An all-optical scalar and vector spin-exchange relaxation-free magnetometer employing on–off pump modulation

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It is demonstrated that a spin-exchange relaxation-free (SERF) atomic magnetometer can be used for *scalar* measurements with no additional hardware. Because of relaxation processes, an ensemble of alkali atoms needs a constant supply of polarized photons by a pump beam to maintain a polarized state. If the pump beam is shuttered off, the system decays to its equilibrium state. For a low enough relaxation rate and with a magnetic field present, the system will exhibit oscillations at its natural frequencies. In a SERF magnetometer, it happens at the Zeeman resonance frequency of the atoms (Larmor frequency). Thus, shuttering off the pump beam reveals oscillations at the Larmor frequency. From this frequency, one can deduce the scalar value of the applied magnetic field. As a result, *all-optical* scalar measurements can be performed. At the same time, either one or two vector components of the applied field can be measured by using one or two orthogonal probe beams, respectively. In a low-polarization SERF regime, the ground state can be well described by the Bloch equations for the electron spin polarization. By solving the time-dependent Bloch equations [neglecting the diffusion term and assuming that the nuclear slowing-down factor $q(P)$ is constant], the oscillation frequency of the system is obtained. From this frequency, the scalar value of the applied magnetic field is derived. It is shown that applied fields down to 1 nT can be measured with a 0.1% relative uncertainty. Fields down to 50 pT can be measured with a 10% relative uncertainty. The time dependence acquired in the "off" periods is strongly correlated with the Zeeman sublevels population of the atomic ground state and reveals its spin dynamics.
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I. INTRODUCTION

Over the last several years, spin-exchange relaxation-free (SERF) atomic magnetometers have shown the highest sensitivity in the field.[1] A better than 0.16 $fT/\sqrt{Hz}$ at 1 Hz sensitivity threshold has been reported recently.[2] All-optical SERF magnetometers are sensitive only to transverse components of an applied magnetic field and not to its longitudinal component relative to the pump beam. In order to perform scalar measurements, a modification is necessary. An example can be employing an oscillating rf magnetic field at the Zeeman resonance.[3] Such a modification, however, renders the magnetometer to be non-all optical. This complicates the magnetometer and its applications.

In this work we show that an all-optical SERF magnetometer can be used for both scalar and vector measurements. It is shown that turning off the pump beam initiates spin oscillations at the Zeeman resonance, from which the scalar value of the magnetic field can be deduced. Thus by employing an on–off pump beam modulation, the responses during the "on" and "off" periods can be used for measuring the transverse components and the scalar value of the applied magnetic field, respectively. In addition, the on–off pumping allows a better insight into the temporal characteristics of the magnetometer and its physics.

II. THEORETICAL MODEL

The theoretical model of the magnetometer during the on period of the modulation is discussed in Refs. 1 and 4. In order to model the magnetometer during the off period, we calculate the dynamics of the spin system. The dynamics of the spins in a system of alkali atoms in a magnetic field B can be calculated using the density matrix formalism.[4] When the atoms experience a spin-exchange rate that is much faster than the precession in the field, the dynamics of the spins in the ground state can be well described by the Bloch equations for the electron spin polarization[4]:

$$\frac{d\mathbf{P}}{dt} = D\nabla^2\mathbf{P} + \frac{1}{q(P)}\left(g_s\mu_B\mathbf{P}\times\mathbf{B} + R(\mathbf{s}-\mathbf{P}) - \mathbf{P}\sum\Gamma\right). \tag{1}$$

Here t is the time, $\mathbf{P}$ is the electron spin polarization vector, D is the diffusion coefficient, $g_s \approx 2$ is the electron Landé factor, μ_B is the Bohr magneton, $\mathbf{s}$ is the optical pumping vector directed along the pump beam propagation direction and with a magnitude equal to the degree of the circular polarization, R is the optical pumping rate, and $\sum\Gamma$ is the

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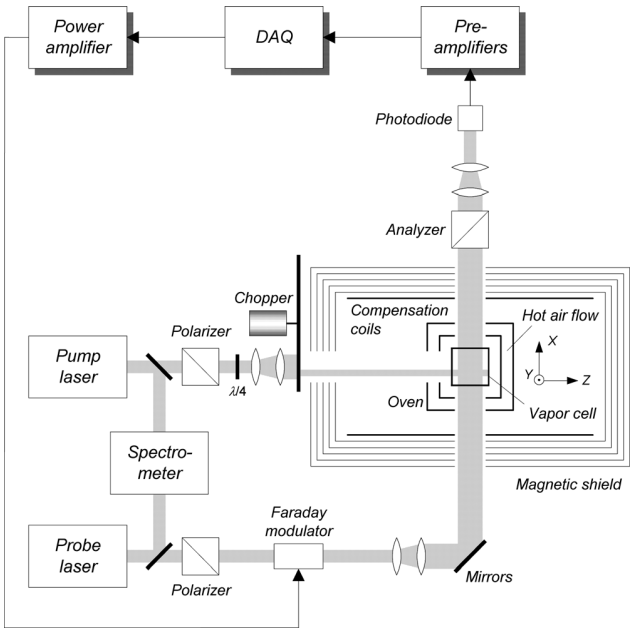

FIG. 1. The experimental setup.

sum of all the depolarization rates. The nuclear slowing down factor denoted by $q(P)$ depends[5] on the nuclear spin of the atom and on the polarization P.

The solution of Eq. (1), for steady state and neglecting the diffusion term, is straightforward,[4] and B_y can be deduced from the magnitude of the optical polarization rotation of a linearly polarized probe beam in the x direction (see Fig. 1).

The exact solution of the time-dependent equations (neglecting the diffusion term) can only be obtained numerically. Taking an alkali atom with nuclear spin $I=3/2$ (potassium or Rb^{87}) and assuming small overall polarization and small variations of $q(P)$, the nuclear slowing down factor can be treated as constant. A reasonable approximation is the low polarization limit $q(0)=6$. The solution[6] for the total polarization is a decaying exponential $\exp(-\sum\Gamma t)$. When the pump laser is directed along the z axis, the probe laser is directed along the x axis, and the y component of the magnetic field (B_y) is nonzero, the solution for the x component of the polarization for the off period of the modulation is given by

$$P_x(t) = P_{0x}\exp\left(-\sum\frac{\Gamma}{q}t\right)\sin\left(\frac{g_s\mu_B Bt}{q}+\Phi\right), \qquad (2)$$

where P_{0x} is the steady-state value[4] of P_x, and B is the scalar value of the magnetic field. The phase angle Φ depends on R, $\sum\Gamma$, and all the components of $\mathbf{B}$. A constant $q=6$ is assumed.

This model also predicts the time dependence of P_y: it oscillates at the same frequency as P_x with a phase difference of $\pi/2$ and decays with the same time constant. The total polarization $P=\sqrt{P_x^2+P_y^2+P_z^2}$ decays exponentially with the same time constant but does not oscillate.[6]

III. EXPERIMENT

A. Experimental setup

The experimental system is depicted in Fig. 1 and is described elsewhere.[5] The cubic vapor cell with a 3 cm side contains 40 Torr of N_2, approximately 2.5 amagat of He, and a drop of potassium metal. An external cavity diode laser, tuned to the $D1$ line of potassium with a spectral width of about 0.3 nm, serves as the pump laser. The pump beam is spatially filtered. The pump beam diameter is 6 mm and its average power density is 10 mW/cm^2. The probe beam is about 4 mm diameter and 10 mW. It is tuned to 0.8 nm from resonance. The nitrogen serves as a quencher to enhance the efficiency of the optical pumping and to keep the atomic system in the ground state. The helium serves as buffer gas to minimize diffusion. The polarization obtained was low (<0.03) due to low degree of the circular polarization.

The cell is placed in a five-layer magnetic shield with compensating magnetic coils. The compensating coils are also used to apply a magnetic field to the cell. The cell is heated up to 453 K by hot air. The potassium vapor density is approximately 6×10^{13} cm^{-3}. The pump laser beam is modulated by a chopper at a rate of 2.5 Hz. The illumination time in each cycle is 100 ms and the off period is 300 ms. Such a scheme has been chosen because the time constant governing the polarization buildup process is $q/(R+\sum\Gamma)$, whereas the time constant governing the polarization decay process is $q/\sum\Gamma$.

After setting all three components of the external magnetic field to as near zero as possible,[1] to demonstrate measurements of arbitrary fields, we used the compensation coils to set B_z at 4.9 nT, and measured the system's response applying B_y values from nearly 0 to 10 nT.

B. Experimental results

Figure 2 shows the polarization rotation at the end of a long illumination period, greater than $q/(R+\sum\Gamma)$, for a series of B_y values, while B_z was kept at 4.9 nT. The experimental results show a good agreement with the expression given by Ledbetter *et al.*[4]

Figure 3 shows the probe polarization rotation after shuttering off the pump beam, for some of the B_y values given in Fig. 2. The presence of $B_z\neq0$ manifests itself in the oscillations of the signal at $B_y\approx0$, and one can clearly

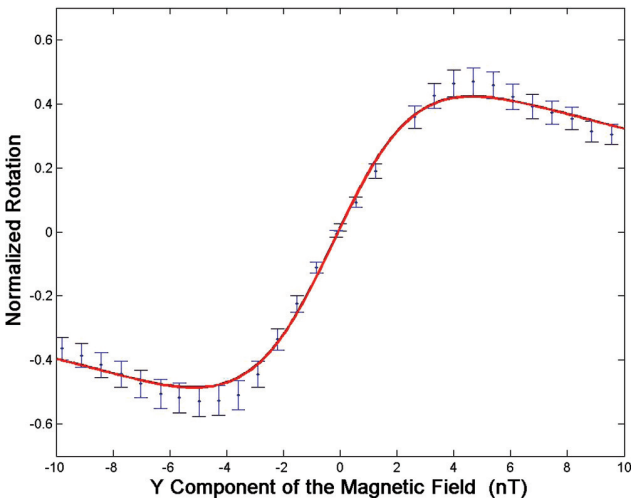

FIG. 2. (Color online) The polarization rotation vs the y component of the applied magnetic field B_y. The continuous line represents the expression given by Ledbetter *et al.* (Ref. 4). The error bars represent the measurements.

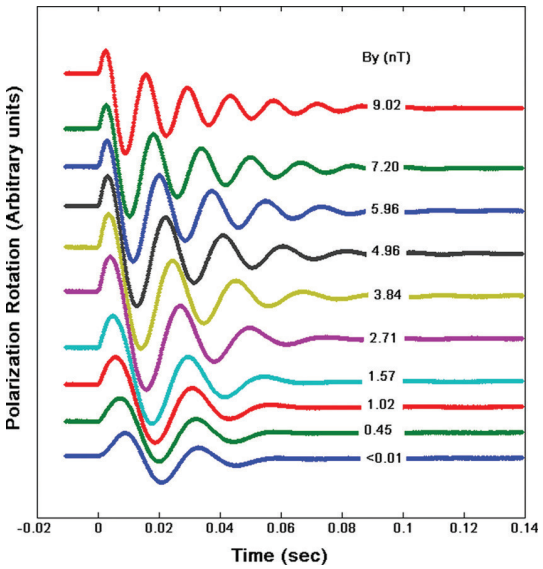

FIG. 3. (Color online) The optical polarization rotation of the probe obtained in an off period of the pump modulation vs time with B_y as a parameter. The turning off time is defined as $t=0$. The x component is kept at $B_x=0$. The z component of the magnetic field is kept constant at $B_z=4.9$ nT. This is the source of the oscillations at $B_y \approx 0$.

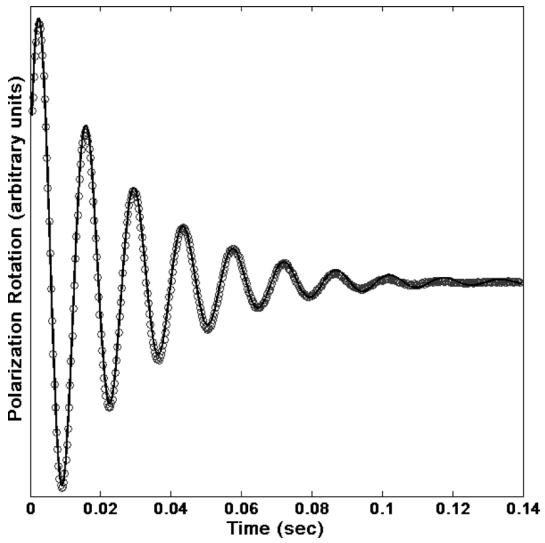

FIG. 4. The optical polarization rotation of the probe obtained in an off period of the pump modulation, for $B_y=9.02$ nT. The continuous line represents a fit to the data with $B=10.4$ nT. The difference is attributed to the z and x components of the applied magnetic field. The component B_x is nearly zero, therefore, $B_z=5.2$ nT.

observe the increase in oscillation frequency with increase in the applied magnetic field.

In Fig. 4 we show the agreement we get when fitting one of the traces in Fig. 3 by using Eq. (2). The relative error in B/q of Eq. (2) is around 0.01%. The slowing down factor used is for zero polarization $q(0)=6$. For small P the relative variation in q during the decay of the polarization to zero is proportional to P^2, so for $P=0.03$ the contributed additional relative error is 0.1%. The value derived for B_z is 5.2 nT, in agreement with the applied constant B_z.

IV. CONCLUSION

We have demonstrated the operation of an all-optical scalar and vector magnetometer operated in the SERF regime. Limiting the steady-state data acquisition time to 100 ms caused some deterioration of the sensitivity of the magnetometer. The deterioration is overcome by repetitive measurements. The necessity to observe at least the first peak in the oscillation limits the minimum measurable field to 50 pT with a 10% uncertainty.

The oscillations we observe when the pump beam is shuttered off originate from the transfer of the polarization from the z direction to the x and y directions. This implies changes in the Zeeman levels' population ratios. The overall polarization P does not oscillate but decays exponentially. A detailed explanation of this phenomenon requires solving the rate equations of the density matrix of the atomic system. We are going to address this in our future research.

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