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Transverse relaxation determination based on light polarization modulation for spin-exchange relaxation free atomic magnetometer*

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A transverse relaxation determination of spin-exchange relaxation free (SERF) magnetometer based on polarization modulation technique is proposed. Compared with the radio-frequency (RF) excitation and light intensity excitation methods used in SERF magnetometer, the light polarization modulation method has a high stability in low-frequency range, which indicates a more accurate transverse relaxation measurement.

Keywords: spin-exchange relaxation free (SERF) magnetometer, linewidth, optical polarization modulation

PACS: 32.70.Jz, 32.30.Dx, 32.60.+i, 32.80.Xx **DOI:** 10.1088/1674-1056/27/7/073201

1. Introduction

Recently, spin-exchange relaxation free (SERF) atomic magnetometers[1–4] based on the detection of Larmor precession of optically pumped atoms,[5–7] have approached sub-femtotesla sensitivity.[8] Additionally, higher spatial resolution and non-cryogenic operation make SERF magnetometer enable new applications including the possibility of mapping non-invasively the cortical modules in the brain,[9,10] which has the potential to be an alternative of SQUID magnetometer for biomagnetism.[11] The principle of SERF magnetometer is illustrated in Fig. 1. A circularly polarized pump beam, which propagates along the z axis, polarizes the atomic spin, and the atomic spin precession is induced by the ambient magnetic field along the y axis. The polarized atomic medium possesses circular birefringence, which is proportional to the ambient magnetic field. A linearly polarized beam, which is along the x axis and perpendicular to pump beam direction, propagating along the x axis is then used to probe the atomic spin precession. In this scheme, the probe light detects the spin precession in the y direction.

The sensitivity limit of SERF magnetometer given by the transverse spin relaxation time T_2 is

$$\delta B = \frac{1}{\gamma\sqrt{nT_2Vt}}, \tag{1}$$

where n is the density of atoms, γ is the gyromagnetic ratio, V is the cell volume, and t is the measurement time. Thus, precise measurement of T_2 is critical when assessing the influence of relaxation on the operation and sensitivity of atomic magnetometers.

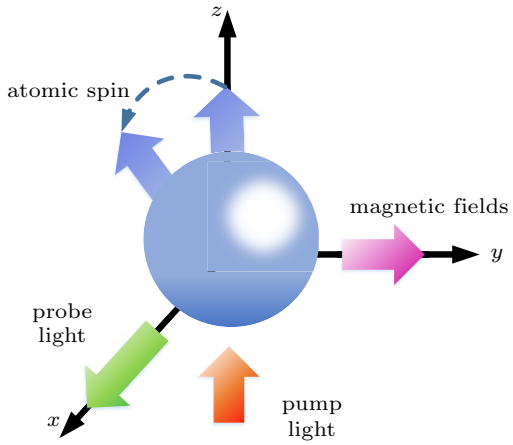


Fig. 1. (color online) General schematic of SERF atomic magnetometer.

T_2 can be obtained by measuring the magnetic resonance linewidth of the atomic spin.[12] The most conventional method of determining the linewidth of the SERF magnetometer is light intensity excitation method.[13] In this method, the intensity of pump beam is modulated by chopper, which will induce resonant coherent precession of the polarized atomic spins when the modulation frequency approaches the Larmor frequency. As the SERF magnetometer operates in a low magnetic field, the Lamor frequency is several Hertz. Thus, the chopper has a bad stability in this frequency range. Besides, the acoustic-optical modulator (AOM) and electro-

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optical modulator (EOM) both can modulate the light intensity. However, the diffraction beam exported by AOM has a different propagating direction, which may not be suitable for SERF magnetometer, especially for online measurement. On the other hand, the EOM operates in the high frequency range, and suffers a high deterioration in low frequency.

In this paper, an SERF linewidth determination based on the polarization modulation technique which is used in Bell Bloom magnetometer[14] is utilized. A liquid crystal modulator is used to modulate the pump light polarization instead of the light intensity. In this method, the pump beam polarization is modulated by the liquid crystal, which modulates the polarization of the atomic spin in a similar way to light intensity excitation method.[15] When the modulation frequency is equal to the Larmor frequency, the atomic precession is resonant with the pump beam polarization modulation. A resonance model of the linewidth determination based on the light polarization modulation technique for SERF magnetometer is derived. Experiments are carried out to demonstrate the effectiveness. The experimental results show that this method is independent of the beam intensity and a preferable stability in low-frequency range, which overcomes some deficiencies of the light intensity excitation method.

2. Principle

The transverse relaxation time T_2[16] in the SERF atomic magnetometer is given by

$$\frac{1}{T_2} = \Gamma_{\mathrm{SD}} + \frac{1}{T_2^{\mathrm{SE}}}, \tag{2}$$

where Γ_{SD} is the spin destruction relaxation, $\frac{1}{T_2^{\mathrm{SE}}}$ is the contribution of spin-exchange collisions to relaxation and is given by[17]

$$\frac{1}{T_2^{\mathrm{SE}}} = \frac{\omega_0^2}{2\Gamma_{\mathrm{SE}}}\left[1 - q(0)^2(2I+1)^2\right], \tag{3}$$

with I being the nuclear spin and Γ_{SE} being the spin-exchange relaxation. For low polarization and small magnetic field, spin exchange relaxation is quadratic in the magnetic field. The $q(S)$ is the nuclear slowing-down factor as a function of atomic spin S, and for nuclear spin with $I = 3/2$, it is expressed as

$$q(S) = \frac{6+2S^2}{1+S^2}. \tag{4}$$

The value of the transverse relaxation time can be measured by measuring the linewidth of the magnetic resonance curve $\Delta\omega$, which is

$$\Delta\omega = \frac{1}{T_2}, \tag{5}$$

where $\Delta\omega$ is the half width at half maximum (HWHM) of the magnetic resonance curve for atomic spin polarization, which can be described by Bloch equation[18] as follows:

$$\frac{\mathrm{d}\boldsymbol{S}}{\mathrm{d}t} = \gamma^{\mathrm{e}}\boldsymbol{S}\times\boldsymbol{B} + R(\boldsymbol{S}_0 - \boldsymbol{S}) - \frac{\boldsymbol{S}}{T_2}, \tag{6}$$

where $\boldsymbol{S}$ is the atomic spin vector, $\boldsymbol{B}$ is the magnetic field, γ^{e} is the gyromagnetic ratio, and $\boldsymbol{S}_0$ is the polarization of the atom modulated by the crystal phase modulator, and expressed as

$$S_0 = \frac{1}{2}sRT_2^{-1}, \tag{7}$$

with s being the optical pumping beam polarization factor with magnitude equal to the degree of circular polarization. The response of the system is given by the steady-state solution to Eq. (6) as follows:

$$S_x = \frac{1}{4}RS_0\frac{\Delta\omega\sin(\omega t) + (\omega-\omega_0)\cos(\omega t)}{(\Delta\omega)^2 + (\omega-\omega_0)^2}. \tag{8}$$

According to Eq. (8), the polarization of pump light is modulated by a liquid crystal phase modulator with the phase modulation function of $\delta = \delta_0\cos\omega t$ and its degree of the circular polarization is modulated as

$$s = \sin\delta. \tag{9}$$

The pump rate of the atoms is modulated as

$$R = \frac{I_0\sigma\sin\delta}{Ah\nu}, \tag{10}$$

where I_0 is the pump light intensity, σ is the absorption cross-section for pump light, A is the pump light transverse section area, h is the Plank constant, and ν is the pump light frequency. Substituting Eq. (10) into Eq. (8), the first harmonic response of the magnetic resonance signal is

$$S_x = \frac{1}{8}\left(\frac{I_0\sigma\sin\delta}{Ah\nu}\right)^2 T_2^{-1}\left[\frac{1}{(\Delta\omega)^2 - (\omega_0-\omega)^2}\right]^{1/2}. \tag{11}$$

The magnetic resonance curve can be depicted according to Eq. (11). The linewidth represents the transverse relaxation of the magnetometer for a given ambient magnetic field. For a near-zero magnetic field, the transverse relaxation time T_2 can be obtained from Eq. (2). However, according to Eq. (11), the signal amplitude is dependent on the modulation depth of crystal liquid modulator. As the SERF magnetometer detects extremely weak signal, the modulation depth should be optimized. The simulating response signal with the function of the modulation depth is shown in Fig. 2. The phase modulation depth changes from 0 to π, and the signal amplitude increases to a maximum value at $\pi/2$ and attenuated to zero when the phase modulation depth turns to π. Thus, the signal will be maximum if the phase modulation depth is fixed to $\pi/2$.

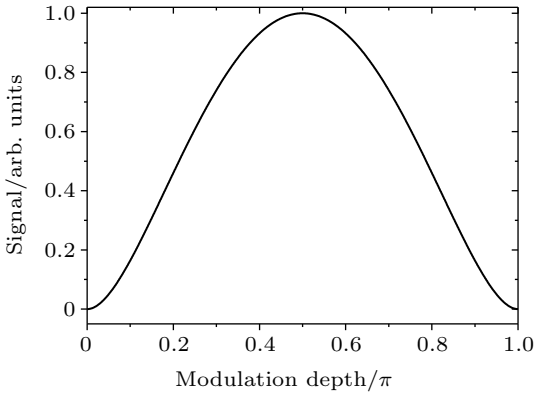


Fig. 2. (color online) Relationship between signal and modulation depth.

3. Experimental setup and procedure

The experimental setup is shown schematically in Fig. 3. A small drop of potassium (K), 60 Torr nitrogen (N_2) (for eliminating radiation trapping and improving optical pumping efficiency), and 3 atm helium (He) buffer gas (for reducing the rate of the diffusion of atoms from the central part to the cell walls) are enclosed in a 2 cm × 2 cm × 2 cm glass cell as the sensitive unit in SERF atomic magnetometer. High-density alkali-metal atoms are necessary for the SERF atomic magnetometer, therefore, an alternating current (AC) electric heater is used to heat the cell to 200 °C at which temperature the saturated K vapor concentration is about $[\mathrm{K}] = 7.1388 \times 1016\ \mathrm{cm}^{-3}$.

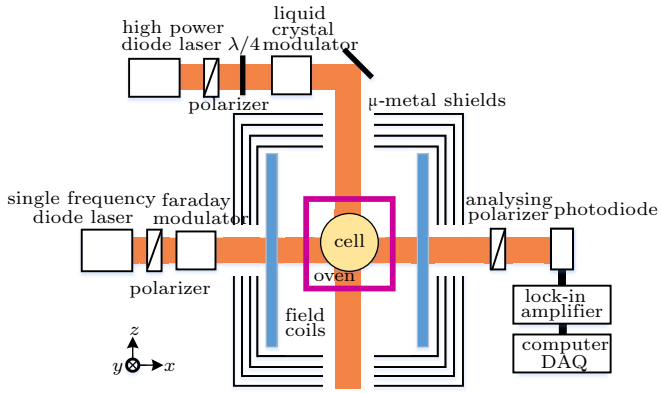


Fig. 3. (color online) General schematic of SERF atomic magnetometer.

A DFB diode (model 6910, New Focus, USA) with a wavelength stabilized at 770 nm and an output power of 2.5 mW produces the pump light used to polarize alkali atoms. Having passed through a polarizer and a quarter waveplate (the angle included between their optical axes is 45°) the laser becomes circularly polarized. The beam polarization is modulated by a liquid crystal phase modulator (LCR-1-NIR, Thorlabs) following the waveplate, which has a $\lambda/2$ phase retarder with a 2 V driven voltage for pump beam.

The probe beam with 1.46 mW power is produced by another DFB laser diode (model 6910, New Focus, USA), which is red-detuned about 200 GHz from D2 line (766 nm) of the K atoms. The probe beam passes through a linear polarizer to generate a linear polarization probe beam. When the SERF magnetometer sense the magnetic field, the polarization of the probe beam changes. The polarization of the probe beam is measured using Faraday modulation technique.[19] A Faraday modulator is followed by a reflector to modulate probe beam polarization at 5 kHz. After the shields, the polarization of the probe beam is analyzed with a crossed linear polarizer. The output signal is obtained by irradiating the probe beam onto a photodiode. The optical rotation is extracted from the first harmonic of the Faraday modulation frequency with a lock-in amplifier (model HF2LI, Zurich Instrument, Switzerland) and the atomic spin magnetic resonance signal is deduced from the first harmonic of the liquid crystal phase modulator modulation frequency with a second lock-in amplifier (SR830, Stanford, USA).

In SERF atomic magnetometer, ambient magnetic fields should be cancelled to avoid broadening the resonance linewidth. A set of four-layer μ-metal magnetic shields with a shielding factor of 5×10^5 is mounted outside the cell and the heater to counteract the geomagnetic magnetic field.[20] In addition, the magnetometer is calibrated by using a known magnetic field. By using different bias magnetic fields, a set of magnetic resonance curves are measured. Fitting the relationship between the bias magnetic field and the linewidth of the resonance curve, the linewidth of the SERF atomic magnetometer is obtained.

4. Experimental results and discussion

Figure 4 shows the magnetic resonance curves for different bias magnetic fields. The dots represent the amplitudes of the atomic spin resonance signal versus modulation frequency and fit to Eq. (9). The fitting results are in good agreement with the experimental data, which proves the validity of this method applied to the SERF magnetometer.

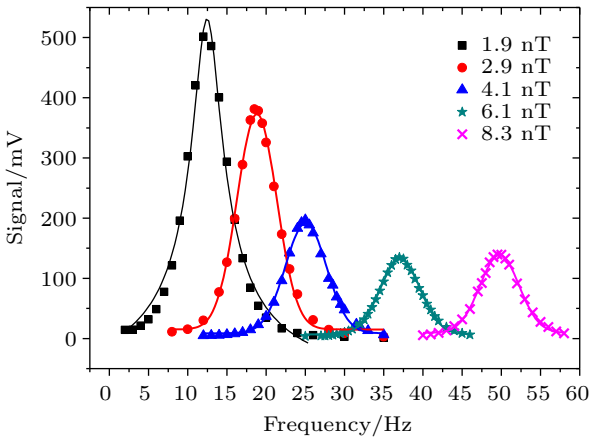


Fig. 4. (color online) (color online) Magnetic resonance curves for different bias magnetic fields. Dots: resonance signal versus modulation frequency. Line: fitline of resonance signal fitting to Eq. (9).

In order to compare the light intensity excitation method with the light polarization modulation method, the magnetic resonance curve is measured with light intensity excitation method for replacing the liquid crystal phase modulator with a chopper to modulate pump beam intensity. Figure 5 shows the magnetic resonance curves obtained with the two methods for a magnetic field of 1.9 nT. The black dots represent the measurements from the light intensity excitation method, while the red dots are obtained by the light polarization modulation method. The resonance curve fitted by both methods are plotted as solid lines. The fitted linewidth by the light polarization modulation method is 2.005 Hz, and that with the light intensity method is 2.105 Hz. The light polarization modulation method presents a better *R*-square than the light intensity excitation method as shown in Table 1, which means a more precise measurement from the light polarization modulation method. It should be noted that the difference between two methods mainly arises in a low modulation frequency range. For modulation frequency lower than 10 Hz, the signal from light intensity excitation method fluctuates with the fitting line. This is attributed to the chopper modulator, which could hardly generate a modulation frequency lower than 10 Hz, thereby losing the signal of the measurement. The experiment results show that the light polarization modulation method has a better resonance signal in low modulation frequency, which will cover the shortcomings of the light intensity excitation method in the same range.

Table 1. Fitting parameters for Fig. 5.

Equation		$y=a/\sqrt{((x-b)^2+c^2)}+d$	
Light polarization modulation method		Adj. *R*-Square	0.99299
		value	standard error
	a	1378.557	83.49494
	b	12.45563	0.04963
	c	−2.00558	0.10932
	d	−139.224	12.77515
Light intensity modulation method		Adj. *R*-Square	0.98943
		value	standard error
	a	1607.506	159.49685
	b	12.40964	0.05948
	c	−2.10508	0.17035
	d	−186.191	26.1404

Figure 6 shows the curves of linewidth versus magnetic field, measured by light polarization modulation and light intensity excitation method for different bias magnetic fields. The black dot shows the linewidth measured by light polarization modulation method, while the red dot is from the light intensity excitation method. The data are measured at magnetic fields ranging from 1.9 nT to 2.6 nT. As the magnetic field increases, the corresponding increase in spin-exchange relaxation leads to the broadening of the resonance linewidth. In the light polarization modulation method, the SERF linewidth is 1.985 Hz with the experimental dots fitting to Eq. (3) and the *R*-square is 0.9951, while the linewidth measured by light intensity excitation method is 2.075 Hz and its *R*-square is 0.9876. The linewidth measured by the light polarization modulation method is narrower than by the light intensity excitation method in a low magnetic field. The calculation transverse relaxation according to Eq. (3) for our experimental conditions is 1.722 Hz, which means that the light polarization modulation method has a better measurement precision for atomic magnetometer. This phenomenon is caused by the chopper with a poor frequency stability below 10 Hz, which induces the fitting error for light intensity excitation method. The light polarization modulation method has a better *R*-square, which means a smaller fitting error. The difference between the experimental results and the theoretical calculations is caused by the noise of liquid crystal modulator, which has a response time on the order of ms, and thus limiting the modulation precision.

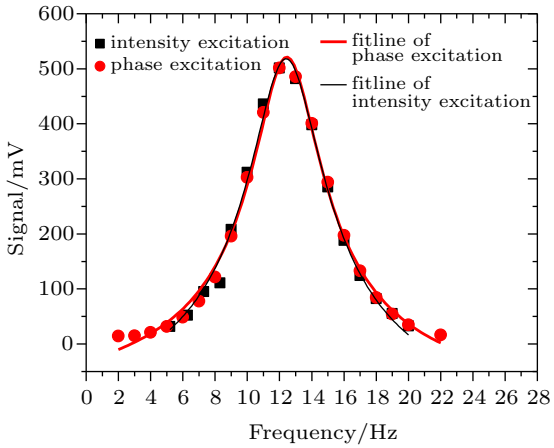


Fig. 5. (color online) Magnetic field curves measured by light polarization modulation method and light intensity excitation method. Black dots: experimental data from light polarization modulation method. Black line: fitline from light polarization modulation method. Red dots: experimental data from light intensity excitation method. Red line: fitline from light intensity excitation method.

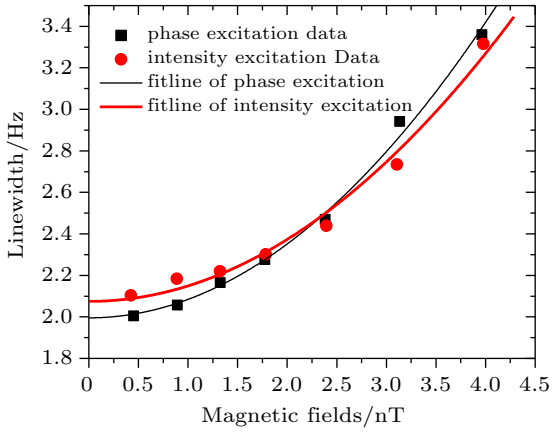


Fig. 6. (color online) Comparison between light polarization modulation method and light intensity excitation method. Red dots: linewidths from light polarization modulation method for different bias magnetic fields. Black dots: linewidths from light intensity excitation method for different bias magnetic fields. Red solid line: fitline of the linewidth from light polarization modulation method. Black solid line: fitline of linewidth from light intensity excitation method.

5. Conclusions and perspectives

Determination of linewidth for SERF magnetometer based on the polarization modulation technique to measure the transverse relaxation is demonstrated. It is achieved by a liquid crystal phase modulator to modulate the pump beam polarization, and the experimental results verify the feasibility of this method. Furthermore, a contrastive experiment is carried out by the light intensity excitation method and shows the same trend, indicating that this method is immune to the instability of the frequency modulation for the light intensity excitation method, which reduces the fitting errors for acquiring the transverse relaxation. The transverse relaxation measured by the light polarization modulation method is closer to theoretical calculation for the SERF magnetometer, which means a better measurement precision than the precision the light intensity excitation method can reach.

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