Self-oscillating rubidium magnetometer using nonlinear magneto-optical rotation

P. D. D. Schwindt, L. Hollberg, and J. Kitching
Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305

(Received 22 August 2005; accepted 17 October 2005; published online 14 December 2005)

The detection of nonlinear magneto-optical rotation (NMOR) of polarized light through alkali atomic vapor is a highly sensitive technique for measuring magnetic fields. We demonstrate that when using frequency modulated light to excite the NMOR resonance, it is possible to cause the system to self-oscillate. The NMOR signal is not a simple replica of the sine wave modulation of the light, but rather contains many higher harmonics of the modulation frequency, and we implement two ways of processing the signal to recover the fundamental modulation frequency in the feedback loop and induce self-oscillation. Self-oscillation simplifies and reduces the power consumption of the electronics required to operate a magnetometer, making the NMOR technique attractive for commercialized magnetic sensors.
[DOI: 10.1063/1.2136885]

At the National Institute of Standards and Technology we are working to drastically miniaturize vapor-cell-based atomic devices by taking advantage of the techniques of microelectromechanical systems (MEMS).[1,2] MEMS fabricated devices offer greatly reduced power consumption and reduced cost through high volume, wafer-based production. Recently, we demonstrated a chip-scale atomic magnetometer (CSAM) sensor head with a size less than 12 mm^3 while sacrificing little in performance.[3] This CSAM did not measure the Larmor frequency of the atoms directly but measured instead the hyperfine splitting between two magnetically sensitive Zeeman sublevels in the $F=1$ and $F=2$ ground states of ^{87}Rb. The determination of the Larmor frequency and thus the magnetic field was complicated by the need to subtract the hyperfine splitting from the frequency measurement limiting the accuracy and long-term stability of the measurement. Our original CSAM also required a stable, yet tunable, local oscillator operating at gigahertz frequencies, which adds significantly to the power consumption and expense of a complete device. To simplify future CSAMs, we plan to implement a magnetometry scheme that measures the Larmor frequency directly. As was recognized long ago,[4] further simplification can be achieved if the magnetometer can be made to self-oscillate, eliminating the need for a local oscillator.

Recent developments in the use of frequency modulated (FM) light to excite the magnetic resonance promise to further simplify an optically pumped magnetometer (OPM) by eliminating the need for a rf coil to excite the magnetic resonance.[5,6] In many OPMs, the alignment of the rf coil relative to the optical axis is a significant source of systematic error.[4] There is also an orientation error of approximately 1 nT in Cs and Rb OPMs because optical pumping is done with circularly polarized light, giving rise to an asymmetrical resonance line.[7,8] The use of frequency modulated light with linear polarization eliminates both of these systematic errors. Frequency modulation is easily implemented with diode lasers through modulation of the injection current, making it suitable for miniaturization in a CSAM. Budker *et al.* have shown that FM light can be used to excite a nonlinear magneto-optic rotation (NMOR) resonance, extending the field range of NMOR-based magnetometers up to the Earth's field.[6] The sensitivity of the technique is in principle expected to exceed 1 fT/$\sqrt{\text{Hz}}$. Here, we demonstrate that the FM NMOR magnetometer can be made to self-oscillate using two different methods of feedback in magnetic fields ranging up to the Earth's field.

A schematic of our experimental apparatus is shown in Fig. 1. We use a vertical cavity surface emitting laser (VCSEL) tuned to the $D1$ line to illuminate a vapor cell (diameter 3.5 cm) filled with isotopically enriched ^{87}Rb. The beam from the VCSEL is collimated to a diameter of ~1.3 mm and is attenuated to ~62 μW. The interior of the cell is coated with an antirelaxation paraffin layer, and the cell is placed inside a two-layer magnetic shield containing a solenoid that applies a magnetic field along the propagation direction of the light. The cell is placed between a linear polarizer and an analyzer oriented at 45° with respect to each other. Each output beam of the analyzer is directed to a separate photodetector, and the signals from the two detectors are subtracted in a balanced receiver to provide a measure of the polarization rotation caused by the atoms.

The FM NMOR resonance[6] is produced by a simultaneous pump and/or probe interaction of the linearly polarized light with the atomic vapor. To excite the resonance, we modulate the VCSEL injection current at twice the Larmor frequency such that the peak-to-peak amplitude of the modulation of the laser frequency is 1.38 GHz, roughly three times the Doppler width of the optical resonance. The center frequency of the laser is optimally tuned to the low-frequency side of the $F=2 \rightarrow F'=1$ transition such that the laser is approximately on resonance when it reaches its maximum frequency during the modulation cycle (Fig. 2). When the laser frequency is on resonance, an atom in the laser beam is optically pumped by the linearly polarized light into an aligned state along the direction of the light's polarization.

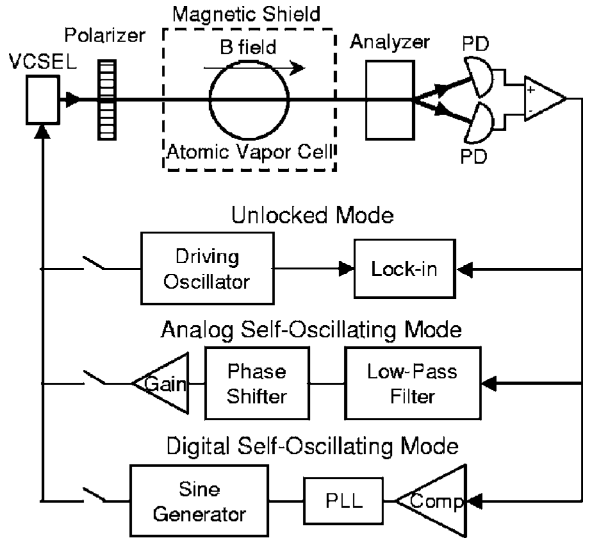

FIG. 1. Schematic of the magnetometer. The difference signal from the two photodetectors (PDs) is sent to the various electronics required for operation in the different modes. A mode of operation is selected by closing the appropriate switch.

After the atom exits the laser beam, the atomic alignment precesses at the Larmor frequency due to the magnetic field. Because the state of atomic polarization is symmetric, the atomic alignment returns to the same state after half the Larmor precession period. Thus, with light modulated at twice the Larmor frequency, the atomic alignment is resonantly driven as the atom moves in and out of the laser beam. We probe the atomic alignment with the light by detecting a rotation of the light polarization at the output of the cell. Optical rotation occurs when the atomic alignment is at an angle to the light polarization, and the light is maximally rotated when both the light is on resonance and the atomic alignment is at a 45° angle relative to the light polarization. As seen in Fig. 2, the FM NMOR signal shows optical rotation in opposite directions depending on the sign of the angle between the atomic alignment and the laser polarization.

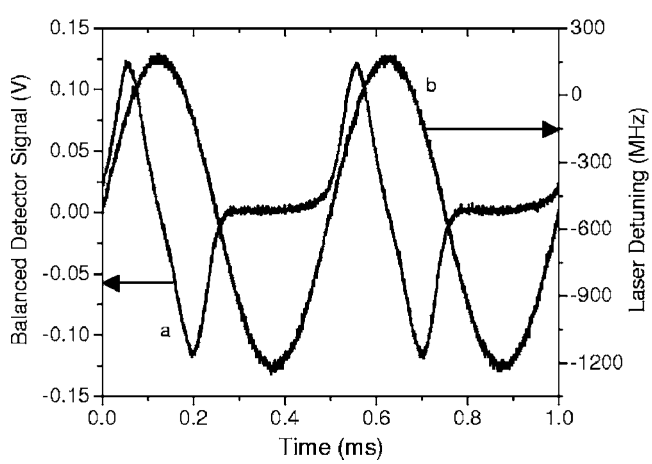

FIG. 2. The FM NMOR signal (a) derived from subtracting the two photodetector signals is plotted as a function to time (unlocked mode), giving a measure of the optical rotation. The driving oscillator, modulating the laser frequency, is operating at 2 kHz (going through two cycles in the data plotted), and the laser frequency relative to the peak of the Doppler-broadened $F=2 \rightarrow F'=1$ transition is plotted (b).

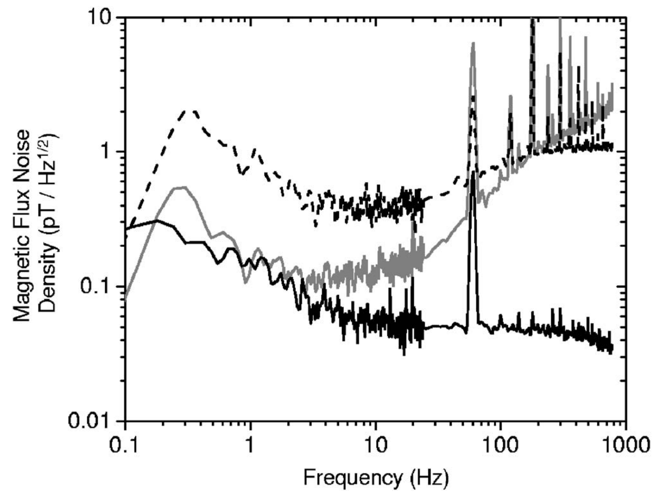

FIG. 3. The magnetometer noise spectra for the unlocked mode (black line), the analog self-oscillating mode (gray line), and the digital self-oscillating mode (dashed line) when operating in a 143 nT field.

We operate the experiment in three modes: the unlocked mode, the analog self-oscillating mode, and the digital self-oscillating mode (Fig. 1). In the unlocked mode an external driving oscillator modulates the VCSEL current, and the FM NMOR signal from the balanced receiver is sent to a lock-in amplifier with the original modulation as the reference. When the frequency of the oscillator is swept about the FM NMOR resonance frequency, a dispersive line shape is observed at the in-phase output of the lock-in amplifier. The measured sensitivity of the magnetometer in the unlocked mode is plotted in Fig. 3 and is $\sim 0.15\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$ at 1 Hz bandwidth. In the unlocked mode we manually tune the driving oscillator to the nominal FM NMOR resonance to measure the magnetic field. A magnetometer using lock-in detection that automatically acquires and locks to the FM NMOR resonance would require the additional complication of a microprocessor, especially in light of the fact that there is another, lower amplitude FM NMOR resonance when the VCSEL is driven at the Larmor frequency.

If the magnetometer is made to self-oscillate, its control system can be greatly simplified. To make the FM NMOR system self-oscillate, the output wave form from the balanced receiver needs to emulate the input wave form before it is fed back to the VCSEL. As shown in Fig. 2, the output wave form is not a simple replication of the input modulation, and in the analog self-oscillating mode we use a four-pole low-pass filter to attenuate all harmonics but the fundamental frequency. To tune the roll-off frequency of the low-pass filter and the phase shifter, we first run the magnetometer in the unlocked mode and send the output signal of the balanced receiver through the analog components. The roll-off frequency is set to 1.25 times the frequency of the driving oscillator, and the phase shift and gain are set such that the output of the analog components overlaps the output of the driving oscillator when viewed on an oscilloscope. Then the driving oscillator is removed and the analog output is connected to the VCSEL. The magnetic field is then determined by simply counting the frequency of the analog output. We observe self-oscillation in fields ranging from 35 to 35 000 nT, and the sensitivity of the magnetometer in the analog self-oscillating mode is shown in Fig. 3 and is

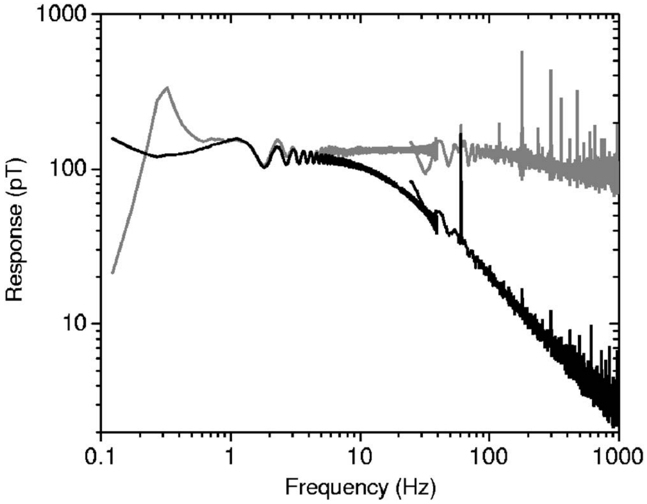

FIG. 4. The response of the magnetometer in the unlocked (black line) and analog self-oscillating (gray line) modes to a 125 pT modulation in the magnetic field is plotted as a function of the field modulation frequency. The peak and roll-off of the response of the analog self-oscillator at low frequency is an artifact of the measurement system.

$\sim$0.15 pT/$\sqrt{\text{Hz}}$ at 1 Hz bandwidth in a 143 nT field.

A comparison of the noise spectra of the magnetometer (Fig. 3) shows that at frequencies above 20 Hz the noise in the analog self-oscillating mode increases proportionally to the frequency, while the noise in the unlocked mode is approximately white. This frequency corner corresponds to the linewidth of the FM NMOR resonance 27 Hz. At higher frequencies, the response of the magnetometer in the unlocked mode decreases proportionally to the inverse of the frequency (Fig. 4), and thus the signal-to-noise ratio decreases at the same rate. In the analog self-oscillating mode the gain in the feedback loop keeps the frequency response flat (Fig. 4), but the noise increases with frequency so the signal-to-noise ratio at any given frequency remains the same for the two cases. However, the flat frequency response of the self-oscillator is an advantage that allows straightforward detection of high-frequency magnetic signals. Below 0.3 Hz the noise in the digital and analog self-oscillating modes is shown to decrease sharply, which is an artifact of the noise measurement system when the magnetometer is self-oscillating.

An obvious disadvantage of the present analog self-oscillating mode is that the low-pass filter needs to be tuned as the magnetic field changes. For example, if the magnetic field is slowly increased while the roll-off frequency and phase shifter are held constant, at first the magnetometer still self-oscillates, but because the low-pass filter has a frequency dependent phase shift, the total phase shift around the loop will increase as the oscillation frequency approaches the roll-off frequency. A change in the total phase causes a systematic error in the measurement of the magnetic field. A deviation in the phase shift around the loop causes a frequency shift proportional to $\tan(\delta\phi)\Delta\omega$, where $\delta\phi$ is the change in phase shift and $\Delta\omega$ is the width of the resonance. When the oscillation frequency surpasses the roll-off frequency, there is not enough gain in the loop and the system no longer oscillates.

To avoid the problems associated with our analog self-oscillating mode, we implemented a digital phase-locked loop (PLL) to lock a voltage-controlled oscillator (VCO) to the FM NMOR signal. In this digital self-oscillating mode, a comparator creates a digital signal from the FM NMOR signal where the rising edge of the digital signal is triggered from the steepest slope on the FM NMOR signal. The PLL uses an edge-triggered phase detector to compare the phase of the rising edge of the comparator signal to the rising edge of the VCO. With the VCO tracking the FM NMOR oscillation frequency we can digitally synthesize a sine wave at the oscillation frequency with the appropriate phase shift. We find that with the magnetometer in the digital self-oscillating mode the PLL can acquire and track the FM NMOR oscillation frequency over the full locking range of the PLL (1–6.9 kHz or 71–490 nT in this case[9]). The magnetic field is found by counting the frequency of the VCO, and the sensitivity is plotted in Fig. 3 and is $\sim$0.8 pT/$\sqrt{\text{Hz}}$ at 1 Hz bandwidth. The sensitivity of the digital self-oscillating mode is degraded somewhat because the PLL was not properly optimized. The PLL and sine generator are easily implemented with five low-cost, off-the-shelf integrated circuits. With more carefully designed electronics, the sensitivity should be equivalent to the other two methods, and the size and power consumption of the electronics could be greatly reduced for use in a CSAM.

Practical magnetometry is frequently done in the Earth's field, which ranges from approximately 20 to 70 μT, and we have performed a limited study of the operation of our magnetometer at these fields. We have observed self-oscillation up to 500 kHz (35 μT) in the analog mode, but the sensitivity is reduced. This is mainly due to the nonlinear Zeeman effect. In ^{87}Rb there are five Zeeman sublevels in the upper hyperfine ground state ($F=2$), and with the modulation frequency at twice the Larmor frequency, a resonance between every other Zeeman state is excited. Thus, we are exciting three resonances simultaneously at low fields. However, in the Earth's field the center frequency of each resonance is no longer equal,[7] and the separation between the outer resonances depends quadratically on the field strength with a coefficient of 0.058 Hz/μT^2. At 500 kHz, the resonance linewidth is broadened by a factor of 3. With the broadening, a decrease in the resonance amplitude is observed and the combination gives rise to the decrease in sensitivity.

With our goal being to develop a CSAM, the size of the cell will be reduced to a volume of $\sim$1 mm^3. At this cell size the resonance linewidth will be on the order of 1 kHz compared to the sub-10 Hz linewidth for a large wall coated cell. Therefore, the contribution of the nonlinear Zeeman terms to the resonance width will be a small fraction of the resonance width in the Earth's field range. Nevertheless, it will likely be advantageous to use ^{133}Cs rather than ^{87}Rb because the quadratic dependence of the frequency difference between the outer resonances for Cs has a coefficient of 0.032 Hz/μT^2, giving an improvement of almost a factor of 2.[4] Potassium-39, on the other hand, has a much larger quadratic coefficient at 0.85 Hz/μT^2 due to its small hyperfine splitting, and therefore, each resonance is separated by hundreds of hertz in the Earth's field, allowing the use of a single resonance. In fact, the most sensitive OPM to date, operating in the Earth's field, was made using ^{39}K.[10] However, the linewidth in small cells may yet be too large to resolve the separate lines, and self-oscillation is not easily achieved because of the separate resonance lines. Another possibility for eliminating the adverse effects of the nonlinear Zeeman effect is to excite only the highest polarization moment of the atom,[11] but again self-oscillation is difficult because of the relatively low amplitude of the resonance.

In summary, we demonstrate that an OPM based on nonlinear magneto-optical rotation can be made to self-oscillate by feeding back the FM NMOR signal to the laser injection current. With analog components providing the feedback, the magnetometer has similar sensitivity to the unlocked mode of the magnetometer, but in the present implementation the low-pass filter needs to be manually tuned to track the magnetic field. The use of a digital PLL, however, allows the magnetometer to operate independently over a broad frequency range limited only by the locking range of the present PLL. With the appropriate electronics, the magnetometer range in the digital self-oscillating mode could span many decades, and the sensitivity could be equivalent to that of the analog mode. When operating in the Earth's field we observe a degradation of the FM NMOR signal due to the nonlinear Zeeman effect that can be reduced by using Cs rather than ^{87}Rb. Additionally, the degradation will be less significant in a microfabricated cell, where the linewidth would be already quite broad. FM NMOR appears to be a favorable technique to implement in a CSAM because of the elimination of the rf coil found in traditional OPMs. The rf coil is difficult to implement in a chip-scale device and is a significant source of systematic error. The FM NMOR magnetometer is even more attractive for a CSAM when it is made to self-oscillate because the required electronics become simpler and more compact and consume less power. The self-oscillating magnetometer also has a flat frequency response making it well suited for high bandwidth applications.

The authors gratefully acknowledge valuable advice from D. Budker, H. G. Robinson, S. Knappe, V. Shah, and M. Prouty, and thank H. G. Robinson for fabrication of the Rb vapor cell. This work was supported by the Microsystems Technology Office of the U.S. Defense Advanced Research Projects Agency (DARPA).

[1] L.-A. Liew, S. Knappe, J. Moreland, H. Robinson, L. Hollberg, and J. Kitching, Appl. Phys. Lett. **84**, 2694 (2004).
[2] S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, J. Kitching, L.-A. Liew, and J. Moreland, Appl. Phys. Lett. **85**, 1460 (2004).
[3] P. D. D. Schwindt, S. Knappe, V. Shah, L. Hollberg, J. Kitching, L.-A. Liew, and J. Moreland, Appl. Phys. Lett. **85**, 6409 (2004).
[4] A. L. Bloom, Appl. Opt. **1**, 61 (1962).
[5] H. Gilles, J. Hamel, and B. Cheron, Rev. Sci. Instrum. **72**, 2253 (2001).
[6] D. Budker, D. F. Kimball, V. V. Yashchuk, M. Zolotorev, Phys. Rev. A **65**, 055403 (2002).
[7] T. Yabuzaki and T. Ogawa, J. Appl. Phys. **45**, 1342 (1974).
[8] C. D. Hardwick, Geophysics **49**, 2024 (1984).
[9] This frequency range was chosen to cover 2 kHz, where most of our measurements were taken. With the appropriate choice of electronic components, the PLL could cover the Earth's field range or any other field range of choice.
[10] E. B. Alexandrov, M. V. Balabas, A. S. Pasgalev, A. K. Vershovskii, and N. N. Yakobson, Laser Phys. **6**, 244 (1996).
[11] V. V. Yashchuk, D. Budker, W. Gawlik, D. F. Kimball, Yu. P. Malakyan, and S. M. Rochester, Phys. Rev. Lett. **90**, 253001 (2003).