Characterisation of Rocking Ratchet with Cold ^{87}Rb Atoms

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Abstract

A rocking ratchet phenomenon of directed transport is demonstrated. This has been realised with cold rubidium atoms in one dimensional dissipative optical lattice with $lin\perp lin$ configuration. The temperature of the cold atomic cloud is measured by time of flight technique with $29\mu k$. The atom number trapped in the MOT is determined using absorption imaging to be 5.6×10^6 atoms. The results show the influence of the atomic current amplitude by varying the lattice beams parameters. One of the lattice beams is modulated with different modulation depths. It shows that highest modulation values have a higher atomic current. The current amplitude is also depending on the modulation frequencies. The results indicate the possibility of existence the vibrational frequency. The harmonic amplitude ratio varied and found the ratchet current is growing with increasing the amplitude of one of the lattice beams and at a certain value goes down.

Keywords: Optical lattice, laser cooling, rocking ratchet

1. Introduction

Transport phenomena are a very interesting topic in many fields of science like physics, chemistry, and biology [1]. Brownian motors, or ratchets, are microscopic devices that turn random fluctuations into directed motion in the absence of a bias force. Ratchets are useful for the understanding of how nanoscale motors can work under the influence of substantial thermal motion. Ratchets are an intriguing phenomenon that has attracted the attention of the scientific community for their numerous applications, such as electron pumps [2] or particle separation devices [3]. The archetypal of a ratchet device is the rocking ratchet or general AC driven ratchets. Rocking ratchets can be realised by using either an asymmetric spatial potential and zero mean symmetric driving force, or a symmetric spatial potential and a temporal asymmetric driving force, which is used in this work. The principle of a rocking ratchet is a spatially symmetric potential is rocked, or tilted, by a time asymmetric zero average force. This force drives the system out of equilibrium and breaks the system symmetry. Therefore, a directed atomic current can be generated [4,5].

The rocking ratchet scheme considered is based on a temporally asymmetric bi-harmonic drive and a spatially symmetric periodic potential. The underlying mechanism of rectification is the so-called Harmonic Mixing [6]. The anharmonicity of the optical potential causes the medium to be nonlinear. Thus, it becomes able to mix the harmonics with frequencies ω_d and $2\omega_d$ with phase difference $\emptyset$ and to generate a current. This current is proportional to the sine of the relative phase $\emptyset$ between driving harmonics ($I \propto sin\emptyset$) [7]. Basically, in harmonic mixing mechanism, all possible higher harmonics and their relative sum and difference are generated. When the driving frequencies are commensurable ($n\omega_{d_1} = m\omega_{d_2}$) with n and m integer, the DC response also will appear [8, 9]. The driving force relevant to our experiment is given by [9]:

$$F_d(t) = F_0[Acos(\omega_d t) + Bcos(2\omega_d t + \emptyset) \qquad (1)$$

where F_0 is the overall amplitude of the driving force, $\omega_d = \frac{2\pi}{T}$ is the driving frequency with time T, A and B are the driving force amplitudes and $\emptyset$ is the relative phase between the harmonics, which controls the symmetry of the system and therefore the generation of a current. In addition to the requirement of out of equilibrium settings, a ratchet has to possess a type of asymmetry to be able to generate a directed current. Symmetry analysis is the tool that is used to predict whether directed transport is possible or not. According to Curie's principle, generation of a current is expected when the system does not have any symmetry, which would prevent it [1].

2. Experimental work

A rocking ratchet can be implemented experimentally by using an optical lattice [10,11]. Optical lattices can be defined as periodic potentials produced by the interference of two or more laser beams. It was suggested for the first time when Letokhov proposed the possibility of cooling and confining the atoms in the potential wells by the dipole force that results from the light shift [12].

Dissipative optical lattice is laser beams configuration of the $lin \perp lin$ optical lattice. “lin” denotes the polarisation in a standing wave formed by two laser beams that propagate in opposite direction (z and -z), and have orthogonal linear polarisation along x and y respectively. The optical lattice creates a spatial modulation of the laser field polarisation. By interacting with the atomic states, a periodic modulation of the light shift of the ground state sublevels is produced. For this configuration, the interaction between the laser fields and the atoms reduces the kinetic energy and then localises the atoms in the optical potential.

The experiment is performed with ^{87}Rb atoms trapped in a magneto-optical trap (MOT). For the operation of the experiment, there are many important factors such as the alignment of the MOT laser beams, their polarisation and frequency. The beams must be aligned by the retro-reflected method. Each pair of the beams should have opposite circular polarisation to the other one. Figure (2) shows the schematic of the MOT. The main part is a glass cell (30x30x100mm^3) attached to an ion pump to produce a vacuum of below 10^{-9}mbar. The rubidium source is a pair of Saes getters connected to an electrical feedthrough. In order to control the experiment and acquire the data, two computers are used with a LabView program. The first computer is used to control all the experimental parameters and their arrangement in a time sequence. The computer control consists of a digital PCI-card with 64 channels (Viewpoint DIO-64) and 2 analogue output cards with 8 channels each (NI PCI-6731). The timing resolution is 1μs. There are two modes to control the experiment: MOT mode and sequence mode. When we use the sequence mode to run the experiment, the first step is loading the atoms in (3 s) time by turning the MOT beams (-2.5Γ detuning) and the magnetic field on. Then, for (15 ms), the detuning is changed to -7Γ to reduce the MOT temperature. The final temperature was around 30μK.

Then the lattice beams are switched on while the magnetic field and the MOT beams are switched off. After 1ms the modulation of one of the AOMs is ramped up from 0 to maximum value in 1ms and then the system is driven for a variable amount of time. This is followed by 1 ms time of flight, in which the lattice beams are switched off, to compensate for eventual delays and to make sure that during the imaging phase there is no other light present. After that, we take in a short time 3 absorptive images with 0.144ms exposure time, the first two with imaging beam switched on, the last one just with the ambient background of the lab. Between the images is a 25ms waiting time to allow the camera to get ready again. From those images the optical density is calculated and then displayed and fitted with a 2D Gaussian curve. The parameters of the fit are displayed as well and then stored in a file. After that the sequence starts again. The second computer is used to acquire, save and analyse the images obtained by a CCD camera. The configuration is created via interacting the cold atoms cloud with two counter propagating laser beams which have linear orthogonal polarisation $lin \perp lin$ configuration. Each laser beam is passed through an acousto-optical modulator (AOM) to shift the frequency down with respect to the atomic transition. Each AOM is driven by a function generator with the same carrier frequency (SMY01 and SMT02) to modulate the amplitude. A double pass AOM controls the main lattice beam before splitting it into two lattice beams. Another function generator (Agilent 33220A) produce a signal of sinusoidal form which is utilised to modulate the frequency of one of the lattice beams signal generators. A 1D rocking ratchet is realised for cold ^{87}Rb atoms by using a driven optical lattice. To perform a ratchet experiment, many steps must be performed: loading the MOT, cooling the atoms and turning on the optical lattice. Then, modulate the frequency of one of the lattice beams and generate a zero mean force. The relationship between the frequency and phase modulation is a differential one, $\omega(t) = \dot{\alpha}\,(t)$, where $\alpha(t)$ is the phase modulation. Driving the system out of equilibrium and breaking the symmetries is a method used to tilt the lattice and reduce the potential well which leads to generate the current. It depends on many factors such as amplitude, phase and frequency of the driving. In this work, a bi-harmonic force is applied with frequencies ω_1 and ω_2 (with $\omega_2=2\omega_1$). In addition, there is phase difference ($\emptyset$) between the driving forces to create a periodic force that breaks the system symmetries.

3. Experimental Results

The data which are presented here is the experimental results of a one dimensional rocking ratchet experiment for ^{87}Rb cold atoms. The presented data demonstrates the control of the atomic transport by tuning some of the system parameters. The particles current is generated as a result of applying an AC force by modulating the frequency of one of the optical lattice beams.

For these measurements, it is important to calibrate the camera (CCD) to transform measurements done in camera pixels into absolute values. This is done by measuring the movement of the centre of mass with different expansion times of the

MOT as shown in Fig. 1. Because the atoms will fall under the influence of gravity, the gravity force is used for this purpose to obtain the calibration ratio 12.5 μm/Pixel.

To be able to measure the temperature of the MOT, The width of the MOT is measured as a function of the free expansion time as shown in Fig. 2. The temperature is 29.5μK. The velocity of the cloud is measured with ω_1=45KHz (Amp_1=0.8V) and ω_2=90KHz (Amp_2=0.2V), as a function of different driving times 16.9 mm/sec. The number of the atoms trapped in the MOT was also determined using the absorption imaging technique to be 5.6×10^6 atoms. The measurements are taken by varying the modulation, frequency ratio and amplitude ratio applied to the lattice beams as a function of the atomic current amplitude.

3.1. Current amplitude vs. modulation

Studying the magnitude of the atomic current as a function of one of the lattice beams modulation reveals several distinguishing features of the ratchet effect. Fig. 3 shows the atomic centre of mass velocity as a function of the phase difference between the driving force harmonics. The velocity is expressed in terms of the recoil velocity $V_r = \frac{\hbar k}{M}$ (for ^{87}Rb D_2 line $V_r = 5.88\ mm/s$).

The data are taken for different modulation depths. The red lines in the graph represent the best fits of the data with the function $f(x) = \frac{V}{V_r}\sin(\phi + \phi_0)$. This graph provides a clear insight on the key feature of the ratchet so that the highest modulation values have the biggest current (sine amplitude). This can be attributed to the strong shaking of the lattice which induces higher current. Fig. 4 summarises the relation between the amplitude of the sines and the driving force. It can be seen that there are two maxima (at 200 KHz/V and 900 KHz/V) with ω_1=50 KHz and ω_2 =100 KHz driving frequencies and a fixed modulation ratio. However, the best sines that have best fit and lower deviation from the sine function are in the lower values area.

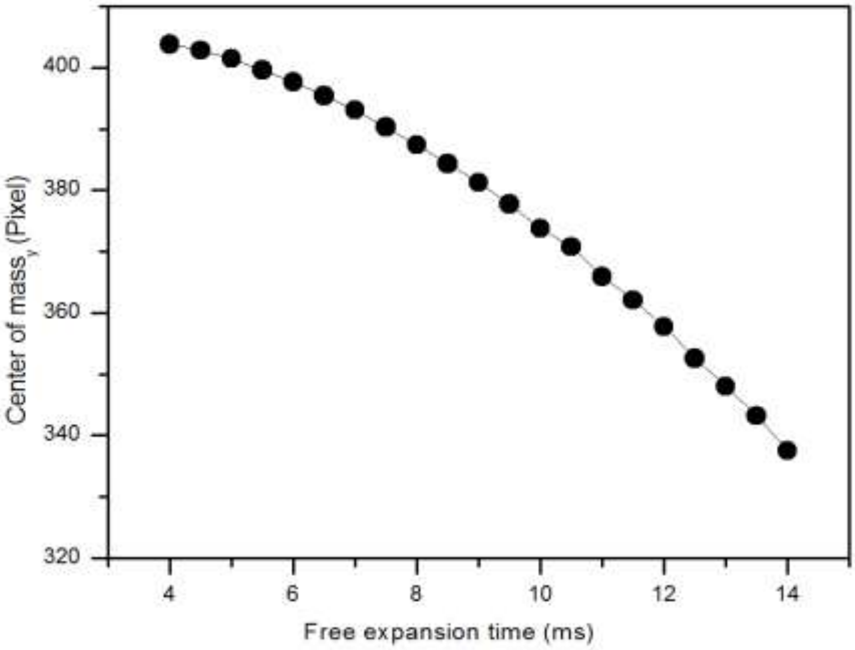

Figure. 1. The centre of mass of the MOT as a function of the free expansion time.

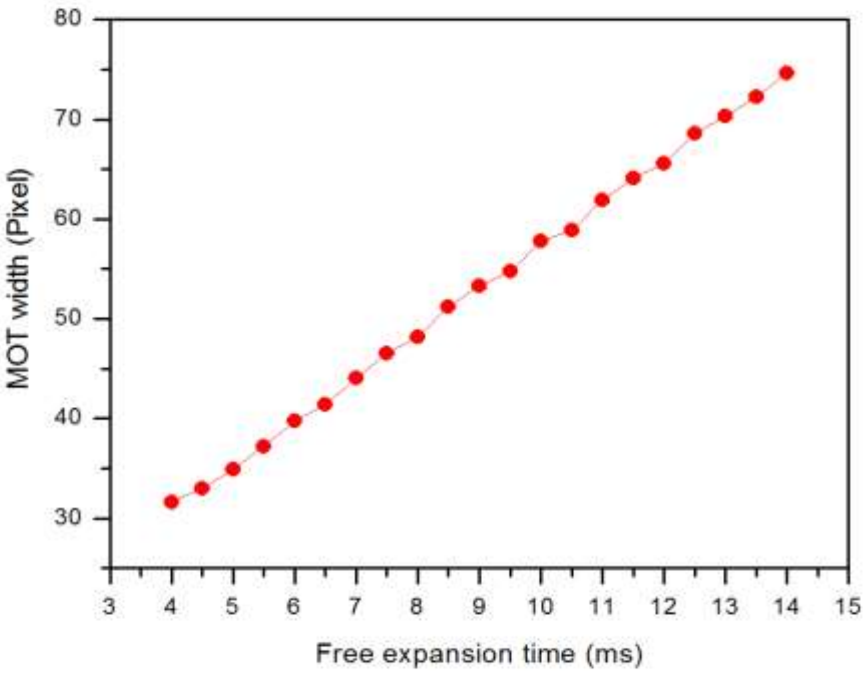

Figure. 2. The MOT width as a function of the free expansion time of the MOT revealing the temperature of the cloud.

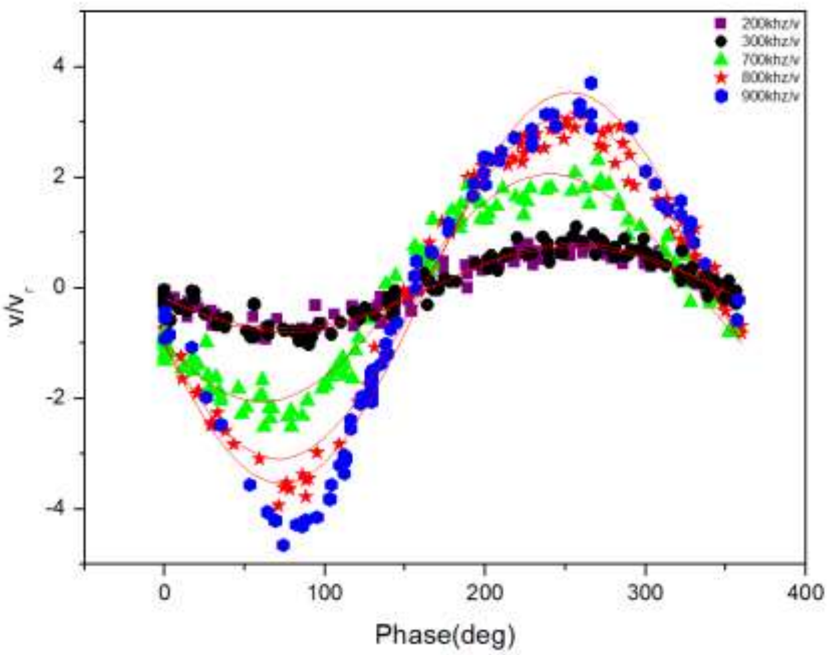

Figure. 3. The centre of mass velocity, in units of the recoil velocity ($V_r = \hbar k/M$), as a function of the phase between the two harmonics.

3.2. Current amplitude vs. frequency ratio

Fig. 5 exhibits the sine current amplitude dependence on the modulation frequencies. The largest current is obtained for $\omega_1 = 45\ KHz$ and $\omega_2 = 90\ KHz$. This may indicate existence of the vibrational frequency. When the frequency increases beyond this value, the current will decrease accordingly.

3.3. Current amplitude vs. modulation ratio amplitude

The relationship between the amplitude of the sine and the harmonics amplitudes ratio is studied while keeping the amplitude of the ω_{1-} force constant at 0.8V. In addition, the frequencies ratio is constant as well at ω_1=45 KHz, ω_2=90 KHz which have the highest atomic current from the previous experiment. As shown in Fig. 6, the ratchet current is growing when we increase the amplitude of the first force. However, at a certain value the current goes down.

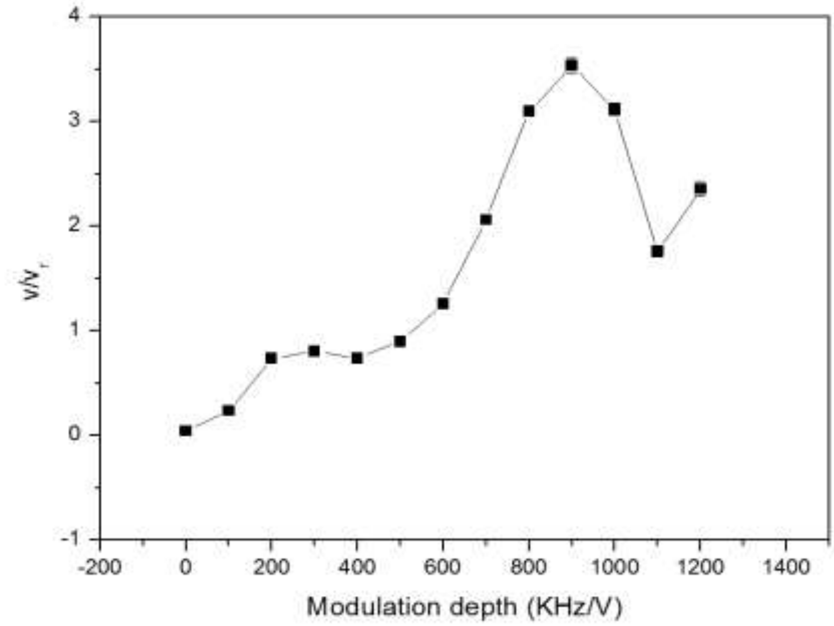

Figure. 4. The sine amplitude as a function of the modulation depth.

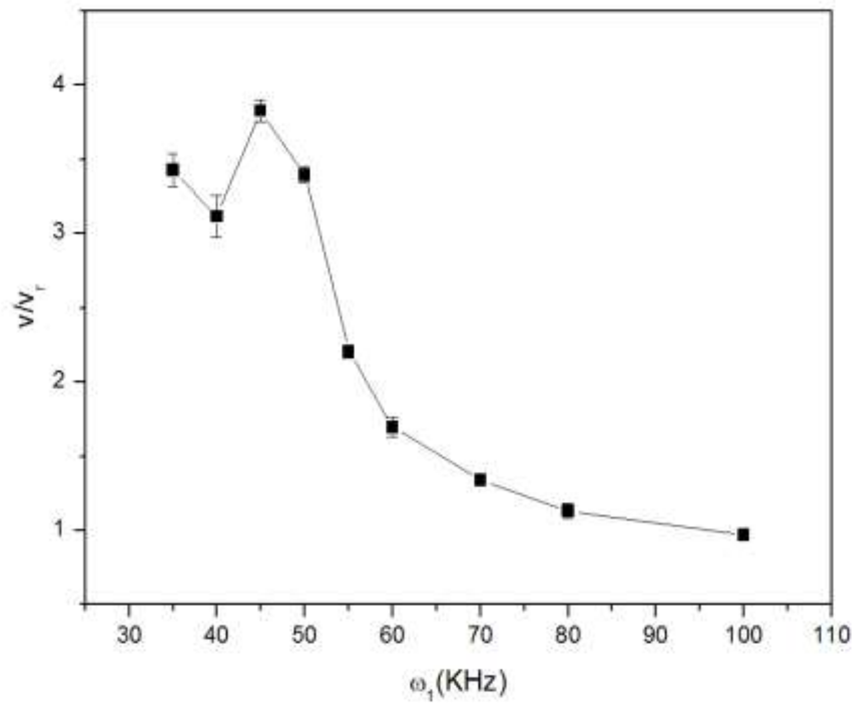

Figure. 5. The sine amplitude over different modulation frequencies. The graph is plotted with $\omega_{1.}$

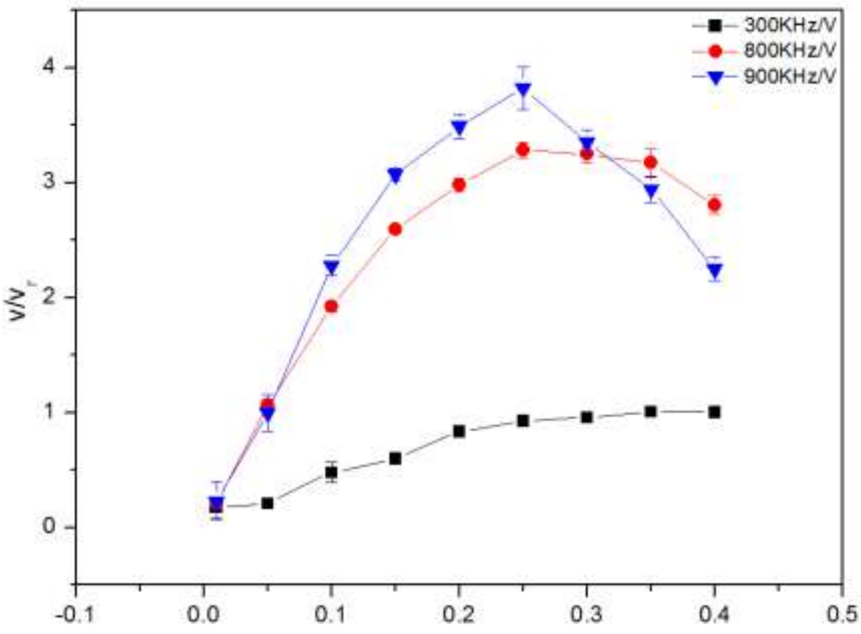

Figure. 6. The current amplitude over one of the amplitude modulation with keeping the other amplitude constant (0.8V).

4. Conclusion

One dimensional rocking ratchet for cold atoms in a driven optical lattice is realised and characterised. The relationship between atomic current amplitude (sine amplitude) and the ratchet system parameters is studied and analysed. The system is characterised by measuring the trap temperature and the atom number. In addition, it is found that there is a dependence of the sine amplitude on the modulation frequency and amplitude ratio modulation. There is an ability of controlling the directed motion in 1D. The results show the possibility of producing the directed motion of the rubidium atoms when applying time-asymmetric forces. These forces are produced by adding two sine waves as a driving force with different frequencies and suitable phase difference between them. Controlling the symmetry is also studied which can direct the ratchet motion. Characterising the rocking system has an importance for a future study in controlling the atomic current or generating an ultra-cold atom in Bose-Einstien Condensate.

Conflict of Interests.
There are non-conflicts of interest .

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الخلاصة

تم دراسة خصائص ظاهرة التيار الذري الهزاز (Rocking ratchet) باستخدام ذرات الربيديوم المبردة ^{87}Rb داخل الشبكة البصرية ذات بعد واحد $lin \perp lin$ (Configuration). تم قياس درجة حرارة الغيمة الذرية الباردة باستخدام تقنية زمن الطيران (Time of Flight) وهي $29\ \mu k$.

تم حساب عدد الذرات المقتنصة في المصيدة البصرية المغناطيسية باستخدام التصوير بالامتصاص وكانت بحدود (5.6×10^6) ذرة. النتيجة بينت تغير سعة التيار الذري عند تغيير معلمات الشبكة البصرية. تم تضمين احد اشعة الشبكة البصرية الليزرية بموجات ذات شدات مختلفة حيث تم ملاحظة أعلى تيار ذري عند اكبر عمق تضمين و ان سعة التيار تعتمد ايضاً على ترددات التضمين وان النتيجة بينت امكانية وجود تردد اهتزازي (Vibrational frequency) كما تم ملاحظة تغير سعة التيار الذري بتغيير سعة الموجه المضمنه لاحد الاشعة للشبكة البصرية وبذلك يتم التحكم بالتيار الذري عن طريق تغيير معلمات الشبكة البصرية.

الكلمات الدالة: الشبكة البصرية ، التبريد بالليزر، التيار الذري.