

Normalized detection by using the blow-away signal in cold atom interferometry

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Abstract: We propose and realize a simple normalized detection scheme for cold atom interferometry. The detection of population in final atomic states is normalized to the blow-away fluorescence during initial state preparation. In this way, the detection system and procedure are both simplified. The reduced sensitivity to amplitude noise in atom interference signal is experimentally verified. Both amplitude noise in atom source and short term phase noise of interference fringes are suppressed by more than a factor of 10 with normalized detection.

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OCIS codes: (020.1335) Atom optics; (120.1880) Detection; (140.3550) Laser, Raman.

References and links

1. M. A. Kasevich and S. Chu, "Atomic interferometry using stimulated Raman transitions," *Phys. Rev. Lett.* **67**(2), 181–184 (1991).
2. M. A. Kasevich, and S. Chu, "Measurement of the gravitational acceleration of an atom with a light-pulse atom interferometer," *Appl. Phys. B* **54**(5), 321–332 (1992).
3. A. Peters, K. Y. Chung, and S. Chu, "Measurement of gravitational acceleration by dropping atoms," *Nature* **400**(6747), 849–852 (1999).
4. S. M. Dickerson, J. M. Hogan, A. Sugarbaker, D. M. S. Johnson, and M. A. Kasevich, "Multiaxis inertial sensing with long-time point source atom interferometry," *Phys. Rev. Lett.* **111**(8), 083001 (2013).
5. L. Zhou, Z. Y. Xiong, W. Yang, B. Tang, W. C. Peng, Y. B. Wang, P. Xu, J. Wang, and M. S. Zhan, "Measurement of local gravity via a cold atom interferometer," *Chin. Phys. Lett.* **28**(1), 013701 (2011).
6. Z. K. Hu, B. L. Sun, X. C. Duan, M. K. Zhou, L. L. Chen, S. Zhan, Q. Z. Zhang, and J. Luo, "Demonstration of an ultrahigh-sensitivity atom-interferometry absolute gravimeter," *Phys. Rev. A* **88**(4), 043610 (2013).
7. M. J. Snadden, J. M. McGuirk, P. Bouyer, K. G. Haritos, and M. A. Kasevich, "Measurement of the Earth's gravity gradient with an atom interferometer-based gravity gradiometer," *Phys. Rev. Lett.* **81**(5), 971 (1998).
8. J. M. McGuirk, G. T. Foster, J. B. Fixler, M. J. Snadden, and M. A. Kasevich, "Sensitive absolute-gravity gradiometry using atom interferometry," *Phys. Rev. A* **65**(3), 033608 (2002).
9. F. Sorrentino, A. Bertoldi, Q. Bodart, L. Cacciapuoti, M. de Angelis, Y.-H. Lien, M. Prevedelli, G. Rosi, and G. M. Tino, "Simultaneous measurement of gravity acceleration and gravity gradient with an atom interferometer," *App. Phys. Lett.* **101**(11), 114106 (2012).
10. G. W. Biedermann, X. Wu, L. Deslauriers, S. Roy, C. Mahadeswaraswamy, and M. A. Kasevich, "Testing gravity with cold-atom interferometers," *Phys. Rev. A* **91**(3), 033629 (2015).
11. T. L. Gustavson, P. Bouyer, and M. A. Kasevich, "Precision rotation measurements with an atom interferometer gyroscope," *Phys. Rev. Lett.* **78**(11), 2046 (1997).
12. J. K. Stockton, K. Takase, and M. A. Kasevich, "Absolute geodetic rotation measurement using atom interferometry," *Phys. Rev. Lett.* **107**(13), 133001 (2011).
13. A. V. Rakholia, H. J. McGuinness, and G. W. Biedermann, "Dual-axis high-date-rate atom interferometer via cold ensemble exchange," *Phys. Rev. Appl.* **2**(5), 054012 (2014).
14. J. B. Fixler, G. T. Foster, J. M. McGuirk, and M. A. Kasevich, "Atom interferometer measurement of the Newtonian constant of gravity," *Science* **315**(5808), 74–77 (2007).
15. G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli, and G. M. Tino, "Precision measurement of the Newtonian gravitational constant using cold atoms," *Nature* **510**(7507), 518–523 (2014).

16. D. S. Weiss, B. C. Young, and S. Chu, "Precision measurement of the photon recoil of an atom using atomic interferometry," *Phys. Rev. Lett.* **70**(18), 2706–2709 (1993).
17. A. Wicht, J. M. Hensley, E. Sarajlic, and S. Chu, "A preliminary measurement of the fine structure constant based on atom interferometry," *Phys. Scr. T* **102**, 82–88 (2002).
18. H. Müller, S. W. Chiow, Q. Long, C. Vo, and S. Chu, "A new photon recoil experiment: towards a determination of the fine structure constant," *Appl. Phys. B* **84**(4), 633–642 (2006).
19. A. Bonnin, N. Zahzam, Y. Bidel, and A. Bresson, "Simultaneous dual-species matter-wave accelerometer," *Phys. Rev. A* **88**(4), 043615 (2013).
20. L. Zhou, S. T. Long, B. Tang, X. Chen, F. Gao, W. C. Peng, W. T. Duan, J. Q. Zhong, Z. Y. Xiong, J. Wang, Y. Z. Zhang, and M. S. Zhan, "Test of equivalence principle at 10^{-8} level by a dual-species double-diffraction Raman atom interferometer," *Phys. Rev. Lett.* **115**(1), 013004 (2015).
21. S. Y. Lan, P. C. Kuan, B. Estey, D. English, M. B. Justin, A. H. Michael, and H. Müller, "A clock directly linking time to a particle's mass," *Science* **339**(6119), 554–557 (2013).
22. S. Dimopoulos, P. W. Graham, J. M. Hogan, M. A. Kasevich, and S. Rajendran, "Gravitational wave detection with atom interferometry," *Phys. Lett. B* **678**(1), 37–40 (2009).
23. J. M. Hogan, D. M. S. Johnson, S. Dickerson, T. Kovachy, A. Sugarbaker, S. W. Chiow, P. W. Graham, M. A. Kasevich, B. Saif, S. Rajendran, P. Bouyer, B. D. Seery, L. Feinberg, and R. Keski-Kuha, "An atomic gravitational wave interferometric sensor in low Earth orbit (AGIS-LEO)," *Gen. Relativ. Gravit.* **43**(7), 1953–2009 (2011).
24. D. F. Gao, P. Ju, B. C. Zhang, and M. S. Zhan, "Gravitational-wave detection with matter-wave interferometers based on standing light waves," *Gen. Relativ. Gravit.* **43**(7), 2027–2036 (2011).
25. E. Rocco, R. N. Palmer, T. Valenzuela, V. Boyer, A. Freise, and K. Bongs, "Fluorescence detection at the atom shot noise limit for atom interferometry," *New J. Phys.* **16**, 093046 (2014).
26. G. W. Biedermann, X. Wu, L. Deslauriers, K. Takase, and M. A. Kasevich, "Low-noise simultaneous fluorescence detection of two atomic states," *Opt. Lett.* **34**(3), 347–349 (2009).
27. G. W. Biedermann, "Gravity tests, differential accelerometry and interleaved clocks with cold atom interferometers," PhD. thesis, Stanford University, (2007).
28. D. A. Steck, "Rubidium 85 D Line Data," <http://steck.us/alkalidata> (2013).

1. Introduction

With the development of cold atom physics and related experimental techniques in recent years, cold atom interferometry [1] becomes a useful tool and has been widely applied in precision measurements and fundamental physics study, including measurements of gravitational acceleration [2–6], gravity gradient [7–10], rotation [11–13], the Newtonian gravitational constant [14, 15] and the fine structure constant [16–18], tests of general relativity [19, 20], definition of kilogram [21] and detection of gravitational wave [22–24]. Due to uncontrollable vibration and fluctuations of magnetic field, environmental temperature, laser intensity, laser frequency, etc., the number of atoms involved in an atom interferometer fluctuates randomly, and the fluctuation contributes to the amplitude noise in interference signal. However, since the proportion of atoms in each hyperfine ground state after the interference process is independent of total atom number, the amplitude noise can be suppressed by normalized detection. The conventional normalized detection includes two-state sequential detection [6, 25] and two-state simultaneous detection [26, 27]. The schematic diagram of the involved states and transitions in the normalized detection processes is shown in Fig. 1 (for ^{85}Rb atoms employed in our work, the corresponding levels are shown in the brackets). In sequential detection, firstly the atoms in state $|1\rangle$ are detected and blown away by a detection laser which is resonant with the transition $|1\rangle \rightarrow |4\rangle$, then the atoms in state $|2\rangle$ are repumped to state $|1\rangle$ by a repumping laser which is resonant with the transition $|2\rangle \rightarrow |3\rangle$, and the first detection step is repeated. Finally, by simple numerical processing, the two detected signals are converted to atom numbers in the two ground states $|1\rangle$ and $|2\rangle$, and their relative population is obtained. In simultaneous detection, atom wave packets of two ground states are spatially separated firstly, then the atoms in state $|2\rangle$ are repumped to state $|1\rangle$, and finally the two groups of atoms are detected at the same time. By this method, the noises contributed from the detection laser can be further rejected. However, to spatially separate the two atom wave packets, a laser beam size 50% larger than the atom cloud size is needed [27], which may pose an additional constraint to the atom temperature or the free evolution time when the beam size is fixed. In addition, though both methods can reach

satisfying signal-to-noise ratio (SNR), in most critical sense, the detection procedure and the module structure deserve to be simplified.

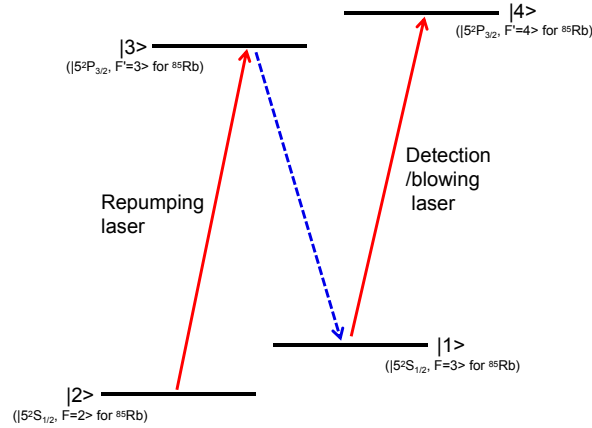


Fig. 1. A schematic diagram of the involved states and transitions in the normalized-detection processes. $|1\rangle$ and $|2\rangle$ are the lower hyperfine states, $|3\rangle$ and $|4\rangle$ are the upper hyperfine states. For ^{85}Rb D_2 transition hyperfine structure, $|1\rangle$ and $|2\rangle$ correspond to the states $|5^2S_{1/2}, F = 3\rangle$ and $|5^2S_{1/2}, F = 2\rangle$, $|3\rangle$ and $|4\rangle$ correspond to the states $|5^2P_{3/2}, F' = 3\rangle$ and $|5^2P_{3/2}, F' = 4\rangle$, respectively.

In this paper, we design and realize a simple normalized detection scheme for cold atom interference signal. The normalized detection is realized by determining the ratio of the fluorescence, I_F/I_{blow} , where I_F is the fluorescence intensity of atoms populated in one of the two evolved $m_F = 0$ states after coherent manipulations, I_{blow} is the blow-away fluorescence intensity of useless atoms during the initial state preparation. In this method, neither repumping process nor repumping beam is needed. The atoms are excited only once after the coherent manipulations, only one beam and one detector are employed to perform blowing away and normalized detection. The experiment results demonstrate that this method has reduced sensitivity to amplitude noise. Under simulated severe conditions, both the amplitude noise in atom source and the corresponding short-term phase noise of interference fringes are suppressed by more than a factor of 10, while the SNR is 100:1.

2. The principle and experimental apparatus

The experiment is based on a Mach-Zehnder type (M-Z) atom interferometer implemented by using a three-pulse ($\pi/2 - \pi - \pi/2$) stimulated Raman transition [1–5]. The Raman transitions couple the two ground hyperfine $m_F=0$ states of ^{85}Rb , $|5^2S_{1/2}, F = 2, m_F = 0\rangle$ and $|5^2S_{1/2}, F = 3, m_F = 0\rangle$. A typical atom interference process contains 5 steps: cold atom loading, launching, initial state preparation, coherent manipulation and final state detection. The schematic diagram of experimental setup and the sequence of experimental parameters are shown in Fig. 2. Atoms are pre-cooled in a two-dimensional magneto optical trap (2D-MOT), a pushing laser pulse is then employed to transfer the atoms to a three-dimensional MOT (3D-MOT) through a hole of 10 mm in length and 2 mm in diameter. The hole is for maintaining differential vacuum between the two chambers. About 10^8 atoms are trapped in the 3D-MOT within 200 ms, then the power and frequency of cooling laser (I_{cool} and f_{cool}) are changed to realize the vertical moving molasses and polarization-gradient cooling (PGC). The atoms are pumped to state $|F = 3\rangle$ by switching off the cooling laser (I_{cool}) before switching off the repumping laser (I_{rep}). When

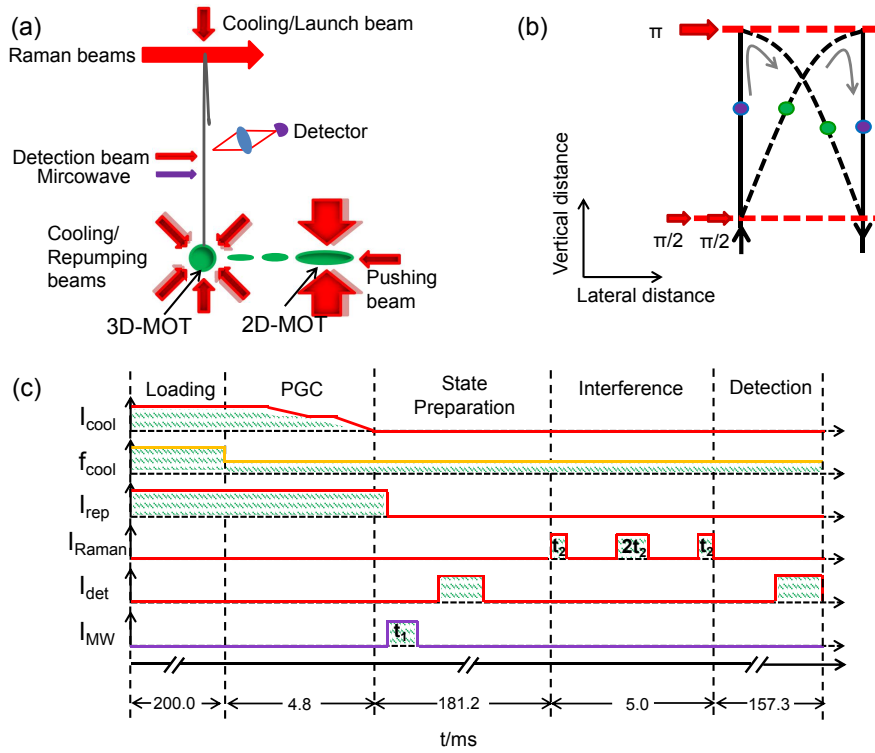


Fig. 2. Schematic diagrams of experiments. (a) Experimental setup. Three pairs of cooling beams for 3D-MOT are in the [0,0,1] configuration, and the repumping beams are overlapped with the horizontal cooling beams. (b) A schematic diagram of interference process. (c) Experimental time sequence for normalized detection. $t_1=120 \mu\text{s}$ and $t_2=12 \mu\text{s}$ are the time periods of the microwave π -pulse and Raman $\pi/2$ -pulse.

the atoms move upward to the state preparation/detection region, a magnetic field is applied to break the degeneration of different m_F states, and a $120 \mu\text{s}$ microwave π -pulse (I_{MW}) generated by a horn antenna outside the window of the vacuum chamber is applied to transfer atoms from $|F = 3, m_F = 0\rangle$ to $|F = 2, m_F = 0\rangle$. The remaining atoms in $|F = 3, m_F \neq 0\rangle$ states are removed by a horizontal blowing/detection beam (I_{det}) which is resonant with the transition $|F = 3\rangle \rightarrow |F' = 4\rangle$. A photodetector is used to record the blow-away fluorescence. Then a sequence of three Raman pulses ($\pi/2 - \pi - \pi/2$) spaced by a time $T=2.5 \text{ ms}$ is applied (I_{Raman}) to manipulate the atoms when they reach the interference region and thus forms an interferometer. Finally, when the atoms fall back to the state preparation/detection region, the blowing/detection pulse is switched on (I_{det}) once again and the resulting fluorescence from the atoms in state $|F = 3\rangle$ is imaged again onto the detector. Without Raman manipulation, atom number in $|F = 3, m_F = 0\rangle$ after state preparation and 300 ms free falling is measured to be about 3×10^5 . Since the fluorescence of the removed atoms is in proportional to the total number of atoms, the normalized atom number of the final state can be given by a ratio:

$$N = \frac{I_{F=3}}{I_{blow}} \quad (1)$$

where I_{blow} and $I_{F=3}$ are the fluorescence intensities recorded during the initial state preparation and the final state detection, respectively.

In the experiments, two homemade distributed feedback (DFB) lasers are employed as the

seed lasers of cooling beam, pushing beam, blowing/detection beam and repumping beam. The frequency of one DFB laser is locked to $^{85}\text{Rb}:|F = 3\rangle \rightarrow |F' = 3, 4\rangle$ crossover transition via saturated absorption spectroscopy, the laser frequency is then shifted by an acousto-optical modulator (AOM). A tapered amplifier (TA) is used to amplify the output of the DFB laser, and the output of the TA is split into five beams as 2D-MOT cooling beam, 3D-MOT cooling beam, cooling/launching beams, and pushing/blowing/detection beam. Another DFB laser is locked to the $|F = 2\rangle \rightarrow |F' = 1\rangle$ transition, and amplified by a 150 mW slave diode laser (SDL). The output of the SDL is split into two beams for 2D-MOT repumping and 3D-MOT repumping, respectively. An extended cavity diode laser (TOPTICA DL-pro-780 L) is used as the seed laser for Raman beam, and its frequency is stabilized 1.5 GHz to the red side of transition $|F = 3\rangle \rightarrow |F' = 2\rangle$. A fiber phase modulator (F-EOM, Photline NIR-MPX800-LN-05) is employed to generate two Raman lasers with frequency difference of 3.03 GHz (^{85}Rb hyperfine splitting). A TA is used to amplify the Raman beams, and an AOM is employed as the beam switch.

3. Experimental results

3.1. The normalized detection of initial states

To evaluate the fidelity of the normalized detection, we switch off the Raman laser and only perform normalized detection for the initial state. Since all atoms are populated in $|F = 2, m_F = 0\rangle$ state after initial state preparation, and the detection laser is resonant with transition $|F = 3\rangle \rightarrow |F' = 4\rangle$, we pump the atoms from $|F = 2\rangle$ to $|F = 3\rangle$ by a vertically oriented repumping beam before they arrive in the detection region. A triangle-wave signal is used to modulate the intensity of the pushing beam to introduce an artificial severe noise. The comparison between the integrations of the original and the normalized time of flight (TOF) signal is shown in Fig. 3, where the blue squares are original signal, and the red dots are normalized signal. The original signal linearly depends on the intensity of pushing beam. The peak-peak variation is $\pm 25.0\%$, and the relative standard deviation is 13.5%. While the normalized signal does not depend on the intensity of pushing beam, giving the peak-peak variation of only $\pm 2.4\%$ and the relative standard deviation of 1.4%, the amplitude noise is suppressed by a factor of 10 with normalization.

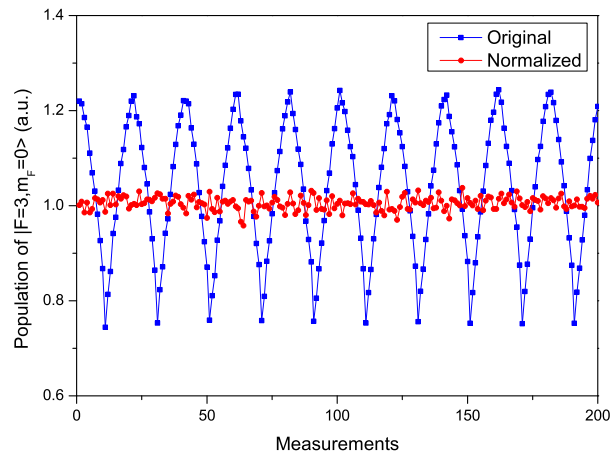


Fig. 3. The normalized detection of atom initial state. The blue squares are the original signal and the red dots are the normalized signal.

For laser induced fluorescence methods, the laser intensity noise and frequency noise are main sources of the detection noise. In the present scheme, the blow-away signal and the

final population signal are recorded asynchronously, thus these noises cannot be rejected as common mode in normalized detection. Since each data point is derived from 5-ms integration, the intensity stability and the frequency stability of detection beam are also evaluated at the integration time of 5 ms. The corresponding intensity noise and the frequency noise are measured to be 0.4% and 16 kHz respectively. The photon scattering probability of atoms is [28]

$$R = \frac{\Gamma}{2} \frac{s}{1 + s + 4x^2} \quad (2)$$

where $s = I/I_s$ is the saturation parameter and $x = \Delta/\Gamma$, Δ is the detuning to transition $|F = 3\rangle \rightarrow |F' = 4\rangle$ and $\Gamma = 6.067$ MHz is the natural linewidth. According to Eq. (2), for $s \sim 0.5$ and $\Delta \sim 0$, the detection noise induced by the laser intensity is calculated to be 0.4%, and that induced by the laser frequency is calculated to be less than 0.1%. Furthermore, the background noise, coming from the detector itself and the stray lights, is measured to be 0.1% when our signal amplitude is 60 mV. In this method, the number of distilled atoms in $|F = 2, m_F = 0\rangle$ is not strictly in proportion to that of rest atoms in $|F = 3\rangle$. That is because during the state preparation, the fluctuation of the microwave π -pulse also brings other non-common mode noise. By alternately measuring the noises of final fluorescence intensities with and without microwave-based initial state preparation, the maximum detection noise caused by the microwave fluctuation (microwave π -pulse noise) is evaluated to be about 1.0%. The ultimate limitation to the detection noise is the quantum projection noise, which is estimated to be 0.2% for the atom number of 3×10^5 in present experiment. Contributions mentioned above to the normalized detection noise are listed in Table 1. The microwave π -pulse noise is the limitation to present normalized detection.

Table 1. List of main noise sources of normalized detection

Noise source	Noise size
Frequency fluctuation of detection laser	$\leq 0.1\%$
Intensity fluctuation of detection laser	0.4%
Stray light and detector noise	0.1%
Microwave fluctuation	1.0%
Quantum projection noise	0.2%
Total	1.1%

To study the mechanism of the microwave π -pulse noise, we measure the intensity noises of the microwave generator, the intensity noises of microwave field in free space and near one of vacuum chamber windows. We switch the operation mode of microwave generator from CW mode to pulsed mode, and the measurement for each noise is repeated. As is shown in Table 2, the noises of the microwave generator are extremely low and can be ignored; the noise due to vacuum chamber under pulsed operating mode is much larger than that in other cases. Moreover, when we adjust the output power of the microwave field for 0.2 dB, the atom number changes about 0.9%, which is approximately equal to the noise limit. Therefore, the performance of this method is mainly limited by the switching oscillation of the microwave field inside the vacuum chamber.

3.2. The normalized detection of atomic interference signal

The phase noise in Doppler insensitive interference fringe, which is caused by Raman laser fluctuation and vibration, is 5 orders of magnitude smaller than that of a Doppler sensitive one, while the phase noises caused by amplitude fluctuation are the same for both Doppler insensitive and Doppler sensitive fringes. Therefore, we use Doppler insensitive interference

Table 2. The measured intensity noise of microwave in different cases

Noise type	Noise size (dB)	
	CW mode	pulsed mode
Noise of microwave generator	≤ 0.01	≤ 0.01
Noise of microwave field in free space	0.02	0.03
Noise of vacuum chamber radiation	0.05	0.19

fringe to evaluate the performance of our normalized method. The duration of $\pi/2$ pulse is 12 μs and T is 2.5 ms. The intensity of pushing beam is randomly modulated between 42 μW and 122 μW to imitate amplitude noise. The Doppler insensitive interference fringes with imitated amplitude noise are shown in Fig. 4. Each 2π -phase cycle is composed of 20 steps. The fringe phases are extracted by sine fitting, and each phase data point is obtained from 2 cycles' data or 40 points. The Allan deviations of fringe phases are shown in Fig. 5.

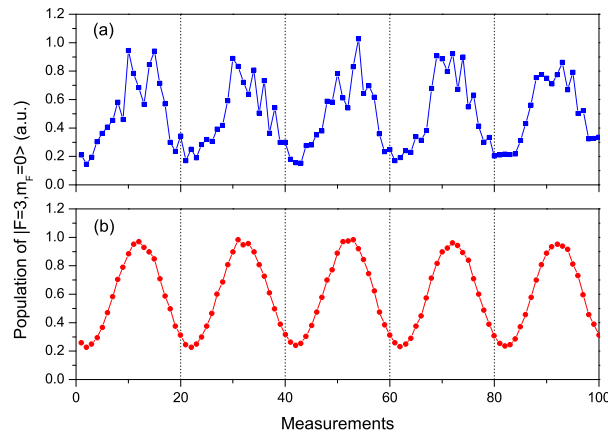


Fig. 4. Doppler-insensitive interference fringes without (a) and with (b) normalized detection.

The atom interference fringes become noisy when the intensity of pushing beam is modulated, and the phase noise increases with the increase of modulation depth. The short term ($t < 200$ s) noise without normalization is 10 times higher than that of non-modulated fringe phases. However, the short term noise of normalized fringes is almost the same as that of non-modulated ones. Since the amplitude noise is white noise, the contribution to the total phase noise decreases with the increase of the integration time. Therefore, with the increase of integration time, the Allan deviation value of normalized signal approaches that of original signal.

4. Conclusion

In summary, we have demonstrated a simple normalized detection scheme for cold atom interference signal. The detection of population in final atomic states is normalized to the blow-away fluorescence during initial state preparation. By this method, both the detection procedure and the structure of the detection module are greatly simplified, that may be helpful for making simpler and portable interferometers. This method has reduced sensitivity to amplitude noise, and both the amplitude noise in atom source and the short term phase noise of interference fringes are suppressed by more than a factor of 10. The SNR of this detection method is currently about 100:1. Since the microwave fluctuates in initial state preparation, the number of distilled atoms is not strictly in proportion to that of the rest atoms, thus the microwave π -pulse noise

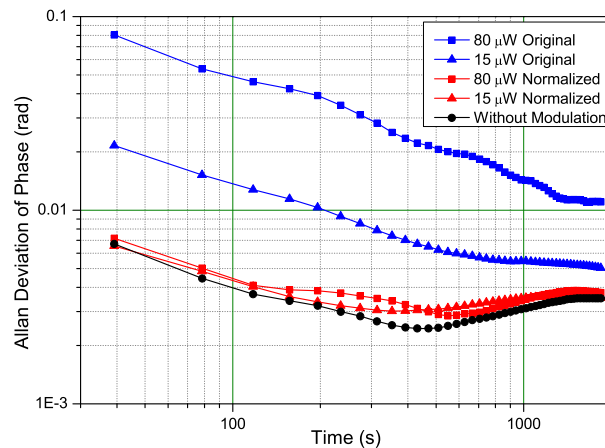


Fig. 5. The Allan deviation of fringe phases with imitated amplitude noise by random modulation. The blue squares are original signals with pushing beam power randomly modulated within a range of $80\ \mu\text{W}$ ($42\ \mu\text{W} \sim 122\ \mu\text{W}$), the blue triangles are original signals with pushing beam power randomly modulated within a range of $15\ \mu\text{W}$ ($42\ \mu\text{W} \sim 57\ \mu\text{W}$). The red squares are normalized signals with a modulated range of $80\ \mu\text{W}$, the red triangles are normalized signals with a modulated range of $15\ \mu\text{W}$, and the black circles are signals without modulation.

is the main limitation to SNR in our present experiments. While, this problem does not exist in traditional detection which normalized to the post-selected fraction. However, the microwave noise is mainly caused by the switching oscillation of the microwave field inside the vacuum chamber, it can be suppressed by utilizing a well-designed microwave cavity rather than a horn antenna to reduce the switching oscillation. To employ Raman laser, which has better spatial coherence, to perform state selection is another option.

Funding

National Key Research and Development Program of China (2016YFA0302002) by the Ministry of Science and Technology of the People's Republic of China (501100002855); National Natural Science Foundation of China (NSFC) (11504411, 91536221, and 11227803).