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An Off-Axis Rotating Atom Trap

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An off-axis rotating atom trap

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Abstract: We present a novel configuration of a magneto-optical trap for cold atoms. The trap is very simple in design, employing only a small permanent magnet and an external Helmholtz bias coil. The trap's principal advantage is that the entire volume of the overlapping laser beams can be used for atom guiding and manipulation. An especially interesting effect is the rotation of the trapped atoms in circular motion as the permanent magnet is rotated. Clouds containing on the order of $2*10^6$ atoms are rotated up to 60Hz forming a 5 mm diameter ring. This rotation can potentially be used in studying the behavior of cold atoms in 2-dimensional potential as well as applications for rotational sensors. We also present a classical theoretical model to simulate the experiment.

OCIS codes: (020.7010) Trapping

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1. Introduction

As part of our efforts at the Naval Research Laboratory on ultra cold atoms and integrated Bose-Einstein condensates for possible use in remote gravitational and inertial sensors, we have discovered a novel configuration of a Magneto-Optical Trap (MOT). In a standard MOT the required gradient in magnetic field is accomplished with anti-Helmholtz coils which involve multi turned coils to produce the necessary magnetic field configuration. A serious drawback is that the trapped atoms are only confined to the one single field null at the center of the quadrupole field (although some deviations are allowed using separate external bias fields). Generally, manipulating and guiding atoms outside this region becomes difficult. In our system we use a simple permanent magnet with canceling external bias field to generate the equivalent quadrupole field. The laser cooled atoms are confined in a single null but the position can now be manipulated by simply moving the magnet in space. For example, the trapped atoms can be spun off-axis, creating a circular motion by simply spinning the permanent magnet.

A magnetic storage ring of cold atoms has already been demonstrated [1]. Very recently Bose-Einstein Condensate was created in a ring shaped magnetic waveguide [2]. Moreover, numerous experiments have shown atom guides around current-carrying wires that have been used to demonstrate various atomic beam splitters, atom conveyors, and magnetic microtraps [3-10]. So far, using current carrying wires for splitting and guiding has either produced fragmentation or unsuccessful splitting [11-12]. By controlling and manipulating such ultra cold atoms it is envisioned that much higher sensitivity can be achieved for atomic inertial sensors. This work evolves directly from our efforts to develop more practical and simple sensors. To our knowledge, it has never been shown that the position of an atomic MOT can be moved as freely as in this work.

The ring geometry is a sought after configuration for atom interferometers. This is because the phase sensitivity of an atomic ring gyroscope is many orders of magnitude higher than that of an optical ring gyroscope when both operate as Sagnac interferometers. For this reason, theoretically, the atom ring gyroscope enjoys a factor of 10^{11} higher sensitivity over its optical counterpart [13]. Our Laboratory is interested in actual development of rotational and inertial sensors (gyroscope, gradiometers, etc.). Therefore, a first major step toward the development of such sensors requires answering a substantial question: is it possible to implement a design where the atoms can be manipulated freely and with flexibility. In this work, we demonstrate the off-axis rotation of a magneto-optical trap that remains robust under a high number of revolutions. The MOT is formed and is directly rotated by moving its quadrapole trap.

The magnetic B field is generated by the external Helmholtz coil and the permanent magnet so that the total field is given by

$$\vec{B}(\vec{r}) = \left[\frac{1}{4\pi} \int \frac{\rho_m(\vec{r}\,')(\vec{r}-\vec{r}\,')}{|\vec{r}-\vec{r}\,'|^3} d^3r' \right] - \vec{B}_{ext} \quad (1)$$

where ρ_m is the induced magnetic charge density (proportional to magnetic strength) and $\vec{r}$ and $\vec{r}\,'$ is the magnet and the position vectors respectively. $\vec{B}_{ext}$ is the magnetic field generated by the external Helmholtz coil.

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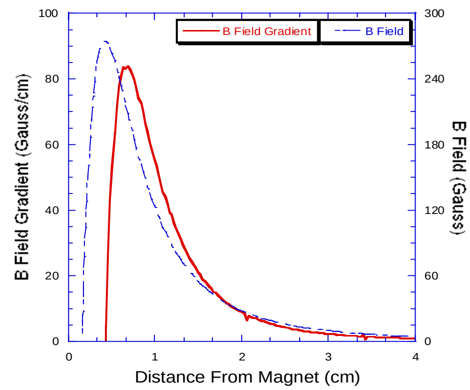

Fig. 1. Plot of measured magnetic B field and Gradient

The axial magnetic field at the center axis is measured for the ring magnet which was used in our experiment and is plotted in Fig. 1. The ring magnets have a 12 mm OD, 8 mm ID and a thickness of 3 mm and are made of neodymium with Nickle plating. There is 10 Gauss/cm at around 2cm from the surface. The absolute value of the magnetic field at the same position is 10 Gauss, which makes it easy to create with a compensating external coils. We have also demonstrated MOT with magnets of different dimensions, such as a ring magnet of 6mm OD, 3mm ID and 3mm thickness, a disc magnet of 6 mm OD and 2 mm thickness. It turned out the exact dimension and strength of the magnets are not very important. In the "far field" they all behave like a magnetic dipole. This also demonstrated the robustness of this configuration.

2. Experiment

In order to incorporate miniaturized systems for further development into possible "fieldable" sensors, we make our chamber a small compact system. Our design is shown in Fig. 2. The vacuum cell is a shortened glass-to-metal adapter (MDC part number 460010) with a 30 mm diameter glass window (Edmund part number G47-521) glued onto the end with Epo-Tek 353ND. The glue is cured at 120 ˚C before mounting onto the chamber. The rest of the chamber consists of one CF 6-way cross and one CF nipple occupying no more than 0.5 L of volume. We use a Physical Electronics Titan 20s 20 L/s ion pump.

The chamber is baked out to a maximum 150˚C at the cell and 200˚C for rest of the chamber for approximately 5 days. Extreme care must be taken in gradually increasing and then decreasing the temperature. The thermal expansion mismatch of the glue and the window material and the cell could prove catastrophic if a too sudden drop in temperature is attempted. We achieve low 10^{-9} conditions of UHV.

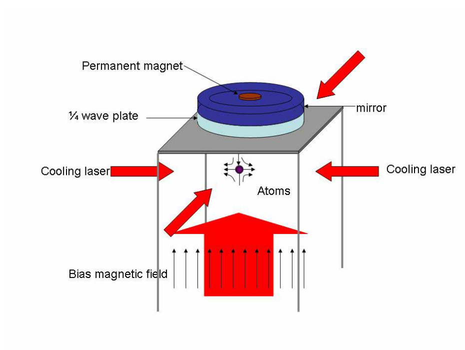

Fig. 2. Experimental set up.

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In Fig. 2, the order of layers (from bottom to top) is: glued-on window, quarter wave plate, mirror, and the magnet. These are all placed outside the vacuum cell. This system is purposely designed so that the shape of magnet can be changed without breaking the vacuum for future experiments. Hence this is one of the key advantages for using a permanent magnet. Other typical magnetic guiding experiments use the wires and coils which are placed inside the vacuum where any change in guiding geometry requires breaking the vacuum and starting the whole new chamber assembly/bakeout repeatedly. However, for this experiment, the advantage in using external permanent magnets for setting up atoms guiding allows flexibility, therefore, capable of testing various magnetic atom guides by simply changing the magnet's geometry and strength for various future experiments. A vertical set of bias coils, in the Helmholtz configuration, provides an external bias field that is uniform on the axis. The resulting field gradient in the vertical direction is at least 10 G/cm. By adjusting the external Helmholtz coil, a field gradient of 10 G/cm, can be achieved with a calculated mean trap frequency of ω = 23 kHz, damping coefficient Γ = 200 kHz and a trap depth of 222 mK. The MOT can be formed anywhere below the window and its vertical position can be easily varied by applied current to the Helmholtz coil. The volume of the overlapping laser beam is about 25 mm^3 which allows the MOT to move freely inside this volume as long as the null is provided. We use a New Focus Vortex TLM 7000 laser system at 780 nm with 50 mW and split its expanded and collimated output into five beams (the four horizontal beams are non-retro-reflecting). All beams are set to the standard $\sigma^+ - \sigma^-$ polarization. Each beam has intensity of 3 mW/cm^2 and is 25 mm in diameter.

3. Off-axis rotating magneto-optical trap

The MOT is about 1 mm in diameter. During rotation we do not see obvious loss of the number of trapped atoms while rotating which means this simple configuration is very stable.

Figure 3 shows a single frame of a rotating MOT. Here, the magnet is attached off-axis (2.5 mm) to a rotor with variable speed and spun fast. When subjected to rotation, the MOT follows the position of the magnetic field null. This is a clear demonstration of the ease with which the position of the MOT can be manipulated in our new configuration. With standard anti-Helmholtz trap, this is very hard to achieve. Furthermore, while the MOT is rotating, we varied the external magnetic field from 7.5 to 15 Gauss. This change in external field directly changed the vertical position while the MOT is rotating. As seen in the movie http://rsd-www.nrl.navy.mil/7210/7215/ColdAtoms/Rotation_MOT.html as long as the quadrupole null remains inside the overlapped laser beam region, about 25 mm^3 in our case, the manipulation is quite simple and no significant loss is observed. We spin the atoms up to 60Hz. Considering that the maximum rotational velocity is 0.9 m/s and the capture velocity is 2 m/s there is no significant change in loading and loss dynamics. The atom will always be loaded from the low velocity tail of the Maxwell-Boltzmann distribution.

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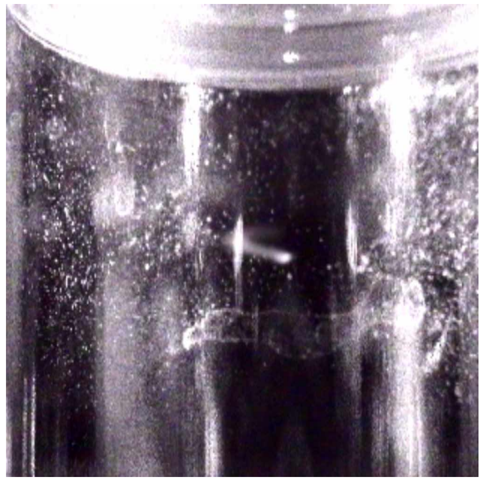

Fig. 3. Rotating MOT. An over exposed image as the MOT is rotated 60Hz.

According to our theory (see Section 4), the radius of off axis rotating atoms should decrease at very high speeds. However, the required rotating speed where significant changes in radius are expected is on the order of few tens of kHz. We were unable to tell whether there is any change in radius at 60 Hz rotation. An improved, high speed imaging system as well as faster rotor (or alternate methods using coils) will be employed in our future investigations.

The most significant achievement in this work is that the MOT is freely manipulated without any concomitant movement of the fixed coils. This is one major advantage over traditional magneto-optical trap and also simplifies the experimental set up. The MOT is also very stable and robust. We were able to spin the MOT as long as the laser frequency remained locked. Within a typical MOT lifetime of 5 seconds, the atoms make 300 revolutions in our system; far more than demonstrated before with storage ring [1]. This is advantageous for potential sensor application.

By increasing the current applied to external bias coils and cycling off the laser beams it would be possible to form a magnetic trap and load atoms into it while rotating with a stronger magnet. In addition, we could also envision taking the usual steps of polarization gradient cooling, optical pumping, and rf evaporation to realize Bose Einstein Condensation in this configuration.

The ring geometry is a key step towards eventual development of highly sensitive inertial sensors. This work is an important first step towards realizing such endeavor. Therefore, we are designing a permanent magnet configuration that could be used to form a static ring MOT. The static ring structure MOT is an ideal geometry where rotational sensors and gyroscopes can be realized and be tested.

4. Theory of an off-axis rotating Gaussian trap

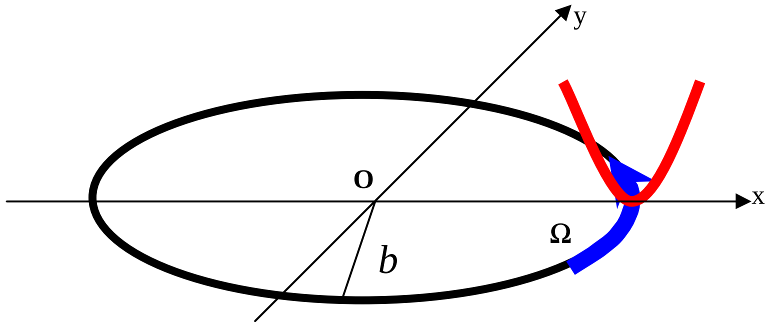

Fig. 4. A trap potential rotates around the origin O=(0,0) with an angular frequency Ω in the x-y plane. The distance from the trap center to the original point O is b .

For simplicity, let's consider the trap itself in Fig. 4 as a two-dimensional (2D) potential, $U(x,y)$, in its own central reference frame. The rotating time-dependant potential in the lab reference frame is expressed by

$$U(\vec{r},t) = U(x - b\cos\Omega t, y - b\sin\Omega t)\,, \tag{2}$$

where $\vec{r} \equiv (x,y)$ is the displacement from the origin O, b is the distance from the trap center to the rotation axis, and Ω is the rotational angular frequency. The equation of motion of an atom in such a rotating potential is

$$m\frac{d^2}{dt^2}\vec{r} = -\beta\frac{d}{dt}\vec{r} - \nabla U(\vec{r},t) \tag{3}$$

where m is the mass of the particle, and β is the damping coefficient. To simulate the physics of a rotating MOT, we numerically investigate a rotating Gaussian-shape trap that has a finite trapping size σ. This trap is modeled as

$$U(x,y;t) = -\frac{1}{2}m\omega^2\sigma^2 Exp\left[-\frac{1}{\sigma^2}\left((x-b\cos\Omega t)^2 + (y-b\sin\Omega t)^2\right)\right] \tag{4}$$

where ω is the local trapping frequency at the trap. Its time-averaged effective potentials are plotted in Fig. 5. When the rotation radius is smaller than the trapping size, i.e., $b/\sigma \le 1$, there is an effective central attractive potential. However, as the rotation radius becomes larger than the trapping size, i.e., $b/\sigma > 1$, the effective central attractive potential disappears.

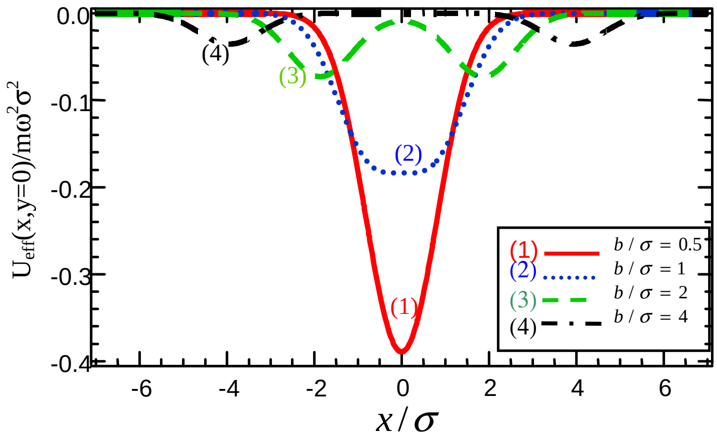

Fig. 5. Time-averaged effective potential of a rotating Gaussian-shape trap along x axis with different rotating radius: (1) $b/\sigma = 0.5$, (2) $b/\sigma = 1$, (3) $b/\sigma = 2$, and (4) $b/\sigma = 4$.

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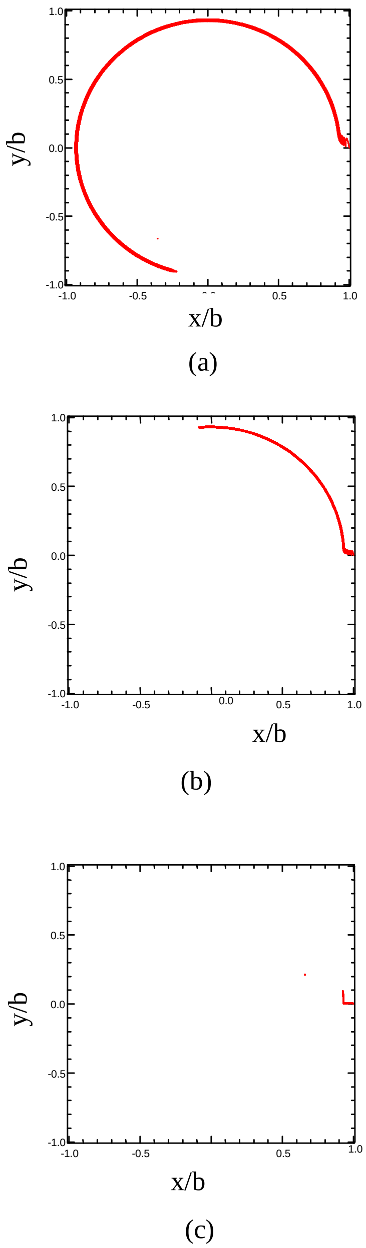

Fig. 6. The motion orbit of an atom in a rotating Gaussian-shape trap starting from the initial position (b , 0) with the following parameters: Γ/ω=4, σ/b =1/2, and total time of Δt=6,000/ω. (a) Ω/ω=0.5, (b) Ω/ω=1, (c) Ω/ω=4.

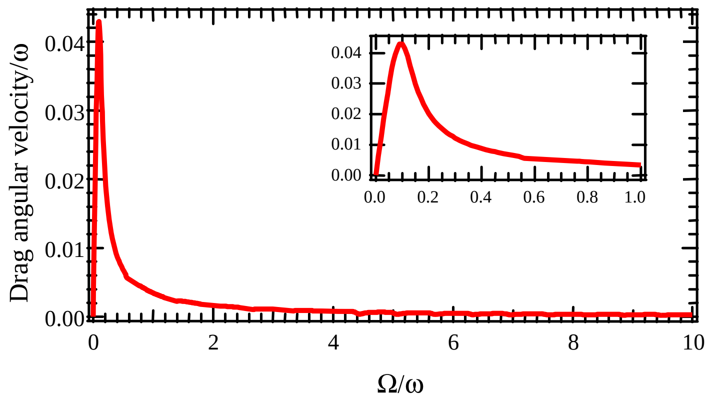

Fig. 7. The drag angular velocity vs. rotation frequency of an atom in a rotating Gaussian-shape trap starting from the initial position (b, 0) with the following parameters: $\Gamma/\omega=4$, $\sigma/b=1/2$.

Figure 5 also shows an interesting phenomenon for a rotating trap with $b/\sigma > 1$. Under these conditions, the atoms see an effective ring-shaped static trapping potential when the rotation frequency is high ($\Omega \gg \omega$). In Fig. 6, we plot the orbit of an atom starting from the initial position (b, 0) with the following parameters: $\Gamma/\omega = 4$, $b/\sigma = 1/2$, and total time of $\Delta t=6{,}000/\omega$. As the rotation frequency Ω increases, the atoms move less along the rotation direction. Therefore, the velocity with which the atoms are dragged along with the trap indeed decreases with increasing the rotation frequency. We plot this drag velocity in Fig. 7 as a function of the rotational speed. When this drag velocity approaches the same order as the atom's thermal velocity, the atoms can experience an effective static ring trap.

5. Conclusion

We have demonstrated a trap which allows easy manipulation of cold atoms. Specifically, the off axis rotating trap is an interesting effect with possible extensions to ring-based atom interferometry and rotation sensors of the future. Research involving the development of rotational sensors must investigate the dynamics of moving potentials. The rotational speed in our experiment was ramped up to 60 Hz and the effects of atom loading and loss will be studied in the our future experiment. Experimentally, ascertaining the varying temperature of the MOT in rotation is somewhat difficult and is being planned for in-dept experiment using absorption imaging technique. Furthermore, theoretical studies of the dynamics of moving potentials suggest that a very fast rotating MOT is an excellent system for measuring ultra high speed rotations. This technology could also have direct application in coupling cold atoms into hallow core fibers.

This initial report of fast rotating MOT is a result in coming up with a configuration which allows total freely moving MOT without the need for current carrying magnetic waveguides. The system is a multiple parameter dependent dynamic system and has great potential for studying the damping and spring constant dependence of the motion of the MOT as well as temperature variation which results by such motion.

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