Towards Precision Measurements at UASLP

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Abstract. Atomic interferometry is a very sensitive technique to measure small forces. Here we present an overview of the progress towards interferometric measurements in our laboratory. We characterize the magnetic field noise and describe the strategies to minimize the sensitivity to magnetic field fluctuations. We introduce as well a system for Raman excitation with minimum phase noise and the frequency filtering needed to implement it. Finally, we demonstrate atomic interferometry with a frequency sensitivity of 3 Hz.

1. Introduction
Laser cooling is a widely used technique nowadays. The control achieved over the atomic sample improves the precision of different measurements in physics. The best example is that of atomic clocks where 18 digits of precision have been achieved in the determination of time [1]. The use of interferometric techniques is largely responsible for the continuous improvement of measurements. Cold atoms are well suited for such techniques since they allow for coherence times of several seconds [2,3]. In our group we are particularly interested in the measurement of small forces. Here cold atoms have been used to study the gravitational force [4], variations of gravity at short distances [5], interactions of atoms with surfaces [6,7] and the weak force [8,9].

The separated oscillatory fields method of Ramsey is at the heart of an atomic interferometer [10]. In this method a $\pi/2$ pulse creates a coherent superposition between two hyperfine levels. The system is then left to evolve for a time $T$, and a second $\pi/2$ pulse is applied to read the relative phase between the two levels. An ideal atomic interferometer must have high sensitivity and it should not be affected by environmental perturbations. Magnetic field variations are often a concern, but it is possible to choose energy levels that remain unperturbed by those fluctuations.

Here we present our progress on atomic interferometry. We explore different ways to suppress the sensitivity to magnetic field fluctuations. Also, the use of a phase modulator allows for the excitation of Raman transitions with a minimum of phase noise. The flexibility of the system opens the door to complex excitation schemes.
2. Atomic interferometry

In this section we present the basic concepts of an atomic interferometer applied to gravimetry. Two ground hyperfine levels \(|g_1⟩, |g_2⟩\) are connected via a Raman transition that uses vertical counter propagating lasers of frequency \(\omega_1\) and \(\omega_2\). The lasers have a detuning \(\Delta\) with respect to an excited state to selectively induce a two photon transition. The counter propagating Raman transition is sensitive to the velocity of the atoms along the laser beam propagation. The velocity \(v_z\) dependence of the detuning given by

\[ \delta = \omega_2 - \omega_1 - \omega_0 - 2k(v_z + \hbar k/m), \]  

(1)

with \(\omega_0\) the hyperfine splitting, \(k\) the laser wave vector magnitude and \(m\) the mass of the atom. The velocity dependence originates from the Doppler effect of the atoms as they change their velocity during free fall.

To implement a gravimeter we start with the atoms in the state \(|g_1p⟩\), where the \(p\) represents a particular value of momentum along \(z\). A \(\pi/2\) Raman pulse creates an equal superposition of the two ground states. The Raman pulse changes the internal state as well as the atomic momentum by \(2\hbar k\). After some free evolution time the state is given by

\[ |\Psi(t)⟩ = \left(|g_1p⟩ - ie^{i\Phi(t)}|g_2p + 2\hbar k⟩\right)/\sqrt{2}. \]  

(2)

The relative phase depends on the energy difference \((E_2 - E_1)\) of the two levels that includes the hyperfine splitting and the gravitational potential

\[ \Phi(t) = \int \frac{E_2 - E_1}{\hbar} dt = \omega_0 t + \left(\frac{mg}{\hbar}\right) \int (z_2 - z_1) dt. \]  

(3)

A \(\pi\) pulse is applied after a free evolution time \(\tau\) to reverse the momentum difference of the two hyperfine levels. To close the interferometer, a \(\pi/2\) pulse is applied after an additional free evolution time \(\tau\). The position difference in Eq. 3 comes from the momentum kick during the splitting process. The contribution of the last term is \(2gk\tau^2\right)\) right before the second \(\pi/2\) pulse and is what gives the sensitivity to the gravitational acceleration \(g\).

3. Magnetic sensitivity of atomic levels and transitions

The sensitivity to magnetic field has some advantages. Atomic magnetometers are used in medical applications [11], quantum measurements [12] or searches for physics beyond the Standard Model [13]. Measurements in magnetic field gradients can be used to obtain spatial information, as it is the case for example in Nuclear Magnetic Resonance [14]. Here the atoms are resonant only at a particular position which can be selectively excited. The same idea can be extended for the case of cold gases where two sequential position measurements separated by a time delay provides a way to measure the velocity [15, 16].

For gravimetry applications, however, magnetic field fluctuations become a source of noise. The energy of an atomic level shifts in a magnetic field due to the Zeeman effect [15], which gives an additional contribution to the relative phase evolution of Eq. 3. The states with \(m_F=0\) have no linear Zeeman shift and are thus preferred for interferometric measurements. The hyperfine transition between \(m_F = 0\) levels (the clock transition) allows for long coherence times [3]. Also, in the case of \(^{87}\text{Rb}\), the hyperfine transition between \(|F = 1, m_F = -1⟩\) and \(|F = 2, m_F = 1⟩\) is quite insensitive to magnetic field fluctuations at 3.2 Gauss [17], and shows long coherence times as well [18]. Each of the levels in this last transition are sensitive to the magnetic field whereas the transition remains insensitive to magnetic fluctuations. Combining these two transitions we will look for reduced magnetic sensitivity at a tunable field.
Figure 1 shows the measured magnetic field noise at our laboratory. We measure the noise with a magneto resistance sensor (Honeywell HMC1002) and we digitize the signal using a DAQ card (NI USB-6289). The magnetic variations are dominated by line noise and its harmonics. Reducing magnetic noise using feedback is not the best strategy since it adds broadband noise. Instead we apply narrow band corrections only at the line frequency and harmonics using coils in Helmholtz configuration. Adjusting the phase and amplitude of the correcting signal we manage to selectively reduce each peak in the noise spectrum (60 Hz, 180 Hz, etc.) by more than an order of magnitude. The power supplies nearby are responsible for most of the noise we observe. We verified that the noise decays as $1/r^2$ as you move away from the supply as expected from radiative fields. We moved all the supplies more than 6 m away from the experiment where they give contributions below 10 $\mu$Gauss.

4. Phase modulator for Raman transitions

A Raman transition requires two phase locked lasers with a frequency difference close to the hyperfine splitting (Eq. 1). Having low phase noise is an important requirement for interferometry. A phase lock is usually achieved by sending both laser beams to a detector. The beat note is then compared with a reference signal in an Optical Phase Lock Loop (OPLL) to obtain the feedback that is sent to one of the lasers [19]. Achieving low phase noise with this technique is quite challenging. Alternatively one can obtain both beams from a single laser. Modulating the light either in amplitude or phase produces sidebands that can be used for the extra beam. Since both beams come from the same laser they are automatically phase locked, and the phase noise depends on the quality of the RF source feeding the modulator. This technique is easier to implement and has lower phase noise than the traditional method.

The use of extra beams from modulation has been exploited in laser cooling and trapping. By modulating at the hyperfine splitting frequency one can derive a repumper beam out of the trap laser [20]. Acousto-optical modulators only work for small hyperfine splittings and the beams obtained are spatially separated. Electro-optical modulators work for higher frequencies and the beams propagate in the same direction. This technique was only used for repumping beams since that require less power. We extended the idea for the trapping beams using a fiber modulator and a double pass tapered amplifier [21]. With that system we demonstrated the simultaneous trapping of two different isotopes of rubidium ($^{85}$Rb and $^{87}$Rb) using a single laser and a fiber modulator. The system provided a big simplification for laser cooling since all the
control for the beams was moved from the optical to the RF world, which is easier to work with, cheaper and more reliable.

Light modulators have also been used for exciting Raman transitions [4, 22–24]. The carrier and one sideband work as the Raman pair when the modulation frequency equals that of the transition. The power out of the modulator is small and an amplification stage is needed to boost the power. The amplifier introduces extra phase noise, and when using a tapered amplifier, there is a pedestal of spontaneous emission that limits the coherence of the sample.

Figure 2 shows the ideal system for Raman excitation. The acousto-optical modulator produces the pulses and the electro-optical modulator creates the phase locked beams. The scheme requires a modulator capable of handling high power as it is the case for the Advr WPM-P78P78-AIO that takes up to 250 mW of optical power. The power on a sideband can be as high as 50 mW requiring no amplification stage after it. The two beams follow exactly the same path, therefore vibration insensitivity is also obtained except for the last mirror. The system offers the possibility of complex excitation patterns by replacing the RF source with an arbitrary wave generator.

Figure 2. System for Raman excitation using a phase modulator. AOM: acousto-optical modulator, EOM: electro-optical modulator. The retro reflecting mirror is at the end on the right.

5. Frequency filtering

An amplifier is required after the modulator in the Raman system of Fig. 2 whenever the output power is not high enough. Tapered amplifiers produce a broad pedestal of spontaneous emission besides the amplified beam. The pedestal is many orders of magnitude smaller, but still produces significant scattering due to nearly resonant contributions. In our previous work with dipole traps [25], we removed the resonant contribution using heated Rb cells. Still the lifetime of the dipole trap was limited by the scattering from the pedestal.

Figure 3. Fraction of transmitted light as a function of wavelength for the double pass interference filter with (solid red line) and without (dashed blue line) tapered amplifier. Inset: double pass schematic.

We have implemented two frequency filters to spectrally clean the beam out of the tapered amplifier, one based on an interference filter and the other on a diffraction grating. For the first one, we use a sharp low pass interference filter (Semrock LP02-785RU, transition width 7.9
nm) that blocks wavelengths below 785 nm. The cut off wavelength can be tuned by changing the incidence angle. For a dipole trap in rubidium we use a beam at 785 nm. The interference filter blocks the D2 line components at 780 nm but not those on the D1 line at 795 nm. To block high frequencies we direct the beam again towards the interference filter, but we use it in reflection this second time. The double pass operation introduces a sharp tunable band pass filter (Fig. 3). We get 75% central transmission and 25 dB attenuation when we are 2.5 nm away from the band center.

![Figure 4](image-url) Fraction of transmitted light as a function of wavelength for the grating filter. Red solid curve is a Gaussian fit.

The interference filter is very easy to use and works well for beams detuned by several nm as it is the case for a dipole trap, but it might not be sharp enough for the Raman beams that require smaller detunings. There we use instead a frequency filter based on a diffraction grating, similar to a monochromator. The grating we use (Edmund Optics 43-848) gives good diffraction efficiency (90%) at 780 nm. We spatially filter the light with a pinhole, expand and collimate the beam before the grating. The diffracted beam goes through a lens (f=20 cm) that focus the beam to the frequency filtering pinhole (25 µm). Figure 4 shows the characterization of the filter. We get 77 % central transmission and 30 dB attenuation when we are 0.3 nm away from the band center.

6. New vacuum system

We have improved our vacuum system for the measurements with microwaves and Raman beams (Fig. 5). The Pyrex vacuum cell reduces problems with Eddy currents and has better optical access. The vacuum system is quite compact and it is pumped with a NexTorr D100-5 pump that combines a 100 l/s getter pump and a 5 l/s ion pump. The pump produces no vibration and introduces magnetic field gradients smaller than 20 mG/cm at the position of the atoms. We reach pressures close to $10^{-10}$ Torr that translate into lifetimes of around 10 s (limited by the Rb dispenser).

![Figure 5](image-url) New vacuum and imaging system.
We monitor the atoms using fluorescence with a double relay imaging system (1:1 amplification). The system uses best form lenses to reduce aberrations and we place an iris after the first relay to minimize background light. It has a numerical aperture of 0.3, a theoretical resolution of 1.5 μm and collects 2.3 % of the light emitted by the atoms. A 50-50 splitter in the imaging system sends light to a CCD camera and a photo diode connected to a DAQ card.

7. Atomic interferometric fringes

With the new vacuum system we have been able to demonstrate molasses to 3 μK. We apply optical pumping to put more than 88% of the atoms in the $|F = 1, m_F = 0\rangle$ state of $^{87}\text{Rb}$. We excite Rabi oscillations between hyperfine or Zeeman levels. Figure 6 shows the interferometry fringes we get using the clock transition. The fringes have a width of 50 Hz determined by the 10 ms separation between pulses. With this interferometer we achieve a frequency precision of 3 Hz. We have also observed interferometric fringes in the other magnetic insensitive two photon transition ($|F = 1, m_F = -1\rangle$ to $|F = 2, m_F = 1\rangle$). This requires simultaneous excitation with microwaves using a horn and RF from a homemade resonant antenna.

![Figure 6](image)

**Figure 6.** Interferometry fringes using microwaves in the clock transition. Each $\pi/2$ pulse is 20μs long and they are separated by 10 ms.

8. Conclusion

We demonstrated atomic interferometric in our laboratory with a frequency precision of 3 Hz. The interferometry required the construction of a new vacuum system and the implementation of different components for coherent manipulation of the atoms. We introduced a system for Raman excitation with a minimum of phase noise based on a fiber modulator. Its implementation requires frequency filtering that we achieved using a double pass interference filter with a pass band 2.5 nm wide, or alternatively with a blazed diffraction grating with a width of 0.3 nm.

Acknowledgments

This work was supported by CONACyT, UASLP, FAI and Fundación Marcos Moshinsky. We thank Jonathan Espinosa and José Rocha for their assistance with electronics.

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