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Continuous Dynamic Rotation Measurements Using a Compact Cold Atom Gyroscope *

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We present an experimental demonstration of the rotation measurement using a compact cold atom gyroscope. Atom interference fringes are observed in the stationary frame and the rotating frame, respectively. The phase shift and contrast of the interference fringe are experimentally investigated. The results show that the contrast of the interference fringe is well held when the platform is rotated, and the phase shift of the interference fringe is linearly proportional to the rotation rate of the platform. The long-term stability, which is evaluated by the overlapped Allan deviation, is 8.5×10^{-6} rad/s over the integrating time of 1000 s.

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Atom interferometers (AIs) have been successfully applied in many scientific and technical fields.^[1–9] The progress of AIs is accelerating the development of inertial instruments, including the atom gravimeter,^[10–12] the atom gradiometer,^[13–15] and the atom gyroscope (AG).^[16,17] The AG has high sensitivity, and it becomes a potential sensor in the inertial navigation.^[18] The AG can also be used to measure the rotation of the Earth,^[19,20] and it is a powerful tool for the study of geophysics.^[21]

The principle of the AG is based on the Sagnac effect of atom interference loops. It was verified by the optical Ramsey spectroscopy of thermal AIs in a rotating frame,^[22] and the absolute rotation measurement was first demonstrated by a thermal AG,^[23] where the contrast of the interference fringe is decreased when the frame is rotated. This is mainly caused by the velocity distribution of thermal atoms, and it is not conducive to applications including the inertial navigation when the dynamic measurement is considered in the different rotating frames.

The cold AI may avoid the influence of velocity distribution due to the better coherence of cold atoms. In principle, the cold AG is better than the thermal one, and it is a new rotational sensor for the high-precision inertial navigation. Previous works on cold AGs mainly focused on improving the stationary sensitivity by enlarging the interference area using the double-diffraction technique,^[24] suppressing the common phase noise using dual AIs^[25] and composite-light-pulse configuration.^[26] Recently, in the stationary frame, the short-term sensitivity of 100 nrad/s/Hz^{1/2} and the long-term stability of 1 nrad/s are demonstrated in a cold AG, which are the best level of the cold AG at present.^[27] However,

in an actual application, it is necessary to continuously measure the dynamic rotation, thus it is important to investigate the characters of the cold AG in the rotating frame.

In this Letter, we present an experimental demonstration of the rotation measurement using a compact cold AG. The cold atoms are manipulated by three counter-propagating Raman pulses. The atom interference fringes are observed in the stationary frame and the rotating frame, respectively. The contrast of the interference fringe is well held at different rotation rates, and it is not affected by the atomic velocity distribution when the platform is rotated. The phase shift due to Sagnac effect is observed by rotating the platform, and the relationship between the phase shift of the interference fringe and the rotation rate of the platform is investigated.

The experimental setup, which is similar to that in our previous works,^[28,29] is mounted on a rotation platform. The ⁸⁵Rb atoms are first loaded into a magneto-optical trap (MOT) from the background vapor, and then they are launched by the optical moving molasses, with a velocity of 2.5 m/s and an angle of 14.0° with respect to the gravity direction. The polarization-gradient cooling is synchronously applied when the atoms are accelerated in the MOT region. Thus an atom fountain is formed with low-temperature atoms, where the atoms are propagating along a parabolic trajectory.^[29] After the atoms are prepared in one ground state, they are operated by three Raman pulses. The population of another ground state is detected by the laser induced fluorescence, and the cold atom interference fringes are observed by scanning the phase of Raman lasers.

To build the cold AG, the counter-propagating Ra-

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man lasers are used to coherently manipulate the cold atoms. The diagram of the counter-propagating lasers is shown in Fig. 1(a). A pair of Raman lasers (ω_0 and $\omega_0 + \delta$), which are perpendicular to the gravity direction, are applied when the atoms undergo the apogee of the parabolic trajectory. These Raman laser beams with the horizontal linear polarizations are reflected by a mirror. Another pair of Raman lasers (ω_0 and $\omega_0 + \delta$) with the vertical linear polarizations are counter-propagating after double-passing a $\lambda/4$ plate. The two pairs of Raman lasers are completely overlapped by carefully adjusting the angles of the mirror. There are several combinations of Raman transitions in Fig. 1(a), which are caused by the counter-propagating and the co-propagating Raman laser pairs due to their imperfect polarizations. To avoid these influences, the propagating direction of Raman lasers is inclined at an angle of 6.0° , with respect to the perpendicular direction of atomic trajectory. When they are manipulated by the counter-propagating Raman lasers, the atoms obtain two-photon recoil momentums and the populations are transferred in the different states as shown in Fig. 1(a). Therefore, the atom interference loop is formed by using three Raman pulses ($\pi/2 - \pi - \pi/2$), as shown in Fig. 1(b). The atoms in the state $F = 2$ are split into the states $F = 2$ (solid line) and $F = 3$ (dashed line) by the first pulse, and both of them are reflected by the second one. The atomic wave packets are recombined by the third pulse, and the atom interference process occurs.

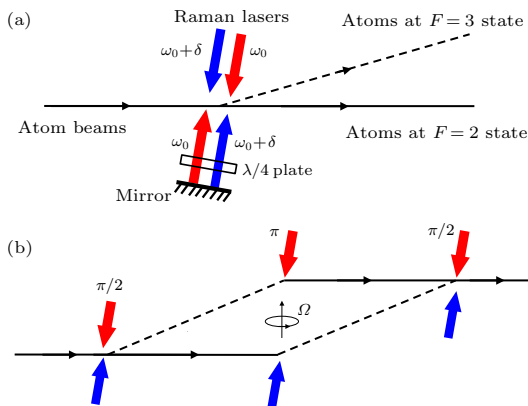


Fig. 1. (Color online) Schematic diagrams of the counter-propagating Raman lasers (a) and the cold atom gyroscope built by three counter-propagating Raman pulses (b). Here ω_0 and $\omega_0 + \delta$ are the frequencies of the two Raman lasers, and δ is frequency difference between them. The experimental setup is mounted on a rotation platform, and the rotation rate is measured by modulating the platform.

Due to the fact that the Raman transitions are sensitive to the atomic velocity and the velocity distribution in the counter-propagating configuration, the Raman pulses should be narrow enough to increase the atom numbers that participated in the interference process. To increase the Rabi frequency, the powers of the Raman lasers should be increased as much as possible. In our experiment, the durations of the Ra-

man pulses are several tens of microseconds, which require that the powers of the Raman lasers should be several hundreds of milliwatts. The Raman lasers are generated by the ± 1 order diffraction beams of a 1.5 GHz acousto-optic modulator (Brimrose GPF-1500-200-780).^[28] A feedback loop is applied to suppress the phase noise at the low frequency band.^[30] Then, the Raman lasers with the same linear polarizations are injected into a homemade tapered amplifier. With this method, the Raman lasers with the frequency difference of 3.0 GHz and the total powers of 800 mW are achieved.

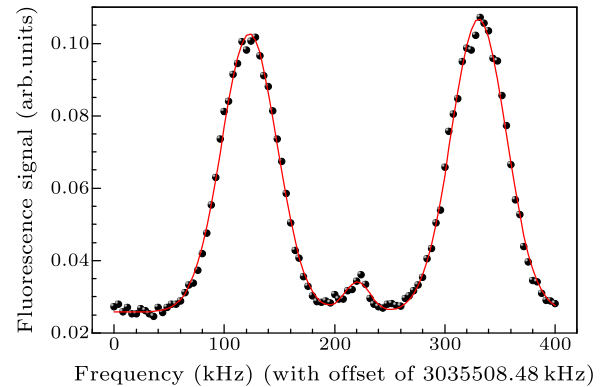


Fig. 2. (Color online) The dependence of the Raman transitions on the two-photon detuning. The Raman transitions are observed with the counter-propagating Raman lasers (left and right peaks). The middle peak corresponds to the co-propagating Raman transition, due to the imperfect linear polarization of Raman lasers.

The Raman lasers are sent to the interference area by a polarization maintaining fiber, and they are collimated by an aspheric lens with the diameter of 35 mm. In the experiment, the Raman lasers, with the total powers of 170 mW, the diameter of 27 mm at $1/e^2$ and the pulse durations of 15–30 μ s, are used to coherently manipulate the cold atoms. To suppress the ac Stark shift, the power ratio of the Raman lasers is carefully adjusted to 3.6:1, when one-photon detuning of 1.5 GHz is considered.^[31] With two-photon detuning scanned by a microwave generator, the Raman transitions are observed, as shown in Fig. 2. Due to the Doppler shifts, the Raman transitions, caused by the counter-propagating and the co-propagating Raman lasers, are completely separated. Therefore, three transition peaks are observed as shown in Fig. 2. The left peak is induced by the counter-propagating Raman lasers ($\omega_0, \omega_0 + \delta$), while the right peak is obtained by the counter-propagating Raman lasers ($\omega_0 + \delta, \omega_0$). Due to their imperfect polarizations, the middle peak is caused by the co-propagating Raman lasers. When the transit time of 30.0 μ s is only considered in the experiment, the width of Raman transitions should be 30.0 kHz. However, the actual width is 50.2 kHz in the counter-propagating Raman transitions (left and right peaks). This is mainly caused by the atomic velocity distribution with the temperature of 3.9 μ K.

Based on two-photon recoil momentums, the cold

AG is built by the counter-propagating Raman lasers, as shown in Fig. 1(b). When the atoms are prepared in the state of $F = 2, m_F = 0$ (solid line), they are manipulated by three Raman pulses. The population of the state of $F = 3, m_F = 0$ (dashed line) is given by^[17,18]

$$P = 1 + \frac{1}{2} \cos(\Delta\Phi), \quad (1)$$

where $\Delta\Phi$ is the total phase, including the phase shift induced by the Sagnac effect. In addition, the phases of the Raman lasers are imprinted on the states of the atoms. After the atoms are split, deflected and recombined, the total phase is written as

$$\Delta\Phi = 2\mathbf{k}_{\text{eff}} \cdot (\Omega \times \mathbf{v})T^2 + \phi_1 + \phi_2 + \phi_3, \quad (2)$$

where ϕ_j is the phase of the j th Raman pulse, $\mathbf{k}_{\text{eff}}$ is the effective wave vector of the Raman lasers, $\mathbf{v}$ is the atomic velocity in the horizontal plane, which is 0.6 m/s in our experiment, T is the free evolution time between two adjacent pulses; Ω is the rotation rate of the frame, and $2\mathbf{k}_{\text{eff}} \cdot (\Omega \times \mathbf{v})T^2$ is the phase shift caused by the Sagnac effect. From Eqs. (1) and (2), the atom interference fringes can be obtained by scanning ϕ_j .

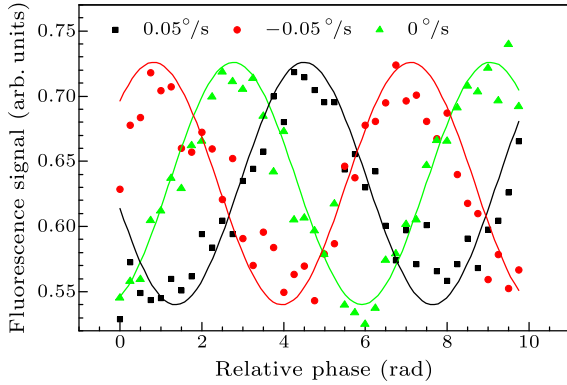


Fig. 3. (Color online) The interference fringes versus the rotation rates of the platform. The initial phases are 1.21 ± 0.05 rad (green triangles) without the rotation, while 2.93 ± 0.06 rad (black squares) and -0.65 ± 0.07 rad (red dots) with the rotation rates of $0.05^\circ/\text{s}$ and $-0.05^\circ/\text{s}$.

The atom interference fringes are displayed as the population of the state $F = 3, m_F = 0$. An electro-optical modulator (EOM, New Focus 4002) is inserted in one path of the Raman lasers, and the differential phase of the Raman lasers is scanned by adjusting the voltage of the EOM. When the platform is rotating, its rotation rate is detected and calibrated by a goniometer (Renishaw RESM), which has an angle resolution of 0.008 arc-second. The platform is driven by a dc torque motor, and the rotation rate is a constant during the measurements. By carefully adjusting the pulse durations of Raman lasers, Raman pulse sequences ($\pi/2 - \pi - \pi/2$) are applied to manipulate cold atoms. When we scan the phase of one Raman laser, the atom interference fringes at different rotation rates are observed. As shown in Fig. 3, the fringe

without rotating the platform is shown in green triangles, and the fringes are observed when the platform is modulated with the rotation rates of $0.05^\circ/\text{s}$ (black squares) and $-0.05^\circ/\text{s}$ (red dots), respectively. They are fitted by the sinusoidal functions, which are consistent with Eq. (1). The contrast of the fringes are more than 14.7% with and without rotating the platform. Due to the Sagnac effect, the initial phases are shifted when the platform is rotated, which are consistent with Eq. (2). Fortunately, the contrasts with and without rotating the platform are completely the same. This implies that the sensitivity is not affected when the platform is slowly rotated. In principle, the dynamic range (the maximum rotation rate) is limited by the thermal velocity distribution of cold atoms. With the numerical simulation, the dynamic range can be up to $1.5^\circ/\text{s}$ in our experimental setup. However, in this work, the lasers are sent to the vacuum setup by using optical fibers due to the fact that the vacuum setup and the optical device are separately mounted on the different tables. The fibers will be twisted together if the platform is quickly rotated, which limits the measurements in our experiments.

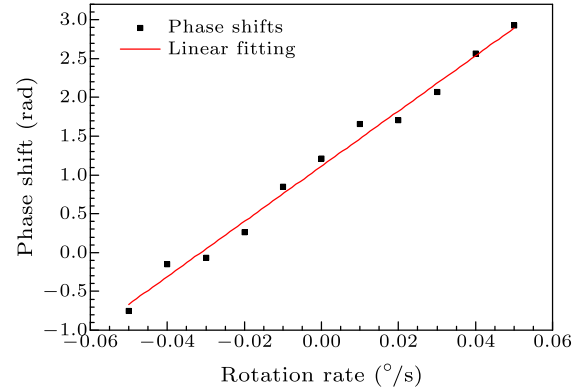


Fig. 4. (Color online) The dependence of the phase shift of the fringe on the rotation rate of the platform. The phase shifts (black squares) are caused by the Sagnac effect, and the linear relationship is perfectly verified (red line).

For a good AG, the linear relationship is necessary in the whole dynamic range. Here the dependence of the phase shift on the different rotation rate is investigated. Similar to Fig. 3, the fringes are obtained with the different rotation rates of the platform. Their initial phases are extracted as shown in Fig. 4. The result shows a perfect linear relationship between the phase shift and the rotation rate. After the linear fitting, the scale factor is $34.0 \pm 1.2 \text{ rad}/(^{\circ}/\text{s})$, which is consistent with the theoretical value of $33.9 \text{ rad}/(^{\circ}/\text{s})$ for $2T = 20 \text{ ms}$. The dominant error sources are the amplitude noise and the acceleration phase shift in the different positions when the platform is rotated. Moreover, as the platform is rotated by an air-bearing motor, the fluctuation of the rotation rate and the magnetic field will also influence the measurement.^[32] From Fig. 4, the relationship between the phase shift

of the interference fringe and the rotation rate of the platform is a perfectly linear function, which implies that the continuous dynamic rotation can be measured by the cold compact AG.

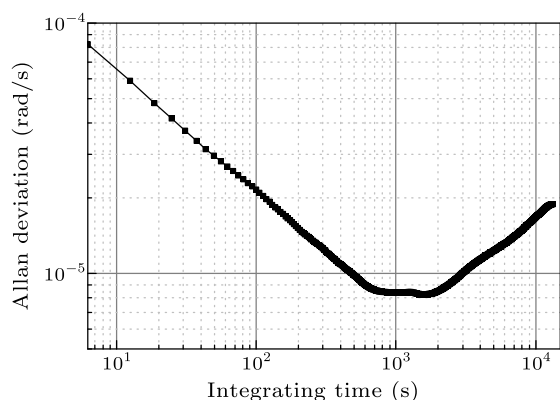


Fig. 5. Allan deviation (overlapped) of the AG. Obviously, the short-term sensitivity is $2.2 \times 10^{-4} \text{ (rad/s)[Hz]}^{-1/2}$, and the long-term stability is $8.5 \times 10^{-6} \text{ rad/s}$ over the integrating time of 1000 s.

To evaluate the performance of the cold AG, the square wave modulation method is used during the measurements. In the experiment, the outputs are set to two adjacent mid-fringe points by adjusting the voltage of the EOM, where the signals are most sensitive to the rotation. The square wave voltages are alternately modulated. The populations of $P(\Delta\Phi)$ and $P(\Delta\Phi + \pi)$ are measured, where the common noise is suppressed by subtracting $P(\Delta\Phi)$ from $P(\Delta\Phi + \pi)$. In the experiment, the data were taken to be about 29 h, and each data is obtained for 6.2 s. The Allan deviation (overlapped) of the measurements is shown in Fig. 5. The short-term sensitivity is $2.2 \times 10^{-4} \text{ (rad/s)[Hz]}^{-1/2}$. The long-term stability is $8.5 \times 10^{-6} \text{ rad/s}$ over the integrating time of 1000 s. The performance becomes worse when the integrating time is longer than 2000 s. The short-term sensitivity is limited by the vibration noise, and the long-term stability is limited by the temperature drift in our lab.

In conclusion, we have built a compact cold AG. The atom interference fringes are observed in the stationary frame and the rotating frame, respectively, and the contrast is well held. The phase shift induced by the Sagnac effect is investigated by modulating the rotation rate of the platform. The perfect linear relationship between phase shift of the fringe and rotation rate of the platform is observed by rotating the platform. The experimental results imply that the atomic velocity distribution does not limit the sensitivity of the cold AG. The continuous dynamic rotation can be measured by the compact cold AG. The performance of the cold AG can be improved by using a dual-loop configuration, reducing the common phase noise and improving the laser stability in the future.

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