Gravity acceleration measurement based on Atom interferometry

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Abstract. Cold atom interferometer based on two-photon stimulated Raman transition has been proved to be a promising way to measure g with higher precision. In this work, we first introduce the principle of atomic interference gravimetry, including the interaction between the atoms and light, the interferometry with the Raman beams and the measure of the g. Then our gravity acceleration measurement system will be introduced, including atomic fountain, Raman system and detection system. With this device, we can get the value of the g, with the uncertainty in the order of ten minus seven.

Keywords: Gravity acceleration, Atom interferometry, Atomic fountain, Raman transition

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1. Introduction

In 1991, Steven Chu and Mark Kasevich proposed the atom interferometry with three Raman pulses[1]. They measured the value of gravity with that kind of atom interferometry. After that, there are more and more works which concentrate on the gravity measured by atom interferometry[2-4]. What’s more, it can be used to measure the gravitational constant[5], the inclination[6]. There are also some gravimeters based on coherent Bragg diffraction of freely falling cold atoms[7]. The compact Gravimetric Atom Interferometer is also developed to make the gravimeter portable and movable[8]. The gravimeter also can be used to test the universality of free fall with atoms in different spin orientations[9].

In this article, we first introduce the basic theory of the Gravity acceleration measurement based on Atom interferometry. Then we introduce the experiment setup. At last, the results of this experiment will be showed.

2. Theory

The principle of gravity acceleration measurement based on Atom interferometry has been described before[10]. Figure 1 is the sketch map of the interferometry. Through the figure we can find the atom internal state evolution through two ways after the first half \( \pi \) pulse. Then finally combined together with a \( \pi \) pulse and another half \( \pi \) pulse. We can get the interference fringe by detecting the population of the atom internal state. In this kind of atom interferometry, there are two mechanisms which contributes to the phase of the interferometry’s fringe: the phase shift contributed by the gravity and the phase shift contributed by frequency sweeping of the Raman light.
\[ \phi = k_{\text{eff}} g T^2 - \alpha T^2 \]

\( g \) is the local gravitational acceleration, \( T \) is the interval time in figure 1, \( k_{\text{eff}} = k_1 - k_2 \) is the effective wave vector, \( \alpha \) is the chirp rate of the Raman beams.

\[ \phi = k_{\text{eff}} g T^2 - \alpha T^2 \quad (1) \]

We can get fringe by sweeping the \( \alpha \). In the atom’s interference fringe, the minimum in the fringe in relation with \( \phi = k_{\text{eff}} g T^2 - \alpha T^2 = 2n\pi, n = 0,1, \ldots \) The value of \( g \) is determined by the case of \( n = 0 \). For \( n=0 \), the fringe will always be the trough for arbitrary interval time. This can help us to deduce the value of the gravity acceleration.

3. Experiment setup
Our system consists of several parts (see figure 2). The left side is the vacuum system where the atomic fountain and atom interference happen. The right side is the optical system with two layers correspond to magnetic optical trap (MOT) system and Raman system individually.
The cold atoms are captured in the MOT which combines the optical part (see figure 3(a)) and the magnetic part which generated by a pair of anti-helmholtz coils. In the experiment, we locked the cooling laser on the cross of $5S_{1/2}, F = 2 \rightarrow 5P_{3/2}, F' = 2$ and $5S_{1/2}, F = 2 \rightarrow 5P_{3/2}, F' = 3$ by the Dichroic Atomic Vapor Laser Lock (DAVLL). Then acoustic optical modulators (AOMs) are used to make the light slightly red detuned to cooling the atoms. Besides that, we also have a repumping light to get the atoms which dropped to $5S_{1/2}, F = 1$ state back to the cooling cycle. Through the figure 3(a), we can find that there are two AOMs to control the upper three beams and the lower three beams individually which is a necessary condition for the atomic fountain. The atoms will be thrown upward when frequency of the upper beams was detuned smaller than the lower. The velocity and the height of the fountain are determined by the frequency difference. While in order to make the atomic fountain temperature lower and the fountain height higher, we do the moving molasses after launching stage by ramping down the light intensity and increasing the detuning.

![Figure 3. The optical system for the MOT(a) and the Raman(b).](image)

The sketch map of the atomic fountain is shown in figure 4. Besides the atomic fountain, we still need the Raman system to get the interference fringe. The Raman light is locked by the electrooptic modulation phase lock, the main problem for this method is the 0 order and the ±1 order after the EOM cannot be divided. The combined light will has obviously power fluctuation which has an adverse effect on the atom interferometer. To overcome this problem, we use the grating as the frequency selection device. We inject the modulated light to a homemade external cavity diode laser (ECDL), which can filter the 0 order light that has a 6.8GHz shift with the mode which we chose. What’s more, this light can be used as the seed for the taper amplifier. The detuning of 1GHz is produced by an AOM, the main Raman laser’s frequency was frequency shifted before locked on the transition line.

Detection system (as figure 5 shows) is also needed in the experiment which can help us to deduce the atom’s temperature and the population of the states. We use a thin light as the detect light. With the difference of the atom’s velocity, the time it gets to the detection area is different. The photodiode’s signal is changed with time. So it denotes the velocity attribution of the atoms which can be used to do the Gauss fitting to get the temperature. For the state detection, we have two layers of detection system with a repumping light in the middle. After the atoms in $F = 2$ state be detected, the repumping light will get the atoms in $F = 1$ state to $F = 2$ state. So we can judge the number of the atoms in $F = 1$ state by the signal which detected later.
4. Experiment results

We first measure the atomic fountain’s temperature to judge whether the fountain is OK or not. Through the fitting in figure 6, we can get the temperature is about 10 μK, which can satisfy our need in the gravimeter.

For the Raman process, the very important thing is to choose the proper time of the Raman pulse. By changing the time of the Raman duration we can get a Rabi oscillation, through which we can got the proper Raman duration for the subsequent experiment as shown in figure 7.
In the experiment, we use signal generator (Keysight E8257D) to sweep the frequency. Then get the population of the atoms in the F=2 state through our detect system. We can get the atom interference fringe through scanning the chirp rate. In order to get the gravity acceleration absolute value, we choose different atomic free flight times, measure the Raman interference fringe individually to judge the center place which has a relationship with the value of the gravity acceleration (see figure 8). The red diamonds, blue rectangles, black dots correspond to different interval time 10 ms, 15 ms, 20 ms. By fitting the data, we can see that the three cases all have a maximum at a special point which is the place corresponds to n=0. We can get the value of gravity through the exact value of $\alpha$ in the special point.

![Figure 8. The atoms population change with different chirp rate.](image)

In order to investigate the stability of gravity acceleration measurement, we continuous measure the value and got the Allan deviation as the figure 9 shows.

![Figure 9. The Allan deviation of the gravity measurement.](image)

5. Conclusions
In this article, we proposed our gravimeter system and some results. The gravimeter is based on atom interferometry. The atomic fountain is realized by applying a frequency shift between the upper and lower light. The Raman system is accomplished by injection-locking of a master laser to a slave laser. The interference fringe and Allan deviation have been showed. We will try to make the atomic fountain temperature lower next. With a higher fountain, we can prolong the interval time. The longer interference time will lead to a more precise value of the gravity.

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