Versatile two-dimensional potentials for ultra-cold atoms

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Abstract: We propose and investigate a technique for generating smooth two-dimensional potentials for ultra-cold atoms based on the rapid scanning of a far-detuned laser beam using a two-dimensional acousto-optical modulator (AOM). We demonstrate the implementation of a feed-forward mechanism for fast and accurate control of the spatial intensity of the laser beam, resulting in improved homogeneity for the atom trap. This technique could be used to generate a smooth toroidal trap that would be useful for static and dynamic experiments on superfluidity and persistent currents with ultra-cold atoms.

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1. Introduction

Before the experimental realization of Bose-Einstein condensation (BEC) [1], the phenomenon of superfluidity was studied almost exclusively in the context of superfluid helium [2]. One of the theoretical difficulties with this system is that liquid helium is not dilute, and so making progress with microscopic theory is troublesome. In contrast, interactions in dilute Bose-condensed gases are weak, which enables accurate modeling of these quantum many-body systems, both with the mean-field Gross-Piteavskii equation, and with more advanced quantum simulation techniques. Combined with the flexibility of experiments on ultra-cold atoms, it seems that dilute gas BECs are potentially useful systems to further develop our understanding of superfluidity.

A number of experiments probing the superfluidity of condenstates have been performed. Raman *et al.* provided evidence of a critical velocity by moving a tightly focussed blue-detuned laser through a trapped condensate and found that above a certain speed there was significant heating [3]. Marago *et al.* [4] observed that a single frequency irrotational scissors mode excitation existed in a BEC, as compared with two thermal modes with different frequencies above the critical temperature. The observation of vortices [5] and vortex lattices [6] also provides evidence of the superfluidity of a BEC.

An important consequence of superfluidity is the phenomenon of persistent currents, where fluid flow in a multiply connected potential exhibits no measurable dissipation. For example, in 1964 Reppy and Depatie were able to set up a flow of superfluid helium in a torus shaped vessel that showed no reduction in angular momentum over a 12 hour period [7]. Performing similar experiments with a Bose-Einstein condensate could be expected to provide useful information about the superfluid behavior of these systems.

The observation of persistent currents with a BEC requires the construction and loading of a toroidal shaped trap. A large number of theoretical papers on BEC in toroidal traps have been written over the last ten years, and a number of proposals and demonstrations of ring traps have been described in the literature. These include magnetic traps [8, 9, 10], rf-dressing [11] and optical methods using spatial light modulators [12]. Most of these traps tend to be large, which would give increased sensitivity for e.g. Sagnac interferometry, but are problematic for the study of superfluidity. In particular it is difficult to ensure homogeneity of the potential over a large area, or form a multiply-connected condensate delocalized over the entire ring structure. Significantly, Ryu *et al.* [13] recently reported the first observation of a persistent current in a

multiply-connected BEC in a magnetic trap plugged with an optical dipole potential. However, the lifetime of the superflow was limited to 10 s due to a drift of the magnetic trap relative to the dipole potential, and the trap depth varied about the the torus (although the variation was less than the chemical potential of the BEC.) For a careful study of superfluidity it is desirable for the toroidal trap to have a constant potential depth about the entire ring, with fluctuations much smaller than the chemical potential.

By spatially scanning a focussed laser beam at a frequency much higher than the atoms can respond to, a range of time-averaged 2D potential geometries can be created. This procedure is similar of the original Time Orbiting Potential (TOP) trap developed by Petrich *et al.* in the original quest for BEC [14]. A number of time-averaged traps have been realized in the past, in particular [15, 16, 17] who used blue-detuned beams for trapping thermal atoms and [18] who scanned their CO_2 to increase the volume of capture in the transfer of their atoms from their MOT to dipole trap. Recently, Lesanovsky *et al.* [19] proposed a time averaging procedure for adiabatic rf potentials and magnetic fields to generate a smooth 3D ring trap for atoms; however this is yet to be realized in practise.

In this work we propose a versatile, all-optical trap based on a fast-scanning laser beam using a two-dimensional acousto-optical modulator (AOM). We focus in particular on generating a smooth toroidal trap, and we show that that using a feed-forward system we can produce a relatively small and homogeneous ring potential suitable for experiments concerning superfluidity. Moreover, we show that this system is a versatile tool for producing basically any 2D static or dynamical potential. Trapping in the third dimension perpendicular to the ring can be provided, for example, by a light sheet provided by a second laser, resulting in a fully three-dimensional trap for ultra-cold atoms.

2. Theory of a ring trap

Ultra-cold atoms may be confined in a conservative all-optical potential using a focused laser beam that is sufficiently far detuned from the atomic transition so as to prevent spontaneous emission. For a static laser beam with spatial intensity $I(\vec{r})$ and detuning $\Delta = \omega_L - \omega_A$ from the optical transition frequency ω_A, the optical dipole potential is given by

$$U(\vec{r}) \approx \frac{3\pi c^2}{2\omega_A^3} \frac{\Gamma}{\Delta} I(\vec{r}) \tag{1}$$

for large detunings [20]. When such a beam is scanned sufficiently fast in a periodic manner, the dipole potential should be time-averaged over one cycle. For a beam with a two dimensional intensity profile $I(x,y) = \frac{2P}{\pi w^2} \exp\left(\frac{-2(x^2+y^2)}{w^2}\right)$ scanned in a ring with radius a, the resulting radial dependent average intensity is

$$I(r) = \frac{4P}{w^2} \exp\left(\frac{-2(r^2+a^2)}{w^2}\right) \mathscr{I}_0(\zeta), \tag{2}$$

where $\mathscr{I}_0(\zeta)$ denotes the modified zeroth-order Bessel function with $\zeta = 4ar/w^2$ and w the beam waist of the focused beam trap. The trap minimum occurs at $r = a$, and has a radial trapping frequency of

$$\omega_r = \sqrt{\frac{2\kappa}{m} P \exp(-\frac{4a^2}{w^2}) \left[\frac{64a^2}{w^6}(\mathscr{I}_0(\zeta) - \mathscr{I}_1(\zeta)) - \frac{8}{w^4}(\mathscr{I}_0(\zeta) - \mathscr{I}_1(\zeta))\right]}, \tag{3}$$

with $\mathscr{I}_n$ the modified n-th order Bessel functions and $\kappa = -\frac{3\pi c^2}{2\omega_A^3} \frac{\Gamma}{\Delta}$. We find that $\omega_r \propto 1/\sqrt{a}$ for $a > w$ (Fig. 1).
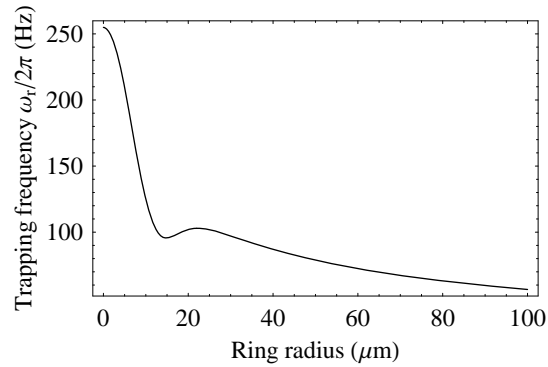
Fig. 1. Trapping frequencies as a function of ring size for a beam waist of 25μm. The minimum in this plot shows the regime where the radius a of the ring is of the same size as the focus of the laser focus and the minimum of the potential in the center of the trap < 0.

3. Experimental setup and results

To create a ring potential an intensity locked, red-detuned laser beam is rapidly scanned in space using a two-dimensional AOM (IntraAction, DTD-274HD6), with two independent AOMs mounted perpendicularly with respect to the diffraction directions. The deflection angle of a beam in an AOM depends only on the frequency of the traveling radio frequency (rf) wave inside the crystal. Therefore, by modulating the rf frequencies that are fed into the crystals the beam can be scanned in arbitrary 2D patterns. These scanning frequencies are high compared to the trapping frequencies preventing the atoms from following the beam movement. Rapid scanning frequencies also prevent parametric heating that takes place close to the trapping frequencies and multiples thereof [21]. When changing the angle of deflection the diffraction efficiency of the AOM and therefore the intensity of the deflected beam varies. To create homogenous intensity distributions this variation needs to be compensated by controlling the rf power fed into the AOM. This is possible as the diffraction efficiency of an AOM is linear to the rf power driving it.

As the variation in intensity with deflection angle is deterministic, a feed forward technique is used to compensate for the intensity variation. A small amount of the trapping beam is split onto a photodiode to measure the power to control the light distribution, while the remainder of the beam is imaged on a CCD camera. The diameter of the photodiode is 800 μm, much bigger than the ring diameter. The photodiode is fast enough to resolve single scans of the beam thus creating an intensity profile of the ring. To compensate for the changes in diffraction efficiency the inverse of this intensity profile is then mixed with the rf signal driving one of the two AOMs and fed into this AOM (see Fig. 2).

Using this setup stable toroidal traps are created. For these traps the laser beam is focused down to a spot size of 25 μm and then scanned to create a ring radius of 44 μm. The scanning speed is 51 kHz, well above any of the resulting trapping frequencies. Using the feed forward technique described above, the intensity fluctuations about the ring are less than 1.5%. Here, we observed no correlation between the noise and the initial intensity fluctuations or the frequency modulation of the rf. We therefore conclude that the remaining noise level is due to electronic noise. Further analysis shows that for our setup the noise was limited by the noise of the photo diode. In principle, the limit in intensity stability of the this method is only restricted to the initial laser fluctuation and the accuracy of the rf synthesizer and electronics, which is better than typically 10^{-3}. The 2D AOM operates at relatively low efficiency/rf-power, where the
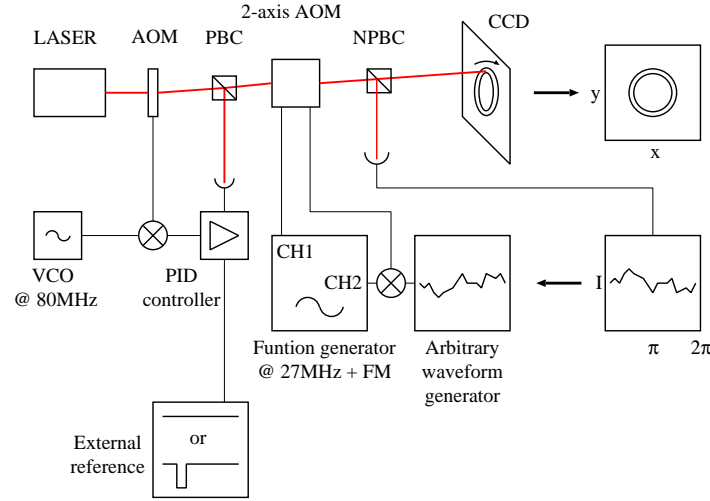
Fig. 2. Feed-forward technique to cancel the effect of different diffraction efficiencies depending on the angle of deflection. When the intensity locked laser beam is scanned it is imaged on a CCD camera and some part of it is deflected onto a photo diode. The photo diode gives an intensity profile that is then inverted and mixed with the rf signal that drives the AOM. Extra modulations of the intensity over the ring can be accomplished with an additional signal to the intensity lock.

deflected laser power is linearly proportional with the rf-power. It should be noted that using a feedback system would be preferential, but electronically far more complicated, as this would require a relatively high frequency feedback system.

To study superfluidity with a BEC, it is desirable that the bottom of the ring potential should be as smooth as possible. Therefore, the spatial intensity distribution throughout the trap should be as homogenous as possible, and in particular fluctuations in trap depth should be much smaller than the chemical potential of the condensate. In the Thomas-Fermi approximation for a condensate in a ring trap with a trapping frequency of ω_z in the z direction we find

$$\mu = \hbar\sqrt{\omega_r\,\omega_z}\sqrt{\frac{3Na_s}{4a}}, \tag{4}$$

where $g = 4\pi\hbar^2 a_s/m$, m is the atomic mass and a_s is the the s-wave scattering length.

In the case of a trap with beam waist $w= 25$ μm, ring radius $a = 44$ μm, power $P = 5$ mW and at a wavelength of 1064 nm, this gives a trap depth of 479 nK, and a corresponding variation in trap depth of 7.2 nK. The trapping frequency in the radial direction of such a trap is $\omega_r = 2\pi \cdot 83$ Hz and assuming a trapping frequency in z-direction of $\omega_z = 2\pi \cdot 350$ Hz and $2 \cdot 10^5$ atoms in the BEC one gets a chemical potential of $\mu = 36$ nK. Comparing the chemical potential to the fluctuation of the trap depth one can easily see that this trap is a feasible tool for the investigation of superfluidity in degenerate gases.

In order to load a BEC into such a ring potential, we propose to start with a cloud of cold atoms created in a crossed dipole trap, consisting of a focussed laser beam and a sheet of light in the horizontal plane with respect to gravity, crossing the focus of the first laser beam. Atoms can be evaporated in such a trap close to or beyond T_c, after which the focus of the first beam can be rotated as described above with increasing amplitude and further evaporation can be applied. Alternatively, the cold atoms from the all-optical, static trap can be loaded instantaneously into an overlapping ring trap, as proposed by Wright *et al.* [22].
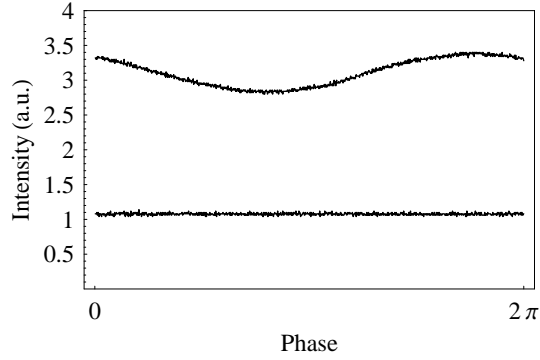
Fig. 3. Intensity profiles of the rings without (top curve) and with (bottom curve) feed-forward. Corresponding CCD images are shown in figure 5, where the first image shows the uncorrected and the second image the corrected ring.
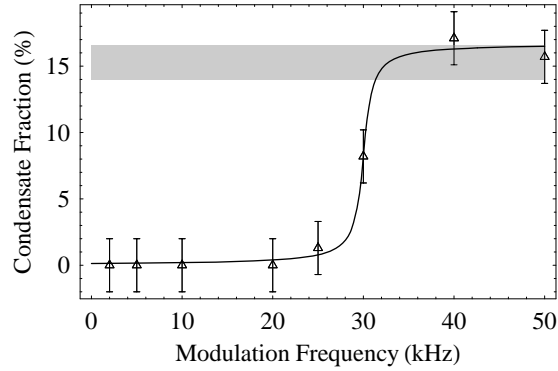

Fig. 4. Condensate fraction of a BEC in a magnetic trap with an optical dipole trap superimposed run with a 20% on/off duty cycle. Initial condensate fraction without dipole trap was 15.3% and is indicated in gray. The line through the data points acts only as a guide to the eye.

4. Time-averaged optical potential for a BEC

As described above, for the ring trap the rotation frequency of the beam has to be much higher than the trapping frequencies for the potential to be time-averaged and to prevent parametric heating. Consequently, an atom in this ring potential experiences an optical trap with a duty cycle of typically 20%.

To test the time-averaging effect of such a trap the following experiment was performed. A thermal cloud close to the critical temperature T_c was created in a cigar-shaped magnetic trap, with trapping frequencies of 160×6.8 Hz, on a chip [23] after which the trap was overlapped with a dipole trap with a beam waist of 11 μm crossing the middle of the long axis of the trap. For a dipole trap with a depth of 250 μK this results in the formation of a BEC with a 15.3% BEC fraction in equilibrium due to the change in the density of states [24]. Subsequently, the same experiment was performed where the intensity of the laser was increased by a factor of five but modulated with a duty cycle of 20% to ensure the same time-averaged trap depth. Figure 4 shows the condensate fraction as a function of the modulation frequency, showing that above a frequency of 30 kHz the condensate fraction approaches the same value as for a DC
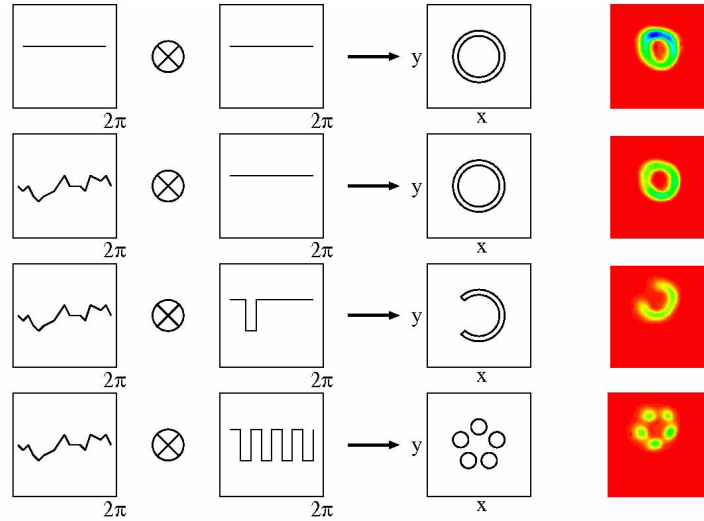
Fig. 5. Different possible waveforms for the function generator controlling the feed-forward technique and the function generator controlling the PID circuit and the resulting patterns. The top pattern shows a uniform distribution for both function generators resulting in a ring with non-uniform light distribution. For all the other cases the first generator is used to cancel the effects of different diffraction efficiencies and the second generator to create patterns of laser power leading to a uniform ring, horse shoe and ring lattice, respectively. The size of the images is 330 x 330μm.

optical trap (indicated with gray). The rotation frequencies in the presented ring trap is 51 kHz, with a maximum possible frequency of 100 kHz, and is therefore sufficiently high for the trap to be time-averaged when ultra-cold atoms close to T_c are considered.

5. Arbitrary and dynamic 2D potentials

As well as the correction signal, it is possible to add an extra modulation signal that is also synchronized with the rf-modulation frequency f_s. This results in a static and arbitrary intensity modulation on top of the 2D potential. For this we use the reference input of the intensity lock of the setup (PID circuit, see Fig. 2). To show the feasibility of this method to produce various other 2D trapping geometries, a horse shoe shape and a ring lattice with five lattice sites have been created and stabilized (Fig. 5).

To create 2D potentials that vary with time we can, for example, introduce a small difference in the frequency of the rf modulation and the frequency of the extra intensity modulation f_p in such a way that the pattern rotates with the difference of the two frequencies, $f_d = |f_s - f_p|$. In this manner, for example, a ring lattice can be slowly created with excellent control over all trapping parameters and could be used to initiate persistent currents as suggested in [12]. Another method of introducing angular momentum to the system would consist in a dip in laser power that is slowly moved around the ring to stir the BEC, similar to the technique used to stir a BEC with a blue detuned laser beam (e.g. [6]).

In a similar fashion we can arbitrarily adjust the shape and the depth of the potential as a function of time, where the spacial resolution is limited by the waist of the laser focus. The temporal resolution is merely limited by the ratio between size of the laser beam in the AOM-crystal and the sound of speed in the crystal or by the electronics used, which for both is better than 100 μs.

6. Conclusion

We have made use of a feed-forward technique to generate a new, versatile all-optical ring trap that should be suitable for the investigation of superfluidity and persistent currents in Bose-Einstein condensates. It could also be a suitable platform for interferometry and Josephson tunneling experiments [25]. This could lead to potential applications in the field of sensitive rotation sensors and SQUID-like devices. Our system enables us to arbitrarily control the depth and shape of the potential in an accurate and controlled manner. It could therefore be used to produce other 2D trapping geometries and is a useful tool for both static and dynamic experiments with degenerate gases.