probe and pump beams, because the magnetic field to be measured is aligned with the beam propagation direction, making the plane of free precession orthogonal to the beam and leading to no precession projection along the beam. However, the probe beam and the pump beam have different dead zones along two orthogonal directions, enabling the mutual compensation of their dead zones and the realization of a dead-zone-free atomic magnetometer by fusion detection.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The schematic diagram of the experimental setup for the dead-zone-free pulsed atomic magnetometer is illustrated in Fig. 4. The sensitive core of the system is a 10-mm-diameter spherical vapor cell filled with pure ^{87}Rb whose $\gamma \simeq 2\pi \times 7$ Hz/nT and N_2 buffer gas at a pressure of 430 Torr. The cell is enclosed in a boron nitride oven that provides a uniform thermal environment and is heated to a typical operating temperature of 100 °C with an alternating electric current. The oven is centered in a set of triaxial field coils (with only the x -axis coils shown) that are driven by a current source to generate the magnetic field to be measured. Besides, a pair of RF coils outside the oven is placed concentrically with the cell, providing the pulsed RF field along the y axis. All of these are housed within a four-layer cylindrical μ -metal magnetic shield to suppress the ambient noise contributions and reduce the environmental magnetic field disturbances.

The pump and probe beams are generated by two distributed Bragg reflector lasers, and both beam widths are set to a diameter of 2.7 mm. The pump laser is tuned to the ^{87}Rb D1 line and the beam is transmitted via a polarization-maintaining fiber to an AOM, working in a pulsed regime. The pump beam output from the collimator becomes circularly polarized light

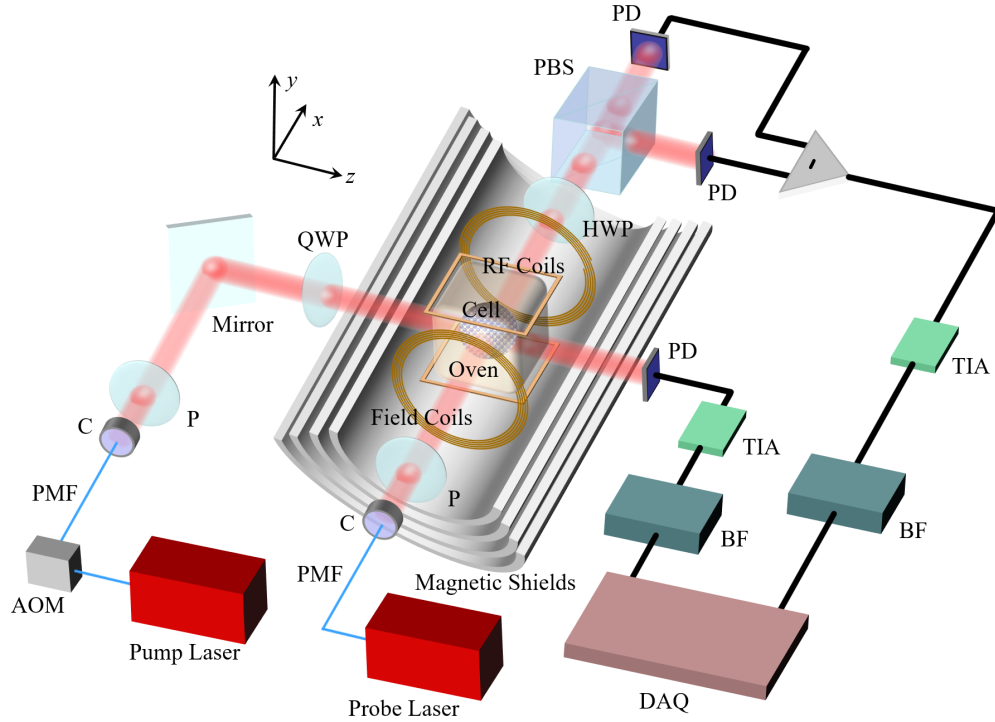


FIG. 4. Schematic diagram of the experimental setup. AOM, acousto-optic modulator; PMF, polarization-maintaining fiber; C, collimator; P, polarizer; QWP, quarter-wave plate; HWP, half-wave plate; PBS, polarizing beam splitter; PD, photodetector; TIA, transimpedance amplifier; BF, band-pass filter; DAQ, data acquisition card.

after passing through a polarizer, a mirror, and a quarter-wave plate, and it then travels along the z axis through the cell with a peak power of 25 mW. The power of the beam is reduced to 200 μ W during the probe stage, and a photodetector is used to detect the light intensity signal that contains spin precession information, as the absorption coefficient of circularly polarized light is modulated by the evolution of spin polarization, according to Eq. (11). The probe laser produces a continuous probe beam far detuned from the D1 line, and the fiber-coupled output passes through a polarizer to form linearly polarized light with a power of 600 μ W. According to Eq. (10), the evolution of spin polarization induces a change in the optical rotation angle of the probe beam propagating along the x axis through the cell. This optical rotation angle signal is detected by a balanced polarimeter, which comprises a half-wave plate, a PBS, and two photodetectors configured in differential mode. The optical signals from the pump and probe beams are both converted to electrical signals by photodetectors and then amplified by transimpedance amplifiers. Bandpass filters with a 4 kHz bandwidth centered at the Larmor frequency are used to suppress low-frequency fluctuations and high-frequency noise, and the filter outputs are recorded by a DAQ at a sampling rate of 2 MHz for analyzing the FID signal.

In accordance with the timing pulse sequence shown in Fig. 1(b), the acousto-optic modulator and RF coils are driven by a signal generator, and the FID period is set to 2 ms with a 30% duty cycle of the pump stage. The duty cycle of the RF stage is set to 1.5% to balance the requirement for achieving complete manipulation and reducing polarization decay during this process. A 10 μ T magnetic field to be measured is provided by the field coils, and its orientation can be adjusted

by changing the currents applied to three axes of the coils. Since the required rotation angle for the polarization varies across different conditions, the amplitude of the RF pulse is individually adjusted to maximize the FID signal for each specific magnetic field orientation, ensuring the spin polarization is fully rotated into the transverse plane. The slowly varying component of atomic evolution in Eq. (9) is eliminated by the bandpass filter, and the voltage signal acquired by the data acquisition card can be modeled as

$$V(t) = V_0 \sin(\gamma B_0 t + \psi) e^{-R_{12}t} + \varepsilon, \quad (12)$$

where V_0 is the FID amplitude, ψ is the signal initial phase, and ε is the noise.

To validate the performance of the dead-zone-free magnetometer, the FID amplitude for different orientations of $\mathbf{B}_0$ in three major orthogonal planes is measured in the experiment. The results for probe and pump beams are presented in Fig. 5, where it can be seen that the experimental results are in good agreement with the theoretical curve fitted using Eq. (9). As evident from the top row of Fig. 5, the FID signal output from the probe beam exhibits a single-axis dead zone along the probe beam's propagation direction, which arises from the inability to detect the free precession of spin polarization. Besides, Fig. 5(c) reflects the real FID amplitude for tilted magnetic field orientations, as the probe beam lies within the free precession plane, preventing the output FID amplitude from being reduced by spatial projection. The FID amplitude reaches a maximum when $\mathbf{B}_0$ is aligned with the pump beam. In this case, the value of B_1 is set to 1200 nT to induce a 90° rotation of spin polarization during the RF stage, because the polarization established during the pump stage is parallel to $\mathbf{B}_0$. As $\mathbf{B}_0$ deviates from the pump beam, a decrease in the

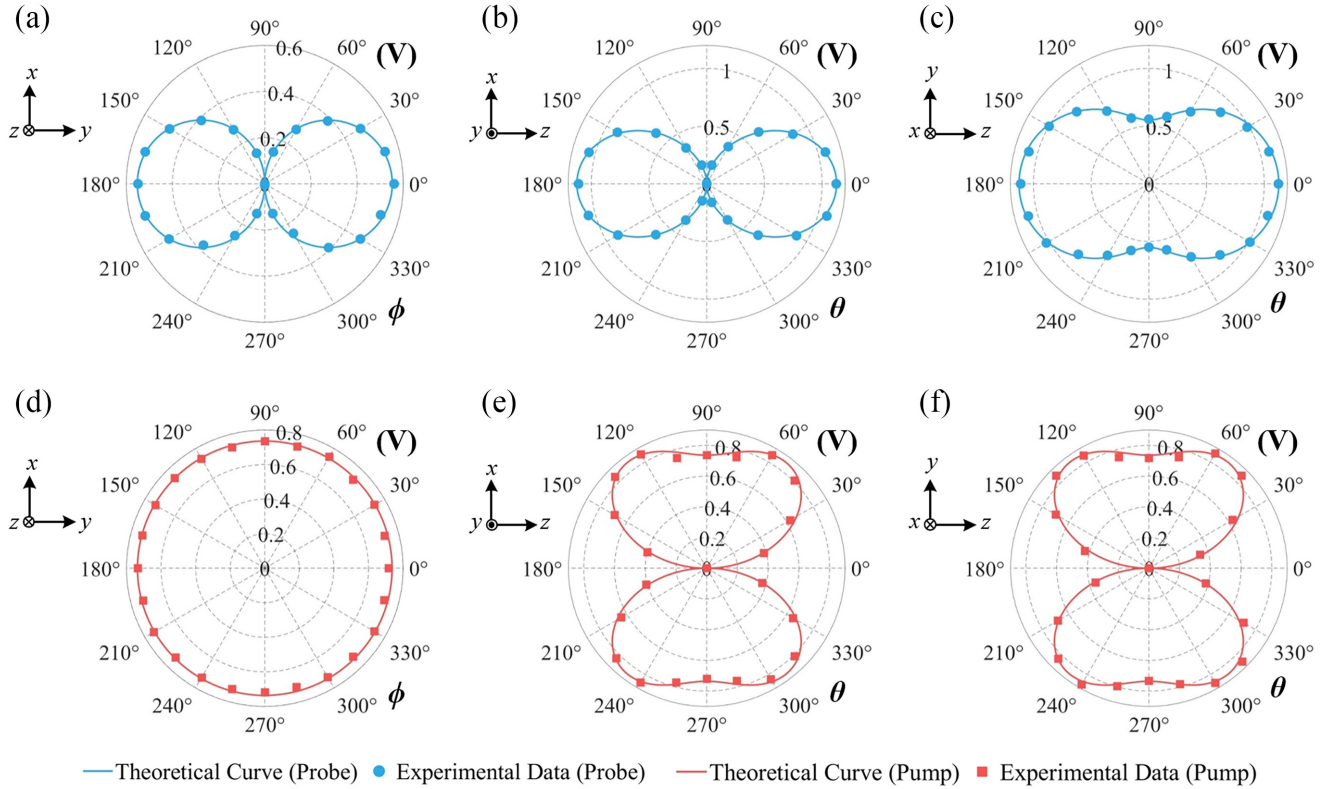


FIG. 5. Polar diagram of the FID amplitude output from the probe beam in (a) the xy plane, (b) the xz plane, and (c) the yz plane and from the pump beam in (d) the xy plane, (e) the xz plane, and (f) the yz plane. The blue and red dots refer to the experimental data of the probe and pump beams, and the blue and red lines indicate the fitted theoretical curves.

FID amplitude is caused by the diminished degree of spin polarization built up by synchronous optical pumping. The magnetometer exhibits the same behavior with the all-optical scheme when $\mathbf{B}_0$ lies in the xy plane, as the polarization prepared during the pump stage is fully orthogonal to the field, making the RF pulse unnecessary. Therefore, the value of B_1 is set to zero in this case. The bottom row of Fig. 5 shows that the FID signal output from the pump beam has a single-axis dead zone along the pump beam's propagation direction, which shares the same cause as the dead zone observed for the probe beam. Additionally, the FID amplitude remains constant throughout the xy plane, and it has an identical distribution in the other two major orthogonal planes, because the polarization established by optical pumping and the beam output only depend on θ . As θ increases, the FID amplitude first rises from zero and then gradually decreases, due to spin polarization degree and precession projection along the beam contributing together. The outputs of pump beam and probe beam exhibit different dead zones along two orthogonal directions, which proves that the system can effectively suppress the dead-zone effect and enable dead-zone-free measurement by fusing the information of two beams. Furthermore, the FID amplitude of one beam reaches a relatively high level when $\mathbf{B}_0$ lies within the dead zone of the other beam, holding the potential to ensure the magnetometer maintains high sensitivity across all magnetic field orientations.

The magnitude of magnetic field is attained by fitting the data to the model given in Eq. (12), and Fig. 6(a) shows a single FID trace in a magnetic field of 10 μT . Each FID

signal train is recorded over a period of 10 s, and a fitting routine is applied to each individual FID trace to generate time-domain magnetic field data. To estimate the sensitivity of the magnetometer, the spectral density analysis is performed on the magnetic field data corresponding to each field orientations in the experiment. Figure 6(b) shows the sensitivity of the probe beam output when $\mathbf{B}_0$ is aligned with the pump beam, with the noise floor of the FID magnetometer measured at 0.6 $\text{pT}/\text{Hz}^{1/2}$. Figure 6(c) illustrates the sensitivity of the pump beam output when $\mathbf{B}_0$ is aligned with the probe beam, and the corresponding noise floor is 1.3 $\text{pT}/\text{Hz}^{1/2}$. The peaks observed at 50 Hz for both cases are caused by power-line interference. The noise analysis of the FID magnetometer can be performed using the Cramér-Rao lower bound (CRLB), which quantifies the statistical uncertainty of extracting the magnetic field from a discrete signal. For the magnetic field extracted from a discrete FID trace, the CRLB condition under the limit of high sampling rate can be expressed as [58]

$$\sigma_{\text{CR}} \geq \frac{\sqrt{12C}}{\gamma(V_0/\rho)T_r^{3/2}}, \quad (13)$$

where V_0/ρ is the signal-to-noise ratio, ρ is the voltage spectral noise density at the Larmor frequency, and T_r is the readout time. C is the corrective factor accounting for spin depolarization, which is given by

$$C = \frac{N^3}{12} \frac{(1 - z^2)^3(1 - z^{2N})}{z^2(1 - z^{2N})^2 - N^2 z^{2N}(1 - z^2)^2}, \quad (14)$$

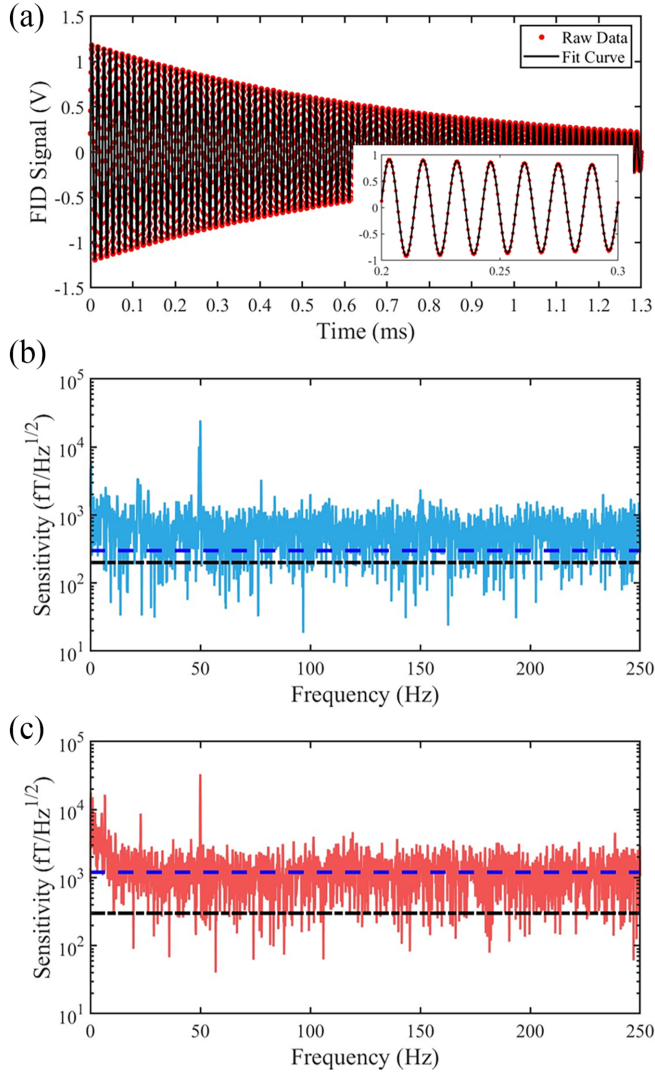


FIG. 6. (a) Typical FID signal (red dots) with corresponding fitting curve (black line) acquired in a 10 μT magnetic field. The inset displays 100 μs of data to make the oscillations and the fit clearly visible. (b) The sensitivity of the probe beam output when $\mathbf{B}_0$ is aligned with the pump beam. (c) The sensitivity of the pump beam output when $\mathbf{B}_0$ is aligned with the probe beam. The blue dashed line and the black dot-dashed line represent the technical noise and the photon shot-noise level, respectively.

where $N = T_r/\Delta t$ is the number of the data points in FID trace, Δt is the sampling time interval, and $z = e^{-R_r\Delta t}$. Assuming the noise is white, the spectral noise density in units of $\text{T}/\text{Hz}^{1/2}$ can be calculated as [59]

$$\rho_{\text{CR}} = \sigma_{\text{CR}}/\sqrt{f_{\text{bw}}}, \quad (15)$$

where $f_{\text{bw}} = 1/(2T)$ is the Nyquist bandwidth and T is the FID period. By turning off the pump beam modulation and measuring the average voltage noise density centered at the Larmor frequency, the contribution of technical noise in the system can be calculated using Eq. (15). The blue dashed lines in Figs. 6(b) and 6(c) represent the technical noise levels of the magnetometer, which are 0.3 and 1.2 $\text{pT}/\text{Hz}^{1/2}$, respectively. Besides, the photon shot-noise density of two beams

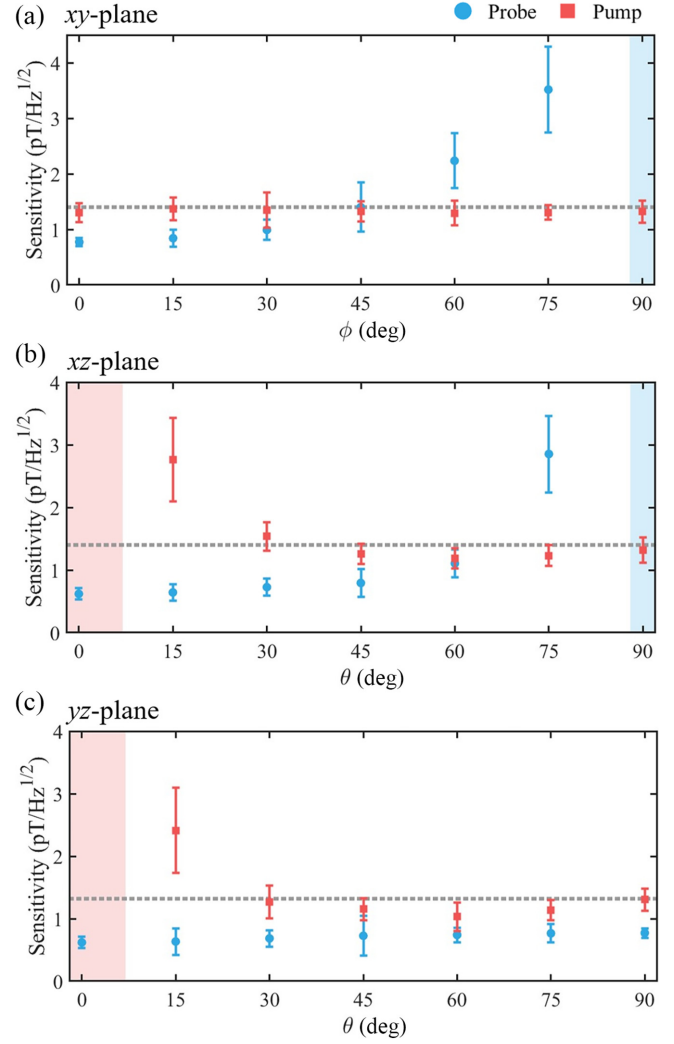


FIG. 7. Variation of the magnetometer sensitivity when $\mathbf{B}_0$ lies in (a) the xy plane, (b) the xz plane, and (c) the yz plane. The blue dots and red squares represent the sensitivities of the probe and pump beam outputs, respectively, with the blue and red regions denoting their corresponding dead zones. The error bars for the sensitivities of the probe and pump beams are, respectively, enlarged by a factor of 6 and 3 to ensure clear observability. The gray dotted line indicates a sensitivity level of 1.4 $\text{pT}/\text{Hz}^{1/2}$.

can be estimated as $\rho_{\text{sn}} = G\sqrt{2eP_{\text{det}}\mathcal{R}}$, where G is the transimpedance amplifier gain, e is the electron charge, P_{det} is the light power reaching the photodetector, and $\mathcal{R}$ is the detector responsivity [60]. The photon shot-noise levels in Figs. 6(b) and 6(c), respectively, are 0.2 and 0.3 $\text{pT}/\text{Hz}^{1/2}$, indicated by the black dot-dashed lines. Compared with the absorption of circularly polarized light, the FID signal detected by the optical rotation angle of linearly polarized light exhibits a better sensitivity and technical noise level. This can be attributed to the suppression of optical common noise in the balanced differential detection as well as the detuned polarization wave of the probe beam, which provide a higher-quality FID signal and lower the noise bound. Given that the sensitivity of the magnetometer is still limited by the magnetic field and technical noise, further reducing the noise from the current source

and electric devices could enable the sensitivity to reach the photon shot-noise level. Besides, lengthening the coherence time of spin polarization can effectively reduce the corrective factor given in Eq. (14), which provides another method to improve the performance of the sensors.

Figure 7 shows the variation of the magnetometer sensitivity when $\mathbf{B}_0$ lies in three major orthogonal planes. The error bars calculated as the standard deviation of nine measurements are enlarged to make them clearly visible. As observed in Fig. 7(a), the pump beam output has a relatively consistent sensitivity around $1.3 \text{ pT/Hz}^{1/2}$, which is attributed to the uniform FID amplitude in the xy plane. As ϕ varies from 0° to 90° , the sensitivity of the probe beam output gradually decreases from $0.8 \text{ pT/Hz}^{1/2}$. The probe beam output exhibits a 2° conical dead zone centered at $\phi = 90^\circ$, because the noise of magnetometer overwhelms the weak FID signal, thereby preventing the detection of magnetic field. Figure 7(b) illustrates that the pump beam output exhibits a 7° conical dead zone centered at $\theta = 0^\circ$. As θ varies from 0° to 90° in the xz plane, the sensitivity of the pump beam output initially improves, reaching a optimal value of $1.2 \text{ pT/Hz}^{1/2}$ at $\theta = 60^\circ$, before slowly decreasing to $1.3 \text{ pT/Hz}^{1/2}$. In contrast, the sensitivity of the probe beam output shows a monotonic decrease starting from $0.6 \text{ pT/Hz}^{1/2}$. As shown in Fig. 7(c), the sensitivity of the pump beam output in the yz plane follows a similar variation trend to that in the xz plane, with the probe beam output achieving favorable sensitivity around $0.7 \text{ pT/Hz}^{1/2}$. It can be seen that when the sensitivity of one beam decreases sharply, the other beam still exhibits excellent sensitivity. This complementary behavior ensures the magnetometer maintains a sensitivity in the range of $0.6\text{--}1.4 \text{ pT/Hz}^{1/2}$ across all magnetic field orientations by fusing two beams' information, which holds potential for realizing high-sensitivity magnetic field measurement in practical mobile applications.

IV. CONCLUSION

In summary, we propose a dead-zone-free orientation-based pulsed atomic magnetometer, solving a fundamental

problem of “dead zone” in high-sensitivity magnetic field measurements. This magnetometer employs a modulation scheme combining synchronous optical pumping and RF pulse manipulation, allowing the spin polarization to undergo free precession in all magnetic field orientations. An orthogonal pump-probe light configuration is used to detect the FID signal in two perpendicular directions, and the fusion of information from two beams enables the mutual compensation of their dead zones, thereby eliminating the dead zone of the magnetometer. We develop a comprehensive theoretical model of the spin polarization evolution for arbitrary magnetic field orientation in detail and conduct corresponding simulation analyses to validate the feasibility of the dead-zone-free magnetometer. The experimental results show that the magnetometer achieves dead-zone-free measurement and exhibits a sensitivity ranging from 0.6 to $1.4 \text{ pT/Hz}^{1/2}$ across all magnetic field orientations. Our research contributes significantly to the advancement of pulsed atomic magnetometers and is suitable for mobile applications with varying magnetic field orientations. Future work will concentrate on improving the sensitivity of the magnetometer, including the suppression of sensor noise and atomic spin relaxation. With the growing demand for high-performance magnetic field sensing, this work will bring insights into the total-field OPMs and their various mobile applications in unshielded environments.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain sensitive personal information. The data are available from the authors upon reasonable request.

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- [1] I. K. Kominis, T. W. Kornack, J. C. Allred, and M. V. Romalis, A subfemtotesla multichannel atomic magnetometer, *Nature (London)* **422**, 596 (2003).
 - [2] J. Allred, R. Lyman, T. Kornack, and M. V. Romalis, High-sensitivity atomic magnetometer unaffected by spin-exchange relaxation, *Phys. Rev. Lett.* **89**, 130801 (2002).
 - [3] K. Wei, Z. Xu, Y. He, X. Ma, X. Heng, X. Huang, W. Quan, W. Ji, J. Liu, X. Wang, *et al.*, Dark matter search with a resonantly-coupled hybrid spin system, *Rep. Prog. Phys.* **88**, 057801 (2025).
 - [4] S. Wang, J. Lu, K. Zhang, L. Zhao, Y. Qi, and J. Fang, Zero-field atomic magnetometer to extract longitudinal magnetic field, *Phys. Rev. Res.* **7**, L032024 (2025).
 - [5] O. Alem, T. H. Sander, R. Mhaskar, J. LeBlanc, H. Eswaran, U. Steinhoff, Y. Okada, J. Kitching, L. Trahms, and S. Knappe, Fetal magnetocardiography measurements with an array of microfabricated optically pumped magnetometers, *Phys. Med. Biol.* **60**, 4797 (2015).
 - [6] S. Su, Z. Xu, X. He, G. Zhang, H. Wu, Y. Gao, Y. Ma, C. Yin, Y. Ruan, K. Li, and Q. Lin, Vector magnetocardiography using compact optically-pumped magnetometers, *Heliyon* **10**, e29092 (2024).
 - [7] R. Wyllie, M. Kauer, R. T. Wakai, and T. G. Walker, Optical magnetometer array for fetal magnetocardiography, *Opt. Lett.* **37**, 2247 (2012).
 - [8] E. Boto, N. Holmes, J. Leggett, G. Roberts, V. Shah, S. S. Meyer, L. D. Muñoz, K. J. Mullinger, T. M. Tierney, S. Bestmann, G. R. Barnes, R. Bowtell, and M. J. Brookes, Moving magnetoencephalography towards real-world applications with a wearable system, *Nature (London)* **555**, 657 (2018).

- [9] Y. Ma, Z. Qiao, M. Yu, Y. Wang, Y. Chen, G. Luo, P. Yang, Q. Lin, L. Zhao, Y. Zhang, *et al.*, Single-beam integrated hybrid optical pumping spin exchange relaxation free magnetometer for biomedical applications, *Appl. Phys. Lett.* **121**, 114001 (2022).
- [10] H. Xia, A. Ben-Amar Baranga, D. Hoffman, and M. Romalis, Magnetoencephalography with an atomic magnetometer, *Appl. Phys. Lett.* **89**, 211104 (2006).
- [11] G. Oelsner, V. Schultze, R. IJsselsteijn, and R. Stolz, Performance analysis of an optically pumped magnetometer in Earth's magnetic field, *EPJ Quantum Technol.* **6**, 6 (2019).
- [12] G. Oelsner, R. IJsselsteijn, T. Scholtes, A. Krüger, V. Schultze, G. Seyffert, G. Werner, M. Jäger, A. Chwala, and R. Stolz, Integrated optically pumped magnetometer for measurements within Earth's magnetic field, *Phys. Rev. Appl.* **17**, 024034 (2022).
- [13] M. N. Nabighian, V. Grauch, R. Hansen, T. LaFehr, Y. Li, J. W. Peirce, J. D. Phillips, and M. Ruder, The historical development of the magnetic method in exploration, *Geophysics* **70**, 33ND (2005).
- [14] J. Shockley and J. Raquet, Navigation of ground vehicles using magnetic field variations, *Navig.: J. Inst. Navig.* **61**, 237 (2014).
- [15] J. S. Bennett, B. E. Vyhnalek, H. Greenall, E. M. Bridge, F. Gotardo, S. Forstner, G. I. Harris, F. A. Miranda, and W. P. Bowen, Precision magnetometers for aerospace applications: A review, *Sensors* **21**, 5568 (2021).
- [16] W. Xiao, C. Sun, L. Shen, Y. Feng, M. Liu, Y. Wu, X. Liu, T. Wu, X. Peng, and H. Guo, A movable unshielded magnetocardiography system, *Sci. Adv.* **9**, eadg1746 (2023).
- [17] R. Zhang, W. Xiao, Y. Ding, Y. Feng, X. Peng, L. Shen, C. Sun, T. Wu, Y. Wu, Y. Yang, Z. Zheng, X. Zhang, J. Chen, and H. Guo, Recording brain activities in unshielded Earth's field with optically pumped atomic magnetometers, *Sci. Adv.* **6**, eaba8792 (2020).
- [18] M. Limes, E. Foley, T. Kornack, S. Caliga, S. McBride, A. Braun, W. Lee, V. Lucivero, and M. Romalis, Portable magnetometry for detection of biomagnetism in ambient environments, *Phys. Rev. Appl.* **14**, 011002 (2020).
- [19] K.-M. C. Fu, G. Z. Iwata, A. Wickenbrock, and D. Budker, Sensitive magnetometry in challenging environments, *AVS Quantum Sci.* **2**, 044702 (2020).
- [20] D. Hunter, C. Perrella, A. McWilliam, J. P. McGilligan, M. Mrozowski, S. J. Ingleby, P. F. Griffin, D. Burt, A. N. Luiten, and E. Riis, Free-induction-decay magnetic field imaging with a microfabricated Cs vapor cell, *Opt. Express* **31**, 33582 (2023).
- [21] Y. Lu, E. Abdukerim, B. Li, L. Lei, T. Wu, and H. Guo, ^3He absolute magnetometer at geomagnetic field, *Phys. Rev. Res.* **7**, 043106 (2025).
- [22] D. Sheng, S. Li, N. Dural, and M. V. Romalis, Subfemtotesla scalar atomic magnetometry using multipass cells, *Phys. Rev. Lett.* **110**, 160802 (2013).
- [23] S. Smullin, I. Savukov, G. Vasilakis, R. Ghosh, and M. Romalis, Low-noise high-density alkali-metal scalar magnetometer, *Phys. Rev. A* **80**, 033420 (2009).
- [24] Y. Lu, T. Zhao, W. Zhu, L. Liu, X. Zhuang, G. Fang, and X. Zhang, Recent progress of atomic magnetometers for geomagnetic applications, *Sensors* **23**, 5318 (2023).
- [25] H. Huang, H. Dong, H. Hao, and X. Hu, Close-loop Bell-Bloom magnetometer with amplitude modulation, *Chin. Phys. Lett.* **32**, 098503 (2015).
- [26] M. Wang, M. Wang, G. Zhang, and K. Zhao, Study of the optimal duty cycle and pumping rate for square-wave amplitude-modulated Bell-Bloom magnetometers, *Chin. Phys. B* **25**, 060701 (2016).
- [27] D. Hunter, S. Piccolomo, J. Pritchard, N. Brockie, T. Dyer, and E. Riis, Free-induction-decay magnetometer based on a microfabricated Cs vapor cell, *Phys. Rev. Appl.* **10**, 014002 (2018).
- [28] J. Liu, L. Jiang, J. Xu, Y. Chen, X. Li, and Z. Wang, Synchronous RF pulse regulation and adaptive filtering measurement method for free-induction-decay magnetometers, *IEEE Trans. Instrum. Meas.* **74**, 1 (2025).
- [29] S. Li, J. Liu, M. Jin, K. T. Akiti, P. Dai, Z. Xu, and T. E.-T. Nwodom, A kilohertz bandwidth and sensitive scalar atomic magnetometer using an optical multipass cell, *Measurement* **190**, 110704 (2022).
- [30] J. Xu, L. Jiang, J. Liu, J. Liu, Y. Chen, J. Zhu, C. Fang, Q. Shao, Y. Zou, and H. Bai, Free-induction-decay magnetometer based on synchronous optical pumping and RF pulse modulation, *EPJ Quantum Technol.* **12**, 62 (2025).
- [31] D. Hunter, T. E. Dyer, and E. Riis, Accurate optically pumped magnetometer based on Ramsey-style interrogation, *Opt. Lett.* **47**, 1230 (2022).
- [32] *Optical Magnetometry*, edited by D. Budker and D. Kimball (Cambridge University Press, New York, 2013).
- [33] M. H. Acuna, Space-based magnetometers, *Rev. Sci. Instrum.* **73**, 3717 (2002).
- [34] B. Chéron, H. Gilles, and J. Hamel, Spatial frequency isotropy of an optically pumped ^4He magnetometer, *Eur. Phys. J. Appl. Phys.* **13**, 143 (2001).
- [35] V. Schultze, T. Scholtes, F. Wittkämper, and R. Stolz, Dead-zone-free optically pumped magnetometer with small heading error, *IEEE Sens. J.* **25**, 28229 (2025).
- [36] V. Schultze, T. Scholtes, G. Oelsner, F. Wittkaemper, T. Wieduwilt, and R. Stolz, An optically pumped magnetometer with omnidirectional magnetic field sensitivity, *Sensors* **23**, 6866 (2023).
- [37] J. Rutkowski, W. Fourcault, F. Bertrand, U. Rossini, S. Gétin, S. Le Calvez, T. Jager, E. Herth, C. Gorecki, M. Le Prado, *et al.*, Towards a miniature atomic scalar magnetometer using a liquid crystal polarization rotator, *Sens. Actuators, A* **216**, 386 (2014).
- [38] C. Guttin, J. Leger, and F. Stoeckel, An isotropic earth field scalar magnetometer using optically pumped helium 4, *J. Phys.* **IV 4**, C4-655 (1994).
- [39] H. Wang, T. Wu, W. Xiao, H. Wang, X. Peng, and H. Guo, Dual-mode dead-zone-free double-resonance alignment-based magnetometer, *Phys. Rev. Appl.* **15**, 024033 (2021).
- [40] B. Chéron, H. Gilles, J. Hamel, O. Moreau, and E. Noël, Improvement of the spatial amplitude isotropy of a ^4He magnetometer using a modulated pumping beam, *J. Phys.* **III 7**, 1735 (1997).
- [41] M. Tian, L. Jiang, X. Zhao, Y. Chai, J. Liu, Z. Lu, and W. Quan, Dead-zone suppression method of NMOR atomic magnetometers based on alignment and orientation polarization, *Sens. Actuators A* **379**, 115842 (2024).
- [42] G. Bevilacqua and E. Breschi, Magneto-optic spectroscopy with linearly polarized modulated light: Theory and experiment, *Phys. Rev. A* **89**, 062507 (2014).
- [43] A. Ben-Kish and M. Romalis, Dead-zone-free atomic magnetometry with simultaneous excitation of orientation

- and alignment resonances, *Phys. Rev. Lett.* **105**, 193601 (2010).
- [44] H. Wang, T. Wu, H. Wang, X. Peng, and H. Guo, Magneto-optical spectroscopy with arbitrarily polarized intensity-modulated light in ^4He atoms, *Phys. Rev. A* **101**, 063408 (2020).
- [45] A. Pollinger, R. Lammegger, W. Magnes, C. Hagen, M. Ellmeier, I. Jernej, M. Leichtfried, C. Kürbisch, R. Maierhofer, R. Wallner, *et al.*, Coupled dark state magnetometer for the China Seismo-Electromagnetic Satellite, *Meas. Sci. Technol.* **29**, 095103 (2018).
- [46] Q.-Q. Yu, S.-Q. Liu, C.-Q. Yuan, and D. Sheng, Light-shift-free and dead-zone-free atomic-orientation-based scalar magnetometry using a single amplitude-modulated beam, *Phys. Rev. Appl.* **18**, 014015 (2022).
- [47] W. Li, Y. Chang, X. Zhang, W. Luo, X. Wei, and R. Yang, Bell-Bloom magnetometer based on square optical path, *Opt. Express* **33**, 31635 (2025).
- [48] K. Tian, W. Ding, and Z. Wang, Dead-zone-free atomic magnetometer based on hybrid Poincaré beams, *Photon. Res.* **12**, 1093 (2024).
- [49] L. Jiang, C. Zhang, X. Zhao, J. Liu, Z. Lu, and J. Li, Dead-zone-free NMOR atomic magnetometer based on excitation of dual-axis magnetic pulse, *Adv. Quantum Technol.* **8**, 2400475 (2025).
- [50] S. Mehta, G. Samanta, and R. S. Grewal, Dead-zone-free single-beam atomic magnetometer based on free-induction-decay of Rb atoms, *Appl. Phys. Lett.* **126**, 044002 (2025).
- [51] A. Fabricant, I. Novikova, and G. Bison, How to build a magnetometer with thermal atomic vapor: A tutorial, *New J. Phys.* **25**, 025001 (2023).
- [52] T. Wang, W. Lee, M. Limes, T. Kornack, E. Foley, and M. Romalis, Pulsed vector atomic magnetometer using an alternating fast-rotating field, *Nat. Commun.* **16**, 1374 (2025).
- [53] Z. D. Grujić, P. A. Koss, G. Bison, and A. Weis, A sensitive and accurate atomic magnetometer based on free spin precession, *Eur. Phys. J. D* **69**, 135 (2015).
- [54] C. Fang, L. Jiang, J. Liu, Y. Chen, J. Zhu, Q. Shao, Y. Zou, M. Xiang, and W. Quan, Suppression of spin-exchange relaxation in Bell-Bloom magnetometer, *Measurement* **241**, 115695 (2025).
- [55] *High Sensitivity Magnetometers*, edited by A. Grosz, M. J. Haji-Sheikh, and S. C. Mukhopadhyay (Springer, Switzerland, 2017).
- [56] S. J. Seltzer, Developments in alkali-metal atomic magnetometry, Ph.D. thesis, Princeton University, 2008.
- [57] L. Jiang, J. Xu, J. Liu, C. Fang, J. Zhu, Y. Zou, Y. Chen, J. Liu, and X. Zhao, Signal enhancement in single-beam free-induction-decay magnetometers by manipulation of spin polarization, *Opt. Lett.* **50**, 4014 (2025).
- [58] D. Hunter, M. S. Mrozowski, A. McWilliam, S. J. Ingleby, T. E. Dyer, P. F. Griffin, and E. Riis, Optical pumping enhancement of a free-induction-decay magnetometer, *J. Opt. Soc. Am. B* **40**, 2664 (2023).
- [59] V. Lucivero, W. Lee, N. Dural, and M. Romalis, Femtotesla direct magnetic gradiometer using a single multipass cell, *Phys. Rev. Appl.* **15**, 014004 (2021).
- [60] V. Lucivero, W. Lee, M. Limes, E. Foley, T. Kornack, and M. Romalis, Femtotesla nearly-quantum-noise-limited pulsed gradiometer at Earth-scale fields, *Phys. Rev. Appl.* **18**, L021001 (2022).