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Lasers and Optics

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Compact laser system for atom interferometry

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ABSTRACT We describe an optical bench in which we lock the relative frequencies or phases of a set of three lasers in order to use them in a cold atom interferometry experiment. As a new feature, the same two lasers serve alternately to cool atoms and to realize the atomic interferometer. This requires a fast change of the optical frequencies over a few GHz. The number of required independent laser sources is then only three, which enables the construction of the whole laser system on a single transportable optical bench. Recent results obtained with this optical setup are also presented.

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1 Introduction

Within the last decades, atom interferometers have developed into a highly competitive tool for precision measurements [1]. Atomic fountains used as atomic clocks are the best realization of the time unit [2]. Atom interferometry also promises sensors that will be highly sensitive to inertial forces [3–6]. The use of stimulated Raman transitions to manipulate the atomic wave packet has proven to be an efficient way to obtain high accuracy devices [5, 6].

These techniques are now used to realize reliable instruments, with potential applications in inertial navigation, gravity field mapping, metrology, and fundamental tests in space.

In this letter, we describe a robust, compact and versatile laser system for atom interferometers using alkali atoms. Such experiments basically need two different optical frequencies, whose difference remains close to the hyperfine transition frequency. When they are tuned close to the D2 transitions, they are used to cool and repump the atoms in a magneto–optical trap (MOT). When far detuned, and phase locked, they are used to induce stimulated Raman transitions for the interferometer [7]. Since the lasers are not used simultaneously for trapping and Raman transitions, we have implemented a technique to use the same two lasers for both functions. It allowed us to build the whole laser setup on a $60 \times 90\ \mathrm{cm}^2$ optical bench. This setup has been developed for a transportable atomic gravimeter [8], whose present sensitivity is comparable to state of the art instruments.

2 Laser setup

Our laser setup is shown in Fig. 1. A first laser L1 is locked on an atomic transition, using FM-spectroscopy [9] on a saturated absorption signal. This laser constitutes an optical frequency reference and is used in our experiment to detect or push the atoms. A second laser L2 is alternately used as a repumper or as the master Raman laser. Part of the outputs of L1 and L2 are superimposed on a fast photodetector (PD_{12}) (Hamamatsu G4176) and the frequency of the beat note is servo locked by using a frequency to voltage converter. A third laser L3 is used alternately as a cooling or as a slave Raman laser. The frequency difference between L2 and L3 is measured with a second optical beat note on PD_{23}. Finally, both L2 and L3 beams are superimposed and directed through an acousto-optical modulator either to realize the magneto-optical trap or the atomic interferometer.

Both frequency locks of L2 and L3 use the same scheme which is shown in Fig. 2. The optical beat note issued from the photodetector is mixed with a reference oscillator, down to an intermediate frequency (IF). For the L2 lock, this reference is a YIG oscillator, which can be tuned between 3 and 7 GHz.

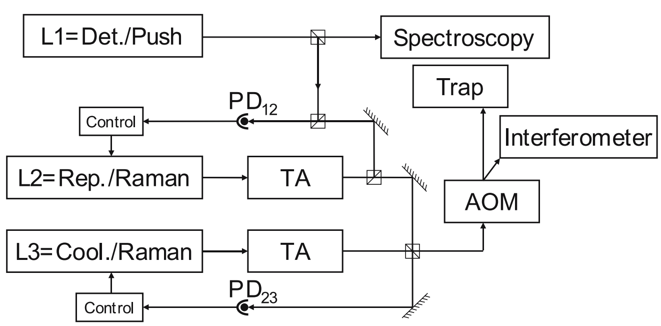

FIGURE 1 Laser setup. The detection laser L1 is locked on a spectroscopy signal. The repumper laser L2 frequency is compared to the detection laser frequency with an optical beat note and is frequency locked. A similar lock is used for the cooling laser L3. Two tapered amplifiers (TA) are used on the repumper and cooling lasers, before they are combined on a polarizing beam splitter cube and sent alternately to the trap or to the interferometer using an acousto-optical modulator (AOM)

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Whereas for L3 we use a fixed 7 GHz frequency obtained by the multiplication of a low phase noise 100 MHz quartz oscillator. The IF signal is then sent into a digital frequency divider in order to fit into the working frequency range (0–1 MHz) of a frequency to voltage converter (FVC) (AD650). A computer controlled offset voltage V_{Set} is subtracted from the output voltage of the FVC. The obtained error signal is integrated once and added to the laser diode current. This correction signal is integrated again and added to the piezoelectric (PZT) voltage which controls the cavity length. To change the laser frequency, one can change V_{Set} for fine tuning or the YIG frequency for larger frequency changes. In addition, computer controlled feed-forward current I_C and voltage V_C are added to the current and PZT drivers to help the lock while changing the laser frequency.

For the phase lock of L3 a second path is implemented. The IF frequency is divided by 2 and compared, in a digital phase and frequency detector (DPFD) [10] (MCH12140), to the signal of a local oscillator at 82.6 MHz which is generated by a direct digital synthesiser (DDS) (AD9852) clocked at 300 MHz. The DPFD delivers an error signal which is added through a high bandwidth servo system (~ 4 MHz) to the laser current. It is also added to the PZT error signal before its last integration. Moreover some switches can be activated so that either the frequency lock loop or the phase lock loop is closed.

3 Atom interferometer

Our interferometer is an atomic gravimeter which measures the acceleration of freely falling ^{87}Rb atoms. Its sensitivity is given by: $\Delta\Phi = k_{eff} g T^2$, where $\Delta\Phi$ is the interferometric phase, k_{eff} is the effective wave vector of the Raman transition, g is the Earth's gravity acceleration and T is the time between the interferometer's Raman pulses.

This frequency locking system is versatile and enables dynamic controlling of the frequency of the two lasers, over the whole experimental sequence. It is possible to first frequency lock the lasers to the frequencies required to cool ^{87}Rb atoms in a MOT. By dividing the total available laser power between a 2D-MOT [11] and a 3D-MOT, the loading rates of 3×10^9 atoms s^{-1} are obtained. Then we turn the magnetic field off and further cool the atoms with σ^+–σ^- molasses down to a temperature of 2.5 μK.

Once the atoms have been released from the molasses, a frequency ramp is applied on the YIG oscillator. This ramp induces a detuning Δ of up to 2 GHz on both L2 and L3 to get the Raman laser frequencies. We also add a ramp on the PZT voltages V_C to induce a 2 GHz sweep so that the laser frequencies stay inside the locking range. Since the PZT mode-hop free tuning range is close to ± 0.6 GHz, it is necessary to change the current setting point of the laser during the sweep. Thus, we also apply a simultaneous feed-forward ramp to the laser injection currents I_C, so that the laser frequencies remain in the middle of the free tuning range. When the servo loop is closed, the lasers stay locked during the whole sequence.

In Fig. 3 the response of the servo system to a frequency ramp of 2 GHz in 2 ms, in open and closed loop configurations is shown. The black curve corresponds to the error signal of L2 in open loop operation. It reflects the difference between the lasers frequency difference and the YIG frequency. The L2 laser frequency remains within 100 MHz from the locking point during the whole 2 GHz ramp. The voltage ramp does not compensate exactly for the sweep because of thermal effects due to the change in the laser current. When the servo loop is closed, the remaining frequency deviation is compensated for. The gray curve shows the residual frequency error of L2 during the sweep, and reveals residual damped oscillations of the PZT.

We then switch L3 to the phase-locked loop (PLL) after the end of the frequency ramp. We aim at obtaining an accuracy of 10^{-9} g which implies that the differential phase between the two Raman lasers remains on average below 0.3 mrad over the duration of the interferometer 2 T [8]. We display in Fig. 4 this phase difference as a function of the de-

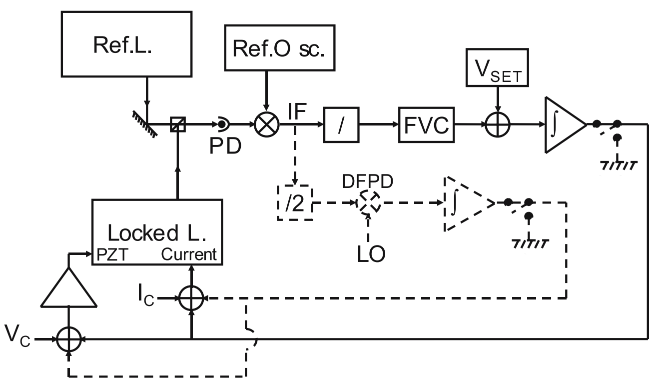

FIGURE 2 Locking electronics. Frequency lock scheme (*solid line*). The optical beat note is mixed with a reference oscillator to an intermediate frequency (IF). The IF is divided and converted to a voltage signal and another voltage V_{Set} is subtracted to obtain the error signal of the lock. This error signal is integrated and then sent to the current driver. It is integrated once more and sent to the PZT driver. Feed-forward corrections I_C and V_C are added to the diode current and to the PZT voltage during the sweep. A phase lock scheme is added to L3 (*dotted line*). The IF is compared to a local oscillator (LO) in a digital phase and a frequency detector (DPFD) delivering the phase error signal. Two switches select which loop is closed

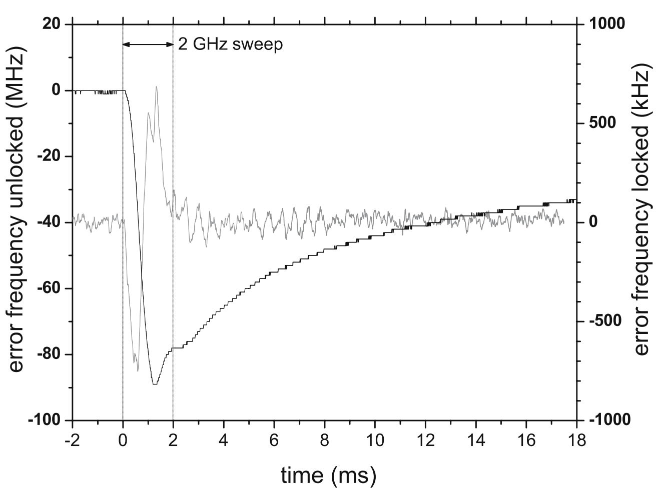

FIGURE 3 L2 frequency error during a 2 GHz sweep imposed in 2 ms. The *black trace* displays the frequency error when the servo loop is opened, and shows a sharp transient edge during the sweep, followed by an exponential like decay. The *gray trace* displays the frequency error when the servo loop is closed

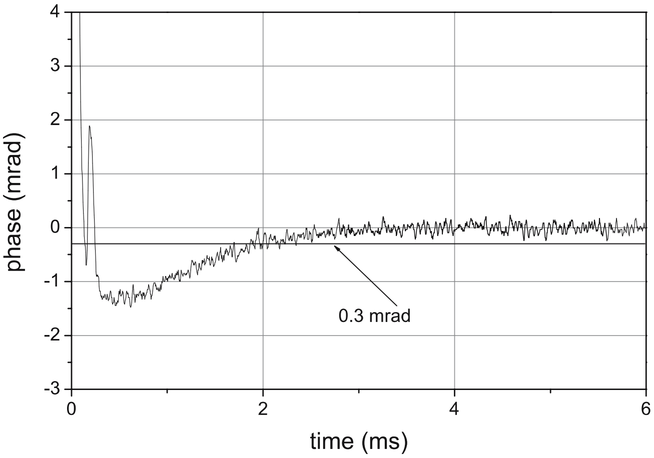

FIGURE 4 Differential phase between the Raman lasers. The PLL is closed at $t = 0$ after the 2 GHz sweep. After 0.5 ms, the phase difference is exponentially decreasing with a time constant of 2 ms

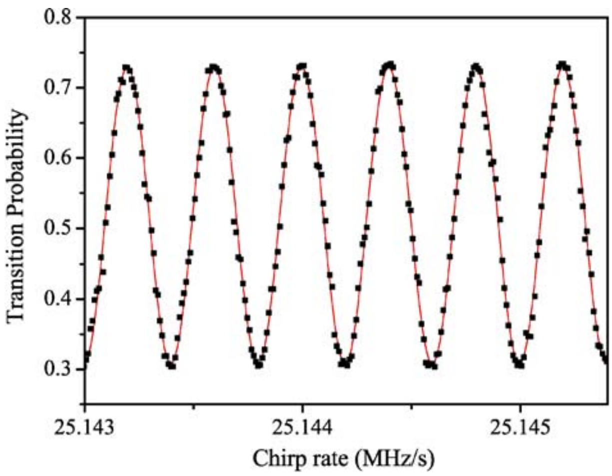

FIGURE 5 Atomic interferometer fringes obtained by scanning the Raman detuning chirp rate during the interferometer. The time between the Raman pulses is $T = 50$ ms. The *solid line* is a sinusoidal fit of the experimental points displayed in *black squares*

lay after enabling the PLL. At the start, the DPFD delivers an error signal proportional to the frequency difference between the divided IF and the LO. This makes the loop behave as a frequency lock loop, with a time constant of a few hundreds of μs. Once the frequency of the divided IF matches with the LO frequency, the DPFD detects the phase difference between them, which makes the loop behave as a phase lock loop. 0.5 ms after the loop is closed, the phase reaches a steady state with a 2 ms time constant exponential decay. The 0.3 mrad criterion is then reached in about 2 ms. We have measured its spectral phase noise density in the steady state [8]. When weighted by the transfer function of the atom interferometer, which acts as a low pass filter, and integrated over an infinite bandwidth, we calculated a total contribution of 0.56 mrad rms of phase noise in the atomic interferometer. This gives a limit to the sensitivity at a level of 6×10^{-10} g $\text{Hz}^{-1/2}$.

We want to emphasize that the Raman detuning Δ can be changed at will and other sweeps can be added in the cycle. This enables realizing of a velocity selective Raman pulse (~ 35 μs), with a detuning of 2 GHz.

This pulse coherently transfers 20% of the atoms from one hyperfine state to the other. The vertical temperature of the selected atoms is then about 1 μK. Spontaneous emission during the selection pulse adds up an incoherent background of atoms, distributed in the original broader velocity distribution. This contribution, small with respect to the initial number of atoms (a fraction of a %), can become significant with respect to the number of selected atoms, especially when the selection is very severe. Increasing the detuning allows reduction of the amount of spontaneous emission. With a 2 GHz detuning, the atoms transferred by spontaneous emission represent about 2% of the selected atoms. After the selection pulse, the detuning is swept back to 1 GHz for the interferometer itself. This allows achievement of a larger Rabi frequency, and thus a better transfer efficiency.

Finally, the phased-locked Raman lasers are used to realize the interferometer. Due to the Doppler effect, the Raman detuning has to be chirped to compensate for the increasing vertical velocity of the atomic cloud. This chirp α, obtained by sweeping the DDS frequency, induces an additional phase shift. The total interferometric phase is then given by: $\Delta\Phi = (k_{\text{eff}} g - \alpha)T^2$. Figure 5 displays the interferometric fringes obtained by scanning the chirp rate. The duration between the Raman pulses is $T = 50$ ms, and the repetition rate is 4 Hz. Compensation of g corresponds to a chirp rate of 25.144 MHz/s, for which the transition probability is minimum. The central fringe thus appears in the interference pattern as a "black fringe". The contrast of the fringes is 42%, and the signal to noise ratio about 35. This corresponds to a sensitivity of 7×10^{-8} g $\text{Hz}^{-1/2}$, limited by residual vibrations of the apparatus. This sensitivity can be improved by a factor of 2 by measuring the acceleration noise with a low noise seismometer (Güralp T40), and then subtracting the phase shift induced by the vibrations to the output phase of the interferometer.

As the value of g is varying due to the earths tides, its measurement can be performed by tracking the position of the central fringe. We apply here a method very similar to the technique used in atomic clocks to lock the interrogation frequency to the atomic transition. A modulation is applied to the chirp rate in order to induce an additional

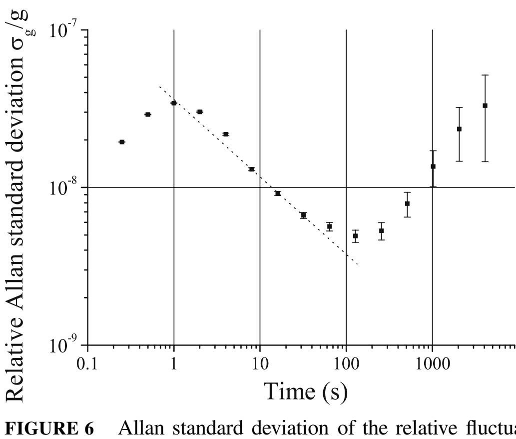

FIGURE 6 Allan standard deviation of the relative fluctuations of g. The time between the Raman pulses is $T = 50$ ms. The *dash line* corresponds to a sensitivity of 3.5×10^{-8} g $\text{Hz}^{-1/2}$

phase shift of ±90°, to probe the interference pattern alternatively on the left and on the right side of the central fringe. From the measurements of the transition probability on both sides, we compute an error signal to lock the (unmodulated) chirp rate to the central fringe using a digital servo loop.

Figure 6 displays the Allan standard deviation of the relative fluctuations of g, σ_g/g. After a few seconds, which correspond to the time constant of the lock loop, σ_g/g decreases as $1/\tau^{1/2}$, where τ is the measurement time. This corresponds to a sensitivity of 3.5×10^{-8} g $\mathrm{Hz}^{-1/2}$, as indicated in the figure by the dashed line. For measurement times larger than 100 s, σ_g/g increases due to the variation of g induced by the earths tides.

4 Conclusion

To conclude, this locking technique allowed us to build with only three lasers, an optical bench providing the required frequencies to cool ^{87}Rb atoms in a 3D-MOT and to realize an atomic interferometer with far detuned Raman lasers.

The system is compact and low power, which can be necessary for transportable or space-based instruments. Moreover, our laser setup is robust and versatile since the lasers routinely stay locked for days and we can change the detuning of the Raman transitions at will.

Our goal for the gravimeter experiment is to reach an accuracy of 10^{-9} g and a sensitivity of a few 10^{-9} g $\mathrm{Hz}^{-1/2}$. Thanks to its compactness, the gravimeter will be transportable to compare it with other absolute gravimeters. It will also be moved close to the LNE watt balance experiment, which aims at measuring Planck's constant and redefining the kilogram [12].

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