A Cold Atomic Beam Interferometer

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We demonstrate an atom interferometer using a laser cooled $^{87}$Rb atomic beam with a velocity of $10 \sim 20 m/s$. Three spatial-separated Raman laser pulses were used to coherently manipulate atomic wave packages. Raman-Ramsey and Mach-Zehnder interference fringes were observed respectively in a distance of 19 mm. The device is operated at a bandwidth of 790Hz with the deduced sensitivity of $4.4 \times 10^{-5} rad/s/\sqrt{Hz}$ for rotations, even with a small enclosed area of 0.07mm$^2$. The use of the low-velocity continuous atomic source in an atom interferometer allows high sampling rate and bandwidth without losing the systematic sensitivity and compactness, which is important for applications in real dynamic environments.

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I. INTRODUCTION

Since their inception in 1991 [1, 2], Light-pulse atom interferometers (LPAI) have shown the potential to be an extremely sensitive sensor in many applications like gravimeter surveys [3, 6], seismic studies [7], inertial navigation [8, 11], tests of fundamental physics [12], and measurements of fundamental constants [13]. A LPAI-based gyroscope has demonstrated an excellent performance on short-term noise, long-term stability, and bandwidth ($\sim 110 Hz$) [9, 14]. But it is a little difficult for a thermal atomic beam interferometer gyroscope to reduce the systematic dimension without discounting sensitivity performance for the high longitudinal atomic velocity ($220 \sim 300 m/s$).

Using cold atoms is a common solution to construct a compact atomic interferometer and a pulse-launched cold atom cloud is usually used as its matter wave source [11, 15, 16]. However in their current forms, the pulsed source based LPAIs are ill-suited to compliment or replace conventional technologies in the more dynamic environment due to their relatively long cycle time and therefore low data rate, which is the inverse of the interferometer cycle time. To date, most reported cold LPAIs demonstrations have operated at a data rate on the order of a few Hertz or less. Although combination of conventional and atom interferometer technologies may be a promising solution to the real application of such cold LPAIs [17, 18], significant advances in performance of a LPAI or the data rate improvement up to the order of 100 Hz or more are required. Another method is the short interrogation LPAI or high data rate LPAI [19, 20], which trade sensitivity for data rate and reduced system demands.

Instead of making a trade between the data rate and sensitivity by using short interrogation LPAI with pulsed cold atomic source, our alternative method is eliminating the dead times (time intervals without atoms in the interference region) by making use of a continuous beam of cold atoms. The use of continuous atomic sources is also helpful to reduce noises induced by intermodulation effects and collision shifts [21, 22]. An atomic fountain clock with a continuous cold atomic beam has been demonstrated with a stability of $6 \times 10^{14}/\sqrt{T}$ [23], which give a good solution to challenges provided by a continuous cold atomic source like shielding the fluorescence from the atomic source, compared with its pulsed counterpart. In this paper, we proposed a new atom interferometer, which used a continuous cold atomic beam as the source and spatial-separated Raman pulses for coherent manipulation of atomic wave-packets. Low-velocity continuous atomic beam allows high sampling rate and bandwidth, without sacrificing systematic sensitivity and compactness. The real-time frequency or phase modulation techniques can also be implemented in such LPAI setup.

II. SETUP

The diagram of the experimental setup is shown in Fig.1. The low-velocity intense atomic beam is generated by a vapor-cell three-dimensional magneto-optical trap (3D-MOT), which was demonstrated in a previous study [24]. The vacuum chamber of the 3D-MOT and that of the atomic beam region are connected only with a 1 mm hole in the center of a $\lambda/4$ plate (QWP1) and a mirror (M1). The atoms are cooled and trapped by...
FIG. 1. (a) Schematic of the experimental layout for the atom interferometer based on a laser-cooled $^{87}\text{Rb}$ atomic beam. BS: beam splitter; M: mirror; HWP: half-wave plate; QWP: quarter-wave plate; PMF: polarizing maintained fiber; FEOM: fiber electro-optic modulator; TA: tapered diode laser amplifier; PMT: photomultipliers. (b) A diagram of the ground states $|1\rangle$ and $|2\rangle$ and the excited state $|e\rangle$. The frequencies $\omega_1$ and $\omega_2$ are used to induce Raman transitions between two ground states. (c) The $\pi/2 - \pi - \pi/2$ pulse sequence is realized by blocking a Gaussian beam with pulse widths of $d = 1.0\ mm$ and intervals of $L = 9.5\ mm$.

Lasers. The cooling laser is tuned to the resonances of $^{87}\text{Rb} \ 5s^2S_{1/2}, F = 2 \rightarrow 5p^2P_{3/2}, F' = 3$, with a typical $\delta = 4 \sim 5\Gamma$ red detuning (where $\Gamma = 6\ MHz$ is the natural linewidth of $^{87}\text{Rb}$) and the repumping laser is tuned to $5s^2S_{1/2}, F = 1 \rightarrow 5p^2P_{3/2}, F' = 2$ transition. Six mutually perpendicular cooling beams are focused on the zero center of the quadrupole magnetic field, which is generated by a pair of anti-Helmholtz coils. The unbalanced 3D-MOT is produced by a tubular cooling beam along the z-axis reflected by QWP1 and M1. The cold atomic beam is launched from the unbalanced 3D-MOT continuously at an angle of $3.7^\circ$ with respect to the horizontal direction. Consequently, the atomic beam is separated from the leaking cooling light beam by the gravity. The most probable longitudinal velocity of the atomic beam varies from 10 m/s to 20 m/s and the atomic flux can be tuned up to $4 \times 10^9$ atoms/s. The atomic beam ejected from the 3D-MOT in the ground state of $F = 2$ is pumped into a single hyperfine $F = 1$ level by the optical pumping laser 1, as shown in Fig.1, which is tuned to the $5s^2S_{1/2}, F = 1 \rightarrow 5p^2P_{3/2}, F' = 2$ transition. The optical apparatus of the Raman lasers is shown in Fig.1. The master laser is a 780 nm external cavity diode laser (ECDL, typical linewidth of 300 kHz, DL Pro, Toptica, Germany), which is frequency-stabilized using an optical meter (WS100, Toptica, Germany) with a large red detuning $\Delta = 1.07\ GHz$ from the $F = 1 \rightarrow F' = 1$ transition as $\omega_1$. The two slave lasers are GaAsP/AlGaAs Fabry-Perot CW diode lasers. Slave laser 1 is injection-locked to the frequency-shifted master laser by an AOM driven by 60 MHz signal, operating with $\omega_1$. Another master laser beam passes through a fiber electro-optic modulator (FEOM, EOspace, USA), driven by a 6.775 GHz ($\omega_00 + 60\ MHz$) RF signal, where $\omega_00 = \omega_1 - \omega_2$ corresponds to the ground-state hyperfine transition of $^{87}\text{Rb}$. Slave laser 2 is synchronized with the -1 sideband of the FEOM output by the frequency-selective sideband injection-locking technique, which was illustrated in our previous work[25]. The 6.775 GHz and the 60 MHz RF source are finally referred to a Cs atomic clock. The 3dB line-width of the beat note between $\omega_1$ and $\omega_2$ is $\sim 1.5\ Hz$. The beams of slave laser 1...
and slave laser 2 are both amplified separately by two semiconductor laser amplifiers (TA1 and TA2, BoosTA, Toptica, Germany), and the intensities could be amplified up to approximately 600 mW. The two beams are then combined into a single-mode polarization-maintaining fiber with crossed polarizations and expanded by a Gaussian doublet fiber coupler with a diameter of 60 mm. Then, the Gaussian beam is blocked by a slice, with three parallel slits with spacings of \( L = 9.5 \text{mm} \) and the same widths of \( d = 1.0 \text{mm} \), which allows the intensity of the two \( \pi/2 \) pulses to be half that of the \( \pi \) pulse in the center of the Gaussian beam, as shown in Fig. 2(a). By adjusting the distance between the lens (\( f = 220 \text{mm} \)) and the fiber, the two \( \pi/2 \) Raman pulse beams, with equal optical paths, could be parallel with the \( \pi \) pulse. Three Raman pulse beams with crossed linear polarization are made opposite circular polarizations with a quarter-wave plate (QWP2). After passing through the atomic beam, the light fields are linearized by another quarter-wave plate (QWP3) and \( \omega_1 \) and \( \omega_2 \) are spatially separated by a polarizing beam splitter (PBS). Only \( \omega_1 \) is retro-reflected through the atomic beam. The counter-propagating Raman laser beams are generated for Doppler-sensitive Raman transitions in the form of \( \sigma^+ - \sigma^+ \) or \( \sigma^- - \sigma^- \). The three Raman beams are set on the same optical table and could be rotated relative to the atomic beam. Removing the QWP2 and blocking the retro-reflected beam allows Raman transitions in Doppler-insensitive geometries.

The first cold atomic beam based interference fringes were observed by varying the optical phase of the \( \pi \) Raman pulse. This was achieved by tilting a phase plate (a 9.53 mm thick optical flat) located at 45° in the \( \pi \) Raman pulse, which is rotated by a piezo-electric transducer (PZT, Pst 150/4/7 bs, Piezomechanik GmbH). The Raman beams are spatially filtered separately, making it convenient to shift only the phase of \( \omega_1 \). The phase of \( \omega_1 \) is shifted by varying the optical path length of \( \omega_1 \) through the glass by adjusting the plate angle. To detect the atomic signals, e.g., the interference fringes, the fluorescence of the \( F = 2 \) state atoms induced by the detection laser beam (\( F = 2 \rightarrow F' = 3 \)) is continuously collected by a photomultiplier tube (PMT, H7422-50, Hamamatsu, Japan). A constant bias magnetic field along the Raman beams for Zeeman holding is applied over the entire interaction length by a set of four wires driven by a \( \sim 4 \text{A} \) current running along the interaction length of the vacuum chamber (not shown in Fig.1).

### III. RESULT

The velocity and flux of the MOT-based cold atomic beam were measured by the time-of-flight (TOF) method, which was realized by plugging the atomic beam and simultaneously recording the falling edge of the fluorescence signal of atoms in \( F = 2 \) state. The spectrum of the atomic velocity was deduced from the TOF signal, as shown in Fig.2(a). The most-probable longitudinal velocity of the atomic beam was adjusted to be \( v_{z0} = 15 \text{m/s} \), with a velocity distribution of \( \delta v_z = \sim 3.5 \text{m/s} \) (FWHM) by changing the polarizations of cooling lasers and the magnetic field gradient. The atomic flux was tuned to \( \sim 1 \times 10^9 \) atoms/s, which was high enough to measure the signal of the interferometer by collecting the fluorescence of atoms in \( F = 2 \) state directly.

The atoms were populated into \( F = 1 \) ground state after the atoms launched from the 3D-MOT. They were asymmetrically distributed in all ground-state hyperfine \( m_F \) levels as shown in Fig.2(b) with a blue dash line, which was the spectrum of Raman transitions driven by \( \pi \) pulse. As shown in Fig.2(b) with a black solid line, we used another linear polarized optical pumping beam, 2, to further pump atoms into \( F = 1, m_F = 0 \) level (\( \Delta m = 0, \pm 1 \)) from other \( m_F \) hyperfine levels. The alignment of the bias magnetic field and the Raman beams is important to get high state preparation efficacy, or 7.
Raman peaks instead of 3 peaks will occure because π and σ Raman transitions both happen, as is shown in Fig. 2(b). In this setup, we should minimize the magnitude of the π transition of \( F = 1 \rightarrow F' = 0 \), otherwise atoms in \( F = 1, m_F = 0 \) level would be ill dispersed into other magnetic field sensitive ground-state hyperfine levels, as shown in Fig. 2(b) with the red dot line.

Continuous Raman beams with a constant width of \( d = 1.0\, \text{mm} \) for one pulse were used to manipulate the continuous cold atomic beam. The duration time \( \tau = d/v_x \) of the Raman pulse was constant, where \( v_x \) is the longitudinal atomic velocity with a velocity distribution as shown in Fig. 2(a). The Rabi frequency \( \Omega_\text{eg} \) was adjusted by varying the intensities of Raman lasers of \( \omega_1 \) and \( \omega_2 \), and therefore the Rabi phase \( \phi = \Omega_\text{eg} \tau \) could be set as \( \pi/2 \) or \( \pi \). The corresponding spectra driven by the Doppler-sensitive \( \pi/2 - \pi - \pi/2 \) Raman pulse sequence were shown in Fig. 3. The amplitudes of the spectra driven by two \( \pi/2 \) pulses were adjusted to be equal and to be half the value of the π pulse. By tilting the Raman beams slightly apart from the perpendicular direction with the atomic beam, the Doppler-sensitive transition peaks were exactly shifted from peaks of the residual Doppler-insensitive transitions as a result of the impure polarizations of Raman lasers. Doppler shifts and recoil shifts were compensated by offsetting the difference of \( \omega_1 - \omega_2 \). The transversal velocity spread of the atomic beam was approximately \( \pm 6.5\, \text{cm/s} \) (FMHW), which was estimated from the \( \sim 336\, \text{kHz} \) linewidth of the profile driven by the π pulse (\( \tau = 67\, \mu\text{s} \)).

In the implement of cold atom interferometer with Raman pulses, it is difficult to fulfill the stringent requirements with respect to the parallel alignment of the separated Raman beams. This results from the fact that the beam divergence of the cold atomic beam with slow velocity is larger compared to fast thermal beams with a similar transversal equivalent temperature [14]. Therefore, the Raman beams should be set precisely for the interferometer implement before an interference signal can be seen. The linewidth of the Raman resonance is \( \Delta \delta_{12} \approx 2\pi \frac{\theta}{r} \frac{\Omega_{\text{eg}}}{d} \). For the horizontal alignment, the Doppler shift, \( -k_{\text{eff}} v_x \sin \theta \), in the Raman transition must be smaller than the linewidth \( \Delta \delta_{12} \). This implies \( \theta < 91\, \mu\text{rad} \), while the atomic velocity is \( v_x = 15\, \text{m/s} \) and the Raman pulse widths are \( d = 1.0\, \text{mm} \). By adjusting the distance between the lens and the fiber, and monitoring the feedback light into the fiber, we can achieve \( \theta < 91\, \mu\text{rad} \) between three Raman beams (The fiber core is 5\( \mu\text{m} \) in diameter, and \( NA = 0.11 \)). Otherwise, three separated Raman beams will interact with atoms of different transversal velocities respectively. The vertical Raman beam alignment is equally critical. It could be assumed that three beams generated from the same fiber coupler are substantially parallel in the vertical direction.

The signal of the \( \pi/2 - \pi - \pi/2 \) Mach-Zehnder atom interferometer could be write as

\[
P_e = \frac{1}{2} [1 + \cos(\Phi_a + \Phi_\Omega + \phi_1 - 2\phi_2 + \phi_3)]
\]  \( \text{(1)} \)

where \( \Phi_a \) is the phase shift caused by acceleration; \( \Phi_\Omega \) is the Sagnac phase shift caused by rotation; \( \phi_1, \phi_2 \) and \( \phi_3 \) are effective phases of \( \pi/2 - \pi - \pi/2 \) Raman pulses respectively. We first observed interference fringes by scanning the phase of pulse by the phase plate, and the phase shift of the interferometer output should be twice that of the π pulse. The interference fringes as a function of 2\( \phi_2 \) is shown in Fig. 4, and served to explicitly verify the relationship between the interferometer phase...
shift and the phase of the $\pi$ pulse. The maximum extension of the PZT was 9 $\mu$m, which could yield $\sim 30 \text{rad}$ phase shift of the interference signal. This has been certified by the numerical evaluation of the $\pi$ pulse phase shift as a function of the rotation angle of the phase plate. This phase modulation technique will be used for compensating and modulating the phase of the interferometer signal. For instance, if the phase plate is used in a servo loop to control the optical phase for maintaining a constant gyroscope signal, the rotation information can be read from the servo error signal.

There are several reasons for the contrast reduction of interference fringes. First, the longitudinal velocity spread is primarily responsible for the contrast reduction. Phases of Raman pulses ($\pi$ and $\pi/2$) were set to be optimal for the most probable longitudinal velocity $v_{z0}$ of the atomic beam. The ratio of $n = v_{z0}/\delta v_z = \sim 4$ is larger than that ($n = \sim 1$) with thermal atomic beams[14]. That means that a cold atomic beam with narrow longitudinal velocity distribution may lead to a higher interference contrast in the atom interferometer, compared with its thermal counterpart.

Secondly, the transversal velocity spread of the atomic beam will further decrease the contrast. When we use Doppler-sensitive Raman pulses (co- propagate beams), atoms in the range of $\Delta v_x = \delta_2/k_{c eff}$ will be selected to interact with Raman pulses, where $k_{c eff}$ is the effective wave vector. The linewidth of the Raman transition was $12k\text{Hz}$ and the selected velocity range was about $\Delta v_z = 5mm/s$, when the width of Raman beams was set to be $d = 1.0mm$. This selected velocity range was much less than the measured transversal velocity spread of $\pm 6.5cm/s$. Atoms beyond the range could not be manipulated effectively and the contrast and the signal-noise-ratio of the interference signal were badly decreased. It is a big challenge for a cold atomic beam interferometer to increase the velocity-selected range. It is a valid method to decrease the width $d$ of Raman beams for getting a larger range. At present, we have realized Raman transitions driven by Raman beams with $d = 0.28mm (\Delta v_z = 16.4mm/s)$.

Furthermore, the transverse dimensions of the cold atomic beam will expand after the atoms fly for an extended long period due to the transversal velocities. This thermal expansion of the atomic beam is extremely undesirable in the manipulation of the continuous atomic beam by continuous Raman beams. This gives rise to inhomogeneous Rabi frequencies when atoms in different transverse positions interact with a Raman beam with spatial inhomogeneous intensity distributions, or when similar interactions occur between three individual Raman beams. Consequently, the coherence between Raman pulses and the atomic beam will be decreased by this inhomogeneous average effect. Further sub-Doppler cooling of atoms could be performed to compress the transverse thermal expansion of the cold atomic beam.

Ac Stark shifts must be canceled before the final optimization of horizontal angles of counter propagating Raman beams and the Raman detuning. The intensity ratio between the Raman lasers ($\omega_1$ and $\omega_2$) should be precisely set to cancel ac Stark shifts. And the Raman intensities must be adjusted to yield $\pi$ and $\pi/2$ pulses while maintaining the intensity ratio. Otherwise, ac Stark shifts would mimic Doppler shifts, ill shift Raman transitions, and finally reduce the contrast. Besides, ac Stark shifts are proportional to the laser intensity, and $\pi/2$ and $\pi$ pulses would obtain different shifts if the ratio is set incorrectly. By the numerical simulation of the Raman cold atom interferometer, the contrast of the interference signal will decrease gradually as a function of the increasing of ac Stark shifts, and the fringes will finally vanish when ac Stark shifts are larger than the linewidth of Raman transitions. A servo-loop for stabilizing intensities of Raman lasers will help to avoid disturbances of ac Stark shifts and the incorrect setting of Rabi frequencies.

As shown in Fig.5, the Raman-Ramsey fringes based on the cold atomic beam were observed, which were driven by the two $\pi/2$ Raman pulses in Doppler-insensitive geometries (co-propagating beams), with a field separation length of $2L = 19\text{mm}$ when the $\pi$ pulse was blocked. The longitudinal velocity of the atomic beam was tuned to approximately $v_{z0} = 15m/s$ with velocity distribution of $\Delta v_z = 3.5m/s$ (FWHM). Thus the atomic interrogation time between the two $\pi/2$ pulses was $T = 1.3\text{ms}$, and the corresponding linewidth of the central fringe was $\delta_{Ramsey} = 1/(2T) = 390\text{Hz}$. The cold beam showed higher distinguishability for the Ramsey fringes because of the narrow longitudinal atomic velocity distribution when compared with a thermal atomic beam[26]. Orders higher than the 4th order of the interference fringe, where $n = v_{z0}/\Delta v_z = 4$, can be identified clearly against the velocity averaging effect[27].

![FIG. 5. Raman-Ramsey fringe induced by $\pi/2 - \pi/2$ pulses with co-propagating Raman beams.](image-url)
IV. CONCLUSION

We have presented a light pulse atom interferometer using a continuous cold $^{87}$Rb atomic source. Raman-Ramsey and Mach-Zehnder atomic interference fringe have been observed with this interferometer. Such cold atom interferometer may be used in high precision gyroscope for its high bandwidth and technical flexibility. At present, we have achieved a small area of 0.07 mm$^2$ of the Sagnac loop, and the deduced sensitivity is about $4.4 \times 10^{-9}$ rad/s/$\sqrt{Hz}$ with a 790 Hz bandwidth, while the distance of the interferometer is $2L = 1.9$ cm and the velocity of the cold atomic beam is $v_{\text{c}} = 15$ m/s. The next step of our work is increasing the interferometer distance L to achieve a larger area of the Sagnac loop, by reforming the vacuum system to be more compact and feasible. For instance, the sensitivity could be enhanced up to $6 \times 10^{-9}$ rad/s/$\sqrt{Hz}$ with a ~ 40 Hz bandwidth, if the distance of 2L is increased to 30 cm and the area is increased to 22 mm$^2$ with the atomic velocity of $v_{\text{c}} = 12$ m/s.

The noise level of the atomic interference signal is currently limited by the intense background induced by the scattered lights from the detection beam and Raman beams. The fluctuations of the atom signal mainly result from the jitter of the cold atomic source and the Raman pulses. We are endeavoring to optimize the stabilities of the cold atomic source and the Raman lasers (intensities and coherence).

Compared with its pulsed counterparts, it is easier for a LPAI with a continuous source to be noise-compensated or loop-closed with the application of real-time frequency or phase modulation techniques. The frequency and phase modulations will be added to a spatially separated Raman pulses of our system for noise compensation and closed-loop implementation.

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