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A single laser-operated magneto-optical trap for Rb atomic fountain

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Abstract. A single diode laser and an electro-optic modulator (EOM)-operated magneto-optical trap (MOT) has been developed for a compact atomic fountain. For generating the required cooling and re-pumping laser beams for the MOT, an EOM operating at 6.58 GHz has been used to modulate the input laser beam. In the trapped cold atom cloud, the population in the two ground hyperfine states ($F = 1$ and $F = 2$) of ^{87}Rb atom has been varied by changing the power applied to EOM. Using this MOT, the cold atoms have been launched vertically upwards and the launch velocity of atoms has been measured. Besides being compact, such MOTs can be useful in atom interferometry set-ups where different atom clouds with different initial hyperfine states need to be prepared.

Keywords. Laser cooling; magneto-optical trap; atomic fountain.

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1. Introduction

A magneto-optical trap (MOT) provides a versatile and widely used platform to generate cold atoms for atomic physics studies e.g. generation of degenerate gases and Bose–Einstein condensation (BEC) [1], and development of atom-optic devices for precision measurements and sensing applications, such as atomic clocks [2], cold atom gravimeter [3], cold atom gyroscopes [4]. A compact MOT-based atom-optic devices are generally robust in operation as well as in transportation. The development of a compact MOT set-up requires considerable effort in terms of minimising the number of lasers and reducing the number of optical and mechanical components. The MOT operation for alkali Rb atoms usually involves two-frequency stabilised lasers operating near the cooling and re-pumping transition frequencies. The requirement of a laser operating around re-pumping transition frequency has generally been removed by adopting any of the following two techniques. The first technique involves the use of a single laser with modulation of its current to simultaneously generate frequencies corresponding to cooling and re-pumping transitions [5]. More recently, a new variant of such type of single laser MOT operation has been demonstrated where the laser system sequentially achieves cooling and re-pumping transition frequencies [6], in which single laser alternating-frequency magneto-optical trap (AF-MOT) for ^{87}Rb atoms has been achieved by a frequency jump of 6.6 GHz on a microsecond timescale. The other technique involves using a laser along with an electro-optic modulator (EOM) to generate multiple frequencies at required separation [7–9]. So far, using these single laser-operated MOTs have been restricted either to demonstrate trapping of a single isotope of alkali atoms or to study simultaneous trapping of two isotopes for cold collision studies [7].

In this paper, we report our work on a single laser-operated MOT for developing a compact atomic fountain for atom interferometry applications. We have demonstrated that cold atom population distribution between two ground hyperfine states of ^{87}Rb in the atom cloud can be varied by varying the EOM power. Besides being a simple and compact alternative to the traditional MOT, this kind of MOT can be particularly useful for constructing a set-up like double-atom-interferometer where initial atom clouds in two interferometers need to be in different initial states [10].

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2. Experimental set-up

The cooling and re-pumping transitions in ^{87}Rb atom are shown in figure 1. The re-pumping laser beam is required to pump atoms accumulated in $5^2S_{1/2}$ $(F = 1)$ state to the state $5^2P_{3/2}$ $(F' = 2)$, to bring those into the cycle of cooling transition. The frequency of laser beam exciting the re-pumping transition $5^2S_{1/2}$ $(F = 1) \rightarrow 5^2P_{3/2}$ $(F' = 2)$ should be $\sim$ 6.58 GHz higher than that of the laser beam exciting the cooling transition $5^2S_{1/2}$ $(F = 2) \rightarrow 5^2P_{3/2}$ $(F' = 3)$. In our set-up, the required re-pumping laser beam was generated from the cooling laser beam using a commercial EOM (Make: Qubig, Germany, Model: EO-Rb87-6.6G) operating at $\nu_{RF} = 6.58$ GHz. This is schematically shown in figure 2a. The schematic of MOT set-up is shown in figure 2b. As shown in figure 2a, the input laser beam to EOM is the laser beam at frequency ν_L from an ECDL which is locked at the cooling transition of ^{87}Rb atom. In the output from EOM, both cooling beam at frequency ν_L and re-pumping laser beam with frequency $\nu_L + \nu_{RF}$ are obtained in co-propagating geometry. In addition, a beam at frequency $\nu_L - \nu_{RF}$ is also obtained. At EOM output, the power in cooling and re-pumping beams is typically $\sim$60% and $\sim$20%, respectively, of the input beam power at an EOM power of $\sim$32 dBm. The output beam from EOM was split into three beams and each beam expanded nearly eight times. After using appropriate optical components, six circularly polarised MOT beams were prepared from these three beams. The intensity in each MOT beam is $\sim$12 mW/cm^2 (power $\sim$2 mW) in which cooling and re-pumping parts are in the ratio 3:1 at $\sim$32 dBm of RF power to EOM. For MOT preparation, two MOT beams were passed through the chamber at +45° and −45° with respect to the vertical axis from upward to downward direction. Another two MOT beams were passed through the chamber in counterpropagating direction of these beam. One pair of counterpropagating MOT beams passed along the horizontal axis through the MOT chamber. All six MOT beams crossed one another at the centre of the chamber. The cooling laser frequency was $\sim$12 MHz red-detuned with respect to the cooling transition $5^2S_{1/2}$ $(F = 2) \rightarrow 5^2P_{3/2}$ $(F' = 3)$ of ^{87}Rb using a standard saturated absorption spectroscopy (SAS) technique.

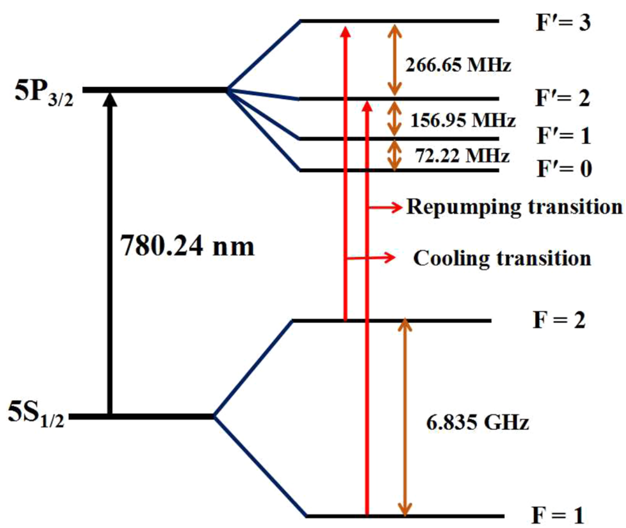

Figure 1. The cooling and re-pumping transitions in ^{87}Rb atom for MOT operation.

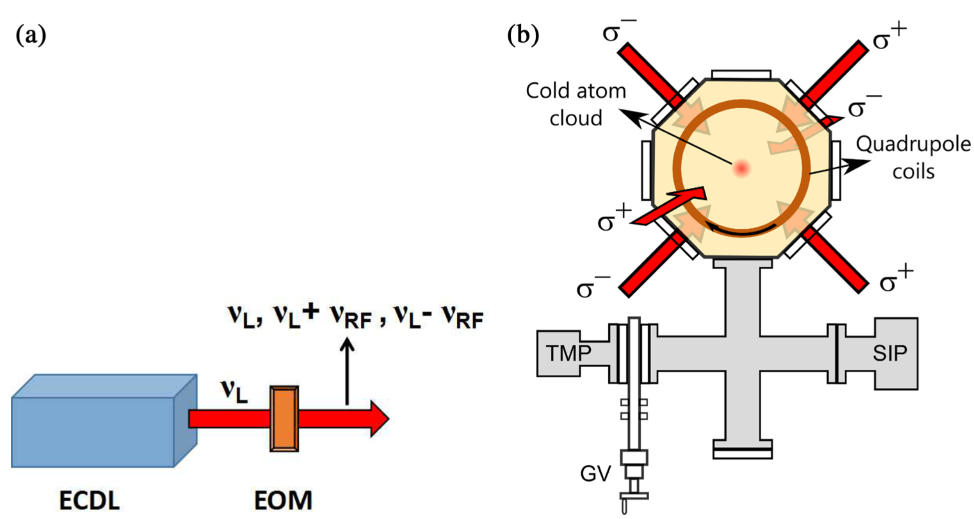

Figure 2. (**a**) Schematic of the generation of cooling and re-pumping laser beams using a commercial electro-optic phase modulator (EOM) operating at 6.58 GHz and (**b**) schematic of MOT set-up; σ − and σ +: Left and right circularly polarised MOT beams; TMP: turbomolecular pump; SIP: sputter ion pump; GV: gate valve.

The set-up, as shown in figure 2b, consists of a stainless steel octagonal chamber evacuated to a pressure of $\sim 1 \times 10^{-8}$ Torr using suitable vacuum pumps. The Rb vapour is injected into the chamber by passing a DC current of ~ 3.2 A through Rb dispenser source. The dispenser source is inserted in the chamber through a vacuum-compatible feed-through. The magnetic field gradient for MOT (~ 10 G/cm) is produced by a pair of quadrupole coils. The RF power applied to EOM was varied to change repumping beam power, which was used for manipulating population in two ground hyperfine states.

For atomic fountain, the vertical launching of cold atoms from MOT has been performed using moving optical molasses. For this, the frequency of two upper MOT beams directed downwards was red-shifted, and the quadrupole magnetic field was switched-off. This launch allows atoms to reach a maximum height above the trap. The studies on launching of cold atoms using this single-laser MOT will be useful for developing a compact atom fountain for atom interferometry set-up for precision measurements.

3. Results and discussion

First, the number of cold atoms in the single-laser MOT was estimated by collecting the probe beam excited fluorescence from the MOT cloud on a calibrated CCD camera [11,12]. The measured cold atom number and the density of the cloud were $\sim 5.0 \times 10^6$ and 8.0×10^9 atom/cm^3 respectively when EOM power was $\sim$32 dBm. The measured temperature of the cold atomic cloud in the MOT was $\sim$200 μK. The number of atoms in the MOT can be increased further by using a higher-power ECDL.

Then, we have studied the controlled variation of the number of cold atoms in two ground hyperfine states $F = 1$ and 2 of ^{87}Rb by varying the re-pumping beam power. The re-pumping beam power was varied by varying the input power to EOM. The number of cold atoms in a chosen hyperfine state was measured by collecting the probe beam-induced fluorescence on the photodiode. For this, a probe laser beam of ~ 0.5 mW power was used. The frequency of the probe beam was tuned, at cooling or re-pumping transition, depending upon the state population was measured. The corresponding fluorescence was collected on a calibrated photodiode. The photodiode signal was converted into cold atom number after applying calibration factor. Data shown (figure 3) by circles and triangles show the measured variation in the number of cold atoms in hyperfine states $F = 1$ and 2 respectively. The sum of these numbers, i.e. total number of cold atoms in $F = 1$ and 2 states, is shown by squares. This total number of atoms in the MOT (as shown by squares in figure 3) is found very close to the total number estimated by collecting the MOT fluorescence on a CCD camera.

With increase in the EOM power, the total number of atoms in the MOT first increases, and then reaches a maximum value before starts decreasing. The increase in the EOM power causes an increase in the re-pumping beam power. Initial increase in the re-pumping beam power results in more transfer of atoms to the cooling cycle, which gives more number of atoms in the MOT. At further higher re-pumping beam power, the total number of cold atoms decrease which may be due to the light-induced collisional losses in the MOT as well as due to power broadening of the re-pumping transition [13].

This control on the number of cold atoms in two hyperfine states ($F = 1$ and 2) in the cloud may be

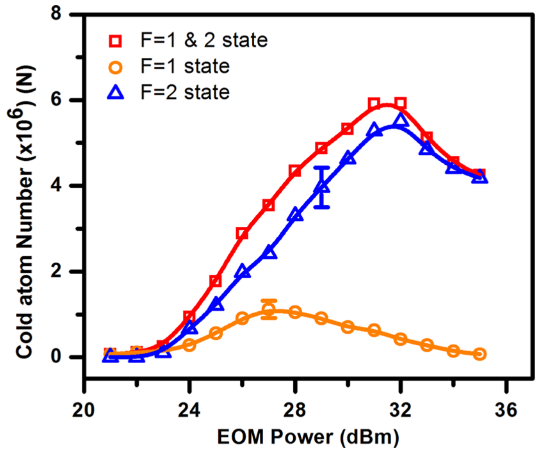

Figure 3. Measured variation in the number of cold atoms in ground states $F = 1$ and 2 with variation in EOM power (dBm). Data shown by circles and triangles represent the number of cold atoms in the ground hyperfine states $F = 1$ and 2 respectively. Sum of the numbers in two hyperfine states is shown by squares. The continuous curves are guides to the eye.

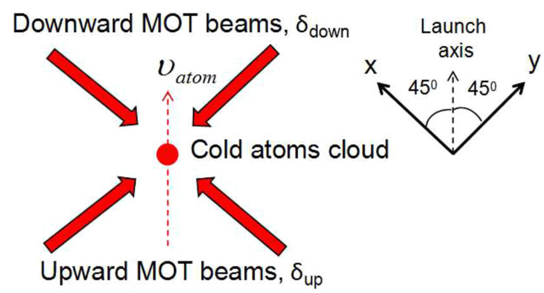

Figure 4. Schematic of the launching of the cold atoms by changing the frequency detuning of the MOT beams.

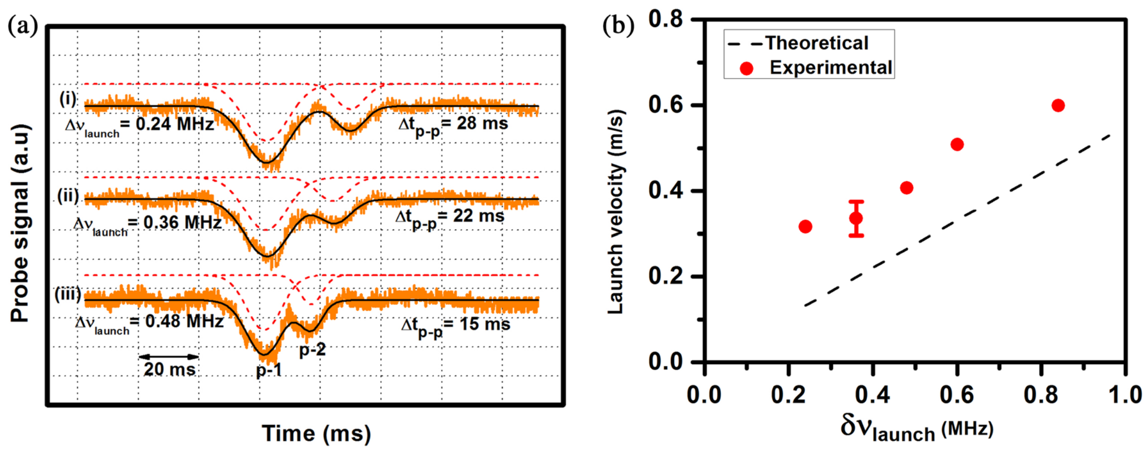

Figure 5. (**a**) Photodiode signals in launch velocity measurements for different values of $\delta\nu_{\mathrm{launch}}$: $\delta\nu_{\mathrm{launch}} = 0.24$ MHz (curve i), $\delta\nu_{\mathrm{launch}} = 0.36$ MHz (curve ii) and $\delta\nu_{\mathrm{launch}} = 0.48$ MHz (curve iii). The black curves are the best fit to the measured signals, and the dashed red curves are the individual curves used for generating the best-fit curve. (**b**) Variation in launch velocity with detuning $\delta\nu_{\mathrm{launch}}$. The error bar is determined from the scatter in the values obtained in repeated measurements.

useful to construct dual hyperfine states interferometers [10]. Our technique for the estimation of the number of atoms in different hyperfine states can also be exploited for optimising the stimulated Raman process in interferometry.

For launching atoms in vertically upward direction in fountain geometry, the frequency of the upper two MOT beams (directed downwards) was red-shifted and the quadrupole magnetic field was switched-off. This results into launching of cold atoms vertically with launch velocity (υ_{atom}). This velocity allows atoms to reach maximum height above the trap.

The schematic of the launching process of atoms is shown in figure 4. The launching of the atoms can be done by introducing different detunings in downward and upward directed MOT beams. This is also equivalent to the condition when the net detuning is provided to either downward- or upward-directed MOT beams [3]. In our case, we have introduced additional red shift in the frequency of downward-directed MOT beams. The final detuning of the downward-directed MOT beams was changed to $\delta_{\mathrm{down}} = \Delta_{\mathrm{L}} - \delta$ ($\Delta_{\mathrm{L}} = \nu_{\mathrm{L}} - \nu_0$ss Δ_{L} is the cooling laser detuning, ν_{L} is the cooling laser frequency, ν_0 is the atomic resonance frequency, δ is the additional detuning introduced), whereas detuning of the upward-directed MOT beams was kept unchanged with $\delta_{\mathrm{up}} = \Delta_{\mathrm{L}}$. The net detuning between counterpropagating beams in a pair in the x-direction (or y-direction) is $\delta\nu_{\mathrm{launch}} = \delta_{\mathrm{up}} - \delta_{\mathrm{down}} = \delta$. Due to this detuning, the atom launch velocity along the x-axis (or y-axis) can be given as $\frac{\lambda\,\delta\nu_{\mathrm{launch}}}{2}$ [14,15]. Therefore, the net launch velocity of an atom along the vertical direction in the laboratory frame can be given by

$$\upsilon_{\mathrm{atom}} = \frac{\lambda\,\delta\nu_{\mathrm{launch}}}{\sqrt{2}}. \tag{1}$$

After the launch of atoms in the vertical direction, the launch velocity (υ_{atom}) was estimated using the formula,

$$\upsilon_{\mathrm{atom}} = \frac{d}{(\Delta t_{p-p})} + \frac{1}{2} g\,(\Delta t_{p-p}) \tag{2}$$

where g is the acceleration due to gravity, d is the separation between the two vertically separated probe laser beams and Δt_{p-p} is the time interval between the two observed absorption peaks when launched atoms crossed these probe beams. In our experiments, we have aligned two vertically separated probe beams, one immediately above the atom cloud and other at separation $d \sim 5$ mm from the first probe. Each probe beam was of size $\sim$1 mm ($1/e^2$ radius) and power $\sim$10 μW. The absorption signal was detected using a sensitive photodiode. The time interval Δt_{p-p} between the absorption peaks due to two probe laser beams was measured by displaying signal on an oscilloscope. Figure 5a shows the experimental signals corresponding to $\delta\nu_{\mathrm{launch}} = 0.24$ MHz (curve i), 0.36 MHz (curve ii) and 0.48 MHz (curve iii) respectively.

figure 5b shows the theoretical (from eq. (1)) and experimental variations in launch velocity with $\delta\nu_{\mathrm{launch}}$. The difference between the experimentally measured launch velocity and the theoretically calculated values (dashed line in figure 5b) could be possibly due to misalignment and intensity imbalance in the MOT beams as well as imperfect switching of the magnetic field during the launch process.

4. Conclusion

By using a single laser system and an EOM, a magneto-optical trap (MOT) for alkali ^{87}Rb atoms has been developed for atomic fountain and atom interferometry applications. The controlled variation in the number of cold atoms in two hyperfine ground states ($F = 1$ and 2) is demonstrated by varying the re-pumping beam power through EOM. We have used this MOT for launching the cold atoms vertically upwards and measured the launch velocity of atoms. Such a single laser-operated MOT systems can be useful in double atom interferometry set-ups where two clouds in different hyperfine states are required.

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