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Compact atomic gravimeter based on a pulsed and accelerated optical lattice

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We present a scheme of a compact atomic gravimeter based on atom interferometry. Atoms are maintained against gravity using a sequence of coherent accelerations performed by the Bloch oscillations technique. We demonstrate a sensitivity of 4.8×10^{-8} with an integration time of 4 min. Combining this method with an atomic elevator allows us to measure the local gravity at different positions in the vacuum chamber. This method can be of relevance to improve the measurement of the Newtonian gravitational constant G.

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Atom interferometry has proven to be a reliable method to realize robust inertial sensors [1–9]. The performance of these devices rivals state-of-the-art sensors based on other methods. The record sensitivity of $8 \times 10^{-9} g$ at 1 s is achieved for the measurement of the gravity acceleration g [10,11], allowing precise determination of the gravity gradient and the Newtonian gravitational constant G [12,13]. In such atom interferometers, the inertial phase shift scales quadratically with the interrogation time. An accurate measurement of the gravity acceleration requires a long time of free fall and should be limited by the size of the vacuum cell in which the measurement takes place. The best performance was obtained using cold atoms launched along a parabolic trajectory of about 1 m [2]. This constraint limits the development of compact and transportable atomic gravimeters necessary to high-precision geophysical on-site measurements. Furthermore, the value of the gravity is averaged over a large height.

Atom gradiometers stemming from free-fall gravimeters are constrained to shorter measurement times. Some of these gradiometers are used to measure the Newtonian gravity constant [12,13]. As related in these references, the largest contribution to the error budget comes from the uncertainty on the atomic cloud position within the fountain and the initial launch velocity of the atoms. To improve the measurement of the G constant, there is a need for a conceptually different gravimeter capable of locally measuring gravity at a well-controlled position.

Several methods were proposed to implement a compact atomic gravimeter. They consist in levitating the atoms by means of the laser light [14–20]. Currently three kinds of experiments based on atoms trapped in a vertical optical lattice are in progress [17–20]: using atoms confined in an amplitude-modulated vertical optical lattice [17], using atom interferometry involving a coherent superposition between different Wannier-Stark atomic states in a one-dimensional (1-D) optical lattice [20], and combining a Ramsey-Bordé interferometer with Bloch oscillations in a quasistationary vertical standing wave [18,19]. In the last experiment atoms interact with the optical lattice in the middle of the interferometer sequence during about 100 ms. They reach the short-term sensitivity of 3.5×10^{-6} g at 1 s. This sensitivity is limited by a contrast decay of the interference fringes due to the decoherence induced by the inhomogeneity of the lattice laser beams [19].

In this paper we demonstrate a method to measure precisely the local acceleration of gravity. The principle is illustrated in Fig. 1. It is based on a Ramsey-Bordé atom interferometer realized by two pairs of $\pi/2$ Raman pulses. In order to compensate the fall of atoms between the pulses, we use a sequence of brief and strong accelerations. The acceleration is based on the method of Bloch oscillations in an accelerated optical lattice. Because the lattice is pulsed we have less decoherence compared to previously described methods where the force is applied continuously.

We obtain a preliminary measurement of the local gravity acceleration with a short-term sensitivity of 7.4×10^{-7} at 1 s. The atoms are maintained within a 4.6-mm falling distance during about 230 ms. Using similar acceleration pulses, it is possible to control precisely the position and the initial velocity of the atoms before the beginning of the atom interferometer.

The principle of the acceleration process consists in transferring to the atoms many photon recoils by the means of Bloch oscillations (BO) [21–23]. This is done by a succession of Raman transitions in which the atom begins and ends in the same energy level, so that its internal state is unchanged while its velocity has increased by $2v_r$ after each transition ($v_r = \hbar k/m$ is the recoil velocity of the atom of mass m when it absorbs a photon of momentum $\hbar k$). BO are produced in a one-dimensional vertical optical lattice which is accelerated by linearly sweeping the relative frequencies of the two counterpropagating laser beams. This leads to a succession of rapid adiabatic passages between momentum states differing by $2\hbar k$. The Bloch oscillation technique offers a remarkable ability to coherently and efficiently transfer photon momenta [24].

In Ref. [19], the configuration of Bloch oscillations in a vertical standing wave has been investigated. The authors have observed a drop of the contrast when the number of Bloch oscillations is increased, limiting this number to 75 (corresponding to 100 ms). This result differs from what was observed in accelerated lattices where a contrast of 30% is observed for 600 BO performed in 4 ms [25]. The contrast decay is due to the speckle pattern, which induces a random force on the atoms. Indeed this force is proportional to the depth U_0 of the optical lattice. The phase imprinted by the

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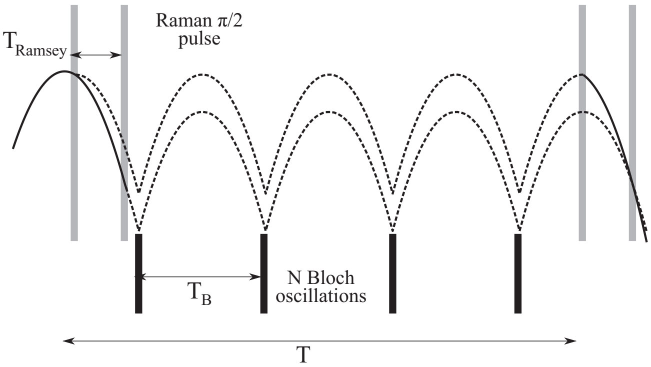

FIG. 1. Principle of the method. We use laser-cooled ^{87}Rb atoms in $F = 2$. They are first prepared with an initial velocity close to zero (trajectory in solid curve); we apply a first pair of $\pi/2$ pulses to select atoms in $F = 1$ (dashed curve). A laser beam resonant with the D_2 line pushes away atoms remaining in state $F = 2$ (those trajectories are not shown in this figure). Then we pulse and accelerate the optical lattice to hold the atoms in $F = 1$ against gravity, in the middle of the atom interferometer sequence.

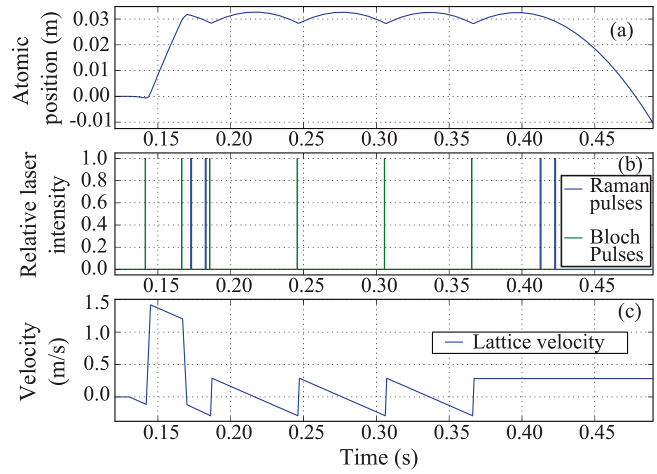

FIG. 2. (Color online) (a) Trajectory of the atoms during the measurement procedure. The atoms are first held at a given position using an atomic elevator. We apply the first pair of $\pi/2$ Raman pulses, and then atoms are maintained against gravity for 230 ms by periodically transferring to them 100 photon momenta. (b) Timing sequence of the Raman and Bloch beams; the two first Bloch pulses are used to perform the atomic elevator. (c) Velocity of the optical lattice vs time.

speckle is proportional to the lattice depth times its duration. However, the critical acceleration which sets the efficiency of Bloch oscillation scales as U_0^2 (adiabaticity criterion), in the weak binding limit [21,22]. In our experiment the depth of the lattice is 10 times as high as in the experiment using a standing wave, whereas the light is switched on for a duration 50 times shorter. The decoherence due to the inhomogeneities of the Bloch laser beams is therefore lower using a sequence of brief and strong accelerations from BO.

We use a Ramsey-Bordé atom interferometer realized by two pairs of $\pi/2$ laser pulses. Each light pulse induces a Doppler-sensitive Raman transition which couples the hyperfine levels $F = 1$ and $F = 2$ of the $^5S_{1/2}$ ground state of ^{87}Rb. The first pair of $\pi/2$ pulses transfers the atoms from the $F = 2$ hyperfine level to $F = 1$ and selects the initial velocity distribution. The second pair measures the final velocity of the atoms by transferring resonant atoms from $F = 1$ to $F = 2$. Note that after the first pair of $\pi/2$ pulses we apply a laser pulse resonant with the D_2 line in order to push away atoms remaining in the state $F = 2$. Atoms in $F = 1$ perform M series of N Bloch oscillations between the two pairs of $\pi/2$ pulses: After the first pair we let the atoms fall during T_B, and then they are shone with the accelerated optical lattice. They acquire a velocity of $2\ N \times v_r$ in the upward direction. The delay T_B is chosen in such a way that the gravity acceleration is perfectly compensated by the coherent acceleration due to Bloch oscillations, i.e., $T_B = 2N v_r/g$. This process is repeated periodically to maintain the atoms against gravity. Figure 1 depicts only the trajectories of atoms in $F = 1$ after the first pair of $\pi/2$ pulses.

To maintain the atoms within a short falling distance, it is necessary to prepare them with an initial velocity close to zero. For this purpose, the atom inteferometer sequence is preceded by the *atomic elevator* sequence [25] (see Fig. 2). It consists of two sets N_1 and N_2 of BO: Atoms are first accelerated in a given direction using N_1 BO. When they reach the chosen position, they are stopped by using N_2 BO in the opposite direction. The final position of the atoms and their velocity are precisely determined by the numbers N_1 and N_2 and the spacing time between the two Bloch pulses. This method allows us to displace the atoms, without losses, at different positions in the vacuum chamber, before starting the measurement of the local gravity.

The experiment is realized in a titanium UHV chamber connected to a glass cell by a differential pumping tube. It is shielded from residual magnetic fields by two layers of μ-metal. The two-dimensional magneto-optical trap (2D-MOT) produces a slow ^{87}Rb atomic beam (about 10^9 atoms/s at a velocity of 20 m/s) which loads during 250 ms a three-dimensional magneto-optical trap. Then a σ^+-σ^- molasses generates a cloud of about 2×10^8 atoms in the $F = 2$ hyperfine level, with a 1.7-mm radius and at a temperature of 4 μK.

The Bloch beams originate from a 3.8-W Ti:sapphire laser pumped by an 18-W@532-nm laser (Verdi G18-Coherent). The output laser beam is split into two paths, each of which passes through an acousto-optic modulator (AOM) to adjust the frequency offset and amplitude before being injected into a polarization-maintaining fiber. The depth of the generated optical lattice is $21E_r$ (for ^{87}Rb the recoil energy is $E_r \simeq$ 3.77 kHz $\times\ h$, where h is the Planck constant) for an effective power of 220 mW seen by the atoms. The Bloch lasers are blue detuned by 30 GHz from the rubidium D_2 line. Under these conditions, the Landau-Zener tunneling and the scattering rate are negligible. The Bloch pulses are shaped by controlling the radio-frequency signal driving the AOMs. The power lattice is raised on in 500 μs, in order to adiabatically load the atoms in the first Brillouin zone. The number of Bloch oscillations is determined by fixing the frequency chirp of the rf signal used to drive the AOMs. The Raman and Bloch beams are collimated to a $1/e^2$ diameter of 11 mm at the output of the polarization-maintaining fibers used to guide light toward the vacuum chamber (for details of the optical setup,

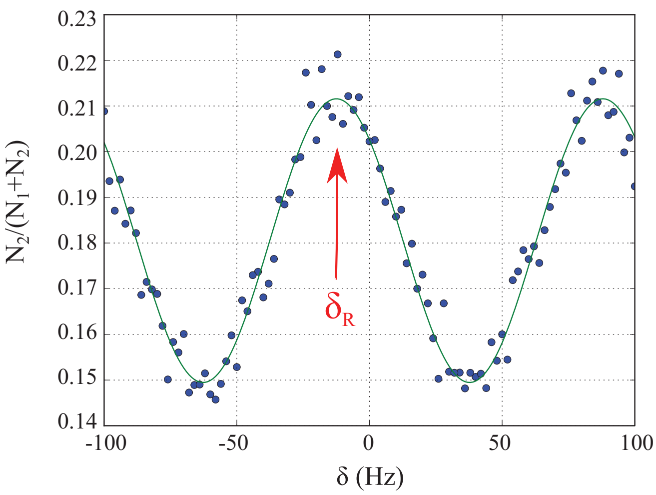

FIG. 3. (Color online) Typical spectrum used to deduce a value of g. The data points show the quantity $N_2/(N_1+N_2)$, where N_1 and N_2 are the populations in the $F=1$ and $F=2$ levels, measured for different values of δ, the change of the Raman frequency between the two pairs of $\pi/2$ pulses. The solid line is a least-squares fit to the data by a $\cos[(\delta-\delta_R)\times T_R]$ function. The position δ_R of the central fringe is determined from this fit.

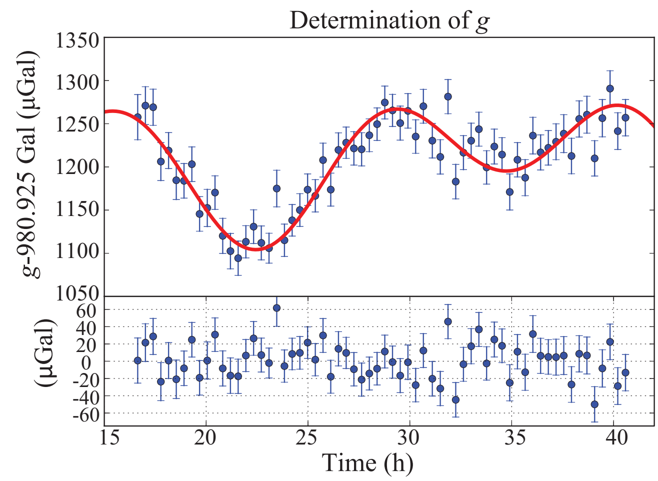

FIG. 4. (Color online) Gravity data taken over one day fitted by the earth tide model. Each data point is deduced from the average over six measurements. The lower curve shows residuals of the fit ($1\ \mu$Gal $=10^{-8}$ m/s^2).

see Refs. [25,26]). The timing sequence of Raman and Bloch pulses during the experiment is presented in Fig. 2(b). The delay T_R between two $\pi/2$ pulses is 10 ms, and the duration of each pulse τ equals 650 μs. Figure 2(c) shows the velocity of the optical lattice as a function of time.

A way to determine the value of g would consist in scanning the value of the delay T between the two pairs of $\pi/2$ pulses, keeping the relative Raman frequency δ unchanged. If the delay T equals exactly $2NM\times v_r/g$, the BO will compensate exactly for the acceleration due to gravity and the two paths of the interferometer will be in phase. In the experiment we set the value of T close but not exactly equal to the expected value. The remaining velocity δv will induce a shift $\delta_R=(k_1+k_2)\times\delta v$ of the position of the fringes when we scan δ. A typical interference fringe obtained with $N=50$, $M=4$, and $T=227$ ms is shown in Fig. 3. The data points show the relative population in $F=2$ measured by the second pair of $\pi/2$ pulses as the Raman frequency δ is scanned. The fringe shift δ_R is determined by a least-squares fit of the experimental data by a $\cos[(\delta-\delta_R)\times T_R]$ function. In practice, we operate the interferometer close to the central fringe, which is previously located by using different values of T_R.

The frequency shift δ_R is related to the local gravity acceleration by

$$g=\frac{1}{T}\times\left(\frac{2NM\hbar k_B}{m_{\rm Rb}}-\frac{\delta_{\rm R}}{(k_1+k_2)}\right), \qquad (1)$$

where $k_{\rm B}$ is the Bloch wave vector and k_1 and k_2 are the wave vectors of the two Raman beams. The ratio $h/m_{\rm Rb}$ between the Planck constant and the rubidium atomic mass $m_{\rm Rb}$ is measured by our group with a relative uncertainty of 1.2×10^{-9} [26]. In Eq. (1), the term $\delta_{\rm R}/(k_1+k_2)$ is small and appears as a correction to the reference value $g_{\rm ref}=2NMv_r/T$. As a consequence, to achieve a precise determination of g, the precision on the value of the Raman wave vectors (k_1 and k_2) is less critical than on the value of the Bloch wave vector.

As the fall distance is small, the systematic errors due to the gradients of residual magnetic fields and light fields are negligible. In practice, to cancel the parasitic effect due to the temporal fluctuations of these fields, we record two spectra exchanging the direction of the Raman beams. We achieve a relative statistical uncertainty of 4.8×10^{-8} on the value of g for an integration time of 4 min. Figure 4 shows a temporal behavior of the gravity measured over 25 h. These data fit well with a local solid Earth tide model [27,28], and the temporal fluctuations of local gravity are dominated by tidal forces.

The sensitivity of the gravimeters is characterized by the Allan standard deviation of the g measurement. Figure 5 shows the Allan standard deviation of the set of 388 determinations

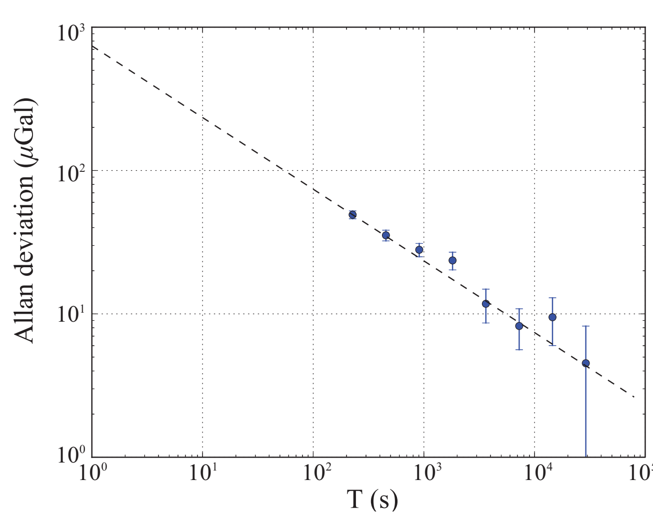

FIG. 5. (Color online) Allan standard deviation of the local gravity, for a delay $T=227$ ms and a number of BO $N=50$ ($1\ \mu$Gal $=10^{-8}$ m/s^2).

of g; it scales as $t^{-1/2}$ (where t is measurement time). The short-term sensitivity, extrapolated to 1 s according to the white noise behavior, is $7.4 \times 10^{-7} g$.

Thanks to the "atomic elevator" sequence, which precedes the measurement of g, it is possible to change the position at which gravity is measured. Because we use BO in the elevator, the acceleration of atoms is well known and it is possible to precisely calculate the displacement of the cloud, using the numbers N_1 and N_2 of BO and the duration of the elevator. Our setup can therefore be used to precisely measure the gravity gradient. However, the sensitivity on g is not high enough to map the gravity gradient, whose order of magnitude is $\sim$310 μGal/m (1 μGal $= 10^{-8}$ m/s^2).

In this work we have focused on the sensitivity of this method. The systematic errors which affect the value of g are similar to the ones identified in usual gravimeters (Gouy phase, wavefront aberrations, Coriolis force, level shifts, etc.) [2,11,29]. They should be investigated and presented in an upcoming article.

In this paper we have demonstrated a method to locally measure the gravitational acceleration. It is based on a Ramsey-Bordé inteferometer and a sequence of Bloch oscillations. We obtain a preliminary sensitivity of 7.4×10^{-7} at 1 s. This sensitivity can be improved using a colder atomic source (100 nK) and by reducing the vibrations to achieve a delay T_R of about 50 ms. With these experimental parameters we should achieve a sensitivity comparable to the state of the art. The key feature of our method lies in the decoherence induced by the fluctuations of the optical lattice, which is substantially reduced compared to similar methods.

We notice that in our atomic interferometer the frequencies of the Raman beams are the same during the first and the second pairs of $\pi/2$ pulses. We can imagine implementing a succession of atom interferometers where the last pair of $\pi/2$ pulses of each interferometer is the first pair of the next one. In such a configuration the phase noise between successive interferometers will be correlated and the Allan variance should decrease as $1/n$ (where n is the number of measurements).

We have elaborated a timing sequence, which allows us to move the atoms toward different positions in the vacuum chamber before performing the local gravity measurement. Potential applications of this method to improve the measurement of the Newtonian gravitational constant G should be investigated. In the experiment reported in Ref. [12], the constant G is determined using a gradiometer, which measures the differential acceleration of two samples of laser-cooled atoms. The change in the gravitational field along one dimension is measured when a test mass is displaced along a distance of 27.940 cm. The main systematic errors come from the uncertainties on the position and the initial velocity of the atoms. More recently the experiment of Tino *et al.* [13] improved the uncertainty on G by one order of magnitude. The main contribution to the systematic error on the G measurement derives from the initial velocity of the atomic cloud and the positioning accuracy of the source masses. The authors claimed that the latter should be reduced by about one order of magnitude by using a laser tracker. We propose to investigate the method described in this paper to reduce the systematic error due to atomic cloud parameters.

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