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Characterization of a velocity-tunable ^{87}Rb cold atomic source with a high-speed imaging technology*

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This paper has developed and characterized a method to produce a velocity-tunable ^{87}Rb cold atomic source for atomic interferometry application. Using a high speed fluorescence imaging technology, it reports that the dynamic process of the atomic source formation is observed and the source performances including the flux and the initial velocity are characterized. A tunable atomic source with the initial velocity of 1.4∼2.6 m/s and the atomic source flux of $2 \times 10^8 \sim 6 \times 10^9$ atoms/s has been obtained with the built experimental setup.

Keywords: cold atomic source, velocity-tunable, high speed fluorescence imaging
PACC: 0777

1. Introduction

Cold atomic source has attracted increasing interest in recent years. These low-velocity atomic sources have been proven to be very useful in a wide variety of experiments whose key feature is the long interaction time of atoms with this apparatus: applications in high resolution spectroscopy have contributed to the realization of high precision frequency standards,[1] low-velocity atomic sources are important in the development of space-qualified, compact, and highly stable atomic clocks because the microgravity conditions in space do not support the use of atomic fountains,[2] slow atom sources used to load atom traps are the starting point of recent experiments on Bose–Einstein condensation,[3] high-flux sources of cold atoms have increased the performances of atomic interferometers,[4−6] particularly those sensing rotational and gravitational effects.

The development of laser-cooling techniques has opened the way to experiments with very slow atoms. Unfortunately, an atomic source that is slowed in one dimension will suffer large transverse divergence as the longitudinal velocity is reduced to a value of the order of the transverse velocity.[7−9] To alleviate this problem, one can use position-dependent trapping forces to compress the source spatially. One promising technique to achieve this is based on magneto-optic trapping (MOT), two-dimensional MOT-based low-velocity atomic source has been reported.[10,11] And three-dimensional MOT-based low-velocity atomic sources have also been reported.[12−14]

In this paper, we develop and characterize a method to produce a velocity-tunable ^{87}Rb cold atomic source for atomic interferometry application. The atomic source preparation system consists of a three-dimensional (3D) magneto-optical trap (3D-MOT), a two-dimensional (2D) optical molasses (2D-OM) and a state preparation. The velocity and flux can be tuned by adjusting the system parameters and measured with high speed imaging technology.

2. Experiment

The cold ^{87}Rb atomic source is generated from a preparation system which is worked in an ultra-high vacuum chamber with a background pressure of 3×10^{-9} Torr (1 Torr=133 Pa). The windows of the vacuum chamber are coated with broadband near-IR (infrared) antireflection coatings. One 1 W diode laser (DLX110, Topical Photonics, Germany) at 780 nm is

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used for the cooling-trapping laser beams, collimating laser beams and state preparation laser beam. Another 150 mW diode laser (DL100, Topical Photonics, Germany) at 780 nm is used for the optical repumping laser beam. The single mode diode laser has an effective linewidth of 1 MHz, and the laser frequency is actively stabilized with a saturated absorption spectrometer for long-term frequency stability. The cooling-trapping laser is detuned 10–30 MHz to the red from the $5S_{1/2},\ F = 2 \rightarrow 5P_{3/2},\ F' = 3$ transition in ^{87}Rb with an acoustic-optical modulator (AOM), the collimating laser is detuned 0–20 MHz to the red from the $5S_{1/2},\ F = 2 \rightarrow 5P_{3/2},\ F' = 3$ transition with an AOM, and the state preparation laser is detuned to the transition from $5S_{1/2},\ F = 2 \rightarrow 5P_{3/2},\ F' = 2$ with an AOM. The repumping laser is locked to the $5S_{1/2},\ F = 1 \rightarrow 5P_{3/2},\ F' = 2$ transition in ^{87}Rb.

Figure 1 is a 3D schematic diagram that shows the generation of the ^{87}Rb source from the preparation system. The 3D-MOT consists of six orthogonal intersecting cooling-trapping laser beams, a repumping laser beam and a pair of anti-helmholtz coils. It is used to cool and trap atoms to form an atomic cloud from background atomic vapor in the vacuum chamber. A hollow cooling-trapping laser beam along the z axis is created by a 1/4 wave plate and a reflector with a 1 mm hole in their center. Therefore, an ^{87}Rb cold atomic source is pushed out by unbalanced radiation pressure along the z axis. The 2D-OM consists of four orthogonal intersecting collimating laser beams. It is used to collimate the atomic source from the 3D-MOT. The state preparation laser is used to pump atoms of the atomic source into ground state $F = 1$ of ^{87}Rb for atomic interferometry.

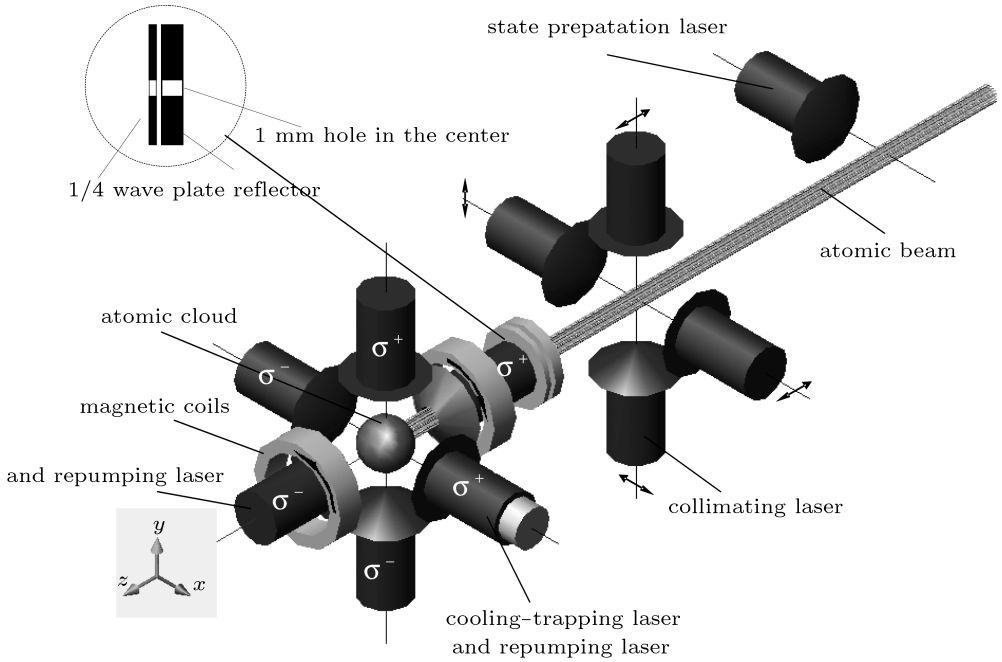
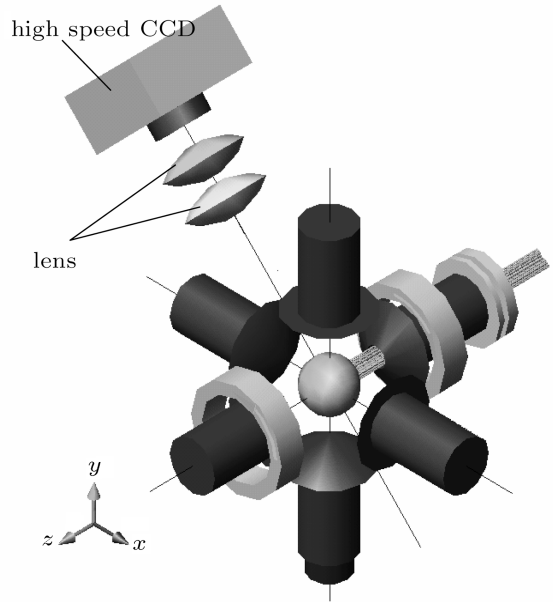


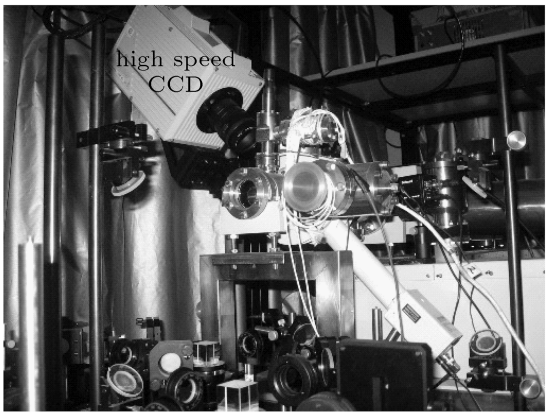
Fig.1. Three-dimensional schematic diagram of the MOT-based ^{87}Rb atomic source machine. Specially, there is a hole in the center of a 1/4 wave plate and reflector placed inside the vacuum chamber, which created a hollowed cooling-trapping laser beam.

A high speed CCD camera (Photron, FASTCAM-SA1) is used for monitoring the formation of atomic source and measuring their performance, as shown in Fig.2.

The dynamic process of loading an atomic source can be observed by high-speed imaging technology with a CCD camera, as shown in Fig.3. The loading process of the atomic beam is sampled by the high-speed CCD camera at a speed of 500 frames per second. It is observed that the atomic cloud starts to form initially from lower potential point, then moves to the center of the 3D-MOT, and finally is pushed out of the 3D MOT. Under current conditions, about 28 ms is taken for the loading of a stable atomic source.



(a)



(b)

Fig.2. The testing system (a) schematic drawing; (b) photo.

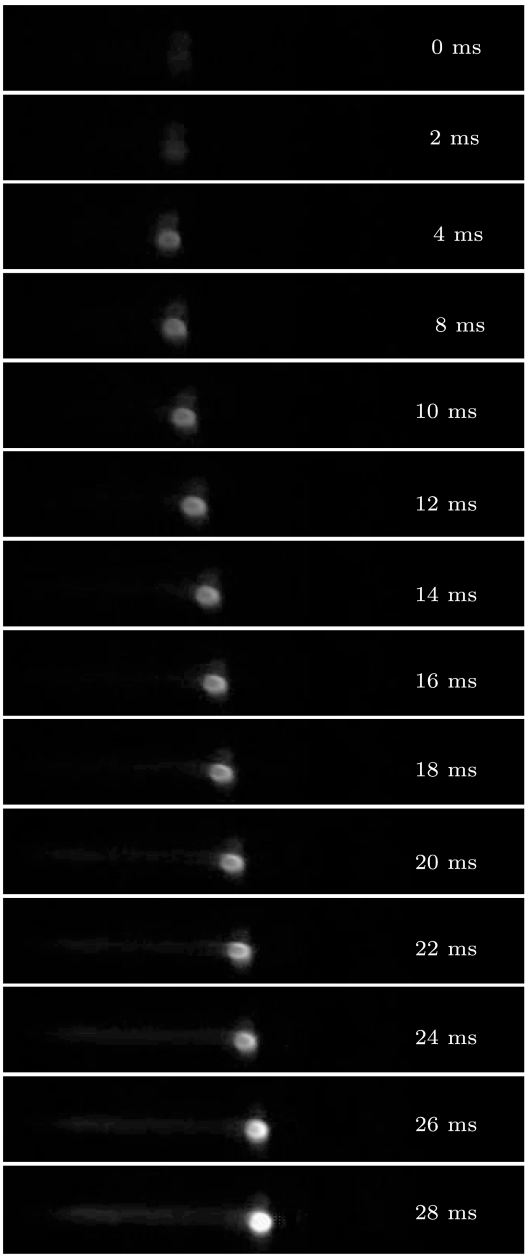


Fig.3. The dynamic process of loading an atomic source (sampling rate is 500 frames/s).

By turning off the 3D-MOT, the dynamic processing of the atomic source release from the 3D-MOT is recorded by fluorescence imaging technology with the CCD camera at the speed of 500 frames per second, as shown in Fig.4. The initial velocity of the atomic source can be calculated by tracking the displacement and time information of a flying atomic source.

The CCD camera and the collecting optical lens are calibrated to allow determination of the atom flux. For a cold-atom beam traveling at an initial velocity $\langle v_z \rangle$ through a distance of Δz, the initial integrated atom flux N_{at} is given as

$$N_{\mathrm{at}} = \frac{P_{\Delta z}}{S} \frac{1}{h\nu} \frac{4\pi}{d\Omega} \frac{v_z}{\Delta z} \left(\frac{2}{\Gamma} \frac{1 + I/I_{\mathrm{s}}}{I/I_{\mathrm{s}}} \right). \qquad (1)$$

where $P_{\Delta z}$ is the intensity of atomic fluorescence, $h\nu$ is a photon energy, S is the calibration factor, $d\Omega$ is the collection solid angle, I/I_{s} is the saturation parameter of laser, and Γ is the natural line-width of the atomic

transition. From Eq.(1), the atomic source flux can be calculated.

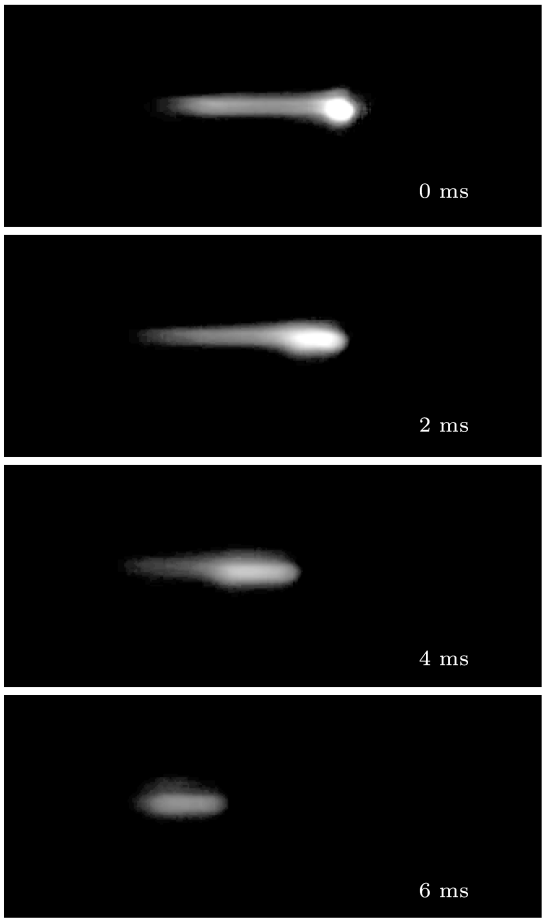


Fig.4. The dynamic process of releasing an atomic source for measuring its velocity (sampling rate is 500 frames/s).

3. Results and discussion

The effects of the cooling-trapping laser and the repumping laser on the initial velocity and flux of the atomic source are studied experimentally.

Figures 5(a) and 5(b) illustrated the initial velocity of the atomic source as a function of the cooling-trapping laser intensity under the detuning of –26.5 MHz and –22.0 MHz respectively. It can be observed that enhancing the cooling-trapping laser intensity leads to higher velocity of the atomic source.

Figure 6(a) and 6(b) showed the flux of atomic source as a function of the cooling-trapping laser intensity under the detuning of –26.5 MHz and –22.0 MHz respectively. It can be observed that the atomic flux is linearly proportional to the saturation parameter of the laser, $I/I_{\rm s}$. It means that the cooling-trapping laser intensity is one important factor for tuning the atomic source.

Figure 7(a) showed the initial velocity of the atomic source as a function of the repumping laser intensity, $I_{\rm repump}/I_{\rm s.}$ It can be observed that enhancing the repumping laser intensity leads to higher initial velocity of the atomic source. Figure 7(b) showed the flux of atomic source as a function of the repumping laser intensity, $I_{\rm repump}/I_{\rm s}$. It can be observed that the atomic flux is proportional to the repumping laser intensity, which is another important factor for tuning the atomic source.

Figure 8(a) showed the relationship between the initial velocity of atomic source and the detuning of cooling-trapping laser, $-\delta$. There exists a local maximum initial velocity of the atomic source at the detuning of about –11.0 MHz, and a local minimum initial velocity at the detuning of about –21.0 MHz. Figure 8(b) showed the atomic source flux as a function of the detuning of cooling-trapping laser, $-\delta$. It can be found that there exists a maximum value of the atomic source flux when the red detuning of cooling-trapping is 22.0 MHz.

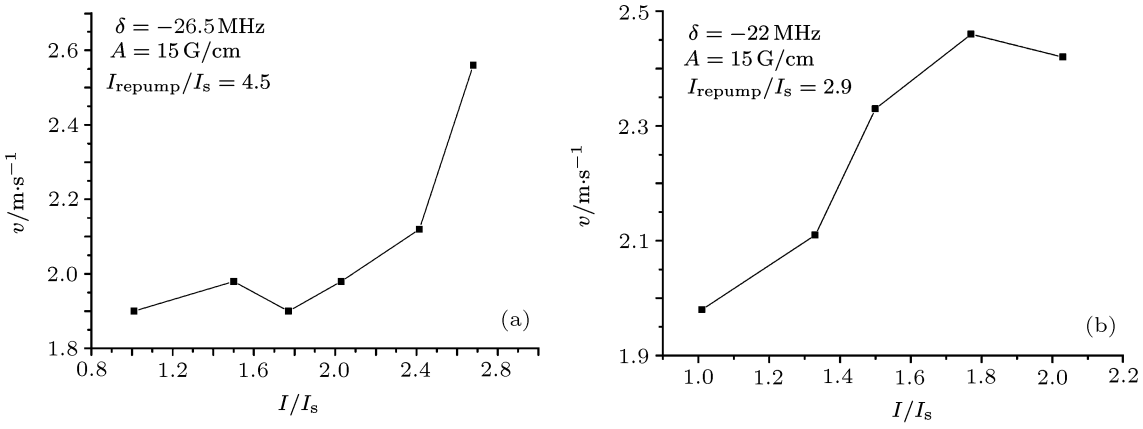


Fig.5. The initial velocity of atomic source as a function of the intensity of cooling-trapping laser source respectively under the detuning of (a) –26.5 MHz, (b) –22.0 MHz.

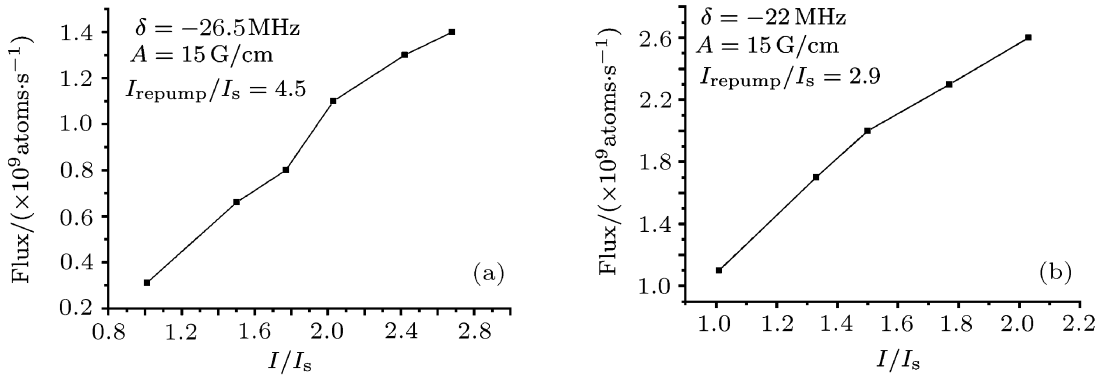


Fig.6. The atomic source flux as a function of the intensity of cooling-trapping laser source, I/I_s, respectively under the detuning of (a) –26.5 MHz, (b) –22.0 MHz.

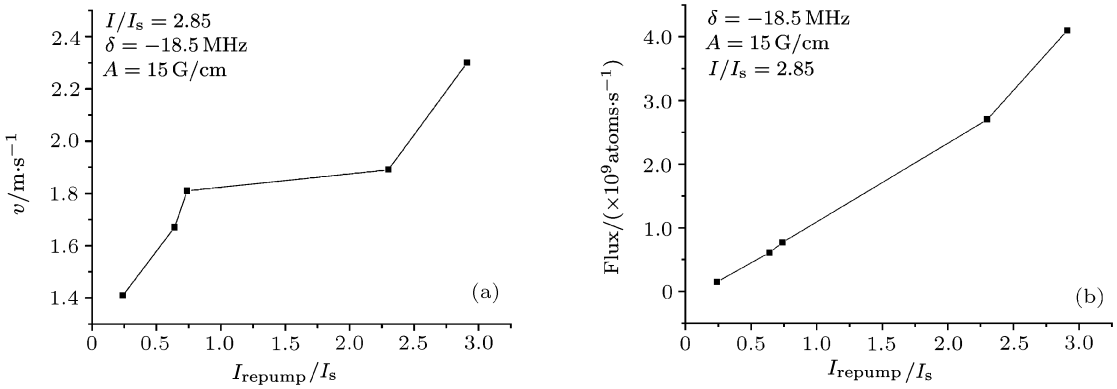


Fig.7. (a) The initial velocity of the atomic source, and (b) the atomic source flux respectively as a function of the intensity of the repumping laser beam, I_{repump}/I_s.

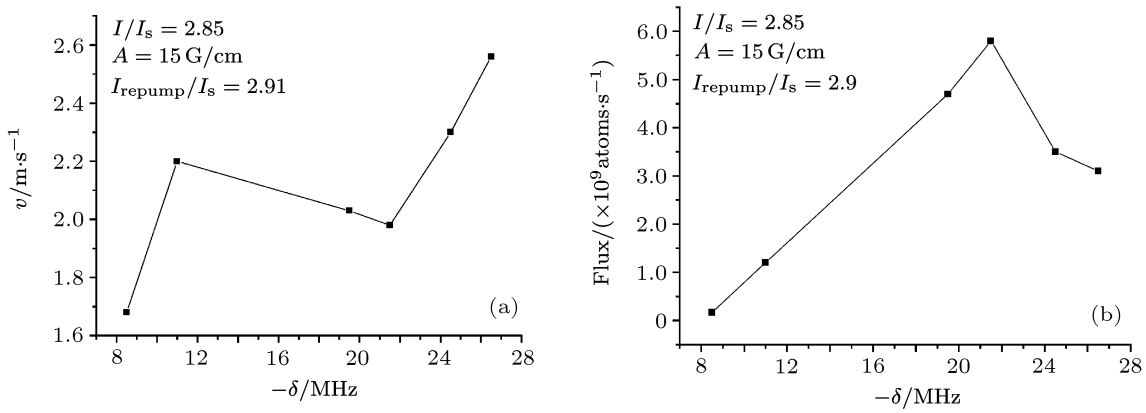


Fig.8. (a) The initial velocity of the atomic source and (b) the atomic source flux respectively as a function of the detuning of the cooling-trapping laser, $-\delta$.

4. Conclusion

In conclusion, we have demonstrated a preparation method of the ^{87}Rb cold atomic source with tunable flux and velocity. High speed imaging technology has been used for characterizing the beam performance and the dynamic mechanism of the beam formation.

It is observed that enhancing intensities of the cooling-trapping laser and the repumping laser can increase velocity and flux of the atomic source efficiently, and therefore they can be functioned for tuning the atomic source. For the detuning of the cooling-trapping laser, there exists the optimum value for the performance of the atomic source.

With the built setup, a tunable atomic source with the initial velocity of 1.4 $\sim$ 2.6 m/s and the atomic source initial flux of $2 \times 10^8 \sim 6 \times 10^9$ atoms/s has been achieved. Further tests are underway for evaluating the source stability, studied effects of the magnetic field and so on.

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