A Self-driving Rb-Xe Spin Oscillator

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Summary—**A self-driving Rb-Xe spin oscillator is demonstrated in theory and experiment. The original photo-detected signal of atom spin oscillation is amplified, phase-shifted and sent back to drive the spins itself coherently. By fine tuning the driving strength and phase, a self-sustaining spin oscillation signal with zero frequency shift is obtained. The effective coherence time is extremely prolonged beyond the intrinsic coherence time of noble gas atomic spins, forming a spin oscillator. Spectral analysis indicates that a frequency resolution of 9 nHz is achieved, which can enhance the sensitivity of magnetic field and angular velocity sensing. Allan deviation analysis shows that the spin oscillator can operate in continuous wave mode like a maser or laser, providing an ideal tool for long term precision measurement physics research.**

Keywords—comagnetometer; coupled Bloch equations; self-driving spin oscillator;

I. Introduction

Inspired by the self-oscillating NMOR magnetometer by Kitching et al. [1], following ideas from feedback oscillator electronics and radio-frequency excitation NMR, we demonstrate here theoretically and experimentally a self-driving spin oscillator based on a typical alkali metal-noble gas comagnetometer [2].

II. METHODS/RESULTS

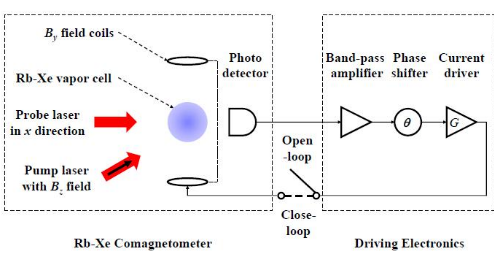

FIG. 1. Experimental schematic of the self-driving Rb-Xe spin oscillator.

The spin oscillator consists of a typical pump-probe Rb-Xe comagnetometer (left) and a driving electronics (right) with tunable gain and phase parameters, as depicted in Fig. 1. The comagnetometer uses a vacuum atomic vapor cell containing Rb-Xe mixture gas at high temperature (about 120 ℃) as the atomic spin media and is placed in a static field in the z direction.

A circularly polarized 795 nm laser with 54 mW power along the z direction shines into the cell to align the rubidium atom spins. The Rb spin polarization was transferred to Xe spins via rapid spin-exchange collisions [3]. Then the polarized Xe spins drive the Rb spins in a classical way [4] and at last a linearly polarized 780 nm laser with 3 mW power along the x direction reads out the Rb spin dynamics over time as the comagnetometer original output signal. The original signal is amplified by a home-made narrow-band amplifier, phase-shifted and fed back to the transverse field coil in y direction, forming a close-loop comagnetometer. The static field B_z is about 30 mG, corresponding to a ^{129}Xe spin oscillation frequency of about 35 Hz.

The spin dynamics of the self-driving spin oscillator is described by the following coupled Bloch equations

$$\begin{aligned}\frac{\partial \mathbf{M}^{\mathrm{Rb}}}{\partial t} &= \frac{\gamma_{\mathrm{Rb}}}{q}\mathbf{M}^{\mathrm{Rb}}\times(\mathbf{B}_0+\lambda\mathbf{M}^{\mathrm{Xe}})+\frac{M_0^{\mathrm{Rb}}\hat{z}-\mathbf{M}^{\mathrm{Rb}}}{qT^{\mathrm{Rb}}},\\ \frac{\partial \mathbf{M}^{\mathrm{Xe}}}{\partial t} &= \gamma_{\mathrm{Xe}}\mathbf{M}^{\mathrm{Xe}}\times(\mathbf{B}_0+\lambda\mathbf{M}^{\mathrm{Rb}}+GM_x^{\mathrm{Rb}}e^{i\theta}\hat{y})+\frac{M_0^{\mathrm{Xe}}\hat{z}-\mathbf{M}^{\mathrm{Xe}}}{T^{\mathrm{Xe}}}.\end{aligned} \tag{1}$$

The driving field strength is determined by the gain factor G and the driving field is in phase or out of phase depending on the phase shift θ. The spin oscillator works in two modes: G=0 open-loop mode and $G\neq0$ close-loop mode. In close-loop mode, it is further found that the oscillator can work in weak or strong feedback states depending on the magnitudes of G. The simulation results show that the self-oscillating is possible at strong G (>100 for typical experimental conditions) and positive θ (between 0° and 180°) values. At strong self-driving operation, the spin polarization can oscillate at a much longer time scale ~1000 s, far beyond the conventional coherence time of spin precession.

In a typical experimental cycle, we first break the link between the Rb-Xe comagnetometer and driving electronics and obtain an open-loop spin oscillation signal, as shown in Fig. 2(a). Then we restore the link, set the electronics driving output at a fix gain and change the phase point by point with an accuracy of about a few degrees. At last, we fix the phase to a point where the close-loop spin oscillation frequency coincides with the open-loop one, that is, the zero frequency shift (ZFS) phase, and record a long-time spin oscillation signal, as shown in Fig. 2(b).

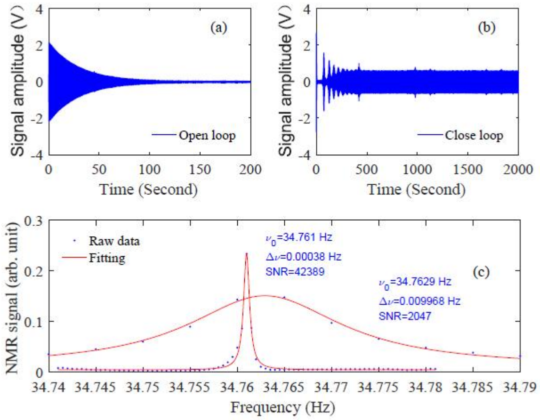

FIG. 2. Spin oscillation signals of the self-driving Rb-Xe spin oscillator in open-loop (a) and close-loop (b) modes, and the corresponding Fourier spectra comparison (c). A linewidth narrowing by a factor of 26 and SNR enhancement by a factor of 21 is achieved when switching from the open loop to close loop modes.

For open loop operation, a spectral linewidth of 0.01 Hz and signal to noise ratio of about 2047 are achieved, as shown in Fig. 2(a). For close loop operation, the spin resonance linewidth is reduced to 0.38 mHz and the signal to noise ratio (SNR) is increased to 42389, as shown in Fig. 2(b). Compared to the open loop operation, the close loop frequency resolution of the ^{129}Xe spin resonance frequency was improved by a factor of about 545, from 4.9μHz down to 9 nHz.

To test the performance of spin oscillator in long term operation, we recorded continuously the spin oscillation for 4000 seconds in the close loop operation and the standard Allan deviation analysis result for the last 3000 seconds is given in Fig. 3. The frequency instability of spin oscillation reaches 3.25 μHz at 500 seconds averaging time, which is equivalent to a bias instability of ≈4.2 °/h for gyroscopic measurement.

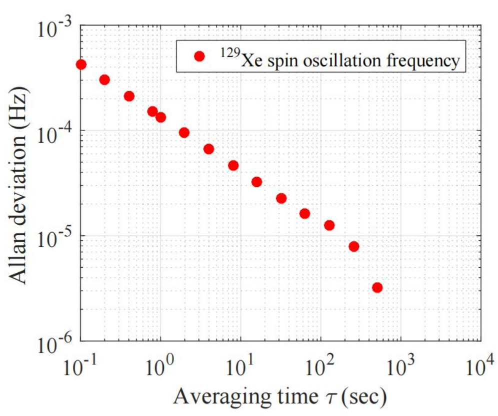

FIG. 3. Allan deviation of the ^{129}Xe spin oscillation frequency in averaging time of 4000 seconds. A frequency instability of 3.25 μHz is achieved at a measuring time of 500 seconds, equivalent to a bias instability of 4.2 °/h.

III. Discussion/Interpretation

Compared to the state of the art accuracy [5], we use a simpler experimental apparatus and shorter sampling time to improve the frequency resolution. In the case of ^{129}Xe with gyromagnetic ratio 11.78 MHz/T, this level of frequency resolution leads to a magnetic field resolution of ≈0.76 fT, sufficient for applications such as the detection of human brain magnetic field [6].

We have been observing the spin oscillation signal with an oscilloscope for several hours in real time and found no sign of decaying at all. Once the loop is open, the spin oscillation starts to decay exponentially again within the intrinsic coherence time of noble gas spins. In this sense, the self-driving spin oscillator can work in continuous wave mode like conventional laser or maser.

IV. Conclusions

In conclusion, we have demonstrated theoretically and experimentally a self-driving spin oscillator based on the Rb-Xe comagnetometer. At strong self-driving operation, the spin oscillation time is extremely prolonged, becoming a non-decaying or self-sustaining oscillator. The frequency resolution of the spin oscillator reaches nHz level, boosting significantly the precision measurement sensitivity with a simple apparatus. The frequency drift of spin oscillator can be stabilized to the ZFS phase point with phase-locking technique. In principle, the demonstrated self-driving spin oscillator scheme can be also applied to the tri-spin comagnetometer such as the Rb-^{3}He-^{129}Xe or Rb-^{129}Xe-^{131}Xe configuration [5, 7] with careful design of dual-channel driving electronics with respect to the two noble gas spin oscillation frequencies. The hybrid atomic spin oscillator can work like laser or maser for long term scientific or practical applications, such as searching for new spin-dependent interactions and earth rotation sensing.

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