Suppression Method of AC-Stark Shift in SERF Atomic Magnetometer

YANG LI, MING DING*, XUEJING LIU, HONGWEI CAI, JUNPENG ZHAO, AND JIANCHENG FANG

School of Instrument Science and Opto-Electronics Engineering, Beihang University, Beijing 100191, China

Abstract: In a spin-exchange-relaxation-free (SERF) atomic magnetometer with ultra-high sensitivity, the AC-Stark shift generated by circularly polarized light results in the attenuation of the SERF atomic magnetometer response, and the virtual magnetic field gradient induced by the AC-Stark shift can reduce the sensitivity of the SERF atomic magnetometer. In this paper, we use a hybrid optical pumping method to address the AC-Stark shift problem. By switching between left-hand and right-hand circularly polarized light and compensating the residual magnetic field of the magnetometer, the AC-stark shift could be reduced and then suppressed effectively.

Index Terms: magnetophotonic devices.

Email: mingding@buaa.edu.cn

1. Introduction

In recent years, magnetic field measurements based on the atomic spin effect have become an important technique in physics. The spin-exchange-relaxation-free (SERF) atomic magnetometer was first introduced by Allred et al. [1]. By operating in the regime with a high atom number density and low magnetic field intensity, the SERF atomic magnetometer can achieve an ultra-high sensitivity. Romalis et al. demonstrated a world-record sensitivity of 0.16 fT/Hz^{1/2} using a gradiometric configuration [2]. SERF atomic magnetometers have very attractive application prospects because of their high sensitivity and spatial resolution combined with non-cryogenic operation, and they have been applied to several areas such as geomagnetism, biomagnetism, and basic physical parameter measurement [3], [4], [5].

As SERF atomic magnetometer research has progressed, limitations of the magnetometer have appeared and impacted its improvement in terms of sensitivity. In magnetic field sensitivity measurements using a single type of alkali metal atom, the light intensity decays rapidly while propagating through the cell because of the high atom number density, resulting in a non-uniform polarization. While the uniformity of the alkali metal atom polarization can be increased by detuning the pumping light, an AC-Stark shift is also introduced, which makes the atoms respond as they are in a magnetic field pointing along the propagation of the laser. The AC-Stark shift affects the linewidth and sensitivity of the magnetometer. In addition, fluctuations in the AC-Stark shift are often uncorrelated and therefore limit the suppression of the common mode noise. Therefore, the suppression of the AC-Stark shift is very important in SERF atomic magnetometers. Kim et al. used two separate pumping lasers, which are detuned in the opposite direction from the D1 line in potassium, to reduce their absorption cross-section, allowing the light to propagate further into the cell to obtain a more uniform spatial pumping profile [6]. However, this method needs two distributed feedback laser diodes and needs to ensure the consistency of the two lights. Sulai et al. of the University of Wisconsin-Madison utilized diffusive atom transport to suppress the AC-Stark effects; their approach was to very strongly optically pump the atoms in a small sub-volume of the atomic magnetometer cell, and then rely on diffusion to transport the polarized atoms to regions of the cell with little or no AC-Stark field [7]. This method requires the limited volume, thus it is not applicable for small cells used in micro-magnetometers.

Hybrid optical pumping methods have been explored in the development SERF atomic magnetometers. This approach was first proposed by Happer et al. [8] and was used for improving the polarization efficiency [9] and uniformity of atoms[10]. In this paper, hybrid optical pumping is used to reduce the AC-Stark shift. Under the same detuning frequency of the pump laser, the AC-Stark shift of the two alkali metals can be different. The AC-Stark shift residual can be measured and eliminated by detuning the pump laser. By altering the left and right circularly polarized light, the virtual magnetic field induced by the AC-Stark shift can be changed while the real magnetic field is preserved. Tuning the frequency of the pumping light cancels out the AC-Stark shift produced by the two kinds of alkali metals. By compensating the magnetic field of different-frequency lasers and different circularly polarized light with the magnetometer response, the zero point of the AC-Stark shift can be determined. This AC-Stark shift suppression method is user-friendly, rapid, and efficient. In this method, one atom with a small atom number density polarizes another atom with a low optical depth, which also can address the polarization uniformity problem.

2. Principle

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In SERF magnetometer, circular polarized light of the atomic resonance is used to polarize atoms, it is the pump light. The atoms will process in an external magnetic field with larmor frequency. A linear polarized light perpendicular to the pump light is used to detect the atomic spin projection in the light direction, it is the probe light. Under the conditions of near zero magnetic field and high atomic number density, the spin relaxation is greatly suppressed and the sensitivity of magnetometer is greatly improved. In general, the pump light direction is z, the probe light direction is x, and the rest direction is y which is most sensitive to external magnetic field change. The overall evolution of the atomic spin can be described phenomenologically by the Bloch equation [11]:

\[
\frac{d}{dt} S = \gamma (B + L) \times S + \frac{1}{q} [R_{op} \left( -s - S - R_{rel} \right) - R_{rel} S]
\]

(1)

where \( S \) is the response of the SERF atomic magnetometer, \( \gamma \) is the gyromagnetic ratio, \( B \) is the magnetic field, \( L \) is the AC-Stark shift mainly caused by pump laser, \( q \) is the nuclear deceleration factor due to the coupling effect of the electron and nuclei, \( R_{op} \) is the relaxation rate caused by the pump light, \( R_{rel} \) is the sum of the other spin-relaxation rates, \( s \) is the photon spin vector. This equation is the basis of the SERF atomic magnetometer analysis.

The AC-Stark shift is mainly caused by pump laser, thus it affects the magnetic field in z direction and lead in the second items of Formula (2). The AC-Stark shift has a great influence on magnetometer signal. In order to suppress the AC-Stark shift, two types of alkali metals, K and Rb, are chosen in experiment. The K atomic number is much less than that of Rb. Although the AC-Stark shift is not affected by the alkali metal density of Rb, the AC-Stark shift of K will be mixed together through fast spin exchange. The total AC-Stark shift is related to the density ratio of K and Rb. The AC-Stark shift due to the oscillating electric field of the light can be written as [12]

\[
L_c = \eta L_K + L_{Rb} = \eta \frac{\Phi \gamma c r_s}{\gamma^2 A} \left[ -D_{K01}(v) + D_{K02}(v) \right] + \frac{\Phi \gamma c r_s}{\gamma^2 A} \left[ -D_{R01}(v) + D_{R02}(v) \right]
\]

(2)

where \( \eta \) is the density ratio, \( c \) is the speed of light, and \( r_s \) is the classical electron radius. The oscillator strength \( f \) is the fraction of the total classical integrated cross-section associated with the given resonance. \( \Phi \) is the photon flux and \( D(v) = (v - v_0) / ((v - v_0)^2 + (\Gamma / 2)^2) \) is the light profile associated with the laser frequency and width of the broadening.

For K–Rb vapor where the density ratio \( \eta = [K]/[Rb] = 1/10 \), the simulation result of the light shift range of 760–800 nm is presented in Fig. 1.

The zero points in the curve indicates that the light shift is eliminated, and the AC-Stark shift disappears. At those points, the AC-Stark shifts caused by pump light and caused by collisions with K atoms are in opposite directions with the same value. Considering the actual situation, since the D1 line (770.108nm) laser of K is used as a pumping light, the light shift zero point around 770.1 nm should be found.

The AC-Stark shift is equivalent to a virtual magnetic field and cannot be distinguished from the real magnetic field. The sum of AC-Stark shift and magnetic field \( B_c \) can be obtained by the compensation method. The SERF atomic magnetometer response with the magnetic field is used for zero the total magnetic field. By setting \( \Phi \gamma c = 0 \) and finding the steady-state
solution of Eq. (1) when the magnetic field changes slowly, the electronic spin components of the x-direction are [11]

$$S_x = S_0 \frac{(R_{op} + R_{rel})(\gamma^e B_x) + (\gamma^e B_y)(\gamma^e B_z)}{(R_{op} + R_{rel})^2 + (\gamma^e B_x)^2 + (\gamma^e B_y)^2 + (\gamma^e B_z)^2}$$

(4)

Based on this equation, scanning the magnetic field in the x-direction or z-direction, and adjusting the other two magnetic fields until the magnetometer output signal is zero, reduce these two magnetic fields to zero. The magnetic field can repeatedly reach zero in three directions. $B_x$, $B_y$, $B_z$ is the components of $B_c$ in three directions. The simulation results of the magnetic field compensation process are presented in the Fig. 2. By applying $B_z$ values from -20 to 20 nT, the magnetometer output signal can appear as the corresponding change when the magnetic field changes from negative to positive. This method is very useful in determining the AC-Stark shift quickly; the magnetic field compensation can be completed in a few minutes and the compensation precision can reach the order of picotesla [13].

![Fig. 2. SERF atomic magnetometer response overturn when (left) $B_x$ changes from 1 to -1 nT and (right) $B_y$ changes from 1 to -1 nT.](image)

By altering the left and right circularly polarized light, the magnetic field direction of the AC-Stark shift changes and the real magnetic field remains.

$$B_c(\sigma^+) = \eta L_K(v) + L_{Rb}(v) + B_r$$

(5)

$$B_c(\sigma^-) = -\eta L_K(v) - L_{Rb}(v) + B_r$$

(6)

where $B_c$ is compensated magnetic field value and $B_r$ is the real magnetic field value. Detuning the pump laser frequency,

$$B_c(\sigma^+) = B_c(\sigma^-)$$

(7)

then

$$L_z = \eta L_K(v) + L_{Rb}(v) = 0$$

(8)

Therefore, the AC-Stark shift can be measured and eliminated by detuning the pump laser and compensating the magnetic field with the left and right circularly polarized light. Magnetometer is no longer affected by the AC-Stark shift.

3. Experimental Setup and Results

The experimental setup is illustrated in Fig. 3. A 25-mm diameter spherical glass cell is filled with K and Rb metal, 60 Torr of N2 as a quenching gas, and 2.5 atm of 4He as a buffer gas. The atomic number density ratio is about $R = K/Rb = 1/180$. The cell is placed in a nonmagnetic PEEK vacuum oven and heated to 210 °C by a twisted pair of resistive wire. The vacuum tank maintains a pressure of 0.1 Pa to reduce thermal diffusion and improve thermal stability.

K atoms are polarized by an external cavity diode laser (6910, New Focus, USA) along the z-direction and the output power is set to 100 mW. The frequency of the pump light can be adjusted by voltage controlled piezo-actuator. The pump light is expanded to 12mm diameter by lens group combination to illuminate the whole atomic vapor cell. After that, it passes through a polarizer and quarter-wave plate, whose optical axis is oriented 45° to each other, and become circularly polarized. The polarization can be adjusted by changing the optical axis orientation of the quarter-wave plate.

A probe light with a power of 3 mW is produced by a distributed feedback laser diode (DL 100, Toptica, Germany), which is detuned about 0.5 nm from the D1 line (795 nm) of the Rb atoms. The probe beam is linearly polarized after a polarizer along the horizontal directions and propagates along the x-direction. After passing through the glass cell, the Rb atom spin polarization is detected. The polarization of the probe light is probed using Faraday modulation technique [14] with 3.6 kHz modulation frequency. A lock-in amplifier (HF2LI, Zurich Instruments, Switzerland) is used to extract the first harmonic of the Faraday modulation frequency.
The cell is located in five cylindrical magnetic shield barrel layers with saddle-compensating magnetic coils. The five-layer set of cylindrical magnetic shields has a high shielding factor with a fixed residual magnetic field. It provide a low-magnetic-field environment below 10 nT to ensure the atoms remain in the SERF region.

The compensating magnetic coils are used to apply magnetic fields to the cell, and the for adjustment is 5 pT, which is far less than the AC-Stark shift and magnetic shield residual. Therefore, the error of the magnetic field compensation method can be ignored.

Fig. 3. Schematic of the K–Rb hybrid SERF atomic magnetometer. The five-layer μ-metal magnetic shields and saddle coils provide a weak magnetic environment. The K circularly polarized light of the D1 line is used as a pump light; it can be adjusted by voltage controlled piezo-actuator. The Rb linearly polarized light of the D1 line is used as a probe light, and a Faraday modulator is added to detect the weak signal where the modulation frequency is 3.6 kHz.

The experimental results are presented in Fig. 4. First, using the left circularly polarized pumping light ($\sigma^+$) to polarize the atoms, the residual magnetic fields were measured at a different pumping light frequency through the magnetic field compensation method, and the curve was then fit with Eq. (3). Secondly, by switching the pumping light to right circular polarization ($\sigma^-$) and repeating the operation above, the intersection points of the two fitted curves are AC-Stark shift zero points.

Fig. 4. Sum of AC-Stark shift and magnetic field for different wavelengths. The triangles are the experimental data of the $\sigma^+$ light, while the squares are those of the $\sigma^-$ light. The fit line was calculated using Eq. (3) and two curve intersection points are obtained.

There are two intersection points on the fitting curves in Fig. 4, (770.012 nm, 1.490 nT) and (770.096 nm, 1.504 nT). Tuning the pumping light frequency to these two points, the AC-Stark shift will disappear. There is a deviation of the two y-coordinates of ~1%; this may have been caused by the fitting error. The two curves are symmetrical about $B = -1.5$ nT, which is the real magnetic shielding residual value.

In order to explore the applicable conditions of this method, three atomic number density ratios $R = 1/150$, 1/275, and 1/500 are simulated. The pumping light power is set to 100mW and the cell pressure broadening is set to 30GHz. It can be seen from the simulation results in Fig. 5 that the AC-Stark shift of the hybrid pumping vapor has two zero points around 770.1 nm when the ratio is 1/150. With the decrease in the atomic number density ratio, the zero point will decrease to only one or none.
Fig. 5. AC-Stark shift for different K–Rb density ratios. The black solid line is the AC-Stark shift simulation curve when K/Rb = 1/150, and it exhibits two zero points. The red dashed line is that when K/Rb = 1/275 and exhibits only one zero point. The blue dotted line is that when K/Rb = 1/500 and exhibits no zero point.

Fewer K atoms imply more uniform polarization of the vapor cell, but the atomic number ratio must be chosen reasonably so there is a frequency zero point that can be used to reduce the AC-Stark shift. In addition, if there is only one AC-Stark shift zero point, this point is also the extreme value point of the curve, which can be used to stabilize the AC-Stark shift. From the simulation results, K/Rb=1/275 is the best atomic number density ratio. However, the atomic number density ratio cannot be accurate controlled in cell fabrication. The accurate control method is needed in cell fabrication and it is the emphasis in the subsequent researches.

4. Conclusions

In this paper, we evaluate a suppression method of AC-Stark shift in a K–Rb hybrid SERF atomic magnetometer. Using two kinds of alkali metal atoms, the AC-Stark shift is eliminated by the SERF atomic magnetometer. The method of compensating the magnetic field with left and right circularly polarized light can rapidly and accurately determine the zero point of the AC-Stark shifts. This method has the potential to improve the sensitivity of SERF atomic magnetometers.

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