Miniature NMR Gyros

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***Abstract*—Spin-exchange pumped NMR gyros scale well to small volumes due to the gentle 1/L scaling of the fundamental NMR relaxation rates with cell size L and their use of imbedded ultra sensitive atomic magnetometers that directly measure the quantum-enhanced field due to the precessing nuclei. This talk will give an overview of the present technology and describe new approaches that promise improved long-term stability.**

I. Introduction

Spin-exchange pumped NMR gyros [1] are a promising technology for achieving high performance in a small package. The basic principle is as follows. The NMR precession frequency for a nucleus in a magnetic field $\mathbf{B}$ and rotating at a rate r about $\mathbf{B}$ is

$$\nu_K = \gamma_K B \pm r \tag{1}$$

where γ_K is the nuclear gyromagnetic ratio and the sign of the gyromagnetic ratio determines whether rotation in a positive sense increases or decreases the resonance frequency.

Using a single nucleus, it is impossible to distinguish rotations from magnetic field fluctuations, hence a second nucleus is generally used as a co-magnetometer. By combining measurements of the resonance frequencies of the two nuclei, rotations can be distinguished from magnetic field changes. Note in particular that since the NMR gyro relies on measurement of the resonance frequency of a quantum system (the atomic nucleus), the rotational scale factor is to a very high degree a constant of nature, independent of any geometric factors.

The following is a brief summary of NMR gyros(see Ref. [1] for many more details), with an eye towards high performance at small volumes.

II. Spin-exchange pumped NMR

A particularly attractive implementation of these basic ideas uses spin-exchange collisions with optically pumped alkali atoms, often Rb, to spin-polarize two Xe isotopes by spin-exchange collisions. The Rb atoms are spin-polarized using optical pumping; hyperfine interactions during collisions transfer the Rb electronic angular momentum to the Xe nuclei. Applying a transverse resonant oscillating magnetic field to each of the nuclei causes them to precess in the usual manner of NMR. The phase shift between the Xe precession and the oscillating field is zero when the oscillating field frequency is on resonance; by detecting this phase shift feedback is used to lock the frequency of the oscillating field to the Xe resonance.

Given that the Rb atoms are themselves ultrasensitive magnetometers, with sensitivities of nG/$\sqrt{\text{Hz}}$ or better, it is natural to detect the precession of the Xe nuclei using the imbedded Rb magnetometer. This replaces the more conventional inductive magnetic field pickup coils that have much poorer SNR. Even better, since the Rb electrons directly probe the Xe nuclei using the hyperfine interaction, there is a quantum enhancement of the effective field detected by the Rb magnetometer. For Xe, this enhancement is huge–the magnetic field seen by the Rb is 500 times larger than the classical magnetic field produced by the Xe nuclei outside the glass cell that contains them.

III. Fundamental Sensitivity

Like any resonator, the precision with which the NMR resonance frequency can be measured is the resonance linewidth divided by the signal-to-noise ratio. The relaxation times that are typically achieved in a Rb-Xe spin-exchange cell with appropriately coated walls is 25 seconds, corresponding to an Fourier linewidth of 6 mHz. Under good conditions, the quantum-enhanced signal from the Xe nuclei approaches 1 mG. With a noise floor of 1 nG/$\sqrt{\text{Hz}}$, the resulting frequency noise of the NMR oscillator is potentially

$$\delta\nu = 1 \text{ mHz} \times \frac{1 \text{ nG}/\sqrt{\text{Hz}}}{1 \text{ mG}} = \frac{1 \text{ nHz}}{\sqrt{\text{Hz}}} = 2\times 10^{-5}\frac{\text{deg}}{\sqrt{\text{hr}}} \tag{2}$$

Absent sources of bias, the potential to achieve these in a (3 mm)^3 cell drives research and development into NMR gyros.

IV. Sources of Bias

The primary known sources of bias in the NMR gyro were illustrated in a recent Northrop-Grumman/Indiana University/UW-Madison collaboration [2]. The Xe-131 isotope is spin-3/2 and therefore has an electric quadrupole moment that couples to electric field gradients during collisions with the cell walls. The quadrupole shift depends strongly on cell preparation and so it varies widely, but with care it can be reduced to 1 mHz or less. The quantum enhancement of the Xe field holds in reverse as well; there is an effective magnetic field from the Rb atoms that serves to shift the Xe NMR frequency. Since this "alkali field" is nearly the same for both Xe isotopes, it cannot be distinguished from a real magnetic field and cancels in a comagnetometer configuration. However, small differences in the Rb-Xe interactions for the two isotopes lead to a small differential field producing a rotation-like shift

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of typically a few hundred microHz between the two NMR resonances.

In order to reach the desired nHz stability level, it is necessary to stabilize these bias sources to a high degree. This has been accomplished to a remarkable extent and Northrop-Grumman's NMR gyro has demonstrated bias stability approaching 0.1 deg/hr or 80 nHz [1].

V. Synchronous Spin-Exchange Optical Pumping

At Wisconsin we are pursuing an alternative NMR gyro design that seeks to maintain the excellent statistical properties of spin-exchange pumped NMR gyros but with greatly reduced bias sensitivity. The basic idea is to cause both Rb and Xe spins to precess in a plane transverse to the bias field. In order to accomplish this in the face of Rb atoms having roughly $1000\times$ greater magnetic moment, we apply the bias field as a sequence of Rb 2π pulses, with the field being close to zero between the pulses [3]. With each bias field pulse, the Xe nuclei precess approximately $2\pi/1000$ radians and so their precession is a sequence of small phase steps that are equivalent to precession in the average magnetic field of the pulse [4]. Using polarization modulation of the Rb pumping light, we have simultaneously polarized and performed NMR on both Xe isotopes. We have demonstrated a $> 5000\times$ suppression of the alkali field. Interestingly, there is no sign of an effect of the Xe-131 quadrupole moment. Theoretically, we expect that the quadrupole interaction will enter only in second order, so that it will be suppressed as compared to longitudinal spin-exchange by a factor of about 10^4. This has yet to be experimentally confirmed.

VI. NMR gyro scaling

Northrop-Grumman has demonstrated relaxation times of 25 seconds in (2 mm)^3 cubic glass cells [2]. It is not at all clear that this is a fundamental limit but in any case the Xe-129 isotope is usually spin-exchange broadened, thus limiting the density of Rb atoms that can be used. As the cell size L decreases, the diffusion loss is proportional to $1/L^2$ and so the Xe density can be increased proportionately. Assuming sufficient laser power, this implies that the Xe field is also proportional to $1/L^2$. With careful engineering, it should be possible to reach the atomic quantum projection noise limit for the magnetometry, which would imply a scaling

$$\delta B = \frac{1}{\gamma_{Rb}}\sqrt{\frac{k[\mathrm{Xe}]}{[\mathrm{Rb}]L^3}} \propto \frac{1}{L^{5/2}}. \quad (3)$$

The overall scaling of the statistical noise is therefore expected to be

$$\delta\nu = \Gamma_{Xe}\frac{\delta B}{B_{Xe}} \propto L^0\frac{L^{-5/2}}{L^{-2}} = L^{-1/2} \quad (4)$$

This is a very gentle dependence on system size and may indeed be overly optimistic, especially as regards the magnetometry and demands on the laser performance. However, it does suggest that from a physics standpoint spin-exchange pumped NMR is a very attractive approach to making miniature high performance gyros.

VII. Conclusions

There has been a renaissance of interest in NMR gyro technology for high performance miniature navigation. A systematic study of performance vs size in a practical system would seem to be of substantial interest.

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