Magnetic-Field-Insensitive Zeeman Resonance Induced by Parametric Modulations

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***Abstract*—In this paper, we introduce a phenomenon that the magnetic resonance frequency is insensitive to the bias magnetic field strength when applying a non-resonant radio-frequency (rf) field under a proper spin- exchange collision rate. We theoretically investigate the factors that resulting in the phenomenon based on density-matrix simulations.**

Keywords—parametric modulations; spin-exchange collision;

I. INTRODUCTION

Conventionally, the comagnetometers can be used to measure anomalous fields due to its inherent insensitivity to magnetic field drift and field gradients [1]. Based on the similar insensitivity property presented in our work, a single species magnetometer can also be developed to search for exotic physics or used for spin control related applications.

II. METHODS/RESULTS

The theoretical model that we used to describe the spin-exchange (SE) effects on atoms is the fundamental density matrix equations. When the coherence time between the two ground-state hyperfine levels of the atoms is quite short, the time evolution of atomic spins in the ground state can be described as [2, 3]

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = A_{\mathrm{hf}}\frac{[\mathbf{I}\cdot\mathbf{S},\rho]}{\mathrm{i}\hbar} + \mu_{\mathrm{B}} g_{\mathrm{s}}\frac{[\mathbf{B}\cdot\mathbf{S},\rho]}{\mathrm{i}\hbar} + R_{\mathrm{SD}}(\varphi-\rho)$$
$$+R_{\mathrm{SE}}[\varphi(1+4\langle\mathbf{S}\rangle\cdot\mathbf{S})-\rho] + R_{\mathrm{OP}}[\varphi(1+2\mathbf{s}\cdot\mathbf{S})-\rho], \quad (1)$$

where ρ is the density matrix of the atoms in ground-state, A_{hf} is the hyperfine coefficient, $\mathbf{I}$ and $\mathbf{S}$ are the nuclear-spin and electron-spin operators respectively, g_{s} is the Landé factor of electrons, μ_{B} is the Bohr's magneton, φ is the pure nuclear part of ρ, $\varphi = \rho/4 + \mathbf{S}\cdot\rho\mathbf{S}$, and $\langle\mathbf{S}\rangle = \mathrm{Tr}[\rho\mathbf{S}]$ is the expectation value of the electron-spin operator. The first two terms of Eq. (1) describe the hyperfine and Zeeman interactions. The third and fourth term describe the relaxation effects, where R_{SD} is the spin-destruction (SD) collisions rate, and R_{SE} is the SE collisions rate. The final term is introduced by the optical pumping at the rate of R_{OP}, and s describes the direction and polarization of the light.

Although Eq. (1) is a relatively precise model to quantitatively study the behavior of atoms, it is usually complicated to be analytically solved. The hyperfine Bloch equation is a comprise between complexity and applicable range of the equations [4],

$$\frac{\mathrm{d}\mathbf{F_a}}{\mathrm{d}t} = \mathbf{F_a}\times\gamma_0\mathbf{B} + M_{aa}\mathbf{F_a} + M_{ab}\mathbf{F_b} + \mathbf{s}G_a R_{\mathrm{OP}}, \quad (2a)$$

$$\frac{\mathrm{d}\mathbf{F_b}}{\mathrm{d}t} = -\mathbf{F_b}\times\gamma_0\mathbf{B} + M_{bb}\mathbf{F_b} + M_{ba}\mathbf{F_a} + \mathbf{s}G_b R_{\mathrm{OP}}, \quad (2b)$$

where $\mathbf{F_a}$ and $\mathbf{F_b}$ are the angular momenta of the two ground-state hyperfine levels respectively, γ_0 is the free atomic gyromagnetic ratio, M_{ij} is a coefficient matrix depending on the R_{SD}, R_{SE}, R_{OP}, and nuclear spin I, the coefficient $G_{(a/b)}$ depends on I as well.

The inset of Figure 1 shows a typical schematic diagram of a magnetic-resonance-based atomic magnetometer, except that the driving field that exciting the Zeeman resonance is a rotating field in x-y plane and an additional non-resonant rf field is applied along y direction. By numerically solving Eq. (2), we obtained the relationship between the R_{SE} and Larmor frequency of the atoms when non-resonant rf fields of different strengths are applied as shown in the inset of Fig. 1.

Figure 1 shows the dependence of the magnetic-resonance frequency on the spin-exchange collisions rate of ^{87}Rb, where the bias magnetic field is B_0 = 20 nT. In the absence of a transverse rf field, the resonance frequency decreases monotonically with the SE rate. It becomes dramatically different when a transverse non-resonant rf field is applied to modulate the atoms, and it is found that there is a minimum precession frequency at a particular SE rate, which is related to the frequency of the rf field. Figure 1 also shows that, by increasing the amplitude of the rf field, the Larmor precession frequency can even become zero, regardless of the non-zero bias magnetic field. Figure 2 shows

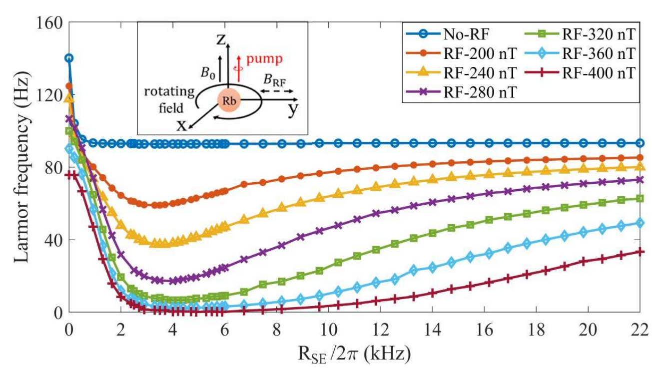

Fig. 1. Dependence of the Larmor frequency on spin exchange rate for different oscillating magnetic field strengths.

the simulation results with fixed SE collision rate $R_{SE}/2\pi = 3.3$ kHz.

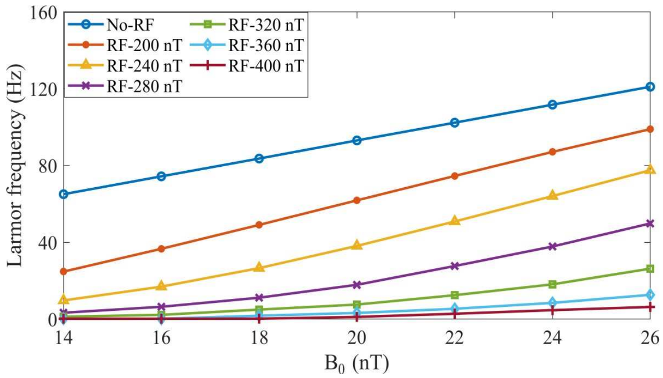

Fig. 2. Dependence of the Larmor frequency on static magnetic field strength for different oscillating magnetic field strengths.

III. DISCUSSION/INTERPRETATION

Previous work indicates both experimentally and theoretically that the atomic Larmor frequency is related to the RF field parameters when the SE collision rate is tuned [5]. We generalize this experiment and model to the case of magnetic resonance and find that the atomic precession frequency shows a quite different characteristic in a non-resonant strong RF field.

It should be noted that, this phenomenon may not be simply explained based on the atomic dressing effect [6], since the SE collisions also play an important role in reducing the effective gyromagnetic ratio. There is a minimum in the dependence of the Larmor frequency on R_{SE} for different oscillating magnetic field strengths as shown in Fig. 1. Besides, the minimum value gradually approaches 0 as the magnetic field intensity of the rf field gradually increases. When the strength of the rf field is 400 nT, the Larmor frequency is almost equal to 0, which does not change with the strength of the bias magnetic field, as shown in Fig. 2. The Zeeman resonance of atoms are insensitive to the bias magnetic field under this circumstance.

This property expends the applicable range of this system to non-magnetic interactions, which are commonly detected by comagnetometers [7,8]. Compared with the traditional co-magnetometer scheme, this system uses only one kind of atoms, which can effectively avoid systematic errors caused by mutual influence between different atomic systems.

IV. CONCLUSIONS

In this work, we present a phenomenon that the magnetic resonance frequency is insensitive to the bias magnetic field under certain circumstances, which can be used in the detection of nonmagnetic interactions, such as dark matters. It may have better performance than the existing detection method using a comagnetometer.

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