In Situ Calibration of Magnetic Field Coils Using Parametric Resonance in Optically-pumped Magnetometers

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***Abstract*—In this article, we propose an in situ method to calibrate the magnetic-field coil systems in optically-pumped magnetometers. The method is based on parametric resonance induced by nonresonant radio-frequency (RF) fields, and is especially suitable for microfabricated single-beam zero-field atomic magnetometers. We have experimentally and theoretically demonstrated this method with a single-beam spin-exchange-relaxation-free (SERF) magnetometer, and the experiment results are in line with theoretical expectations.**

Keywords—parametric resonance; magnetic coil constants; optically-pumped magnetometer; miniaturization;

I. Introduction

The optically-pumped magnetometer is one of the most sensitive instruments for measuring magnetic field, reaching a sensitivity below 1 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ [1-3]. Magnetometers have various applications, such as high-precision fundamental measurements [4-6], detection of nuclear magnetic resonance signals [7,8], and biomagnetic field measurements [9,10]. Almost all kinds of optically-pumped magnetometers need to be operated in an externally applied magnetic field, generated with a series of Helmholtz coils or solenoids. To improve the accuracy of magnetic field measurement, the magnetic coil constants need to be calibrated accurately.

Typically, the magnetic field coils are calibrated with fluxgate magnetometers. However, it may be difficult to place the fluxgate magnetometer at the exact position of interest in some cases, such as when the magnetic field coils are small in microfabricated optically-pumped magnetometer [11,12]. The simulated magnetic field distributions from the known distributions of coil currents are usually match well with the actual situation. For the multi-channel magnetometer with all channels sharing the same magnetic field coils, it is usually assumed that the coil constants are the same for all channels, neglecting the gradient of magnetic field generated by magnetic coils [8]. Therefore, using the atomic medium itself to calibrate the magnetic coil system is more accurate and intrinsically averages the magnetic field around the vapor cell. Most of the calibration methods developed previously are based on magnetic resonance signals [13] or free-induction decay (FID) signals [14,15]. We present an efficient way to calibrate the coils using first-order parametric resonance, which is especially suitable for single-beam atomic magnetometers.

II. Methods/Results

As shown in Fig. 1, a 795 nm DFB laser propagating along z direction is performed as pump and probe light. The laser frequency is tuned to the center of the pressure-broadened ^{87}Rb D1 line. A 5 mm cubic cell, filled with ^{87}Rb and 600 torr N_2, is heated to 160 ℃ and placed inside a cylindrical magnetic shield. The coils inside the shield generate a static field B_0 and an RF field $B_1\cos\omega t$ along y direction.

The overall dynamical evolution of the electron spin polarization $\mathbf{P}$ can be well described by the Bloch equation [16]:

$$\frac{d\mathbf{P}}{dt} = \gamma\mathbf{P}\times\mathbf{B} + R_{\mathrm{OP}}(\mathbf{s}-\mathbf{P}) - \frac{\mathbf{P}}{T_2}, \quad (1)$$

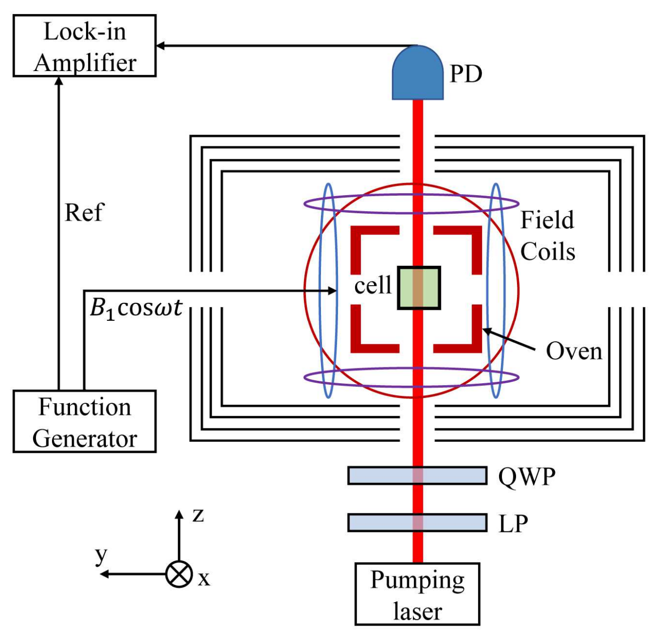

Fig. 1. Schematic of the experiment setup. LP, linear polarizer; QWP, quarter-wave plate; PD, photodetector.

where γ is the gyromagnetic ratio of the ^{87}Rb, R_{OP} is the optical pumping rate, $\mathbf{s} = s\hat{z}$ is the optical pumping vector and T_2 is the phenomenological relaxation time. When magnetic fields along x and z directions are negligible, the magnetic field is written as $\mathbf{B} = (B_0 + B_1 \cos\omega t)\hat{y}$.

When the RF frequency ω is much larger than total relaxation rate $\Gamma = R_{\mathrm{OP}} + 1/T_2$, i.e., $\omega \gg \Gamma$, the solution to (1) is no longer satisfy quasi-steady state approximation but we can still obtain the analytic steady solution as [17,18]

$$P_x + iP_z = iP_0 \sum_{n=-\infty}^{+\infty} \sum_{p=-\infty}^{+\infty} \frac{J_n(\eta) J_{n+p}(\eta)}{\Gamma + i(\gamma B_0 + n\omega)} e^{ip\omega t}, \quad (2)$$

where $P_0 = sR_{\mathrm{OP}}/\Gamma$ is the equilibrium electron spin polarization without magnetic field, J_n is the Bessel function of order n and $\eta = \gamma B_1/\omega$. When the static field B_0 is much smaller than RF field and the RF field is not too much strong, i.e., $B_0 \ll \gamma B_1 \sim \omega$, the solution (2) can be approximately written as

$$P_x + iP_z = iP_0 \sum_{p=-\infty}^{+\infty} \frac{J_0(\eta) J_p(\eta)}{\Gamma + i\gamma B_0} e^{ip\omega t}. \quad (3)$$

The approximate solution indicates that the P_z has a series of harmonics of RF frequency ω, and the oscillation amplitudes reach the maximum at $B_0 = 0$, which means that P_z is on resonant at $B_0 = 0$. Many kinds of absorption-based optically-pumped magnetometers have utilized this zero-order ($n = 0$) parametric resonance to measure weak magnetic fields [11,12].

However, if the RF field is so strong that the higher order $n \neq 0$ parametric resonance cannot be ignored, there are more than one resonance peaks when the offset field B_0 is scanned. For example, for the $n = 1, p = \pm 1$ parametric resonance, the electron spin polarization along z direction can be written as

$$P_z = P_0 J_1(\eta) \mathrm{Re}\left[\frac{\Gamma - i\delta_\pm}{\Gamma^2 + \delta_\pm^2} \left(J_0(\eta) e^{-i\omega t} + J_2(\eta) e^{i\omega t}\right)\right], \quad (4)$$

where $\delta_\pm = \gamma B_0 \pm \omega$ is the detuning. Obviously, the resonance condition is $B_0 = \pm\omega/\gamma$ and we can easily calibrate the field along y direction by scanning the amplitude of B_0 around the resonance point.

By applying an RF field with an amplitude of 140 $\mathrm{nT_{rms}}$ and frequency of 699 Hz along y direction, which indicates that the resonance condition is satisfied at

$$B_0^* = \frac{\omega}{\gamma} = \frac{699\ \mathrm{Hz}}{\frac{14}{3}\ \mathrm{Hz/nT}} \approx 149.8\ \mathrm{nT}. \quad (5)$$

Then we scan the applied current in the coils along the y-direction to control the offset field B_0. As shown in Fig. 2, the parametric resonance signal shows multiple peaks. By fitting the resonance curves, we find the current corresponding to the resonance peak is $I_0 = 1.363$ mA. So we can calibrate the y-direction magnetic coil constant as $\mathrm{Cont}_{\mathrm{coil}}^{y} = B_0^*/I_0 = 110.1$ nT/mA. The result shows that we can calibrate the magnetic coils of magnetometer without fluxgate magnetometer, which has a limited accuracy due to the placement error of the fluxgate-probe and the accuracy of the fluxgate magnetometer itself.

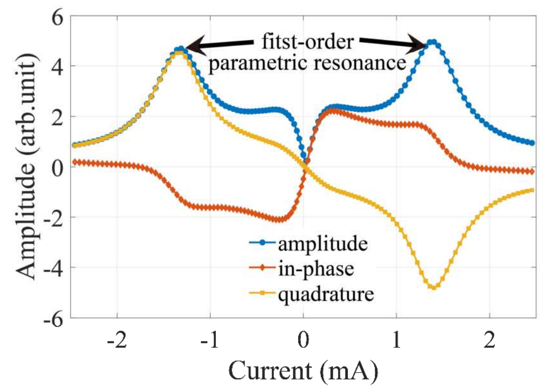

Fig. 2. Parametric resonance experiment result. The multiple peaks indicate zero-order ($n = 0$) and first-order ($n = \pm 1$) parametric resonance.

DISCUSSION/INTERPRETATION

In this experiment, we obtain the magnetic coil constants by scanning the current applied in the magnetic coils to meet the parametric resonance condition. Instead of scanning the current in magnetic coils, we can also fix the current in coils and then scan the RF field frequency to meet the parametric condition to measure the magnetic field generated by the fixed current. Therefore the coil constants are also calibrated. Obviously, this scheme can also be used to measure the magnetic field under a relatively large magnetic field background [19].

During the calibration of magnetic coil constants, the gyromagnetic ratio of ^{87}Rb needs to be carefully selected, because the spin exchange collision can modify the natural gyromagnetic ratio. In our calculation, according to [20], though the offset field and RF field are relatively strong, the atoms are still in the SERF regime that the gyromagnetic ratio is $\gamma = 14/3$ Hz/nT and the relative error of gyromagnetic ratio caused by magnetic field is less than 10^{-3}, i.e., $\delta\gamma/\gamma < 10^{-3}$.

III. CONCLUSIONS

In this work, we present a convenient method, based on parametric resonance, to calibrate the magnetic field coils of atomic magnetometer. This in situ method is especially suitable for microfabricated single-beam zero-field atomic magnetometer, which can conveniently calibrate its magnetic coils without additional external calibrated coils. We have experimentally and theoretically demonstrate this method with a ^{87}Rb single-beam SERF magnetometer, and the experiment results agree with theoretical expectations. This calibration method can avoid the drift of magnetic fields and has potential applications in precision experiments applying magnetic field.

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