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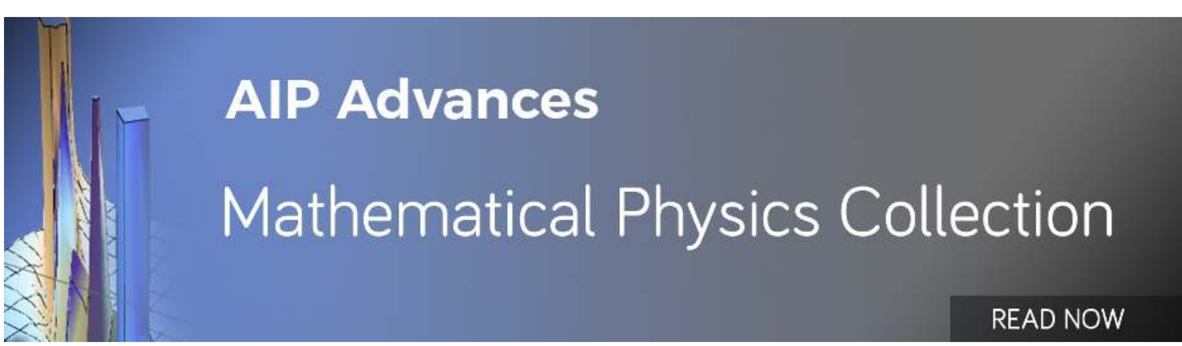

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ABSTRACT

The spin self-sustaining atomic magnetometer has the advantage of $1/\tau$ measurement and great development potential in many applications. In this paper, we investigated the main elements that affect the stability and accuracy of the self-sustaining magnetometer and proposed the methods to improve its performance based on the measurement results. The correlation coefficient between fluctuations of the magnetic field generated by coils and the spin Larmor precession frequency is 0.97, which mainly dominates the stability in a short term. The accuracy of the magnetometer is affected by the power and frequency of the pump light. The Larmor precession frequency coefficient related to the pump light power is 26 mHz/mW, and the effect on the Larmor precession frequency is minimized when the pump light frequency is red detuned by 200 MHz from the ^{85}Rb transition D1 line F = 3 to F′ = 3. The $1/\tau$ measurement time after these corrections can be extended to 10 s, and the sensitivity achieved is 149 fT/$\sqrt{\text{Hz}}$, which is close to the quantum projection noise limit of the system.

I. INTRODUCTION

High precision magnetic field measurements based on the optically pumped atomic systems by monitoring the Larmor precession frequency of the spins are the key to realize various applications. In the areas such as geophysics, resource exploration, navigation, bio-science, medicine, and fundamental physics, it is usually advantageous to use the smallest and highest sensitive possible sensor. Over the past half century, the atomic magnetometers have approached or even surpassed the levels of sensitivity attained by state-of-the-art superconducting quantum interference devices (SQUIDs)[1–6] and are well integrated. For example, the ultra-sensitive spin exchange relaxation-free (SERF) atomic magnetometer operated under a near-zero magnetic field achieved a sensitivity of 0.16 fT/$\sqrt{\text{Hz}}$,[7,8] and solid-state based magnetometers used in large magnetic fields achieved the sensitivity of 1 nT/$\sqrt{\text{Hz}}$.[9] However, a main limitation to the sensitivity of these quantum systems is the coherence time of the atomic spins τ_0,[10]

$$\delta B \approx \frac{1}{\gamma}\frac{1}{\sqrt{\mathrm{N}\cdot\tau\cdot\tau_0}}, \tag{1}$$

where γ is the atomic gyro-magnetic ratio, τ is the time-duration of the measurement, and N is the number of atoms involved in the measurement. Beyond τ_0, the sensitivity decreasing rate deviates to a $1/\sqrt{\tau}$ rule from a faster $1/\tau$ rule. Many methods are investigated to improve the sensitivity performance through two aspects: one is increasing the coherence time τ_0, while the other is developing new methods that can surpass the $1/\sqrt{\tau}$ rule at a timescale larger than τ_0.

The representative progress of the latter aspect was made in 2016 by Xu *et al.*, which is called the self-sustaining magnetometer. In this regime, they generated the spins in coherence with the precession by measuring the phase of the Larmor precession non-destructively and controlling the pump light synchronously with short pulses. Consequently, the Larmor precession signal can self-sustain and persist indefinitely. The precision of the magnetometer increases following a much faster $1/\tau$ rule, and the turning point to the $1/\sqrt{\tau}$ rule emerges after 300 ms, which is nearly ten times longer than τ_0. The sensitivity achieved is 240 fT/$\sqrt{\text{Hz}}$, which is close to the spin projection noise of the atomic spins.[11] On the basis of this method, we demonstrated an atomic magnetic gradiometer by mixing and filtering the different frequency signals from two adjacent magnetometers,[12] a three-axis vector atomic magnetometer by precise compensation in three components of the magnetic field.[13] Then, a mean sensitivity of 20 pT/$\sqrt{\text{Hz}}$ and a frequency response bandwidth of 5 kHz were realized in large magnetic field measurements.[14] Thus, we are well aware of the fact that the self-sustaining method has great development potential, and more research studies will make sense.

In this work, we investigated the systematic effects and proposed the methods to improve the performance of self-sustaining atomic magnetometers. We measured the correlation between the fluctuations of the precession frequency and the magnetic field generated by coils. This coefficient is 0.97 and can be corrected to 0.1. This effect dominates the Allan deviation of spin precession frequency in a short term. The spin precession frequency coefficient related to the pump light power is 26 mHz/mW, while the effect of the pump light frequency on the spin precession frequency is parabolic. When the pump light frequency is red detuned by 200 MHz from the ^{85}Rb transition D1 line F = 3 to F′ = 3, the spin precession frequency is minimized. After all these corrections, the $1/\tau$ measurement time can be extended up to 10 s, and the sensitivity achieved is 149 fT/$\sqrt{\text{Hz}}$, which is close to the quantum projection noise limit of the system.

II. METHOD AND EXPERIMENT

The schematic diagram of the spin self-sustaining magnetometer is shown in Fig. 1. One-dimensional Helmholtz coils are applied to generate a magnetic field inside a five-layer cylindrical magnetic shield. A cylindrical ^{85}Rb vapor cell is mounted at the center of the coil system. A D1 line circularly polarized laser, resonant with F = 3 to F′ = 3, serves as the pump light, and a D2 line linearly polarized laser, resonant with F = 2 to F′ = 3, serves as the repump light. The power of the pump and repump light arriving at the cell is 0.8 mW and 1.6 mW, respectively. It is controlled by the same acousto-optic modulation (AOM) for coherent pumping. The probe laser is red detuned by 4 GHz from the center of the transition line F = 3 to F′ = 3 in the ^{85}Rb D2 line, which traverses the atomic vapor and a Wollaston analyzer for balanced polarimetry detection. The power of probe light is 60 μW. The waist $1/e^2$ of pump and repump light is about 5 mm, and the diameter of probe light is 3 mm. The oscillatory signal from the photodetectors goes through a bandpass filter, a zero-crossing comparator, a trigger, a RF source, and a RF switch. Once the zero-crossing points of the signal are detected, this feedback loop will generate a pulse to control the AOM. The AOM can switch on or off the pump and repump light synchronously. This way, the spins are generated coherently and the signal of spin Larmor precession is a continuous sine wave, as shown in Fig. 2.

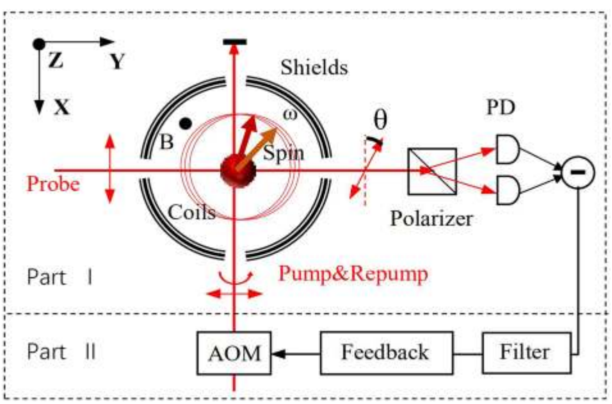

FIG. 1. Experimental setup of the self-sustaining magnetometer: optical pumping and detection (part I) and feedback and control loop (part II). The three lasers come from three independent, external cavity diode lasers, and the 20 mm long, 20 mm diameter cylindrical cell used here is a self-made α-olefin coated cell containing natural abundance rubidium atoms at room temperature. The shielding factor of the μ-metal magnetic shield is better than 10^5. The feedback loop consists of a high speed zero-crossing comparator, a trigger, a RF source, and a RF switch.

The magnetic field is obtained by[15]

$$\omega = \gamma B. \tag{2}$$

Here, γ is 0.47 MHz/G and ω is the Larmor precession frequency. We analyze the sensitivity by recording the frequency sequence of zero-crossing points of the Larmor precession signal using a high speed 16-bit DAQ (data acquisition) card. The Allan deviations[16] $\sigma = \Delta f/f$ display the uncertainty features clearly, and the sensitivity δB can be derived from the Allan deviations by $\sigma f/\gamma$.

Since the Allan deviation of the spin self-sustaining magnetometer is close to 10^{-6} when the measurement time reaches 1 s, a short term stability analysis will make sense. This stability in a short term is mainly affected by the magnetic field fluctuations resulting from the voltage applied to control the coil system. Otherwise, the accuracy of the spin self-sustaining magnetometer is affected by the power and frequency of the pump light currently.

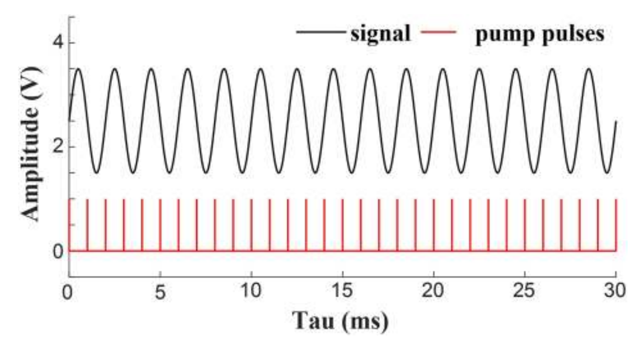

FIG. 2. Spin precession signals observed in the self-sustaining setup. The black line above is the precession signal, and the red line below is the control pulses for pump light. The control pulses are generated when the zero-crossing points are detected.

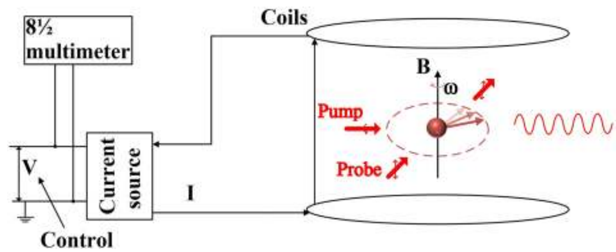

FIG. 3. Schematic diagram of the connection measurement between the magnetic field fluctuations and the precession frequency fluctuations. The $8_{1/2}$ multimeter is used to monitor the control voltage of the current source in real time, and its measurement data are acquired simultaneously with the spin self-sustaining precession frequency.

A. The effect of magnetic field

The external magnetic field of the spin self-sustaining magnetometer is generated by a self-made Helmholtz coil system. The magnetic field to current coefficient is 33 nT/mA. The current applied to coils is controlled by the voltage, and the conversion coefficient is 1 mA/V. Since the magnetic field fluctuations can be reflected by the voltage, the correlation between the fluctuations of the voltage and the Larmor precession frequency can indicate the effect.

The correlation measurement between the magnetic field fluctuations and the Larmor precession frequency fluctuations is shown in Fig. 3. The high precision $8_{1/2}$ multimeter is used to monitor the fluctuations of the control voltage, which is further converted into the fluctuations of the magnetic field and current. The $8_{1/2}$ multimeter records the control voltage signal V_{ci} per 0.7 s, and the DAQ acquires the spin self-sustaining precession signal to obtain the frequency sequence Δf_i simultaneously. The frequency sequence data Δf_i are averaged by 0.7 s to calculate the correlation coefficient between $\Delta\bar{f_i}$ and the control voltage ΔV_{ci} by

$$Corr = \frac{\Delta V_{ci} \cdot \Delta\bar{f_i}}{\sqrt{(\Delta V_{ci} \cdot \Delta V_{ci})(\Delta\bar{f_i} \cdot \Delta\bar{f_i})}}. \tag{3}$$

The correlation coefficient we obtained is 0.97. In order to clarify the results, we convert the fluctuations of the control voltage to current and frequency based on Eq. (2), which is shown in Fig. 4. Obviously, the $1/\tau$ decreasing rule of the Allen deviation will be dominated by the stability of the magnetic field without subtraction.

The $8_{1/2}$ multimeter is also used to calibrate the control voltage, and the magnetic field error is lower than 1 fT.

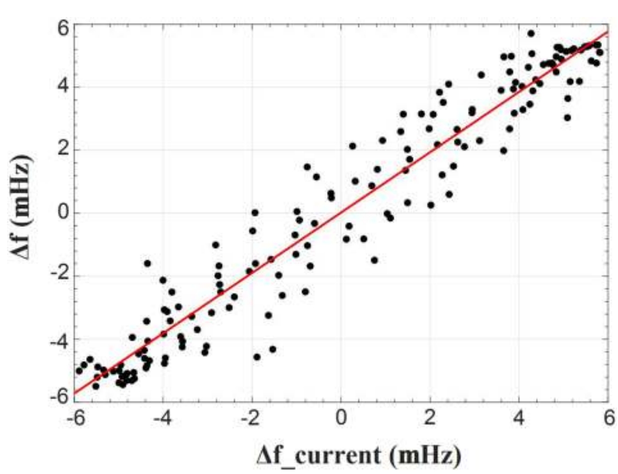

FIG. 4. Correlation measurement results between the magnetic field and the Larmor precession frequency. Δf is the fluctuations of the spin Larmor precession signal, and $\Delta f_{current}$ is the fluctuations of current converted from ΔV_{ci}. The correlation coefficient is 0.97.

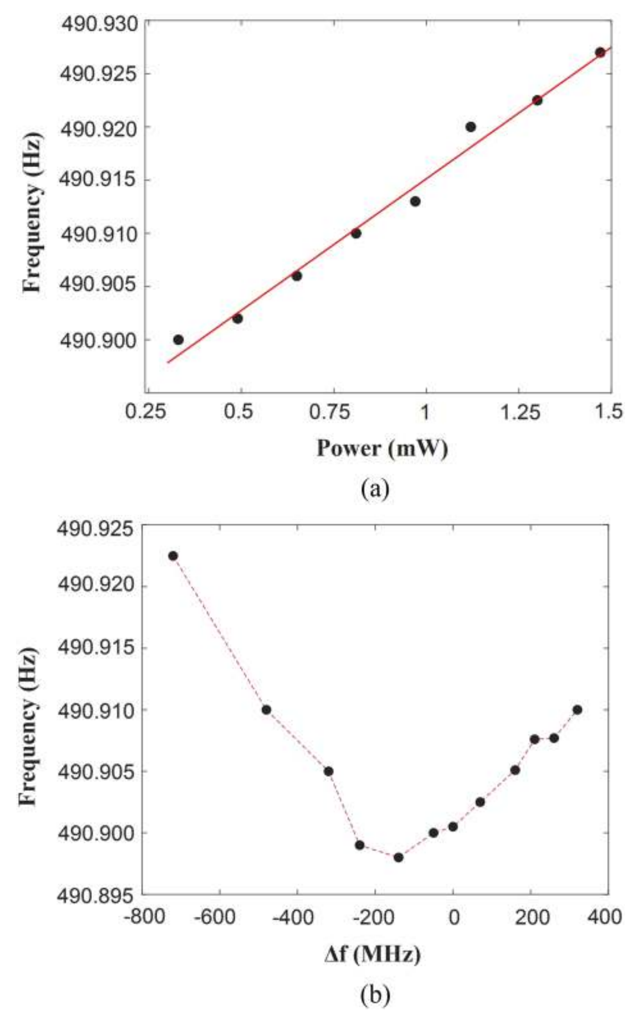

FIG. 5. The effect of the pump light power and frequency on the spin precession frequency. (a) Effect of the pump light power on the spin precession frequency (black point). The slope of the fitting line (red line) is 26 mHz/mW. (b) Effect of the pump light frequency shift on the spin precession frequency. When the light frequency is red detuned from the ^{85}Rb atomic transition D1 line F = 3 to F′ = 3, the spin precession frequency is minimized.

B. The effect of pump light

When the circularly polarized pump light interacts with atomic spins, the equivalent magnetic field $\mu \cdot B_{eff}$ (AC Stark shift) is introduced into the interaction Hamiltonian. The direction of the pseudo-magnetic field is determined by the circular polarization direction. We also find that the spin precession frequency changes with the pump light frequency. Therefore, the existence of a circularly polarized pump light will affect the accuracy of the measurement. On the other hand, the fluctuations of the pump light power and frequency will also affect the stability of the spin self-sustaining precession signal. However, the pumping time of the self-sustaining magnetometer is only 1/100 of the spin precession period, and this effect can be neglected in a short term.

The dependence of the spin precession frequency on the power and frequency of pump light is measured and plotted in Figs. 5(a) and 5(b). It can be found that the spin precession frequency increases with the pump light power and the slope of the fitting line is 26 mHz/mW. Considering that the power we use in the experiment is 0.8 mW, the magnetic field measurement error exceeds 4.4 pT. The effect of the pump light frequency on the spin precession frequency is parabolic. When the light frequency shift is $\Delta f = -200$ MHz, the spin precession frequency is minimized.

III. RESULTS AND DISCUSSION

After the magnetic field fluctuations caused by the control voltage ΔV_{ci} are subtracted from the spin precession frequency fluctuations Δf_i, the correlation coefficient $Corr < 0.1$, and the control voltage no longer dominates the precession frequency fluctuations. The comparison before and after correction is shown in Fig. 6. The new Allen deviation decreases by a $1/\tau$ rule for almost 10 s, and the sensitivity is improved to 149 fT/$\sqrt{\text{Hz}}$ considering that the Larmor precession frequency is 700 Hz. The quantum noise limit of the system estimated according to Eq. (1) is about 100 fT/$\sqrt{\text{Hz}}$.

Many other elements will become dominant of stability beyond 10 s, for example, the power and frequency fluctuations of the pump light, the voltage fluctuations of the feedback loop, and the fluctuations of the environmental magnetic field.

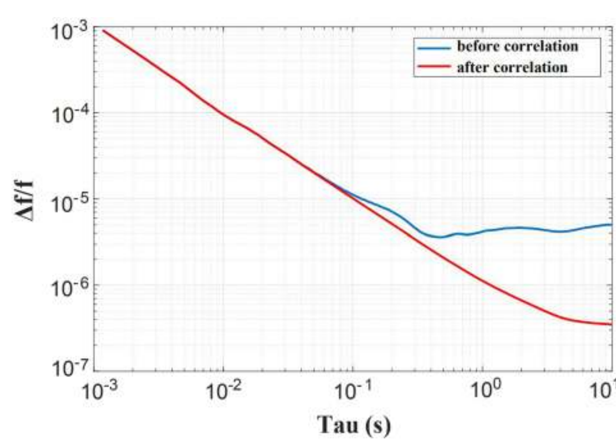

FIG. 6. Allen deviation of precession frequency before and after correction.

The influence of the AC Stark shift can be subtracted directly or compensated by a reflected pump light, and the frequency drift on spin precession can be neglected under the condition of saturated absorption spectrum stabilization. Furthermore, the voltage of the feedback loop can be calibrated by an $8_{1/2}$ multimeter.

IV. CONCLUSION

We analyzed the elements that affect the stability and accuracy of the self-sustaining atomic magnetometer and investigated the method to improve its performance. The stability is mainly dominated by magnetic field fluctuations resulting from the control voltage of coils. The $1/\tau$ measurement time after all corrections can be extended to 10 s, and the sensitivity achieved is 149 fT/$\sqrt{\text{Hz}}$, which is close to the spin projection noise of the atomic spins. The accuracy is affected by the power and frequency of pump light. According to the results we measured, the Larmor precession frequency coefficient related to the pump light power is 26 mHz/mW, and the Larmor precession frequency is minimized when the pump light frequency is red detuned by 200 MHz.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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