Progress toward a Raman-Ramsey Clock Based on a Transverse Cooled Rubidium Beam

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***Summary*—In this paper we reported our progress toward an atomic beam clock based on a transverse cooled rubidium beam. The atomic beam is generated from an atomic oven and collimated via micro-channel arrays and a two-dimensional optical lattice. After optical pumping, the rubidium beam interacts with two spatially separated Raman beams with a $\pi/2-\pi/2$ sequence. High contrast Raman-Ramsey fringes are observed by using fluorescence detection. Preliminary result shows that the estimated frequency stability of the atomic clock reaches $2.6\times10^{-11}/\sqrt{\tau}$. The atomic beam clock is proposed as a part of atomic beam inertial navigation unit for field applications.**

Keywords—quantum frequency standard, atomic clock, atomic beam

I. INTRODUCTION

The cesium beam clock based on magnetic-state selection plays an important role in time-keeping, navigation and telecommunication due to its outstanding long-term stability and high accuracy. The application of optical pumping and detecting improves the short-term stability or other performances of the atomic clock [1-5]. The atomic beam clock based on rubidium has also carried out some experimental exploration because of its higher pumping efficiency compared with cesium [6-8]. In addition, enhancing the collimation of an atomic beam can also improve the utilization efficiency of atoms. The systematic error for a Ramsey clock based on microwave is produced by the distributed cavity phase, frequency pulling effect and microwave leakage. The two-photon stimulated Raman transition provides an alternative way to produce Ramsey fringes as optically separated oscillatory fields, which has been studied theoretically [9] and experimentally [10-11].

Here we show the Raman-Ramsey fringes based on a transversely cooled rubidium atomic beam, by using the separated Raman beams instead of microwave to realize the separated oscillatory fields method.

II. APPARATUS

A schematic diagram of the experimental setup is shown in Fig.1. A rubidium atomic beam in the vacuum chamber is transversely cooled and optically pumped into F=1 state before interacting with two pairs of stimulated Raman transition lasers. The Raman-Ramsey interference signal is observed by detecting the laser-induced fluorescence. In the atomic interference cavity, the current of 2A is applied in the quadrupole to generate a uniform magnetic field of 0.67Gs along the Raman beams. And a μ-metal magnetic shield is used to shield the stray magnetic field.

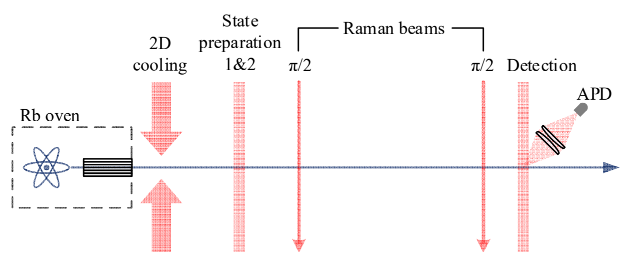

Fig. 1. Schematic of the apparatus.

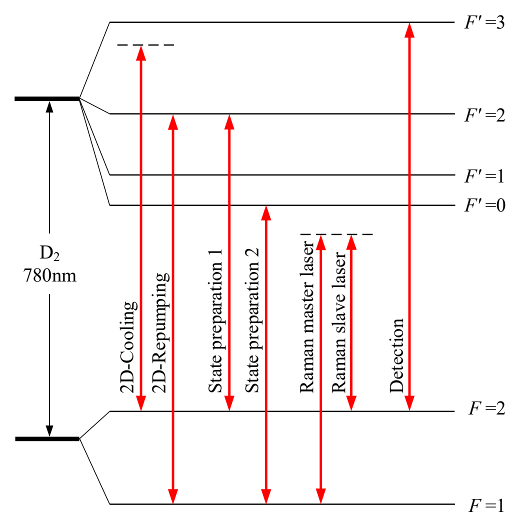

Fig. 2. Rubidium 87 D_2 transition hyperfine structure diagram and laser frequencies required in the experiment.

The atomic oven is filled with natural rubidium, which is heated to 155°C to produce rubidium vapor. The vapor passes through a multi-channel collimator to form an atomic beam, then it is further transversely cooled in two-dimensional optical molasses. A laser tuned to the red of the rubidium F=2 $\rightarrow$ F'=3 transition is linearly polarized and retro-reflected with orthogonal linear polarization. The cooling beam is split by an assembled prism after being expanded to ϕ36 mm, providing two rectangular beams of 7.0 × 2.0cm^2 separately for vertical and horizontal cooling. The intensity and detuning are optimized for a better cooling. The flux of the atomic beam is measured to be 2.2(1) $\times 10^{10}$ atoms/s with mean longitudinal velocity of 175(4)m/s. As the atomic beam passes through two windows separated by 0.6m, we respectively obtain fluorescence image using the resonant detection beam and CMOS camera, and calculate the transverse temperature T=524μK. The linearly polarized state preparation beam consists of two frequencies, parallel to the direction of the Raman magnetic field. The state preparation laser 1&2 tuned to the F=2 → F'=2 and F=1 → F'=0 prepare atoms to the magnetic-insensitive F=1, m_F=0 state.

The Raman master laser is detuned –0.97GHz from the ^{87}Rb $5S_{1/2}$ F=1 → $5P_{3/2}$ F=1 transition to avoid single-photon resonant excitation. The Raman master laser is modulated at 6.835GHz using a fiber-coupled electro-optic phase modulator (EOM) (IXBlue, MPZ-LN-10-00-P-P-FA-FA) to generate the Raman slave laser in 1560nm, before amplification and second harmonic generation (SHG) into 780nm. The Raman lasers are injected into two shapers with a spacing of 270mm/540mm after passing through a 50-50 fiber splitter, corresponding to a theoretical Ramsey line width of 324.07Hz/162.04Hz. We use the custom-adjustable beam shapers to achieve Raman beam shaping. The beam output from the shaper has a Gaussian intensity distribution in the horizontal direction with 160μm width, and a nearly uniform distribution (in other words, the top-hat distribution) in the vertical direction with 35mm height, which is further intercepted to a height of 15mm. A quarter-wave plate is installed in front of the sapphire window on the vacuum chamber to adjust the polarization into circular.

By illuminating the atoms using a laser on resonance with the F=2 → F'=3 cycling transition, we obtain the laser-induced fluorescence of the atomic beam. The fluorescence is detected by an avalanche photodiode (APD) (Hamamatsu, C12703-01) after being collected by a double plano-convex lens system. All laser frequencies are shown in Fig.2, referenced to energy levels of ^{87}Rb atoms.

III. Result and Discussion

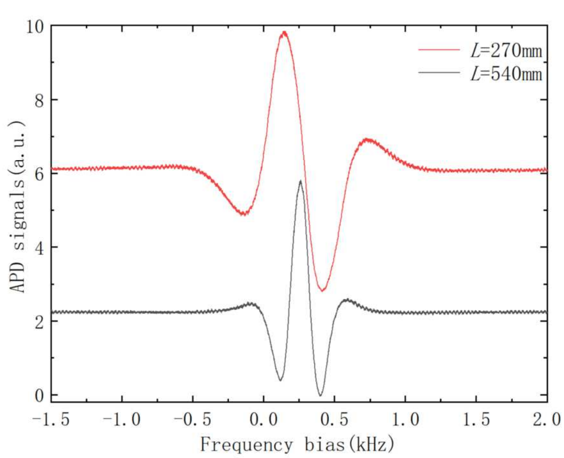

Fig. 3. Raman-Ramsey fringes. Both signals are vertically biased for better presentation.

We perform the continuous Raman-Ramsey interferometry on the transverse cooled atomic beam by scanning the Raman frequency bias. The Ramsey fringes shown in Fig.3 have a line width of 317.97Hz and 161.92Hz for two interaction length, close to the theoretical expectations. The peak-to-valley voltage of the central Ramsey fringe with L=540mm is 5.84V, the background voltage is 19mV, thus the signal-noise-ratio (SNR) is above 300.

The Ramsey fringe with L=540mm has a frequency bias of 261Hz. A second-order Zeeman shift of 192 Hz is due to the 0.67Gs bias magnetic field applied in the interference cavity. The remaining 69Hz frequency bias and the Ramsey fringe asymmetry may be explained by ac Stark shifts induced by Raman beams and Doppler shifts caused by the non-perpendicularity between Raman beams and the atomic beam.

IV. Conclusions

We demonstrate a device that uses a transverse cooled rubidium beam to interact with two spatially-separated Raman beams, and obtain Raman-Ramsey fringes with a SNR of 300.

The preliminary result shows that the estimated frequency stability of the atomic clock is $2.6 \times 10^{-11}/\sqrt{\tau}$, which demonstrates the feasibility of the scheme for a rubidium beam clock. With subsequent construction in electric servo loops and further improvement in optical system, the upcoming rubidium beam clock has a high performance potential.

References

[1] Lutwak R, Emmons D, Garvey R M, et al. Optically pumped cesium-beam frequency standard for GPS-III[R]. DATUM-TIMING TEST AND MEASUREMENT BEVERLY MA, 2001.

[2] Guérandel, Stéphane, et al. "Compact cesium beam frequency standard: improvement of the frequency stability towards the 10-12 tau-1/2 level." Proceedings of the 16th European Frequency and Time Forum. 2002.

[3] Lecomte, Steve, et al. "Performance demonstration of a compact, single optical frequency Cesium beam clock for space applications." 2007 IEEE International Frequency Control Symposium Joint with the 21st European Frequency and Time Forum. IEEE, 2007.

[4] Cao Y, Zhao X, Yang L, et al. Progress in the development of commercial optically pumped Cesium atomic clock[C]//2014 IEEE International Frequency Control Symposium (FCS). IEEE, 2014: 1-4.

[5] Wang Q, Duan J, Qi X H, et al. Improvement of laser frequency stabilization for the optical pumping cesium beam standard[J]. Chinese Physics Letters, 2015, 32(5): 054206.

[6] Arditi, Maurice, and Pierre Cerez. "Hyperfine structure separation of the ground state of 87Rb measured with an optically pumped atomic beam." IEEE Transactions on Instrumentation and Measurement 21.4 (1972): 391-395.

[7] Besedina, A., et al. "Preliminary results of investigation of the high-stable Rubidium atomic beam frequency standard with laser pumping/detection for space application." Proceedings of the 20th European Frequency and Time Forum. IEEE, 2006.

[8] Liu, Chang, et al. "Rubidium-beam microwave clock pumped by distributed feedback diode lasers." Chinese Physics B 26.11 (2017): 113201.

[9] Moler, Kathryn, et al. "Theoretical analysis of velocity-selective Raman transitions." Physical Review A 45.1 (1992): 342.

[10] Thomas, J. E., et al. "Observation of Ramsey fringes using a stimulated, resonance Raman transition in a sodium atomic beam." Physical Review Letters 48.13 (1982): 867.

[11] Feng, Yanying, et al. "Observation of Ramsey fringes using stimulated Raman transitions in a laser-cooled continuous rubidium atomic beam." Applied Physics B 118.1 (2015): 139-144.