A transportable cold atom inertial sensor for space applications

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I. INTRODUCTION

Atom interferometry has hugely benefitted from advances made in cold atom physics over the past twenty years, and ultra-precise quantum sensors are now available for a wide range of applications [1]. In particular, cold atom interferometers have shown excellent performances in the field of acceleration and rotation measurements [2,3], and are foreseen as promising candidates for navigation, geophysics, geo-prospecting and tests of fundamental physics such as the Universality of Free Fall (UFF). In order to carry out a test of the UFF with atoms as test masses, one needs to compare precisely the accelerations of two atoms with different masses as they fall in the Earth's gravitational field. The sensitivity of atom interferometers scales like the square of the time during which the atoms are in free fall, and on ground this interrogation time is limited by the size of the experimental setup to a fraction of a second. Sending an atom interferometer in space would allow for several seconds of excellent free-fall conditions, and tests of the UFF could be carried out with precisions as low as 10^{-15} [4].

However, cold atoms experiments rely on complex laser systems, which are needed to cool down and manipulate the atoms, and these systems are usually very sensitive to temperature fluctuations and vibrations. In addition, when operating an inertial sensor, vibrations are a major issue, as they deteriorate the performances of the instrument. This is why cold atom interferometers are usually used in ground based facilities, which provide stable enough environments. In order to carry out airborne or space-borne measurements, one has to design an instrument which is both compact and stable, and such that vibrations induced by the platform will not deteriorate the sensitivity of the sensor.

We report on the operation of an atom interferometer on board a plane carrying out parabolic flights (Airbus A300 Zero-G, operated by Novespace). We have constructed a compact and stable laser setup, which is well suited for onboard applications. Our goal is to implement a dual-species Rb-K atom interferometer in order to carry out a test of the UFF in the plane. In this perspective, we are designing a dual-wavelength laser source, which will enable us to cool down and coherently manipulate the quantum states of both atoms. We have successfully tested a preliminary version of the source and obtained a double species magneto-optical trap (MOT).

II. ATOM INTERFEROMETRY

Atom interferometers have been demonstrated almost twenty years ago [5] and are now thoroughly understood [6]. A simple way to understand our atom interferometer is as follows. Before the measurement itself, the atoms are cooled and prepared to the correct quantum state, before being released. This means that during the interferometric sequence, they are in pure free-fall. At three precise instants, separated by a time *T*, the atoms are illuminated with a laser, retroreflected on a reference mirror attached to the plane (Fig. 1). This can be seen as creating a ruler, the graduation being the phase of the retroreflected light wave. As they are illuminated, the internal state of the atoms can change, with a probability which depends on the phase of the laser and therefore on their position in the laser ruler. At the end of the interferometric sequence, we measure the proportion of atoms which have undergone the transition, and this measurements gives us a precise information on their acceleration with respect to the reference mirror, in the direction of the laser. In other words, this measurement consists in a precise readout of the position of the center of mass of the atomic cloud with respect to the reference mirror. The probability P for an atom to undergo the transition scales as [7] :

$$P \propto \cos(\Phi).$$

(1)

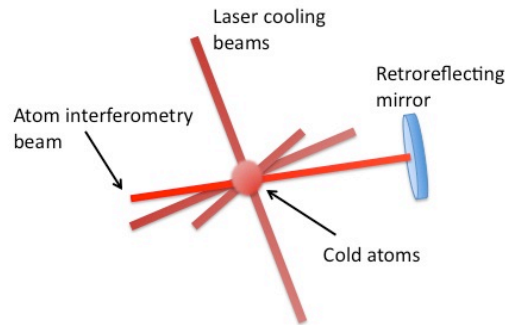In the case of a constant acceleration *a*,

$$\Phi \propto aT^2$$

(2)

Fig. 1. Schematic view of the atom interferometer. The atoms are cooled down to 10 µK. The cooling beams are then turned off for the interferometric measurement, so that the cold atom cloud is in free fall. The retroreflecting mirror defines the phase reference of the laser ruler.

One can see from (2) that the sensitivity of the device to acceleration scales like the square of the interrogation time T. To carry out precise measurements, it is therefore of interest to increase T as much as possible. A way to do this is to be in weightlessness conditions. The experiment will then fall along with the atoms, allowing for long interrogation times. On the ground, T is limited to a fraction of a second by the size of the vacuum cell. In microgravity conditions, free-fall times up to one second have been demonstrated [8], and in space this could be increased even more.

In case the acceleration is not constant, one has to take into account the frequency response of the atom interferometer [9]. The phase shift Φ is the sum of the contribution of all the frequency components. Vibrations are a crucial issue when carrying out acceleration measurements with an atom interferometer, as they will contribute to the acceleration $a(t)$, and therefore to the phase Φ. In the plane, vibrations are up to four orders of magnitude higher than in laboratory-based atom interferometry experiments, and are a real challenge one must face in order to carry out measurements with a high sensitivity.

III. SINGLE SPECIES EXPERIMENTAL SETUP

A. General design

The experiment is made of three sub-units, and comprises a ultra-high vacuum cell in which we cool and manipulate the atoms, a laser source and a microwave frequency reference based on an ultra-stable quartz oscillator. All the components have been tested in microgravity onboard the plane. Altogether, the setup weighs less than 700 kg, and has an electrical power consumption of the order of 1 kW (Fig. 2).

Fig. 2. Experimental apparatus in the plane. The science chamber is protected by a magnetic shield (orange straps, in the front). Behind the science chamber is the rack containing the electrical power supplies and the free-space laser. The bigger unit, on the right, holds the telecom laser source, the 6.8 GHz frequency reference, all the control electronics and the computer.

During the flight, the plane carries out a series of 31 parabolas, each providing about 22 seconds of microgravity. Before each parabola, there is a pull-up phase, which lasts for about 20 seconds, and during which the acceleration is about 1.8g. There is also a 1.8g pull-out phase after the parabola, and about 2 minutes of 1g flight before the next parabola. The experiment is able to operate both during the 0g and 1g phases of the flight.

B. Laser source

Having a very compact and stable laser source is a major challenge one has to face before thinking of sending an atom interferometer in space. In laboratories, the laser systems used to cool down and interrogate the atoms usually rely on Extended Cavity Diode Lasers (ECDLs), and free-space optics. It is possible to miniaturize such systems, and very stable sources have been demonstrated, for example in the Quantus drop-tower experiment, or for the Pharao mission [8,10,11]. In order to cool and manipulate ^{87}Rb, we need a laser source emitting at 780 nm. We have chosen to take advantage of existing fiber optics components in the telecom C-band around 1.5 µm, and generate the final optical frequency by Second Harmonic Generation (SHG) [12,13]. This way, we have a setup which is almost entirely fibered and therefore immune to vibration-induced misalignments. The variety of available components in the C-band allows us to have a versatile setup for the experiment.

Starting from a 1560 nm fibered DFB laser diode, we use a phase modulator to generate optical sidebands at 6.8 GHz in order to address the hyperfine transition of ^{87}Rb [14]. The light is amplified to 5W with an Erbium-Doped Fiber Amplifier (EDFA), and outcoupled from the fiber. It is then sent through a PPLN crystal in a double-pass configuration, which generates the light at 780 nm that is sent into the science chamber via some fibers (Fig. 3). This Second Harmonic Generation (SHG) stage is the only free-space part of the laser system, and has been designed to be as compact and robust as possible.

During the parabolic flight campaigns, the experiment undergoes very strong vibrations during transportation and in the plane, as well as temperature and humidity changes. The laser system is stable enough to operate without any adjustment. Another key feature of our laser source is that we have a single laser, which we use to both cool and interrogate the atoms. The sidebands generated by phase modulation are also intrinsically phase-locked to one another, and since they are carried by the same beam, the system is insensitive to fluctuations induced by path differences.
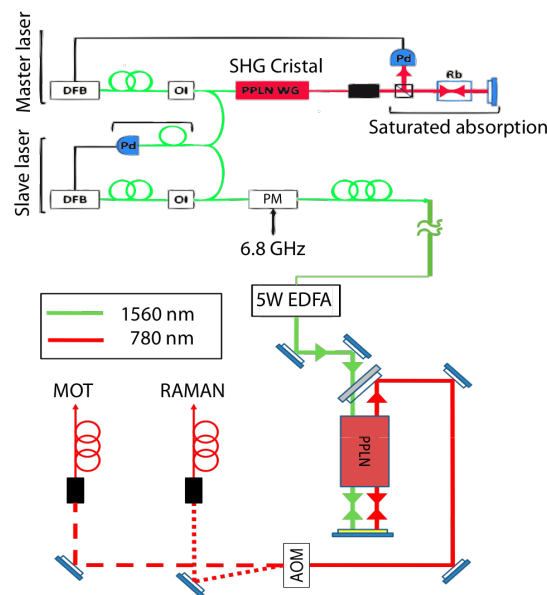

Fig. 3. Compact laser source [13]. A Distributed feedback (DFB) fibered laser diode at 1560 nm is frequency-doubled in pigtailed PPLN waveguide, and the resulting 780 nm light is used to stabilize the laser on a Rb transition. The slave laser is also a 1560 nm DFB, frequency-locked on the master diode via a beatnote. Light from the slave DFB is phase-modulated at 6.8 GHz in order to generate the sidebands needed to cool and address the atoms. It is then amplified to 5W in the EDFA, and frequency-doubled in a PPLN crystal in a double-pass configuration. An acousto-optic modulator (AOM) then sends the light towards the MOT or Raman fibers, to respectively cool and interrogate the atoms.

IV. TOWARDS A TEST OF THE UFF : A DUAL-WAVELENGTH LASER SOURCE

In order to carry out a test of the UFF, one needs to compare the accelerations of two test masses as they fall freely in the Earth's gravitational field. This has been done with macroscopic test masses using torsion balances, and Lunar Laser Ranging (LLR) [15,16]. With cold atoms, a preliminary test has been carried out with [85]Rb and [87]Rb [17]. However, the two Rubidium isotopes have very similar masses and internal compositions, and it would be interesting to test the UFF at the quantum level with two very different objects.

Our idea is to use [87]Rb and [39]K. These two atoms have transitions at wavelengths which are close to one another (780 nm and 767 nm respectively). This makes them ideal candidates for testing the UFF. Both wavelengths can be generated from frequency-doubled telecom lasers, and we have shown that the fact that they are quite close allows for very efficient common mode noise rejection between the two interferometers [4].

To manipulate simultaneously the two atoms, we are constructing a dual-wavelength laser source. We will start from two DFB lasers at 1560 and 1534 nm, and frequency-double them to 780 and 767 nm. In order to have as little differential-mode noise between the two atom interferometers as possible, we will have the two lasers locked on the same frequency reference, by the means of an optical frequency comb specially developed by MenloSystems for the parabolic flights.

A. Frequency-stabilization of the lasers

An optical frequency comb is a femtosecond laser, which emits short pulses at a given repetition rate, typically of the order of 100 MHz. In the Fourier domain, this laser has a broad spectrum with very narrow lines separated from each other by the repetition rate [18]. The frequency of each spectral line can be written as

$$f_n = f_0 + n f_{rep} \qquad (3)$$

where n is the index of the considered line, f_{rep} the repetition rate of the laser, and f_0 the so-called Carrier-Envelope Offset (CEO). It is possible to stabilize both f_0 and f_{rep}, either on an optical or RF reference. This way, the comb is an absolute reference for optical frequencies, covering a very broad spectrum.

Our optical comb has been designed to be as compact as possible. It has a repetition rate of 250 MHz, and covers a spectrum of about 100 nm, between 1500 and 1600 nm. We have two Beat Detection Units (BDUs), which enable us to select comb lines around given frequencies (1560 and 1534 nm), and to make a beatnote between the comb and our continuous wave DFB lasers.

The 1560 nm part of the dual-frequency source will be quite similar to what we have described above for the single-wavelength version. Part of the light from the master laser is sent to the 1560 nm BDU. The resulting beatnote will be used to lock the repetition rate of the comb. This way, the comb will be stabilized on the master laser, which in turn is locked on [85]Rb transition. The 1534 nm DFB will then be locked on the comb via the second BDU. This way, the two lasers can be stabilized on the same frequency reference (a Rubidium transition), and there will be almost no relative drift.

B. Serrodyne modulation for the 1534 nm Potassium laser

Instead of using a master-slave configuration as we have on the Rubidium laser, we have tested a single-laser configuration for the Potassium part of the source. An important challenge is the fact that between the phase of the experiment where the atoms are cooled and the phase where they are interrogated, the laser has to be detuned of several hundreds of MHz. In the Rubidium source, this is done by changing the value of the frequency-lock between the master and slave DFB diodes. For the 1534 nm source, we have implemented a serrodyne modulation technique [19,20].

Shifting the frequency of the electric field can be seen as applying a linear increase to the phase of the electric field. Although it is not possible to do this with a phase modulator, one can carry out an analogous operation by applying a sawtooth waveform, with an amplitude corresponding to a phase of 2π. The modulated electric field E can be written

$$E(t) = E_0 \cos\big(\omega t + \varphi(t)\big) \qquad (4)$$

where E_0 is the amplitude of the electric field, ω the pulsation of the un-modulated light, and $\varphi(t)$ the phase modulation. In the case of a sawtooth waveform,

$$\varphi(t) = \alpha t \, [\text{mod}] \, 2\pi \qquad (5)$$

The efficiency of serrodyne modulation depends on the steepness of the falling edges of the sawtooth waveform. If the edge is not steep enough, spurious sidebands will be created, impairing the quality of the frequency-shifting. The generation of the sawtooth can be easily achieved by means of a passive Non Lienar Transmission Line (NLTL). To achieve a frequency shift of $\alpha/2\pi$, one applies a sine wave of pulsation α on the input of the NLTL, and the output is connected to the input of the optical phase modulator.

Serrodyne modulation is a convenient way to shift the frequency of our laser between the cooling and interrogating phases of the experiment. The frequency shift is very fast compared to a usual frequency lock, and only one laser is needed.

C. Free-space bench

As for the Rubidium system, the Second Harmonic Generation takes place in free-space. Beforehand, the 1560 and 1534 nm lasers are combined, and amplified to 5 W each in a dual-frequency EDFA. They are then outcoupled, and sent through two crystals in a double-pass cascade configuration. The first crystal is phase-match for the frequency-doubling of 1560 nm light. The second crystal is tuned to the 1534 nm phase-matching condition. The 780 nm light is then sent to fibers in a configuration which is similar to the single-wavelength setup. The 767 nm light is first sent through a double-pass AOM, in order to generate a sideband 462 MHz away from the carrier, corresponding to the hyperfine splitting of ^{39}Rb. The reason why do not use phase modulation like we did for the Rubidium laser is that the splitting is much smaller (462 MHz vs 6.8 GHz), meaning that the spurious sidebands created by the modulation and the frequency-doubling would still be close to atomic resonance, and contribute to important parasitic signal.

The dual-wavelength laser source is shown in Fig. 4. As we did for the 780 nm source, we have favored fiber components in the design of the system. The free-space bench will be larger (approx. 40 x 70 cm^2), but we have designed it to be stable enough, using aeronautic-grade aluminium for the optical flat.

V. PRELIMINARY RESULTS

The single-wavelength Rubidium setup has been thoroughly tested, and has enabled us to carry out precision measurements in the zero-G aircraft. We have also tested part of the frequency-comb, and obtained a satisfying behaviour, the femtosecond laser remaining mode-locked throughout the parabolic flight.

We are now assembling and testing the dual-wavelength source. We have shown that it was possible to trap and cool down atoms with a serrodyne-modulated laser, even after the SHG stage, which tends to enhance spurious sidebands. We have also tested the EDFA and the SHG module. Using the 767 nm light and a direct modulation of the DFB diode [21], we have obtained a dual-species K-Rb magneto-optical trap. This is the first step towards a dual-species atom interferometer and a test of the UFF with cold atoms.
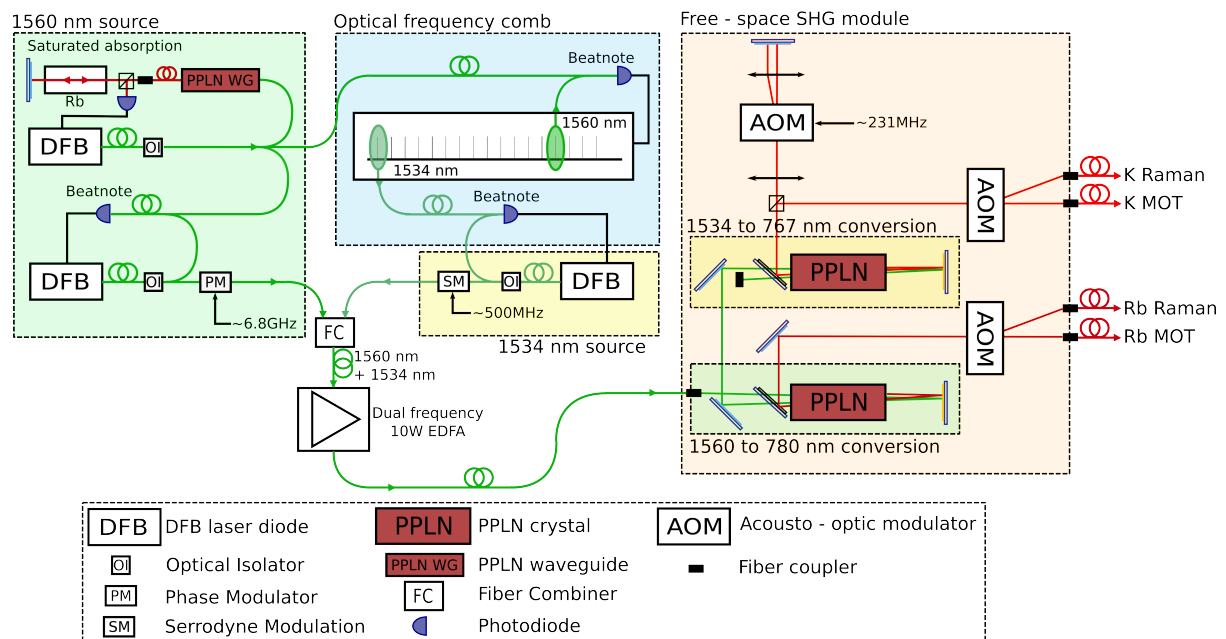

Fig. 4. Dual-wavelength laser source

VI. CONCLUSION

We have constructed a very robust laser source, and shown that it was possible to carry out atom interferometry experiments in a hostile environment like that of an aircraft carrying out parabolic flights. A new laser source is under design, which will give us the possibility to address simultaneously two atomic species in order to test the Universality of Free Fall with cold atoms as test masses. This work also opens the way for terrain measurements with cold atom sensors, in fields such as gravity mapping or inertial navigation.

Furthermore, cold atoms are seen as promising candidates for space-based measurements, in particular for tests of fundamental physics [22]. The design of the laser system for a space mission will be a key point. With our frequency-doubled telecom laser source, we propose an interesting alternative to extended cavity diode lasers. The use of fiber components allows for the implementation of a wide variety of functions in an intrinsically stable and compact setup.

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