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Determining the tilt of the Raman laser beam using an optical method for atom gravimeters

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The tilt of a Raman laser beam is a major systematic error in precision gravity measurement using atom interferometry. The conventional approach to evaluating this tilt error involves modulating the direction of the Raman laser beam and conducting time-consuming gravity measurements to identify the error minimum. In this work, we demonstrate a method to expediently determine the tilt of the Raman laser beam by transforming the tilt angle measurement into characterization of parallelism, which integrates the optical method of aligning the laser direction, commonly used in freely falling corner-cube gravimeters, into an atom gravimeter. A position-sensing detector (PSD) is utilized to quantitatively characterize the parallelism between the test beam and the reference beam, thus measuring the tilt precisely and rapidly. After carefully positioning the PSD and calibrating the relationship between the distance measured by the PSD and the tilt angle measured by the tiltmeter, we achieved a statistical uncertainty of less than 30 μrad in the tilt measurement. Furthermore, we compared the results obtained through this optical method with those from the conventional tilt modulation method for gravity measurement. The comparison validates that our optical method can achieve tilt determination with an accuracy level of better than 200 μrad, corresponding to a systematic error of 20 μGal in g measurement. This work has practical implications for real-world applications of atom gravimeters.

Keywords: atom interferometer, absolute gravimeter, precision measurement, tilt of Raman laser

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1. Introduction

Precision measurement of gravity is of great importance in various fields, including navigation,[1] resource exploration,[2] metrology[3] and geophysics.[4] Atom gravimeters, a promising type of absolute gravimeter, have demonstrated high accuracy[5–8] and high sensitivity,[9–11] and are capable of continuous measurement.[11–13] With their rapid development, atom gravimeters have been taken out of the laboratory[14] and play important roles in absolute gravimeter comparisons[15–19] as well as in field surveys of different modes of transportation, including cars,[20–23] boats[24,25] and planes.[26,27]

Since the output of a gravimeter is the projection of gravity acceleration onto its sensitive axis, any departure of the sensitive axis from the vertical direction introduces errors in gravity measurement. For absolute gravimeters, including both freely falling corner cubes[28,29] and freely falling cold atoms,[16,30–32] this departure from verticality is an important systematic error. In atom gravimeters, the sensitive axis is defined by the direction of Raman laser beams (also applicable to Bragg laser beams[11]). Typically, the tilt of the Raman laser beams in an atom gravimeter is evaluated by intentionally modulating the direction of the Raman laser and recording the corresponding gravimeter output.[16] While this modulation method can achieve precision at the level of tens of microradians, it is quite time-consuming. With the increase in promoting atom gravimeters for real-world applications, there is a growing demand for a more expedient method to determine the tilt of the Raman laser beams.[23] For atom gravimeters with milligal level precision, the requirement for accurate tilt measurement is relatively low, with a precision of only 1.5 mrad being sufficient.[22]

In fact, for freely falling corner-cube gravimeters, an effective optical method has already been developed to align the laser beams along the vertical direction.[28] In this approach, the parallelism of the beams reflected from a liquid surface and a corner cube, respectively, is utilized as an indicator of their verticality. Additionally, there is also related work discussing the alignment of laser beams using optical methods.[30,33,34]

In this paper, an optical method for determining the tilt of Raman laser beams is demonstrated. Here, a position-sensing detector (PSD) is utilized to quantitatively measure the parallelism between the test beam and the reference beam. With careful positioning and calibration, the tilt of the Raman laser beams can be precisely and rapidly determined. A comparison between the optical method and the aforementioned modulation method for determining the tilt of the Raman laser beams validates the effectiveness of our optical method.

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2. Principle

In atom gravimeters, the phase shift is related to gravity as $\Delta\varphi = \boldsymbol{k}_{\text{eff}} \cdot \boldsymbol{g}T^2$,[6] where $\boldsymbol{k}_{\text{eff}}$ is the effective wave vector of the Raman laser beams and T represents the interrogation time between Raman pulses. According to this equation, an atom gravimeter is in general a single-axis accelerometer measuring the projection of $\boldsymbol{g}$ along the direction of $\boldsymbol{k}_{\text{eff}}$. Therefore, the effective direction of the Raman laser beams determines the sensitive axis of the atom gravimeter. In absolute gravity measurements, when the Raman laser beams tilt from the vertical direction with an angle of θ, an error due to this projection will be caused as

$$\Delta g = g(\cos\theta - 1) \approx -g \times \theta^2/2, \tag{1}$$

where a small tilt angle θ is assumed. The tilt of the Raman laser beams is a major systematic error in gravity measurements. For example, a tilt angle of 45 μrad results in a systematic error of 1 μGal (1 μGal $= 10^{-8}$ m$\cdot$s^{-2}).

According to Eq. (1), the error manifests as a parabolic variation along with the tilt angle θ. It is thus natural to modulate the direction of the Raman laser beams and measure the corresponding parabolic variation of the gravity projection to determine the tilt angle θ for atom gravimeters.[16] While this tilt modulation method can achieve a precision of about tens of microradians, it is, however, time-consuming, especially considering that tilt modulation has to be implemented along two dimensions.[31]

As shown in Fig. 1(a), the incident beam $\boldsymbol{k}_1$ and the reflected beam $\boldsymbol{k}_2$ comprise the Raman laser beams; the tilt angle is denoted as θ, owing to the reflected beam being directed back into the fiber, where the coupling efficiency ensures that the reflected beam overlaps with the incident beam to a precision of approximately 10 μrad.[35] This overlap precision has a negligible impact on gravity measurements. Given this minimal effect, our study will primarily focus on the precise measurement of the tilt angle of the incident beam θ, as it is the key parameter that influences the alignment and the accuracy of the gravimeter. Figure 1(b) displays the scheme for measuring the tilt angle θ in our setup.[16]

A diaphragm is employed to reduce the diameter of the beam $\boldsymbol{k}_1$ from approximately 20 mm to about 2 mm, ensuring that the beam remains unobstructed throughout its path. Below the diaphragm, an optical flat (diameter 1 in, parallelism 15 μrad, transmission to reflectance ratio 50%:50%), whose best tilt angle to the vertical direction is 45°, is inserted into the optical path. Under ideal conditions the tilt of the diaphragm and optical flat will not influence the measurement at small tilt angles. The flat divides the beam into two parts.

The reference part, reflected from the upper surface of the flat, propagates horizontally and is then retroreflected by a corner cube (The parallelism tolerance between the incident beam and the reflected beam is better than 15 μrad). This part is finally directed into a two-dimensional PSD (PDP90A, Thorlabs) after passing through a convex lens and the flat again. The test part, after passing through the flat and two windows of the chamber, is reflected by a liquid surface, then reflected from the lower surface of the flat after traveling through two windows once again, and is finally directed onto the PSD after passing through the convex lens.

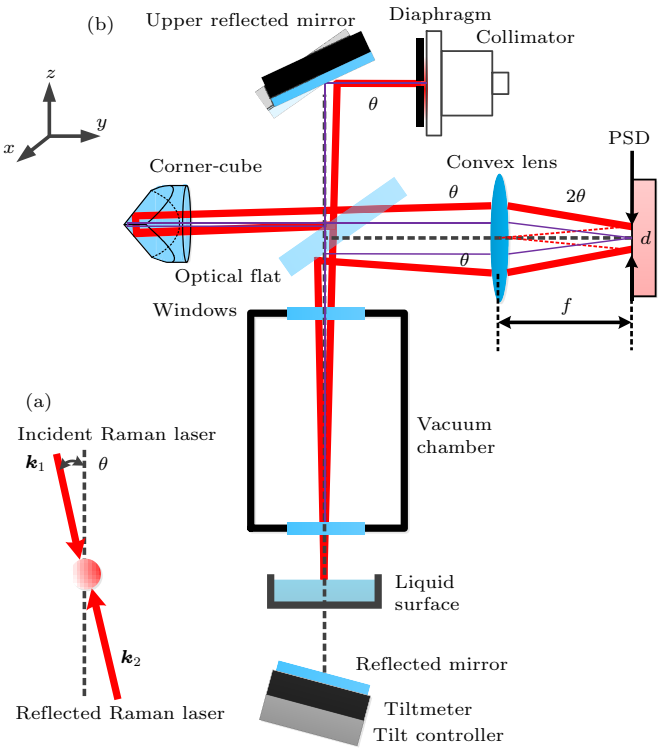


Fig. 1. (a) The configuration of the Raman laser beams. The incident Raman laser beam $\boldsymbol{k}_1$ has an angle of θ versus the gravity direction and the reflected Raman laser beam $\boldsymbol{k}_2$ coincides with the incident beam. (b) The optical system of the tilt measurement device showing the main components of the device. The diaphragm, the optical flat and the liquid container are moved away when conducting gravity measurements.

The liquid surface offers a reference for the vertical direction. In the ideal case, when the incident light is at 0°, the test part is parallel to the reference part, and these two parts, focused by the lens, converge at the focal point, which is captured by the PSD. The entire optical path is illustrated in Fig. 1(b) by purple lines. In fact, the angle between the reference part and the test part when transmitting between the flat and the convex lens is 2θ, given that $\boldsymbol{k}_1$ tilts from the vertical direction with an angle θ, as shown by bold red lines. In the small-angle condition, the angle can be decomposed into two dimensions, namely, $\theta_{x,y}$, where $\theta = \sqrt{\theta_x^2 + \theta_y^2}$. The convex lens and the PSD help measure the parallelism between the reference part and the test part quantitatively, with the PSD placed at the focal plane of the convex lens, giving the tilt angle measurement as

$$\theta_{x,y} = d_{x,y}/(2f), \tag{2}$$

where $d_{x,y}$ is the distance between the two focused spots of the reference beam and the test beam in two dimensions onto the PSD and f is the focal length of convex lens. A tilt measurement precision of 2 μrad can be expected with a focal length of 0.2 m and a typical precision of 0.75 μm for the measurement of $d_{x,y}$ by the PSD.

Compared with the modulation method where each dimension needs to be adjusted separately, using a PSD allows for quick recording of two-dimensional information. When the positions of the spot for the reference beam are measured, the test beam is blocked, and vice versa. Thus, the distance $d_{x,y}$ between the two spots can be deduced from the recorded positions. The tilt angle $\theta_{x,y}$ is then directly obtained through Eq. (2). The diaphragm, the flat and the container containing the liquid can be plugged in and are also removable when gravity measurements are performed, while the corner cube, the convex lens and the PSD are fixed with the gravimeter after being well adjusted. What is also important is to adjust the incident laser vertically and align the reflected laser with the incident laser; these methods are discussed in Section 4.

3. Experiment and results

3.1. PSD position optimization

For the optical method mentioned above, it is crucial to place the PSD at the focal plane of the convex lens to satisfy Eq. (2). To determine the optimized position for the PSD experimentally, the optical flat displayed in Fig. 1(b) is rotated by about 90°. This setup ensures that the two beams reflected from the front and back surfaces of the flat propagate directly towards the convex lens and PSD, as shown in Fig. 2(a). These reflected beams are nearly parallel, with the parallelism being limited only by the parallelism of the optical flat. After passing through the convex lens, these two beams intersect at the focal plane of the lens, which helps optimize the position of the PSD.

The positions of the two beams irradiated on the PSD are recorded sequentially, providing the distance between them. During the optimization, the position of the PSD is adjusted using a displacement platform, and the corresponding distance between the two positions is measured. The results are shown in Fig. 2(b). As expected, the distance changes linearly with the variation of the position of the PSD. By performing a linear fit of the data, the position corresponding to zero distance indicates the optimized PSD position. The uncertainty in determining the optimization position can achieve 0.09 mm. This optimized PSD position should be at the focal point of the lens, because if the PSD deviates from focal point by about 0.09 mm it would introduce an uncertainty with an upper limit of 30 μrad on the tilt angle measurement. Besides, the actual focal distance must be calibrated later.

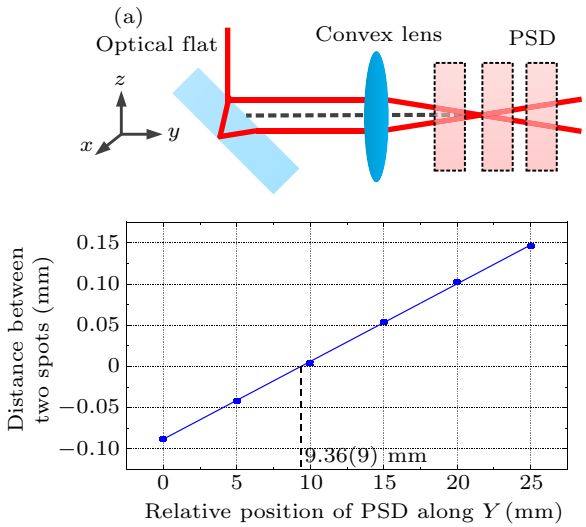


Fig. 2. Scheme and result for optimization of the PSD position. (a) Two nearly parallel beams are generated by the optical flat, and the crossing point along the Y axis serves as the correct position of the PSD. The position of the PSD can be adjusted by a displacement platform. Compared with the setup in Fig. 1(b), the optical flat has been rotated by about 90°. (b) Result for the optimization of PSD position; the distance changes linearly with variation of the position of the PSD.

3.2. Scale factor calibration

The direct output of the PSD consists of three voltages: $D_{x,y}$ and $S_{\rm sum}$. The actual position on the PSD can be calculated by

$$d_{x,y} = L_{x,y} \cdot D_{x,y}/(2 \cdot S_{\rm sum}), \tag{3}$$

where $L_{x,y}$ represent the resistance lengths of the sensor, with $L_x = L_y = 10$ mm. The uncertainty of $L_{x,y}$ is unknown; additionally, the focal length of the convex lens is usually provided with low precision so a scale factor calibration is conducted to eliminate its influence. Substituting Eq. (3) into Eq. (2), calibration is implemented to obtain the scale factors of $k_{x,y}$ that relate $D_{x,y}/S_{\rm sum}$ to the angle $\theta_{x,y}$, namely, $k_{x,y} = 4 \times f/L_{x,y} \approx 0.08$ mrad^{-1}. For calibration, the reflected Raman laser beam $\boldsymbol{k}_2$ acts as the test beam, and its angle can be adjusted by a tilt controller (PI S-340.ISL). The angle variation of the reflected Raman laser beam $\boldsymbol{k}_2$ is monitored by a

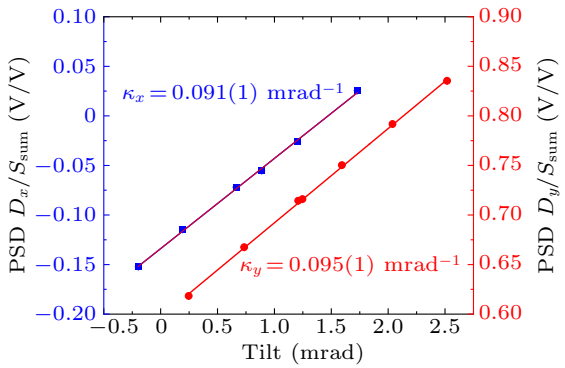


Fig. 3. The scale factors of the optical method for tilt measurement. The blue squares (red circles) represent the variation of PSD versus the relative tilt recorded by the tiltmeter along X (Y). The slopes of the data represent the scale factors.

tiltmeter, while the output of the PSD is simultaneously recorded during the angle variation. The angle is changed along two dimensions, X and Y, and the results are shown in Fig. 3. As expected, the output of the PSD changes linearly with angle variation. The scale factors of $k_{x,y}$ are 0.091(1) mrad^{-1} along X and 0.095(1) mrad^{-1} along Y.

3.3. Tilt measurement

With optimization of the PDS position and calibration of the scale factor, tilt measurement is prepared. For a demonstration, the direction of k_1 is varied at several different tilt angles along X (Y) by changing the tilt angle of the upper reflected mirror. For each tilt angle, tilt is measured using both the optical method and the conventional modulation method for comparison. Here the basic procedure for measuring the tilt of the Raman laser beam using the conventional modulation method is summarized. Firstly, given the angle of the incident Raman laser beam θ_1, gravity measurements are conducted by adjusting the tilt angle $T_{x,y}$ of the reflected mirror in each of the directions X and Y seven times. Based on a parabolic fit of the measurement results, the gravity measurement that keeps the reflected beam vertical is found, which corresponds to a specific angle of the incident Raman laser beam. The benefit of this approach is that it avoids the influence of changes in the reflected laser beam while modulating the incident laser beam. However, this process is time-consuming, as both the incident and reflected Raman laser beams need to be modulated. The results are shown in Fig. 4, where the X and Y axes represent the angle changes in the tilt of the reflected mirror in two dimensions, and the vertical axis represents the relative gravity measurement results. A fit is applied to obtain the gravity measurement value corresponding to the angle of the incident Raman laser beam θ_1.

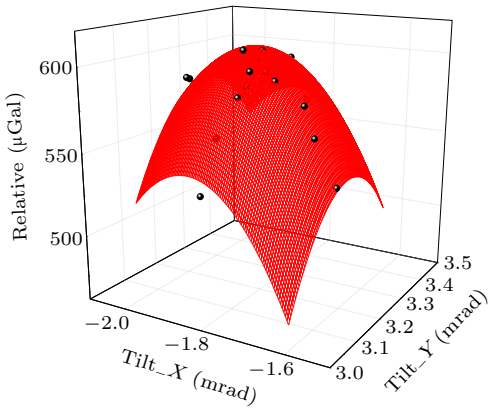


Fig. 4. The results of the reflected laser direction modulation at given incident beam angle. The X (Y) axes represent the readings of tiltmeter. The surface fitting was used to determine the direction of the mirror that makes the reflected beam vertical under the given incident beam angle.

This process is repeated with different tilt angles θ_j of the incident Raman laser beam (where j ranges from 1 to 9), generating nine sets of data for the angles and gravity measurements g_j. The maximum gravity measurement value is then fitted again, and the angle corresponding to this maximum gravity value is set to 0, from which the absolute tilt angles for the nine sets of incident angles are derived. As shown in Fig. 5, these nine sets of tilt angles of the incident Raman laser beam are represented by blue circles.

The results obtained using the optical method are shown in Fig. 5 by the red squares. It is shown that the statistical uncertainty for the optical method is about 30 μrad. Also note that there is a discrepancy between the results of the two methods. The main systematic error most likely arises from the wedge effect of the vacuum windows, as the optical method measures the tilt of the beam outside the vacuum chamber while the conventional modulation method measures the tilt of the beam inside the vacuum chamber. The accuracy is expected to be improved by solving the wedge effect, which also needs attention in freely falling corner-cube gravimeters. However, the discrepancy is less than 200 μrad in this demonstration, corresponding to a systematic error of 20 μGal in g measurement, which is already sufficient for many field applications using atom gravimeters.

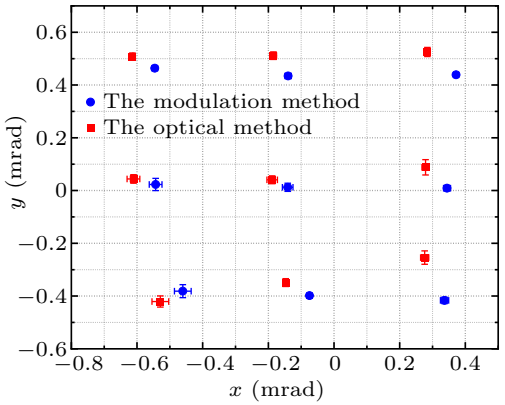


Fig. 5. The tilt of the Raman laser beams measured by two different methods. The red squares represent the measurement result using the optical method and the blue circles represent the measurement result using the conventional tilt modulation method for gravity measurement.

4. Discussion and conclusion

Besides measuring the tilt, it is also convenient to adjust the directions of the beams vertically using the optical method. Firstly, a liquid is inserted and the spot of the test beam reflected from the liquid surface is recorded. Then, the reflected mirror is adjusted to ensure that the reflected beam irradiates at the same position on the PSD with the liquid removed. In this way, the surface normal of the reflected mirror is set at the vertical direction. Finally, the direction of the incident beam is adjusted to guarantee that the test beam irradiates at the same position as that of the reference beam on the PSD. Thus, both the down-shooting beam and up-shooting beam are adjusted vertically.

In conclusion, we have demonstrated an optical method for rapidly determining the tilt angle of Raman laser beams. Optimization of the position of the PSD and calibration of the scale factor were carefully performed. According to the measurement results, a statistical uncertainty for the tilt measurement by this optical method of about 30 μrad can be achieved. Compared with the measurement result obtained using the conventional modulation method, there is a discrepancy of less than 200 μrad, which is most likely due to the wedge effect of the vacuum windows. The demonstrated optical method is expected to be applied in many field applications that use atom gravimeters.

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