Atom Interferometry with the Sr optical clock transition for gravity measurements

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Inertial sensors based on atom interferometers have demonstrated extremely high levels of sensitivity thus allowing for accurate measurements of gravitational interactions. Most such sensors employ multi-photon transitions induced by laser fields to manipulate the atomic wavepackets that enter an interferometer. However, this approach cannot totally suppress the contribution of the laser phase noise to the gravitational signal when two sensors are separated by a large distance. In this article, a proof-of-principle experiment for an interferometer operating on the single-photon clock transition of strontium atoms is described. This configuration can suppress the effect of laser phase noise and therefore provides a promising condidate for the detection of low-frequency gravitational waves.

Keywords: Atom interferometry; gravity measurements; gravitational waves; optical clock transition.

1. Introduction

Recent advances in the manipulation of atomic ensembles have made it possible to exploit the wave nature of matter to build interferometers that are highly sensitive to many fundamental interactions [1]. In particular, due to massive nature of atoms, these devices are sensitive to gravitational interactions and can be configured to measure, for example, gravitational acceleration [2,3], gravity gradients [4,5], gravity curvature [6], and can provide tests of general relativity at the quantum level [7–9]. As compared to macroscopic masses, atomic probes offer a number of key advantages. For example, it is possible to accurately manipulate their motion by using the interaction with laser light. This allows for the construction of analogues to beam splitters and mirrors for matter, thereby allowing for the implementation of atom interferometers. Moreover, atoms are made to travel in vacuum and are therefore immune to undesired forces such as friction or vibrations. Other parasitic effects such as electromagnetic interactions can also be largely suppressed by a careful choice of the atomic species and of the atomic levels employed. Finally, atoms are quantum objects and therefore allow for the testing of gravity in the broad context of quantum mechanics where gravitational effects are usually negligible.

Atom interferometers are also good candidates for the detection of gravitational waves. Indeed, while optical interferometers such as LIGO and Virgo are sensitive to gravitational waves with frequencies larger than about 10 Hz due to seismic noise affecting the motion of the interferometer mirrors, atomic sensors are expected

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to be sensitive in the 1 mHz-10 Hz band, where new interesting sources, such as the coalescence of intermediate and massive black holes and of neutron stars, are expected to appear[10].

Generally, the beam splitters and mirrors of atom interferometers are implemented through multi-photon transitions induced by a couple of counterpropagating laser fields. In a gradiometric configuration, where the gravity difference between two locations is measured by two simultaneous interferometers, the phase noise of the two lasers is largely common mode and is therefore very highly suppressed by the differential configuration. However, when the separation between the two sensors is large, the atomic clouds will sense two counterpropagating fields emitted at different times. During this interval, noise is accumulated in the gradiometer which cannot be canceled and which puts stringent requirements on the laser frequency stability and on the laser platform vibrations. Indeed, it can be shown[11] that the amplitude spectral density of the laser fractional frequency fluctuations $\sqrt{S_f}$ should be at most of the order of the gravitational-wave-induced strain h, or $\sqrt{S_f} \leq h/2$. Based on the predicted gravitational wave amplitudes, the relative frequency fluctuations should not exceed 10^{-21}. Comparing this requirement with the state of the art of lasers locked to ultrastable cavities[12], where $\sqrt{S_f} = 10^{-16}/\sqrt{\mathrm{Hz}}$ at the Fourier frequency of 1 Hz, one can conclude that an improvement of five orders of magnitude in laser frequency stability would be required.

The effects of laser phase noise can be largely suppressed from the output of the interferometer if the transitions are driven by a single laser. Intuitively, this immunity arises because the photon phase does not acquire additional noise in the path between the two sensors. In this situation, a single-photon transition connecting two optically separated stable states must be used. In principle, if an interferometer was operated on such a transition, the low frequency limit of the strain sensitivity would only be set by the coherence time of the transition[13,14]. Such an interferometer would therefore measure the gravitational-wave-induced shift of the time required to travel the distance between the two interferometers and record this interval as a phase shift, via the internal atomic oscillation. Even though there are in principle many atomic species that can fulfill the requirement of having two long-lived states connected by an optical transition, only a few cases have the required immunity to external perturbations. It follows that the atoms usually employed to realize optical atomic clocks, such as Sr or Yb, should also be suitable for this application. However, despite the phase noise immunity of gradiometers operated on a clock transition, several challenges emerge in terms of the required laser system. For example, in order to fully address the atoms in the interferometer, the interrogation laser must have a high frequency stability. Additionally, because the atoms are in free flight, the Doppler effect from different atomic velocities will cause a broadening of the transition so that a high efficiency of the interferometer pulses can only be attained with large optical power.

In this article, a proof-of-principle experiment of a gravimeter and a gravity gradiometer operating on the single-photon $^1S_0$-$^3P_0$ transition of ^{88}Sr is described[15]. In Section 2, the main experimental configuration, including the laser cooled and trapped ensemble of strontium atoms in a vacuum chamber and the interferometry laser, as well as the interferometer sequence, will be described. In Section 3, the main experimental results regarding the gravimeter and the gradiometer will be provided. The amount of observable interferometry laser frequency noise cancellation in the gradiometer will be established. Finally, in Section 4 conclusions and future perspectives for this new kind of sensor will be provided.

2. Experimental setup and sequence

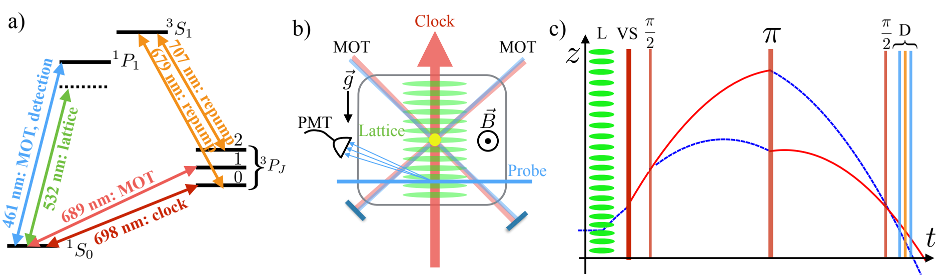

Fig. 1. a) Strontium level diagram showing the main optical transitions for cooling, trapping, interferometry, repumping and detection. b) Simplified drawing of the chamber, PMT: photomultiplier tube, MOT: magneto-optical trap, $\vec{B}$: applied magnetic field. c) Interferometer trajectories with the launch (L), velocity selection (VS), Mach-Zehnder interferometer ($\pi/2 - \pi - \pi/2$) and detection (D) consisting of probing on the blue transition and repumping (orange). The blue dashed (red) lines indicate atoms in the ground $^1S_0$ state (excited $^3P_0$ state).

In our experiment, the starting point is the ensemble of ^{88}Sr atoms. The atoms are laser cooled and trapped in a two-stage magneto-optical trap (MOT) first performed on the dipole-allowed $^1S_0$-$^1P_1$ transition and then on the $^1S_0$-$^3P_1$ intercombination transition (see Fig. 1(a)). This sequence produces almost 10^7 atoms at a temperature of 1.2 μK with typical size of 100 μm at full width at half maximum.

While in the fermionic isotope of strontium, ^{87}Sr, the clock transition is naturally allowed, in the ^{88}Sr boson it is strictly forbidden but can be induced with a static magnetic field. As a result, the laser cooled atoms are loaded in a 1D vertical optical lattice at 532 nm, where they are held for 65 ms. During this time, the current of one of the MOT coils, originally in the anti-Helmholtz configuration, is inverted to produce a homogeneous magnetic field of 330 G used to induce the clock transition. The lattice light is generated by a Coherent Verdi V6 laser which can deliver about 1 W of optical power to the atoms. When collimated to a beam waist of 350 μm, this laser yields a trap depth of $9E_r$, where $E_r = (k_B/2) \times 0.8$ μK is the recoil energy. This depth allows the atoms to be held and launched by accelerating the lattice with reduced losses due to Landau-Zener tunneling. When a single interferometer is implemented, we load the atoms in the lattice and accelerate at $3g$ (g is the gravitational acceleration) the cloud upwards by chirping the frequency of one of the lattice beams (Fig. 1(c)). In our gradiometer experiments, after launching a first cloud, the residual losses are used for a second launch at a slightly different final velocity.

The launching stage produces about 2.5×10^5 atoms in each cloud with a velocity difference $\Delta v = 8.5$ mm/s.

After the cloud preparation, the light from the interferometry (clock) laser is delivered to the atoms. The clock laser light, resonant with the $^1S_0$-$^3P_0$ transition at 698 nm, is produced by a grating-stabilized laser diode which is prestabilized by locking to an intermediate finesse ($F = 10000$) optical cavity and stabilized by locking to a high-finesse ($F = 500000$) ultrastable cavity with an ultra-low expansion spacer. When locked, this laser has a fast linewidth of 1 Hz and an estimated drift on the order of 1 Hz/s[16]. The light from the clock laser is preamplified by optically injecting another diode laser and finally amplified by a tapered amplifier. The light is then coupled into a 10-m single-mode polarization-maintaining fiber which can deliver up to 80 mW of light to the atoms. As opposed to multi-photon Raman or Bragg accelerometers, a single interferometer operated on the clock transition is sensitive to the single laser beam phase imprinted onto the atoms, rather than the phase difference of two counterpropagating beams. As a result, both the intrinsic laser noise and the optical components' vibrations will affect the gravimeter noise. The 10 m-long fiber contributes a large fraction of the noise which we can suppress with a fiber noise cancellation setup[17].

When we operate the gradiometer, we drive an acousto-optic modulator on the clock laser path with two frequency components in order to match the velocity difference of the two clouds after the double lattice launch. This method has the advantage of allowing the two clouds to be addressed separately and imprints a differential phase shift which can be used to characterize the gradiometer sensitivity.

The clock laser is first used to select a narrow velocity class of 10^4 atoms, corresponding to an effective temperature of 1 nK[18]. Following velocity selection, the atoms undergo a Mach-Zehnder $\pi/2 - \pi - \pi/2$ sequence performed through clock laser pulses. A simplified view of the setup of the laser beams for the experiment is shown in Fig. 1(b) while the sequence for a single interferometer is shown in Fig. 1(c).

The interferometer output is detected by collecting the fluorescence induced by a thin sheet of light resonant with the $^1S_0$-$^1P_1$ transition onto a photomultiplier tube. In order to count the atoms in the excited $^3P_0$ state, two repumping lasers (Fig. 1(a)) are shone onto the atoms that transfer the population to the ground $^1S_0$ state where they are detected again by fluorescence collection.

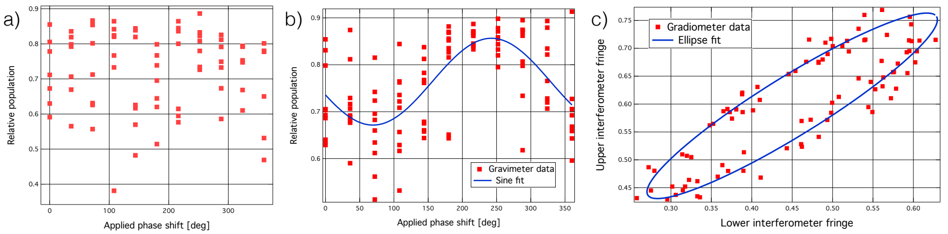

Fig. 2. Gravimeter and gradiometer results for interferometer durations of $2T = 10$ ms. a) Single interferometer fringe without the fiber noise cancellation b) Single interferometer fringe with fiber noise cancellation active. c) Plot of the upper interferometer fringe versus the lower one in the gradiometer configuration. The data show a clear correlation between the two fringes despite the presence of laser phase noise.

3. Gravimeter and gradiometer results

After releasing the atoms from the green optical lattice, we performed some preliminary measurements of the efficiency of the laser pulses resonant with the clock transition for untrapped atoms. The Rabi oscillations between the two interferometer states were measured by shining the clock laser onto velocity-selected atoms for a variable duration and then detecting the population of the two states. With our maximum optical power, we reached a Rabi frequency of $\Omega = 2\pi \times 750$ Hz and observed a damping time of 1.2 ms, with an efficiency limited to about 50% mainly due to the finite velocity distribution width. The consequence of this limited efficiency is a fringe contrast of 30%, which was measured to be constant as a function of the duration of the interferometer up to a time $2T = 10$ ms.

When gravimeter experiments were performed, using the sequence depicted in Fig. 1(c), we compared the fringe visibility with and without the fiber noise cancellation. As shown in Figs. 2(a) and (b), the phase noise induced by the fiber contributes a large amount of noise which can completely wash out the fringe for $2T = 10$ ms. The fringe acquires a clear visibility when the fiber noise cancellation is active. The remaining noise is due to the intrinsic laser frequency fluctuations and to the vibrations of the optical components in the laser's path from the source to the atoms. Although these noise sources appear relatively hard to suppress, it is in principle possible to improve these results by using a laser with better frequency stability and by reducing the vibrations of the optical components.

The potential of interferometry on the optical clock transition should appear in the gradiometer configuration, where a large suppression of the laser phase noise is expected. However, the relatively small separation of the two clouds and the small T of our experiment would yield a negligible signal from the Earth's gradient. As already anticipated, the small velocity difference of the two clouds allows them to be addressed separately and to set an artificial differential phase shift. Using this feature, we performed gradiometric measurements with durations of $2T = 10$ ms. Plotting the upper interferometer fringe against the lower one displays the expected correlation, as shown in Fig. 2(c). With a cycle time of 2.4 s, averaging this signal for $\tau = 400$ s results in an Allan deviation decaying as $\tau^{-1/2}$, an indication of white phase noise. The level of the recorded phase uncertainty lies only a factor of five above the estimated atom shot noise fluctuations. We estimate that this excess noise arises from detection noise.

4. Conclusions and perspectives

In this article, interferometry on the optical clock transition is presented. Results for the gravimeter show the expected sensitivity of the interference fringes to laser phase noise, while in the gradiometer configuration, the expected immunity to laser phase noise is established and operation close to the atom shot noise limit is observed. By further cooling the atoms, by using higher clock laser power and by using the fermion ^{87}Sr for which the clock transition is naturally allowed, this scheme provides a potentially interesting avenue for the detection of low-frequency gravitational waves. Further improvements might include the implementation of large momentum transfer and of atomic squeezing to increase the sensitivity. Other applications are possible with this interferometer such as, for example, the test of the weak equivalence principle for atoms in coherent superpositions of optically separated states.

Acknowledgments

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